National Aeronautics and Space Administration

SMALL BUSINESS

INNOVATION RESEARCH (SBIR)

AND

SMALL BUSINESS

TECHNOLOGY TRANSFER (STTR)

Fiscal Year 2021 General Solicitation

Opening Date: November 9, 2020
Closing Date and Time: January 8, 2021, 5:00 p.m. ET

Fiscal Year 2021 SBIR/STTR Solicitation Notable Changes and Helpful Reminders

Important Submission Reminder

Offerors are strongly encouraged to start the submission process early in order to allow sufficient time for completing their proposal package.

Section 6.3, Deadline for Phase I Proposal Receipt, states that "**A complete Phase I proposal package shall be received no later than 5:00 p.m. EST on Friday, January 8, 2021, via the NASA SBIR/STTR website (http://sbir.nasa.gov), under the Handbooks section."**

Section 6.4, Deadline for Phase II Proposal Receipt, states that **"A Phase II proposal package shall be received no later than 5:00 p.m. ET the last day of the Phase I contract original period of performance via the NASA SBIR/STTR website (http://sbir.nasa.gov) under the Handbooks section."**

Section 6.5, Acknowledgment of Proposal Receipt, states that NASA will acknowledge receipt of electronically submitted proposals upon endorsement by the Small Business Official to the Small Business Official's email address as provided on the proposal cover sheet, as well as to the user who created the proposal, if different. ***If a proposal acknowledgment is not received after submission, the offeror should immediately contact the NASA SBIR/STTR Program Support Office at 301-937-0888 or sbir@reisystems.com***."

An offeror who waits to submit a proposal near the deadline is at risk of not completing the required uploads and endorsements of their proposal. The Electronic Handbook (EHB) will terminate any active submissions at the published deadline of 5:00 p.m. ET on Friday, January 8, 2021, for Phase I offerors or at 5:00 p.m. ET the last day of the Phase I contract original period of performance for Phase II offerors. This termination will result in the offeror receiving an error message, and any remaining parts of the proposal will not be allowed to be uploaded or completed. Failure to complete all required uploads, including endorsements, as indicated in Section 6 of this solicitation will disqualify your proposal from consideration for a Phase I or Phase II contract award.

Introducing the Updated Technical and Business Assistance (TABA)

The John S. McCain National Defense Authorization Act for Fiscal Year 2019 permits SBIR and STTR Phase I and II awardees to enter into agreements with one or more vendors to provide Technical and Business Assistance (TABA). TABA allows an additional supplement to the award ($6,500 for Phase I awards and $50,000 for Phase II awards) and is aimed at improving the commercialization success of SBIR awardees. TABA may be obtained from entities such as public or private organizations, including an entity established or funded by a U.S. state that facilitates or accelerates the commercialization of technologies or assists in the creation and growth of private enterprises that are commercializing technology. TABA may include access to a network of scientists and engineers engaged in a wide range of technologies or access to technical and business literature available through online databases. This also includes product sales, intellectual property (IP) protections, market research, market validation, and development of regulatory plans and manufacturing plans.

For additional information on how to request TABA, please see sections 3.3.13 (Phase I) and 3.4.14 (Phase II), Request for Use of Technical and Business Assistance Funds.

Special Instructions for Phase II Submissions, Part 7: Commercialization and Business Planning

Offerors who submit a Phase II proposal will be required to provide a Commercialization and Business Plan, formerly known as the Commercialization Plan, and will be required to provide a minimum amount of information based on page-length requirements. See section 3.4.4, Part 7: Commercialization and Business Planning for additional information.

Firm Registrations and Certifications

NASA requires offerors to register with the Small Business Administration (SBA), register with System for Award Management (SAM) and also collects certifications from offerors at time of proposal, time of award, and during the lifecycle of the awarded project. These registrations and certifications have been included to match requirements found in the latest SBIR and STTR Policy Directives, located at https://www.sbir.gov/ and under the Federal Acquisition Regulations (FAR).

Offerors should review these requirements found in section "2. Registrations, Certifications and Other Proposal Information" of this solicitation in advance of submitting a proposal. Several of these registrations and certifications may take time to complete and should be completed well in advance of proposal submission.

There are two new certifications that offerors will be required to answer at the time of proposal submission. These are in section 2.3.1 FAR 52.204-24, Representation Regarding Certain Telecommunications and Video Surveillance Services or Equipment (August 2020) and 2.3.2 FAR 52.204-26 Covered Telecommunications Equipment or Services-Representation.

Many of these certifications will look similar to those you may have seen in the past from NASA's SBIR and STTR programs, but with some updated language. You will see one set of certifications twice—once at time of proposal and again at time if selected for an award. The purpose of presenting these certifications at time of proposal is to speed up the award timeline by preparing you for what will be asked of your company by the Contracting Officer at time of award.

Understanding the Patent Landscape

Offerors should indicate in the proposal that a comprehensive patent review has been completed to ensure that there is no existing patent or perceived patent infringement based on the innovation proposed. The U.S. Patent and Trade Office (USPTO) has an online patent search tool that can found at https://www.uspto.gov/patents-application-process/search-patents.

Suggested Page Limits

Within the technical proposal guidelines in sections 3.3.4 (Phase I) and 3.4.4 (Phase II) are suggested page limits for each part of the technical proposal to help you develop a balanced proposal. These are guidelines; they are not strict requirements. Offerors are still required to meet the total page limit requirements as described within this solicitation.

Moon to Mars Campaign

NASA's human lunar exploration plans under the Artemis program call for sending the first woman and next man to the surface of the Moon by 2024 and establishing sustainable exploration by the end of the decade. The agency will use what we learn on the Moon to prepare for humanity's next giant leap – sending astronauts to Mars.

Working with U.S. companies and international partners, NASA will push the boundaries of human exploration forward to the Moon and on to Mars and establish a permanent human presence there within the next decade to uncover new scientific discoveries and lay the foundation for private companies to build a lunar economy.

It all starts with U.S companies delivering scientific instruments and technology demonstrations to the lunar surface, followed by a spaceship, called the Gateway, in orbit around the Moon that will support human and scientific missions, and human landers that will take astronauts to the surface of the Moon. The agency's powerful Space Launch System rocket and Orion spacecraft will be the backbone to build the Gateway and transport astronauts to and from Earth. (See https://www.nasa.gov/topics/moon-to-mars/overview.)

Note: While the program is proud to note that many of our subtopics directly or indirectly support the Moon to Mars Campaign, there are many additional technology areas in this solicitation that are of equal importance to the Agency and the Nation. These include, but are not limited to, Aeronautics, Earth and Planetary (beyond Moon and Mars) Science, Heliophysics, and Astrophysics.

Rights in Data Developed Under SBIR Funding Agreements

The U.S. Small Business Administration (SBA) has adopted a 20-year protection period for appropriately marked SBIR/STTR Data, and SBA intends that this much longer, finite protection period, even with the elimination of extensions to such period, will preserve the incentives for small business concerns (SBCs) to participate in the SBIR/STTR programs. SBA is confident that 20 years will be sufficient to provide data rights protection during the entire development and commercialization process for most technologies in most industries that participate in the SBIR/STTR programs. Additionally, the adoption of a 20-year protection period provides greater consistency with the 20-year protection period that the Government provides for patents issued by the U.S.P.T.O. For a detailed explanation of the data rights, see section 5.7, Rights in Data Developed Under SBIR Funding Agreements.

Space Technology Roadmap Technology Areas (TAs) versus the New NASA Technology Taxonomy

The 2020 NASA Technology Taxonomy is part of an evolution that began with technology roadmaps and the Technology Area Breakdown Structure (TABS) drafted in 2010, followed by updates in 2012 and 2015. The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is composed of 17 distinct technical-discipline-based Taxonomies (TXs) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area, which is the title of that area. Level 2 is a list of the subareas. The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments.

Effective with this solicitation, the subtopics will reference the new Technology Taxonomy in both the subtopic write-ups and also in the summary found in Appendix B: SBIR/STTR and the NASA Technology Taxonomy. The 2015 NASA Technology Roadmaps will be archived and remain accessible for reference via their current internet address (https://www.nasa.gov/offices/oct/home/roadmaps/index.html) as well as via the new 2020 NASA Technology Taxonomy (https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf).

Pointers to Assist You in Finding the Appropriate Subtopic

Subtopic pointers are used to indicate subtopics that are asking for related technologies. Where applicable, these pointers will appear in the subtopic headers to assist proposers with identifying those related subtopics that potentially seek related technologies for different customers or applications. Pointers in conjunction with the focus area listings of subtopics will make it easier for proposers to find all subtopics that may be of interest.

Civilian Commercialization Readiness Pilot Program (CCRPP) Is Back for 2021

CCRPP is an additional funding opportunity available to small businesses with the purpose of accelerating the transition of SBIR- and STTR-funded technologies to commercialization. The funding is a combination of additional SBIR/STTR program investment and NASA or non-NASA entity investment. The program will match between $500,000 and $3 million of external investment. The primary objective of the NASA CCRPP is an infusion or commercialization, not an incremental improvement in technology maturation alone. Technology maturation without infusion or commercialization will not be accepted for CCRPP. For additional information, please see https://sbir.nasa.gov/content/post-phase-ii-initiatives#CCRPP.

Intern Supplement Pilot (at Phase II)

The NASA SBIR/STTR program is planning to pilot an initiative focused on improving the competitiveness and growing the markets of the small businesses that support the U.S. aerospace industry. The goals of this initiative include workforce development, which would be accomplished through student internships paid for by the SBIR/STTR program in support of Phase II awardees. The interns may have NASA work experience and have indicated their career goals are in line with non-Government and nonacademic careers, with an interest in entrepreneurship. Firms will have the opportunity to indicate interest as part of their 2021 SBIR/STTR Phase II proposal. The pool of interns would be provided by NASA, and firms that choose to opt in will be encouraged to support intern diversity, including military veterans.

Contents

1. Program Description

1.1 Introduction

This document includes instructions for two NASA program solicitations with separate subtopics under which small business concerns (SBCs) are invited to submit proposals: the Small Business Innovation Research (SBIR) program and the Small Business Technology Transfer (STTR) program. While the SBIR and STTR subtopics appear in an integrated list in Chapter 9, each subtopic will indicate its program of origin. Program background information, eligibility requirements for participants, information on the three program phases, and information for submitting responsive proposals are contained herein. The fiscal year 2021 solicitation period for Phase I proposals begins on November 9, 2020, and ends at 5 p.m. ET on January 8, 2021.

Note: The NASA SBIR/STTR program does not allow switching from STTR to SBIR, or vice versa, after proposal submission, during the award period of performance, or between Phase I and Phase II.

The NASA SBIR and STTR programs do not fund proposals solely directed toward system studies, market research, routine engineering, development of existing product(s), proven concepts, or modifications of existing products without substantive innovation.

It is anticipated that some SBIR and STTR Phase I proposals will be selected for negotiation of firm-fixed-price contracts approximately during the month of March 2021. Historically, 24 percent of SBIR Phase I proposal submissions receive awards, while 35 percent of STTR Phase I proposals receive awards. About 41 percent of the completed Phase I projects receive funding for Phase II development.

Under this solicitation, NASA will not accept more than 10 proposals to each program from any one firm (20 total) in order to ensure the broadest participation of the small business community. NASA does not plan to award more than 5 SBIR contracts and 2 STTR contracts (7 total) to any offeror. See section 3.1.

Offerors may only submit one Phase II proposal per Phase I award. See section 3.4.1.

Proposals, including all relevant documentation, must be submitted online via the Proposal Submissions Electronic Handbook at http://sbir.nasa.gov. Unsolicited proposals will not be accepted.

1.2 Program Management and Alignment

The Space Technology Mission Directorate (STMD) provides overall policy direction for implementation of the NASA SBIR/STTR programs. The NASA SBIR/STTR Program Management Office (PMO), which operates the programs in conjunction with NASA mission directorates and centers, is hosted at the NASA Ames Research Center. NASA Shared Services Center (NSSC) provides the overall procurement management for the programs.

For the SBIR program, NASA research and technology areas to be solicited are identified annually by the Agency's mission directorates. The directorates identify high-priority research problems and technology needs for their respective programs and projects. The range of problems and technologies is broad, and the list of topics and subtopics varies in content from year to year to maintain alignment with current interests.

The STTR program is aligned with the priorities of NASA's 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework as well as the associated core competencies of the NASA centers.

Again, the range of technologies is broad, and the list of topics and subtopics varies in content from year to year to maintain alignment with current interests.

For information regarding the mission directorates and the NASA centers, see section 7.1.

For details on the research subtopic descriptions by Focus Area, see section 9.

1.3 Three-Phase Program

Both the SBIR and STTR programs are divided into three funding and development stages. These three phases are described in detail on the NASA SBIR/STTR website: http://sbir.nasa.gov/content/nasa-sbirsttr-basics.

Phase I and II

Maximum value and period of performance for Phase I and Phase II contracts:

Phase I Contracts	**SBIR**	**STTR**
Maximum Contract Value	$125,000	$125,000
Period of Performance	6 months	13 months
Phase II Contracts	**SBIR**	**STTR**
Maximum Contract Value	$750,000	$750,000
Maximum Period of Performance	24 months	24 months

Post-Phase II Opportunities for Continued Technology Development

The NASA SBIR/STTR program has two initiatives for supporting its small business partners beyond the basic Phase II award. These are the Phase II Extended (Phase II-E) contract option and the Civilian Commercialization Readiness Pilot Program (CCRPP) contract.

Please refer to http://sbir.nasa.gov/content/post-phase-ii-initiatives for eligibility, application deadlines, matching requirements and further information.

Phase III

Phase III is the commercialization of innovative technologies, products, and services resulting from either a Phase I or Phase II contract. This includes further development of technologies for transition into NASA programs, other Government agencies, or the private sector. Phase III contracts are funded from sources other than the SBIR and STTR programs and may be awarded without further competition.

Please refer to https://sbir.nasa.gov/content/post-phase-ii-initiatives#Phase-III for Phase III information.

1.4 Availability of Funds

All Phase I, Phase II, and post-Phase II awards are subject to availability of funds. NASA has no obligation to make any specific number of awards based on this solicitation and may elect to make several or no awards in any specific technical topic or subtopic.

1.5 Eligibility Requirements

1.5.1 Small Business Concern (SBC)

To receive SBIR/STTR funds, each awardee of a Phase I or Phase II award must qualify as an SBC at the time of award and at any other time set forth in SBA's regulations at 13 Code of Federal Regulations (CFR) 121.701-121.705.

Each Phase I and Phase II awardee must submit a certification stating that it meets the size, ownership, and other requirements of the SBIR or STTR program at the time of proposal submission, award, and at any other time set forth in SBA's regulations at 13 CFR 121.701-121.705. Socially and economically disadvantaged and women-owned SBCs are particularly encouraged to propose.

1.5.2 Place of Performance

Research/Research & Development (R/R&D) must be performed in the United States (see http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions). However, based on a rare and unique circumstance (for example, if a supply, material, or other item or project requirement is not available in the United States), NASA may allow a particular portion of the research or R&D work to be performed or obtained in a country outside of the United States. Proposals must clearly indicate if any work will be performed outside the United States, including subcontractor performance, and justification must be provided. Prior to award, approval by the Contracting Officer for such specific condition(s) must be in writing.

Note: NASA will not approve purchases from or work with countries that appear on the list of Designated Countries. For reference, please see https://www.nasa.gov/sites/default/files/atoms/files/designated_country_list_7-30-20.pdf.

1.5.3 Principal Investigator (PI) Employment Requirement

The primary employment of the Principal Investigator (PI) shall be with the SBC under the SBIR program, while under the STTR program, either the SBC or Research Institution (RI) shall employ the PI. Primary employment means that more than 50 percent of the PI's total employed time (including all concurrent employers, consulting, and self-employed time) is spent with the SBC or RI at time of award and during the entire period of performance. Primary employment with an SBC precludes full-time employment at another organization. If the PI does not currently meet these primary employment requirements, then the offeror must explain how these requirements will be met if the proposal is selected for contract negotiations that may lead to an award. Co-Principal Investigators are not allowed.

Note: NASA considers a full-time workweek to be nominally 40 hours and considers a 19.9-hour or more workweek elsewhere to be in conflict with this rule. In rare occasions, minor deviations from this requirement may be necessary; however, any minor deviation must be approved in writing by the Contracting Officer after consultation with the NASA SBIR/STTR Program Manager/Business Manager.

Requirements	SBIR	STTR
Primary Employment	PI shall be primarily employed with the SBC	PI shall be primarily employed with the RI or SBC
Employment Certification	The offeror must certify in the proposal that the primary employment of the PI will be with the SBC at the time of	The offeror must certify in the proposal that the primary employment of the PI will be with the SBC or the RI at the time

	award and during the conduct of the project	of award and during the conduct of the project
Co-PIs	Not allowed	Not allowed
Misrepresentation of Qualifications	Shall result in rejection of the proposal or termination of the contract	Shall result in rejection of the proposal or termination of the contract
Substitution of PIs	Requires a prior approval from NASA	Requires a prior approval from NASA

1.5.4 Restrictions on Venture-Capital-Owned Businesses

At the current time, small businesses owned in majority part by multiple venture capital operating companies, hedge funds, or private equity firms are not eligible to submit proposals to the NASA SBIR/STTR solicitation.

1.5.5 Joint Ventures and Limited Partnerships

Both joint ventures and limited partnerships are permitted, provided the entity created qualifies as an SBC in accordance with the definition of an SBC here: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. A statement of how the workload will be distributed, managed, and charged should be included in the proposal. A copy or comprehensive summary of the joint venture agreement or partnership agreement should be included on the Technical Proposal upload page.

1.5.6 Required Benchmark Transition Rate

The Phase I to Phase II transition rate requirement applies only to SBIR and STTR Phase I applicants that have received more than 20 (21 or more) Phase I awards over the past 5 fiscal years, excluding the most recent year. These companies must meet the required benchmark rate of transition from Phase I to Phase II. The current transition rate requirement, agreed upon and established by all 11 SBIR agencies and published for public comment at 77 FR 63410 in October 2012 and amended at 78 FR 30951 in May 2013, is that an awardee must have received an average of one Phase II for every four Phase I awards received during the most recent 5-year time period (which excludes the most recently completed fiscal year) to be eligible to submit a proposal for a new Phase I (or Direct-to-Phase II) award. That is, the ratio of Phase II to Phase I awards must be at least 0.25.

On June 1 of each year, the SBA assesses SBIR/STTR awardees using SBIR and STTR award information across all Federal agencies reported on www.sbir.gov to determine if they meet the benchmark requirements. Companies that failed to meet the transition rate benchmark on June 1, 2020, are not eligible to submit a Phase I proposal during the period June 1, 2020, through May 31, 2021. Companies were notified by the SBA if they failed to meet the benchmark and can find their status at any time on www.sbir.gov.

More information on the transition rate requirements is available at https://www.sbir.gov/faqs/performance-benchmarks.

1.6 NASA Technology Available (TAV) for SBIR/STTR Use

Offerors have the option of using technology developed by NASA (Technology Available (TAV)) related to the subtopic to which they are proposing. NASA has over 1,400 patents available for licensing in its portfolio, including many patents related to sensors and materials. NASA has over 1,000 available software codes/tools listed in its Software Catalog (https://software.nasa.gov). While NASA scientists and engineers conduct breakthrough research that leads to innovations, the range of NASA's effort does not extend to commercial product development in any of its intramural research areas. Additional work is often necessary to exploit these NASA technologies (TAVs) for either infusion or commercial viability and likely requires innovation on behalf of the private sector. These technologies can be searched via the NASA Technology Transfer Portal, http://technology.nasa.gov, and may be a NASA-owned patent and/or computer software. Use of a TAV requires a patent license or Software Usage Agreement (SUA) from NASA. TAVs are available for use during both Phase I and Phase II award periods, including any extensions. NASA provides these technologies "as is" and makes no representation or guarantee that additional effort will result in infusion or commercial viability.

Whether or not a firm proposes the use of a NASA patent or computer software within its proposed effort will not in any way be a factor in the selection for award.

Use of NASA Software

If an offeror intends to use NASA software, a Software Usage Agreement (SUA), on a nonexclusive, royalty-free basis, is necessary, and the clause at 48 C.F.R. 1852.227-88, Government-Furnished Computer Software and Related Technical Data, will apply to the contract. The SUA shall be requested from the appropriate NASA Center Software Release Authority (SRA), after contract award.

Use of NASA Patent

All offerors submitting proposals that include the use of a NASA patent must submit an application for a nonexclusive, royalty-free evaluation license. After firms have identified a patent to license in the NASA patent portfolio (http://technology.nasa.gov), a link on the patent webpage ("Apply Now to License this Technology") will direct them to NASA's Automated Licensing System (ATLAS) to finalize their license with the appropriate field center technology transfer office. The completed evaluation license application must be uploaded on the Electronic Handbook (EHB) Proposal Certifications page. Such grant of nonexclusive evaluation license will be set forth in the successful offeror's SBIR/STTR contract. The evaluation license will automatically terminate at the end of the SBIR/STTR contract. License applications will be treated in accordance with Federal patent licensing regulations as provided in 37 CFR Part 404.

In addition to an evaluation license, if the proposed work includes the making, using, or selling of products or services incorporating a NASA patent, successful awardees will be given the opportunity to negotiate a nonexclusive commercialization license or, if available, an exclusive commercialization license to the NASA patent. Commercialization licenses are also provided in accordance with 37 CFR Part 404.

An SBIR/STTR awardee that has been granted a nonexclusive, royalty-free evaluation license to use a NASA patent under the SBIR/STTR award may, if available and on a noninterference basis, also have access to NASA personnel knowledgeable about the NASA patent. Licensing Executives located at the appropriate NASA field center will be available to assist awardees requesting information about a patent that was identified in the SBIR/STTR contract and, if available and on a noninterference basis, provide access to the inventor or surrogate for the purpose of knowledge transfer.

Note: Access to the inventor for the purpose of knowledge transfer will require the requestor to enter into a Non-Disclosure Agreement (NDA) or other agreement, such as a Space Act Agreement. The awardee may be required to reimburse NASA for knowledge transfer activities. For Phase I proposals, this is a time-consuming process and is not recommended.

1.7 I-Corps™

The National Science Foundation (NSF) created the NSF Innovation Corps (I-Corps™) (hereinafter I-Corps) program to develop and nurture a national innovation ecosystem that builds upon fundamental research to guide the output of scientific discoveries closer to the development of technologies, products, and processes that benefit society. NSF's I-Corps training is designed to lower the market risk inherent in bringing a product or innovation to market, thereby improving the chances for a viable business.

The goals of the SBIR/STTR and the I-Corps programs overlap by encouraging the innovation and entrepreneurship of small businesses and enabling those businesses to commercialize their innovations. NASA's SBIR/STTR program releases solicitations for research and development that are of interest to NASA's mission directorates with the goal that the selected technologies will become a success by being transitioned, or infused, into a NASA program, or by commercial success outside of NASA and the Federal Government.

With this goal in mind, NASA, through the SBIR/STTR program, worked with NSF to implement a NASA-specific SBIR/STTR I-Corps program. The NASA I-Corps program enables small businesses, including startup firms, to increase the odds of accelerating the process of developing their SBIR/STTR technologies into a repeatable and scalable business model. The program accomplishes this by putting the firms through a version of the Lean Launchpad/I-Corps process, which includes:

- Developing their business model hypotheses using the Business Model Canvas.
- Testing those hypotheses through the Customer Development Interview process.

The intended results of I-Corps are to enable firms to conduct customer discovery to learn their customers' needs, to obtain a better understanding of their company's value proposition as it relates to those customer needs, and to develop an outline of a business plan for moving forward. For more information on the NASA I-Corps program, see http://sbir.nasa.gov/content/I-Corps. Offerors who are selected for Phase I contract negotiations will be provided the opportunity to participate in the NASA SBIR/STTR I-Corps program as indicated in section 3.3.6. I-Corps awards will be made separately from the Phase I contract as a training grant.

NASA will conduct an abbreviated competition for I-Corps after Phase I offerors are selected for Phase I SBIR and STTR contracts. NASA anticipates awarding a total of approximately 35 grants to SBIR and STTR Phase I awardees. The distribution is expected to be approximately 10 STTR teams and 25 SBIR teams. The amount of funding is up to $10,000 for the shortened version for SBIR firms, and $25,000 for the full I-Corps program for STTR firms.

The I-Corps program may be extended and offered to firms applying for SBIR/STTR Post-Phase II opportunities. Please refer to the NASA SBIR/STTR website to stay up to date on latest details: www.sbir.nasa.gov.

1.8 Technical and Business Assistance (TABA)

The John S. McCain National Defense Authorization Act for Fiscal Year 2019 permits SBIR and STTR Phase I and II awardees to enter into agreements with one or more vendors to provide Technical and Business Assistance (TABA). TABA allows an additional supplement to the award ($6,500 for Phase I awards and $50,000 for Phase II awards) and is aimed at improving the commercialization success of SBIR awardees. TABA may be obtained from entities such as public or private organizations, including an entity established or funded by a U.S. state that facilitates or accelerates the commercialization of technologies or assists in the creation and growth of private enterprises that are commercializing technology.

In accordance with the Small Business Act, NASA may authorize the recipient of a NASA Phase I or Phase II SBIR/STTR award to purchase technical and business assistance services through one or more outside vendors.

These services may, as determined appropriate, include access to a network of non-NASA scientists and engineers engaged in a wide range of technologies, assistance with product sales, intellectual property protections, market research, market validation, and development of regulatory plans and manufacturing plans, or access to technical and business literature available through online databases, for the purpose of assisting such concerns in

1. Making better technical decisions concerning such projects;
2. Solving technical problems that arise during the conduct of such projects;
3. Minimizing technical risks associated with such projects; or
4. Commercializing new commercial products and processes resulting from such projects, including intellectual property protections.

For information on how to request TABA, please see sections 3.3.13 (Phase I) and 3.4.14 (Phase II), Request for Use of Technical and Business Assistance Funds. Technical and business assistance does not count toward the maximum award amount of your Phase I or Phase II contract. Approval of technical and business assistance is not guaranteed and is subject to review by the Contracting Officer. A description of any technical and business assistance obtained under this section and the benefits and results of the technical or business assistance provided will be a required deliverable of your contract.

1.9 NASA Mentor-Protégé Program (MPP)

The purpose of the NASA Mentor-Protégé Program (MPP) is to provide incentives to NASA contractors, performing under at least one active approved subcontracting plan negotiated with NASA, to assist protégés in enhancing their capabilities to satisfy NASA and other contract and subcontract requirements. The NASA MPP, established under the authority of Title 42, United States Code (U.S.C.) 2473(c)(1) and managed by the Office of Small Business Programs (OSBP), includes an Award Fee Pilot Program. Under the Award Fee Pilot Program, a mentor is eligible to receive an award fee at the end of the agreement period based upon the mentor's performance of providing developmental assistance to an active SBIR/STTR Phase II contractor in a NASA Mentor-Protégé agreement (MPA).

The evaluation criterion is based on the amount and quality of technology transfer and business development skills that will increase the protégé's Technology Readiness Levels (TRLs). TRLs measure technology readiness on a scale of 1 to 9. A mentor should attempt to raise the TRL of the protégé and outline the goals and objectives in the MPA and the award fee plan. A separate award fee review panel set up by NASA OSBP will use the semiannual reports, annual reviews, and the award fee plan in order to determine the amount of award fee given at the end of the performance period of the agreement.

For more information on the Mentor-Protégé Program, please visit http://www.osbp.nasa.gov/mpp/index.html.

1.10 Intern Supplement Pilot (at Phase II)

NASA is planning to pilot an Intern Supplement program with the goal of supporting workforce development for technology companies. This will be accomplished through student internships paid for by the SBIR program during the period of performance of Phase II awards. Firms will have the opportunity to indicate interest as part of their 2021 SBIR Phase II proposal. The pool of interns will be provided by NASA, and firms that choose to opt in will be encouraged to support intern diversity, including military veterans.

1.11 NASA Procurement Ombudsman Program

The NASA Procurement Ombudsman Program is available under this solicitation as a procedure for addressing concerns and disagreements concerning the terms of solicitation, the processes used for evaluation of proposals, or any other aspect of the SBIR/STTR procurement. The clause at NASA Federal Acquisition Regulation (FAR) Supplement (NFS) 1852.215-84 ("Ombudsman") is incorporated into this solicitation.

The cognizant ombudsman is:

William Roets
Deputy Assistant Administrator for Procurement
Office of Procurement
NASA Headquarters
Washington, DC 20546-0001
Telephone: 202-358-4483
Fax: 202-358-3082
Email: hq-dl-op-Agency-Procurement-Ombudsman@nasa.gov

Offerors are advised that, in accordance with NFS 1852.215-84, the ombudsman does not participate in any way with the evaluation of proposals, the source selection process, or the adjudication of formal contract disputes. Therefore, before consulting with the ombudsman, offerors must first address their concerns, issues, disagreements, and/or recommendations to the Contracting Officer for resolution. Offerors are further advised that the process set forth in this solicitation provision (and codified at NFS 1852.215-84) does not augment their right to file a bid protest or otherwise toll or elongate the period in which to timely file such a protest.

1.12 General Information

1.12.1 Means of Contacting NASA SBIR/STTR Program

1. NASA SBIR/STTR website: http://sbir.nasa.gov

2. Help Desk: The NASA SBIR/STTR Help Desk can answer any questions regarding clarification of proposal instructions and any administrative matters. The Help Desk may be contacted by:

    a. Email: sbir@reisystems.com
    b. Telephone: 301-937-0888, Monday to Friday between 9 a.m. and 5 p.m. ET
    c. The requestor must provide the name and telephone number of the person to contact, the organization name and address, and the specific questions or requests.

1.12.2 Questions About This Solicitation

To ensure fairness, questions relating to the intent and/or content of research topics in this solicitation cannot be addressed during the open solicitation period. Only questions requesting clarification of proposal instructions and administrative matters will be addressed.

The cutoff date and time for receipt of Phase I solicitation procurement-related questions and answers is January 1, 2021, at 5:00 p.m. ET.

The cutoff date and time for receipt of Phase II solicitation procurement-related questions and answers is 7 calendar days prior to the end of the Phase I contract.

1.12.3 NASA Electronic Handbook (EHB)

NASA uses the EHB for all proposal submissions. See section 6 for more information.

1.13 Definitions

A comprehensive list of definitions related to the SBIR and STTR programs is available at http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. These definitions include those from the SBIR and STTR policy directives as well as terms specific to NASA. Offerors are strongly encouraged to review these prior to submitting a proposal.

2. Registrations, Certifications and Other Proposal Information

2.1 Small Business Association (SBA) Firm Registry

All SBCs that are submitting an application to any SBIR solicitation are required to register with the SBIR Firm Registry. In addition, all SBCs must update their commercialization status through the SBIR Firm Registry. Information related to the steps necessary to register with the SBIR Firm Registry can be found at https://www.sbir.gov/registration.

Each SBC applying for a Phase II award is required to update its commercialization information on the SBA Firm Registry for all its prior Phase II awards. Phase II applicants must have updated their information and commercialization status no more than 6 months prior to the date of a proposal submission.

After an SBC registers with SBA or updates their commercialization information, the offeror must submit a portable document format (PDF) document of the registration and any required certifications with its application following the directions in the EHB.

In the NASA SBIR/STTR Proposal Submissions Electronic Handbook (EHB), the SBC must provide their unique SBC Control ID (assigned by SBA upon completion of the Company Registry registration) and must upload the PDF document validating their registration. This information is submitted to NASA via the Firm Certifications form and is applicable across all proposals submitted by the SBC for that specific solicitation.

2.2 System for Award Management (SAM) Registration

Offerors should be aware of the requirement to register in SAM prior to selection for award.

Note: To avoid a potential delay in contract award, offerors are required to register prior to submitting a proposal. To be eligible for SBIR/STTR awards, firms must be registered under the applicable North American Industry Classification System (NAICS) code. SBIR/STTR Phase I and II awards use NAICS codes 541713 or 541715. Offerors who are not registered should consider applying for registration immediately upon receipt of this solicitation. Offerors and contractors may obtain information on SAM registration and annual confirmation requirements at https://www.sam.gov/SAM/pages/public/index.jsf ***or by calling 866-606-8220. SAM registration and updates to SAM registration have required a processing period of several weeks.***

SAM is the primary repository for contractor information required for the conduct of business with NASA. It is maintained by the Department of Defense. To be registered in SAM, all mandatory information, which includes the Data Universal Numbering System (DUNS) or DUNS+4 number and a Commercial and Government Entity (CAGE) code, must be validated in SAM.

- The DUNS number is a 9-digit number assigned by Dun and Bradstreet Information Services to identify unique business entities. The DUNS+4 is similar but includes a 4-digit suffix that may be assigned by a parent (controlling) business concern. To obtain a DUNS number, please follow instructions at http://www.dnb.com.
- The CAGE code is assigned by the Defense Logistics Information Service (DLIS) to identify a commercial or Government entity. If an SBC does not have a CAGE code, one will be assigned during the SAM registration process.

Note: It is recommended to list Purpose of Registration as "All Awards" on your SAM Registration.

2.3 Federal Acquisition Regulation (FAR) Certifications

SAM contains required certifications offerors may access at https://www.acquisition.gov/browsefar as part of the required registration (see FAR 4.1102). Offerors must complete these certifications to be eligible for award.

Offerors should be aware that SAM requires all offerors to provide representations and certifications electronically via the website and to update the representations and certifications as necessary, but at least annually, to keep them current, accurate, and complete. NASA will not enter into any contract wherein the contractor is not compliant with the requirements stipulated herein.

2.3.1 FAR 52.204-24, Representation Regarding Certain Telecommunications and Video Surveillance Services or Equipment (August 2020)

The Offeror shall not complete the representation at paragraph (d)(1) of this provision if the Offeror has represented that it "does not provide covered telecommunications equipment or services as a part of its offered products or services to the Government in the performance of any contract, subcontract, or other contractual instrument" in the provision at FAR 52.204-26, Covered Telecommunications Equipment or Services—Representation, or in paragraph (v) of the provision at FAR 52.212-3, Offeror Representations and Certifications—Commercial Items.

(a) *Definitions.* As used in this provision—
Backhaul, covered telecommunications equipment or services, critical technology, interconnection arrangements, reasonable inquiry, roaming, and substantial or essential component have the meanings provided in the clause FAR 52.204-25, Prohibition on Contracting for Certain Telecommunications and Video Surveillance Services or Equipment.

(b) *Prohibition*.
(1) Section 889(a)(1)(A) of the John S. McCain National Defense Authorization Act for Fiscal Year 2019 (Pub. L. 115-232) prohibits the head of an executive agency on or after August 13, 2019, from procuring or obtaining, or extending or renewing a contract to procure or obtain, any equipment, system, or service that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. Nothing in the prohibition shall be construed to–

(i) Prohibit the head of an executive agency from procuring with an entity to provide a service that connects to the facilities of a third-party, such as backhaul, roaming, or interconnection arrangements; or
(ii) Cover telecommunications equipment that cannot route or redirect user data traffic or cannot permit visibility into any user data or packets that such equipment transmits or otherwise handles.

(2) Section 889(a)(1)(B) of the John S. McCain National Defense Authorization Act for Fiscal Year 2019 (Pub. L. 115-232) prohibits the head of an executive agency on or after August 13, 2020, from entering into a contract or extending or renewing a contract with an entity that uses any equipment, system, or service that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. This prohibition applies to the use of covered telecommunications equipment or services, regardless of whether that use is in performance of work under a Federal contract. Nothing in the prohibition shall be construed to—

(i) Prohibit the head of an executive agency from procuring with an entity to provide a service that connects to the facilities of a third-party, such as backhaul, roaming, or interconnection arrangements; or

(ii) Cover telecommunications equipment that cannot route or redirect user data traffic or cannot permit visibility into any user data or packets that such equipment transmits or otherwise handles.

(c) *Procedures.* The Offeror shall review the list of excluded parties in the System for Award Management (SAM) (https://www.sam.gov) for entities excluded from receiving federal awards for “covered telecommunications equipment or services”.

(d) *Representation.* The Offeror represents that—

(1) It □ will, □ will not provide covered telecommunications equipment or services to the Government in the performance of any contract, subcontract or other contractual instrument resulting from this solicitation. The Offeror shall provide the additional disclosure information required at paragraph (e)(1) of this section if the Offeror responds “will” in paragraph (d)(1) of this section; and

(2) After conducting a reasonable inquiry, for purposes of this representation, the Offeror represents that— It □ does, □ does not use covered telecommunications equipment or services, or use any equipment, system, or service that uses covered telecommunications equipment or services. The Offeror shall provide the additional disclosure information required at paragraph (e)(2) of this section if the Offeror responds “does” in paragraph (d)(2) of this section.

(e) *Disclosures.*

(1) Disclosure for the representation in paragraph (d)(1) of this provision. If the Offeror has responded “will” in the representation in paragraph (d)(1) of this provision, the Offeror shall provide the following information as part of the offer:

(i) For covered equipment—

(A) The entity that produced the covered telecommunications equipment (include entity name, unique entity identifier, CAGE code, and whether the entity was the original equipment manufacturer (OEM) or a distributor, if known);

(B) A description of all covered telecommunications equipment offered (include brand; model number, such as OEM number, manufacturer part number, or wholesaler number; and item description, as applicable); and

(C) Explanation of the proposed use of covered telecommunications equipment and any factors relevant to determining if such use would be permissible under the prohibition in paragraph (b)(1) of this provision.

(ii) For covered services—

(A) If the service is related to item maintenance: A description of all covered telecommunications services offered (include on the item being maintained: Brand; model number, such as OEM number, manufacturer part number, or wholesaler number; and item description, as applicable); or

(B) If not associated with maintenance, the Product Service Code (PSC) of the service being provided; and explanation of the proposed use of covered telecommunications services and any factors relevant to determining if such use would be permissible under the prohibition in paragraph (b)(1) of this provision.

(2) Disclosure for the representation in paragraph (d)(2) of this provision. If the Offeror has responded “does” in the representation in paragraph (d)(2) of this provision, the Offeror shall provide the following information as part of the offer:

(i) For covered equipment—

(A) The entity that produced the covered telecommunications equipment (include entity name, unique entity identifier, CAGE code, and whether the entity was the OEM or a distributor, if known);

(B) A description of all covered telecommunications equipment offered (include brand; model number, such as OEM number, manufacturer part number, or wholesaler number; and item description, as applicable); and

(C) Explanation of the proposed use of covered telecommunications equipment and any factors relevant to determining if such use would be permissible under the prohibition in paragraph (b)(2) of this provision.

(ii) For covered services—

(A) If the service is related to item maintenance: A description of all covered telecommunications services offered (include on the item being maintained: Brand; model number, such as OEM number, manufacturer part number, or wholesaler number; and item description, as applicable); or

(B) If not associated with maintenance, the PSC of the service being provided; and explanation of the proposed use of covered telecommunications services and any factors relevant to determining if such use would be permissible under the prohibition in paragraph (b)(2) of this provision.

2.3.2 FAR 52.204-26 Covered Telecommunications Equipment or Services-Representation.

As prescribed in 4.2105(c), insert the following provision:

COVERED TELECOMMUNICATIONS EQUIPMENT OR SERVICES-REPRESENTATION (DEC 2019)

(a) Definitions. As used in this provision, “covered telecommunications equipment or services” has the meaning provided in the clause 52.204-25, Prohibition on Contracting for Certain Telecommunications and Video Surveillance Services or Equipment.

(b) Procedures. The Offeror shall review the list of excluded parties in the System for Award Management (SAM) (https://www.sam.gov) for entities excluded from receiving federal awards for “covered telecommunications equipment or services”.

(c) Representation. The Offeror represents that it □ does, □ does not provide covered telecommunications equipment or services as a part of its offered products or services to the Government in the performance of any contract, subcontract, or other contractual instrument.

2.3.3 FAR 52.222-37 Employment Reports on Special Disabled Veterans, Veterans of the Vietnam Era, and Other Eligible Veterans

In accordance with Title 38, U.S.C., section 4212(d), the U.S. Department of Labor (DOL) Veterans' Employment and Training Service (VETS) collects and compiles data on the Federal Contractor Program Veterans' Employment Report (VETS-4212 Report) from Federal contractors and subcontractors who receive Federal contracts that meet the threshold amount of $150,000. The VETS-4212 reporting cycle begins annually on August 1 and ends September 30. Any Federal contractor or prospective contractor that has been awarded or will be awarded a Federal contract with a value of $150,000 or greater must have a current VETS-4212 report on file. Please visit the DOL VETS-4212 website at https://www.dol.gov/agencies/vets/programs/vets4212. NASA will not enter into any contract wherein the firm is not compliant with the requirements stipulated herein.

2.4 Certifications

Offerors must complete the Firm and Proposal Certifications section in the Electronic Handbook (EHB), answering “Yes” or “No” to certifications as applicable. Firms should carefully read each of the certification statements. The Federal Government relies on the information to determine whether the business is eligible for a SBIR or STTR program award. A similar certification will be used to ensure continued compliance with specific program requirements at time of award and during the life of the Funding Agreement. The definitions for the terms used in this certification are set forth in the Small Business Act, SBA regulations (13 CFR Part 121), the SBIR and STTR Policy Directives, and any statutory and regulatory provisions referenced in those authorities.

For Phase I awards, in addition to the final invoice certification and as a condition for payment of the final invoice, a life cycle certification shall be completed in the EHB. The life cycle certification is preset in the EHB, and it shall be completed along with the final invoice certification before uploading the final invoice in the Department of Treasury's Invoice Processing Platform (IPP).

For Phase II awards, two life cycle certifications shall be completed in the EHB. A life cycle certification shall be completed along with the second invoice certification as a condition of payment of the second invoice. Another life cycle certification shall be completed along with the final invoice certification as a condition of payment of the final invoice. The life cycle certifications are preset in the EHB.

If the Contracting Officer believes that the business may not meet certain eligibility requirements at the time of award, the business is required to file a size protest with the SBA, who will determine eligibility. At that time, SBA will request further clarification and supporting documentation in order to assist in the eligibility determination. Additionally, the Contracting Officer may request further clarification and supporting documentation regarding eligibility to determine whether a referral to SBA is required.

2.5 NASA Clauses

The following NASA clauses are necessary to implement restrictions in NASA appropriations. Offerors must comply with these clauses to be eligible for award.

2.5.1 Clause 1852.203-71 Requirement To Inform Employees of Whistleblower Rights

1. The Contractor shall inform its employees in writing, in the predominant native language of the workforce, of contractor employee whistleblower rights and protections under 10 U.S.C. 2409, as described in subpart 1803.9 of the NASA FAR Supplement.
2. The Contractor shall include the substance of this clause, including this paragraph (b), in all subcontracts.

2.5.2 Clause 1852.225-71 Restriction on Funding Activity With China

(a) Definition - "China" or "Chinese-owned company" means the People's Republic of China, any company owned by the People's Republic of China or any company incorporated under the laws of the People's Republic of China.

(b) Public Laws 112-10, Section 1340(a) and 112-55, Section 539, restrict NASA from contracting to participate, collaborate, coordinate bilaterally in any way with China or a Chinese-owned company using funds appropriated on or after April 25, 2011. Contracts for commercial and non developmental items are exempted from the prohibition because they constitute purchase of goods or services that would not involve participation, collaboration, or coordination between the parties.

(c) This contract may use restricted funding that was appropriated on or after April 25, 2011. The contractor shall not contract with China or Chinese-owned companies for any effort related to this contract except for acquisition of commercial and non-developmental items. If the contractor anticipates making an award to China or Chinese-owned companies, the contractor must contact the contracting officer to determine if funding on this contract can be used for that purpose.

(d) Subcontracts - The contractor shall include the substance of this clause in all subcontracts made hereunder.

2.5.3 Clause 1852.225-72 Restriction on Funding Activity With China – Representation

(a) Definition - “China” or “Chinese-owned” means the People’s Republic of China, any company owned by the People’s Republic of China, or any company incorporated under the laws of the People’s Republic of China.
(b) Public Laws 112-10, Section 1340(a) and 112-55, Section 536, restrict NASA from contracting to participate, collaborate, or coordinate bilaterally in any way with China or a Chinese-owned company with funds appropriated on or after April 25, 2011. Contracts for commercial and non-developmental items are excepted from the prohibition as they constitute purchase of goods or services that would not involve participation, collaboration, or coordination between the parties.
(c) Representation. By submission of its offer, the offeror represents that the offeror is not China or a Chinese-owned company.

2.6 False Statements

Note: Knowingly and willfully making any false, fictitious, or fraudulent statements or representations may be a felony under the Federal Criminal False Statement Act (18 U.S.C., section 1001), punishable by a fine and imprisonment of up to 5 years in prison. The Office of the Inspector General (OIG) has full access to all proposals submitted to NASA.

Pursuant to NASA policy, any company representative who observes crime, fraud, waste, abuse, or mismanagement or receives an allegation of crime, fraud, waste, abuse, or mismanagement from a Federal employee, contractor, grantee, contractor, grantee employee, or any other source will report such observation or allegation to the OIG. NASA contractor employees and other individuals are also encouraged to report crime, fraud, waste, and mismanagement in NASA's programs to the OIG. The OIG offers several ways to report a complaint:

NASA OIG Hotline: 1-800-424-9183 (TDD: 1-800-535-8134)

NASA OIG Cyber Hotline: http://oig.nasa.gov/cyberhotline.html

Or by mail:
NASA Office of Inspector General
P.O. Box 23089
L'Enfant Plaza Station
Washington, DC 20026

2.7 Software Development Standards

Offerors proposing projects involving the development of software may be required to comply with the requirements of NASA Procedural Requirements (NPR) 7150.2A, NASA Software Engineering Requirements, available online at http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7150&s=2.

2.8 Human and/or Animal Subject

Offerors should be aware of the requirement that an approved protocol by a NASA review board is required if the proposed work includes human or animal subject. An approved protocol shall be provided to the Contracting Officer prior to the initiation of any human and/or animal subject research. Offerors shall identify the use of human or animal subject in the Proposal Certifications form. For additional information, contact the NASA SBIR/STTR Program Support Office at sbir@reisystems.com . Reference 14 CFR 1230 and 1232.

Note: Due to the complexity of the approval process, use of human and/or animal subjects is not allowed for Phase I contracts.

2.9 HSPD-12

Firms that require access to Federally controlled facilities or access to a Federal information system (Federally controlled facilities and Federal information system are defined in FAR 2.101(b)(2)) for 6 consecutive months or more must adhere to Homeland Security Presidential Directive 12 (HSPD-12), Policy for a Common Identification Standard for Federal Employees and Contractors, and Federal Information Processing Standards Publication (FIPS PUB) Number 201, Personal Identity Verification (PIV) of Federal Employees and Contractors, which require agencies to establish and implement procedures to create and use a Government-wide secure and reliable form of identification no later than October 27, 2005. See https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.201-2.pdf.

This is in accordance with FAR clause 52.204-9, Personal Identity Verification of Contractor Personnel, which states in part that the contractor shall comply with the requirements of this clause and shall ensure that individuals needing such access shall provide the personal background and biographical information requested by NASA.

Note: Additional information regarding PIV credentials can be found at https://csrc.nist.gov/Projects/PIV.

3. Proposal Preparation Instructions and Requirements

3.1 Fundamental Considerations

3.1.1 Multiple Proposal Submissions

Each proposal submitted must be based on a unique innovation, must be limited in scope to just one subtopic, and shall be submitted only under that one subtopic within each program. An offeror shall not submit more than 10 proposals to each of the SBIR or STTR programs (20 total). An offeror may submit more than one unique proposal to the same subtopic; however, an offeror shall not submit the same (or substantially equivalent) proposal to more than one subtopic. Submitting substantially equivalent proposals to several subtopics may result in the rejection of all such proposals. In order to enhance SBC participation, NASA does not plan to select more than 5 SBIR proposals and 2 STTR proposals from any one offeror under this solicitation (7 total).

Note: Offerors are advised to be thoughtful in selecting a subtopic to ensure the proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR/STTR program will NOT move a proposal between subtopics.

3.1.2 Understanding the Patent Landscape

Offerors should indicate in the proposal that a comprehensive patent review has been completed to ensure that there is no existing patent or perceived patent infringement based on the innovation proposed. The U.S. Patent and Trade Office (USPTO) has an online patent search tool that can found at https://www.uspto.gov/patents-application-process/search-patents.

3.2 Proprietary Information in the Proposal Submission

Information contained in unsuccessful proposals will remain the property of the applicant. The Federal Government may, however, retain copies of all proposals. Public release of information in any proposal submitted will be subject to existing statutory and regulatory requirements. If proprietary information is provided by an applicant in a proposal, which constitutes a trade secret, commercial or financial information, it will be treated in confidence, to the extent permitted by law, provided that the proposal is clearly marked by the applicant as follows:

(A) The following "italicized" legend must appear on the title page of the proposal:

This proposal contains information that shall not be disclosed outside the Federal Government and shall not be duplicated, used, or disclosed in whole or in part for any purpose other than evaluation of this proposal, unless authorized by law. The Government shall have the right to duplicate, use, or disclose the data to the extent provided in the resulting contract if award is made as a result of the submission of this proposal. The information subject to these restrictions is contained on all pages of the proposal except for pages [insert page numbers or other identification of pages that contain no restricted information]. (End of Legend); and

(B) The following legend must appear on each page of the proposal that contains information the applicant wishes to protect:

Use or disclosure of information contained on this sheet is subject to the restriction on the title page of this proposal.

Information contained in unsuccessful proposals will remain the property of the applicant. However, the Government will retain copies of all proposals in accordance with its records retention schedule.

3.2.1 Release of Certain Proposal Information

In submitting a proposal, the offeror agrees to permit the Government to disclose publicly the information contained in the Contact Information form and Proposal Summary form, which includes the Technical Abstract and Briefing Chart. Other proposal data is considered to be the property of the offeror, and NASA will protect it from public disclosure to the extent permitted by law, including requests submitted under the Freedom of Information Act (FOIA).

3.3 Phase I Proposal Requirements

3.3.1 General Requirements

A competitive proposal will clearly and concisely (1) describe the proposed innovation relative to the current state of the art; (2) address the scientific, technical, and commercial merit and feasibility of the proposed innovation as well as its relevance and significance to NASA interests as described in section 9 of this solicitation; and (3) provide a preliminary strategy that addresses key technical, market, and business factors pertinent to the successful development and demonstration of the proposed innovation and its transition into products and services for NASA mission programs, the commercial aerospace industry, and other potential markets and customers.

3.3.2 Format Requirements

Note: The Government administratively screens all proposals and reserves the right to reject any proposal that does not conform to the following formatting requirements. Offerors who repeatedly violate solicitation formatting instructions are at higher risk of rejection for nonconformance on subsequent SBIR/STTR proposals.

Page Limitations and Margins

Note: Technical proposal uploads with any page(s) going over the required page limit will not be accepted.

A Phase I technical proposal shall not exceed a total of 19 standard 8.5- by 11-inch (21.6- by 27.9-cm) pages. Proposals uploaded with more than 19 pages will prompt a warning that will prevent the completed proposal from being submitted. Each page shall be numbered consecutively at the bottom. Margins shall be 1.0 inch (2.5 cm). The additional forms required for proposal submission will not count against the 19-page limit.

Suggested Page Limits

Section 3.3.4 gives suggested page limits for each part of the technical proposal. These are guidelines and are not strict requirements. Offerors are still required to meet the total page limit requirements as described above.

Type Size

No type size smaller than 10 point shall be used for text or tables, except as legends on reduced drawings. Proposals prepared with smaller font sizes may be rejected without consideration.

Header/Footer Requirements

Headers must include firm name, proposal number, and project title. Footers must include the page number and proprietary markings if applicable. Margins can be used for header/footer information.

Classified Information

NASA does not accept proposals that contain classified information.

Project Title

The proposal project title shall be concise and descriptive of the proposed effort. The title should not use acronyms or words like "development of" or "study of." The NASA research subtopic title must not be used as the proposal title.

Proposal Package

Each complete proposal package submitted shall contain the following items:

1. Proposal Contact Information (3.3.3.1).
2. Proposal Certifications, electronically endorsed (3.3.3.2).
3. Proposal Summary (must not contain proprietary data) (3.3.3.3).
4. Proposal Budget (including letters of commitment for Government resources and subcontractors/consultants, if applicable) (3.3.3.4).
5. Technical Proposal—10 parts in the order specified in section 3.3.4, not to exceed 19 pages (both SBIR and STTR), including all graphics, with a table of contents (3.3.4).
6. Research Agreement between the SBC and RI (STTR only) (3.3.5).
7. Briefing Chart (must not contain proprietary data) (3.3.7).
8. NASA Evaluation License Application, only if TAV is being proposed (1.6).
9. I-Corps Interest Form (3.3.6).
10. Technical and Business Assistance (TABA) request (optional) (3.3.13).
11. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercial Metrics Survey (CMS)
12. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)
13. For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.

Note: Letters expressing general technical interest or letters of funding support commitments (for Phase I) are not required or desired and will not be considered during the review process. However, if submitted, such letter(s) will count against the page limit.

Note: The EHB will not allow the upload of relevant technical papers, product samples, videotapes, slides, or other ancillary items, and they will not be considered during the review process.

Firm-Level Forms

In addition to the above items, each offeror must submit the following firm-level forms, which must be filled out once during each submission period and are applicable to all firm proposal submissions:

1. Firm Certifications, electronically endorsed (3.3.8)
2. Audit Information (3.3.9)
3. Prior Awards Addendum (3.3.10)
4. Commercial Metrics Survey (3.3.11)

Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

3.3.3 Forms

All form submissions shall be completed electronically and do not count toward the 19-page limit for the technical proposal.

3.3.3.1 Proposal Contact Information

A sample Contact Information form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each contact person and submit the form as required in section 6.

Note: Contact Information is public information and may be disclosed.

3.3.3.2 Proposal Certifications

A sample Proposal Certifications form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

3.3.3.3 Proposal Summary

A sample Proposal Summary form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

Note: The Proposal Summary, including the Technical Abstract, is public information and may be disclosed. Do not include proprietary information in this form.

3.3.3.4 Proposal Budget

A sample of the Proposal Budget form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror must complete the Proposal Budget following the instructions provided with the sample form. The total requested funding for the Phase I effort shall not exceed $125,000. Contextual help is provided on the electronic budget form for additional explanation. Information shall be submitted to explain the offeror’s plans for use of the requested funds to enable NASA to determine whether the proposed price is fair and reasonable.

Note: The Government is not responsible for any monies expended by the firm before award of any contract.

In addition, the following uploads must be submitted in the Proposal Budget form, as applicable:

Proposal Requirements for Use of Government Resources

In cases where an offeror seeks to use Government resources as described in Part 8 of the technical proposal instructions, the offeror shall provide the following:

1. Statement, signed by the appropriate Government official at the affected Federal department or agency, verifying that the resources should be available during proposed period of performance.

2. Signed letter on company letterhead from the contractor's Small Business Official explaining why the SBIR/STTR research project requires the use of Government resources (such as, but not limited to, Federal services, equipment, or facilities, etc.) including data that verifies the absence of non-Federal facilities or personnel capable of supporting the research effort, a statement confirming that the facility proposed is not a Federal laboratory, if applicable, and the associated cost estimate.

Note: Use of Federal laboratories/facilities for Phase I contracts is highly discouraged. Approval for use of Federal facilities and laboratories for a Phase I proposal requires Program Executive approval during negotiations if selected for award.

See Part 8 of the Technical Proposal instructions for additional information on use of Government resources.

Use of Subcontractors and Consultants

Subject to the restrictions set forth below, the SBC may establish business arrangements with other entities or individuals to participate in performance of the proposed R/R&D effort. Subcontractors' and consultants' work has the same place-of-performance restrictions as stated in section 1.5.2.

Note:

1. ***Offerors should list consultants by name and specify, for each, the number of hours and hourly costs.***
2. ***Breakdown of subcontractor budget should mirror the SBC's own breakdown in the Proposal Budget form and include breakdowns of direct labor, other direct costs, and profit, as well as indirect rate agreements.***
3. ***A signed letter of commitment is required for each subcontractor and/or consultant. For educational institutions, the letter must be from the institution's Office of Sponsored Programs.***

> ***STTR: The RI's budget must be submitted at the time of proposal submission, and if the RI is an educational institution, the RI must submit a letter from the institution's Office of Sponsored Programs.***

The following restrictions apply to the use of subcontractors/consultants, and the formula below must be used in preparing budgets with subcontractors/consultants:

SBIR Phase I Subcontractors/Consultants	STTR Phase I Subcontractors/Consultants
The proposed subcontracted business arrangements, including consultants, must not exceed 33 percent of the research and/or analytical work [as determined by the total cost of the proposed subcontracting effort (to include the appropriate overhead (OH) and general and administrative expenses (G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit, if any)]. Occasionally, deviations from these SBIR requirements may occur, and must be approved in writing by the Funding Agreement officer after consultation with the Agency SBIR/STTR Program Manager.	A minimum of 40 percent of the research or analytical work must be performed by the proposing SBC, and a minimum of 30 percent must be performed by the RI. Any subcontracted business effort other than that performed by the RI shall not exceed 30 percent of the research and/or analytical work [as determined by the total cost of the subcontracting effort (to include the appropriate overhead (OH) and general and administrative expenses (G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit, if any)]. Deviations from these STTR requirements are not allowed, as the performance of work requirements are specified in statute at 15 U.S.C. 638(e).

Example:	Total price to include profit	$99,500
	Profit	$3,000
	Total price less profit	$99,500 - $3,000 = $96,500
	Subcontractor cost	$29,500
	G&A	5%
	G&A on subcontractor cost	$29,500 x 5% = $1,475
	Subcontractor cost plus G&A	$29,500 + $1,475 = $30,975
	Percentage of subcontracting effort*	**$30,975/$96,500 = 32.1%**
	***Subcontractor cost plus G&A/Total price less profit**	

- For an SBIR Phase I, this is acceptable because it is below the limitation of 33 percent.
- For an STTR Phase I, where there is a subcontract with a company other than the RI, this is unacceptable because it is above the 30 percent limitation.

See Part 9 of the Technical Proposal for additional information on the use of subcontractors and consultants.

Travel in Phase I

Due to the intent and short period of performance of the Phase I contracts, along with their limited budget, travel during the Phase I contract is highly discouraged unless it is required to successfully complete the proposed effort. If the purpose of the meeting cannot be accomplished via videoconference or teleconference, the offeror must provide rationale for the trip in the proposal budget form. All travel must be approved by the Contracting Officer and concurred by the Technical Monitor.

3.3.4 Technical Proposal

This part of the submission should not contain any budget data and **must consist of all 10 parts listed below in the given order. All 10 parts of the technical proposal must be numbered and titled.** Parts that are not applicable must be included and marked “Not applicable.” A proposal omitting any part will be considered nonresponsive to this solicitation and may be rejected during administrative screening. The required table of contents is provided below:

Phase I Table of Contents

Part 1: Table of Contents *(Suggested page limit – 0.5 page)*

The technical proposal shall begin with a brief table of contents indicating the page numbers of each of the parts of the proposal (see above).

Part 2: Identification and Significance of the Innovation *(Suggested page limit – 5 pages)*

Succinctly describe:

- The proposed innovation.
- The relevance and significance of the proposed innovation to an interest, need, or needs, within a subtopic described in section 9.
- The proposed innovation relative to the current state of the art.

Part 3: Technical Objectives *(Suggested page limit – 1 page)*

State the specific objectives of the Phase I R/R&D effort as it relates to the problem statement(s) posed in the subtopic description and the types of innovations being requested by the subtopic manager(s).

Proposed Deliverables: Indicate the proposed deliverables at the end of the Phase I effort and how these align with the proposed subtopic deliverables described within a subtopic found in section 9.

Note: All offerors submitting proposals who are planning to use NASA Intellectual Property (IP) must describe their planned developments with the IP. The NASA Evaluation License Application should be added as an attachment in the Proposal Certifications form (see section 1.6).

Part 4: Work Plan *(Suggested page limit – 5 pages)*

Include a detailed description of the Phase I R/R&D plan to meet the technical objectives. The plan should indicate what will be done, where it will be done, and how the R/R&D will be carried out. Discuss in detail the methods planned to achieve each task or objective. Task descriptions, schedules, resource allocations, estimated task hours for each key personnel, and planned accomplishments, including project milestones, and shall be included. Offerors should ensure that the estimated task hours provided in the work plan for key personnel are consistent with the hours reported in the Proposal Budget form. If the offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed, and charged should be included here.

STTR: In addition, the work plan will specifically address the percentage and type of work to be performed by the SBC and the RI. The plan will provide evidence that the SBC will exercise management direction and control of the performance of the STTR effort, including situations in which the PI may be an employee of the RI.

Part 5: Related R/R&D *(Suggested page limit – 1 page)*

Describe significant current and/or previous R/R&D that is directly related to the proposal including any conducted by the PI or by the offeror. Describe how it relates to the proposed effort and any planned coordination with outside sources. The offeror must persuade reviewers of his or her awareness of key recent R/R&D conducted by others in the specific subject area.

Part 6: Key Personnel and Bibliography of Directly Related Work *(Suggested page limit – 2.5 pages)*

Identify all key personnel involved in Phase I activities whose expertise and functions are essential to the success of the project. Provide biographical information, including directly related education and experience. Where the resume/vitae is extensive, summaries that focus on the most relevant experience or publications are desired and may be necessary to meet proposal size limitation.

The PI is considered key to the success of the effort and must make a substantial commitment to the project. The following requirements are applicable:

Functions: The functions of the PI are planning and directing the project, leading it technically and making substantial personal contributions during its implementation, serving as the primary contact with NASA on the project, and ensuring that the work proceeds according to contract agreements. Competent management of PI functions is essential to project success. The Phase I proposal shall describe the nature of the PI's activities and the amount of time that the PI will personally apply to the project. The amount of time the PI proposes to spend on the project must be acceptable to the Contracting Officer.

Qualifications: The qualifications and capabilities of the proposed PI and the basis for PI selection are to be clearly presented in the proposal. NASA has the sole right to accept or reject a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.

Eligibility: This part shall also establish and confirm the eligibility of the PI and shall indicate the extent to which existing projects and other proposals recently submitted or planned for submission in fiscal year 2021 commit the time of the PI concurrently with this proposed activity. Any attempt to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI will result in rejection of the proposal. However, for an STTR the PI can be primarily employed by either the SBC or the RI. Please see section 1.5.3 for further explanation.

Part 7: The Market Opportunity *(Suggested page limit – 1 page)*

Phase I applicants should describe both NASA and non-NASA markets and addressable markets for the innovation. Discuss the business economics and market drivers in the target industry. How has the market opportunity been validated? Describe your customers and your basic go-to-market strategy to achieve the market opportunity. Describe the competition. How do you expect the competitive landscape may change by the time your innovation enters the market? What are the key risks in bringing your innovation to market? Describe your commercialization approach. Discuss the potential economic benefits associated with your innovation and provide estimates of the revenue potential, detailing your underlying assumptions. Describe the resources you expect will be needed to implement your commercialization approach.

Note: Companies with no SBIR/STTR awards or fairly recent awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

Part 8: Facilities/Equipment *(Suggested page limit – 1 page)*

If an offeror requests to use Government-furnished laboratory equipment, facilities, or services (collectively, “Government resources”) the offeror shall describe in this part why the use of such Government resources is necessary and not reasonably available from the private sector. See sections 3.3.3.4 and 5.14 for additional requirements when proposing use of such Government resources. The narrative description of resources should support the proposed approach and documentation in the Proposal Budget form.

Note: Use of Federal laboratories/facilities for Phase I contracts is highly discouraged. Approval for use of Federal facilities and laboratories for a Phase I proposal requires Program Executive approval during negotiations if selected for award.

Part 9: Subcontractors and Consultants *(Suggested page limit – 1 page)*

The offeror must describe all subcontracting or other business arrangements and identify the relevant organizations and/or individuals with whom arrangements are planned. The expertise to be provided by the entities must be described in detail, as well as the functions, services, and number of hours. Offerors are responsible for ensuring that all organizations and individuals proposed to be utilized are actually available for the time periods proposed. Subcontract costs shall be documented in the Subcontractors/Consultants section of the Proposal Budget form, and supporting documentation should be uploaded for each (appropriate documentation is specified in the form). The narrative description of subcontractors and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards *(Suggested page limit – 1 page)*

WARNING: While it is permissible with proper notification to submit identical proposals or proposals containing a significant amount of essentially equivalent work for consideration under numerous Federal program solicitations, it is unlawful to enter into funding agreements requiring essentially equivalent work.

If an applicant elects to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other Federal program solicitations, a statement must be included in each such proposal indicating the following:

1. The name and address of the agencies to which proposals were submitted or from which awards were received.
2. Date of proposal submission or date of award.
3. Title, number, and date of solicitations under which proposals were submitted or awards received.
4. The specific applicable research topics for each proposal submitted or award received.
5. Titles of research projects.
6. Name and title of principal investigator or project manager for each proposal submitted or award received.

Offerors are at risk for submitting essentially equivalent proposals and therefore are strongly encouraged to disclose these issues to the soliciting agency to resolve the matter prior to award.

A summary of essentially equivalent work information, as well as related research and development on proposals and awards, is also required on the Proposal Certifications form (if applicable).

3.3.5 Research Agreement (Applicable for STTR proposals only)

STTR: The Research Agreement (different from the Allocation of Rights Agreement; see http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions) is a single-page document electronically submitted and endorsed by the SBC and RI. A model agreement is provided, or firms can create their own custom agreement. The Research Agreement shall be submitted as required in section 6.

All STTR Phase I proposals must provide sufficient information to convince NASA that the proposed SBC/RI cooperative effort represents a sound approach for converting technical information resident at the RI into a product or service that meets a need described in a solicitation research topic.

3.3.6 Process to Participate in the NASA I-Corps Program

Phase I SBIR/STTR offerors must complete a short I-Corps interest Form (see section 1.7 for additional information on the I-Corps program) as part of their Phase I proposal submission. NASA uses this form to determine the level of interest from Phase I offerors to participate in the NASA I-Corps program. Offerors are encouraged to complete the form in its entirety. In the event a large number of offerors express interest, the Government reserves the right to limit the number of offerors invited to submit I-Corps proposals based upon the Government's assessment of the initial summary statements.

Offerors that are selected for Phase I contract negotiations will receive information from the SBIR/STTR PMO describing the process to provide a 5-page proposal to participate in the I-Corps program. Directions for completing the proposal including due dates, training dates, and available training grant funding will be provided via email. Additional details on the program can be found at http://sbir.nasa.gov/content/I-Corps.

3.3.7 Briefing Chart

The 1-page briefing chart is required to assist in the ranking and advocacy of proposals prior to selection and contains the following sections with summary information:

- Identification and Significance of Innovation
- Technical Objectives
- Proposed Deliverables
- NASA Applications
- Non-NASA Applications
- Graphic

It shall not contain any proprietary data or ITAR-restricted data. An electronic form will be provided during the submissions process.

Note: The briefing chart is public information and may be disclosed. Do not include proprietary information in this form.

3.3.8 Firm Certifications

Firm certifications that are applicable across all proposal submissions submitted to this solicitation must be completed via the Firm Certifications section of the Proposal Submissions Electronic Handbook (EHB). The offeror shall answer "Yes" or "No" as applicable. An example of the certifications can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. An electronic form will be provided during the submissions process.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the certifications.

3.3.9 Audit Information

Although firms are not required to have an approved accounting system, knowledge that a firm has an approved accounting system facilitates NASA's determination that rates are fair and reasonable. To assist NASA, the SBC shall complete the questions in the Audit Information form regarding the firm's rates and upload the Federal agency audit report or related information that is available from the last audit. There is a separate Audit Information section in the Proposal Budget form that shall also be completed. If your firm has never been audited by a Federal agency, then answer "No" to the first question and you do not need to complete the remainder of the form. An electronic form will be provided during the submissions process.

The Contracting Officer will use this Audit Information to assist with negotiations if the proposal is selected for award. The Contracting Officer will advise offerors what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate to support the necessary determination on rates.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the audit information.

3.3.10 Prior Awards Addendum

If the SBC has received more than 15 Phase II awards in the prior 5 fiscal years, submit the name of the awarding agency, solicitation year, phase, date of award, Funding Agreement/contract number, and topic or subtopic title for each Phase II. If your firm has received any SBIR or STTR Phase II awards, even if it has received fewer than 15 in the last 5 years, it is still recommended that you complete this form for those Phase II awards your firm did receive. This information will be useful when completing the Commercialization Metrics Survey (CMS) and in tracking the overall success of the SBIR and STTR programs. Any NASA Phase II awards your firm has received will be automatically populated in the electronic form, as well as any Phase II awards previously entered by the SBC during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the addendum information.

3.3.11 Commercial Metrics Survey (CMS)

NASA has instituted a comprehensive commercialization survey/data-gathering process for firms with prior NASA SBIR/STTR awards. If the SBC has received any Phase III awards resulting from work on any NASA SBIR or STTR awards, provide the related Phase I or Phase II contract number, name of Phase III awarding agency, date of award, Funding Agreement number, amount, project title, and period of performance. The survey will also ask for firm financial, sales, and ownership information, as well as any commercialization success the firm has had as a result of SBIR or STTR awards. This information must be updated annually during proposal submission via the EHB. This information allows firms to demonstrate their ability to carry SBIR/STTR research through to achieve commercial success and allows agencies to track the overall commercialization success of their SBIR and STTR programs. The survey should be limited to information requested above. An electronic form will be provided during the submissions process.

Note: Information received from SBIR/STTR awardees completing the survey is kept confidential and will not be made public except in broad aggregate, with no firm-specific attribution.

The Commercialization Metrics Survey is a required part of the proposal submissions process and must be completed via the Proposal Submissions EHB. Companies with no SBIR/STTR awards or only fairly recent awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

3.3.12 Allocation of Rights Agreement (STTR awards only)

An SBC, before receiving an STTR award, must negotiate a written agreement between the SBC and the partnering Research Institution, allocating intellectual property rights, if any, to carry out follow-on research, development, or commercialization. This written agreement must be signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable. A sample Allocation of Rights Agreement is available in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

The SBC must submit this agreement with the proposal by uploading it in the Proposal Budget form. This will help to expedite contract negotiations.

3.3.13 Request for Use of Technical and Business Assistance (TABA) Funds at Phase I

Offerors are not required to request TABA at Phase I, and there is no prerequisite that an offeror must use Phase I TABA funding in order to obtain a Phase II award or request TABA funding at Phase II.

If an offeror decides to request TABA at Phase I, the offeror must request TABA authority from NASA in the Phase I proposal submission. Requests for TABA funding are not reviewed under the technical evaluation of the proposal, and the request for TABA funds will not be part of the decision to make an award. All TABA requests will be reviewed after a proposal is selected for award and during the contract negotiation process.

Offerors selected for Phase I contract negotiations can receive up to $6,500 as a supplement to the Phase I award and can choose their own TABA vendor. Although an offeror can use TABA funding for services they choose per the FY19 NDAA, NASA is encouraging offerors to use the limited amount of $6,500 Phase I TABA funds for the following activities:

1. Development of a Phase II TABA Needs Assessment – If a Phase I offeror plans to request TABA funding at Phase II, the offeror should secure a TABA vendor that can provide services to support the development of a Phase II TABA needs assessment. The goal of the TABA Needs Assessment is to determine and define the types of TABA services and costs the offeror would need if the project was selected for a future Phase II award. The offeror could request up to $50,000 for these Phase II services.
2. Development of a Phase II Commercialization and Business Plan – Offerors that are planning to submit a future proposal for Phase II funding will be required to submit a commercialization and business plan that meets the requirements found in section 3.4.4, Part 7 of this solicitation. NASA is encouraging offerors to use Phase I TABA funding to secure a TABA vendor that can help develop the required elements of the commercialization and business plan so that NASA can evaluate a firm's ability to commercialize the innovation and provide a level of confidence regarding the firm's future and financial viability.

If an offeror chooses to request up to $6,500 for Technical and Business Assistance (TABA) at Phase I, the offeror will be required to provide TABA information by following the directions found in the submissions module of the EHB. Examples of information that will be required are as follows:

- Name, contact information, and company information including DUNS number for TABA vendor(s) that will provide the services under Phase I.
    - Note: All TABA vendors must be a legal business in the United States and NASA will review the U.S. Government-wide System for Award Management (SAM) excluded parties list to ensure the proposed TABA vendor can receive Federal funds. NASA will consider TABA requests that are missing any requested TABA information (e.g., DUNS number, etc.) as incomplete and will not review the TABA request or provide TABA approval under the award.
- Description of vendor(s) expertise and knowledge of providing technical and business assistance services to develop and complete a TABA Needs Assessment for a future Phase II submission, to develop a Commercialization Plan for a future Phase II submission, or other TABA services.
- Itemized list of services and costs to be provided to the TABA vendor.

- Plan to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- TABA costs reflected in the budget forms.

NASA reserves the right to withhold funds requested for TABA until a formal review and approval of the requested vendor is completed. If the proposal is selected for a Phase I award and the offeror demonstrates this requirement sufficiently, as determined by the Government, NASA will permit the awardee to acquire the requested assistance, in an amount up to $6,500 for the Phase I project, as an allowable cost of the SBIR/STTR award. Approval or denial of TABA funding will be provided before award. **The amount will be in addition to the Phase I award value, is not subject to any profit or fee by the requesting firm, and cannot be used in the calculation of indirect cost rates or general and administrative expenses (G&A).** The amount and services will be based on the original Phase I period of performance. Requests for TABA funding outside of the Phase I period of performance or after proposal submission will not be considered.

Schedule of Deliverables and Payments for TABA—Offerors that are approved to receive TABA under a Phase I award will be reimbursed for TABA expenses. Reimbursement for TABA will be based on the awardee providing a TABA end-of-contract report at the end of the contract period of performance.

3.4 Phase II Proposal Requirements

3.4.1 General Requirements

The Phase I contract will serve as a Request for Proposal (RFP) for the Phase II follow-on project. Phase II proposals are more comprehensive than those required for Phase I. Submission of a Phase II proposal is in accordance with Phase I contract requirements and is voluntary. NASA assumes no responsibility for any proposal preparation expenses.

Note: Offerors may only submit one Phase II proposal per Phase I award and cannot submit under a future Phase II RFP.

A competitive Phase II proposal will clearly and concisely

(1) Describe the proposed innovation relative to the current state of the art and the current market.
(2) Address Phase I results relative to the scientific, technical merit and feasibility of the proposed innovation and its relevance and significance to NASA interests.
(3) Provide the planning for a focused project that builds upon Phase I results and encompasses technical, market, financial, and business factors relating to the development and demonstration of the proposed innovation and its transition into products and services for NASA mission programs, other Government agencies, and non-Government markets.

3.4.2 Format Requirements

Note: The Government administratively screens all proposals and reserves the right to reject any proposal that does not conform to the following formatting requirements.

Page Limitations and Margins

Note: Technical proposal uploads with any page(s) going over the required page limit will not be accepted.

A Phase II technical proposal shall not exceed a total of 46 standard 8.5- by 11-inch (21.6- by 27.9-cm) pages. Proposals uploaded with more than 46 pages will prompt a warning that will prevent the completed proposal from being submitted. Each page shall be numbered consecutively at the bottom. Margins shall be 1.0 inch (2.5 cm). The additional forms required for proposal submission will not count against the 46-page limit.

Suggested Page Limits

Section 3.4.4 gives suggested page limits for each part of the technical proposal. These are guidelines and are not strict requirements, with the exception of the minimum page requirement stated for Part 7: Commercialization Plan. Offerors are still required to meet the total page-limit requirements as described above.

Type Size

No type size smaller than 10 point shall be used for text or tables, except as legends on reduced drawings. Proposals prepared with smaller font sizes may be rejected without consideration.

Header/Footer Requirements

Headers must include firm name, proposal number, and project title. Footers must include the page number and proprietary markings if applicable. Margins can be used for header/footer information.

Classified Information

NASA does not accept proposals that contain classified information.

Project Title

The proposal project title shall be concise and descriptive of the proposed effort. The title should not use acronyms or words like "development of" or "study of." The NASA research topic title must not be used as the proposal title.

Proposal Package

Each complete proposal package submitted shall contain the following items:

1. Proposal Contact Information (3.4.3.1).
2. Proposal Certifications, electronically endorsed (3.4.3.2).
3. Proposal Summary (must not contain proprietary data) (3.4.3.3).
4. Proposal Budget (including a letter of commitment from the appropriate Government official if the research or R&D effort requires the use of Government resources) (section 3.4.3.4).
5. Technical Proposal—10 Parts in the order specified in section 3.4.4, not to exceed 46 pages (for SBIR AND STTR), including all graphics, and starting with a table of contents (3.4.4).
6. Research Agreement between the SBC and RI (STTR only) (3.4.5).
7. Briefing Chart (must not contain proprietary data) (3.4.7).
8. NASA Evaluation License Application, only if TAV is being proposed (1.6).
9. Capital Commitments Addendum Supporting Phase II and Phase III (optional) (3.4.6).
10. Technical and Business Assistance (TABA) request (optional) (3.4.14).
11. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercialization Metrics Survey (CMS)
12. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)

13. For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.

Note: Letters expressing general technical interest are not required or desired and will not be considered during the review process. However, if submitted, such letter(s) will count against the page limit. Letters of funding support commitments are allowable for Phase II proposals but will only be considered under Factor 4: Commercial Potential and Feasibility. Letters of funding support commitments should be submitted as part of the Capital Commitments Addendum.

Firm-Level Forms

In addition to the above items, each offeror must submit the following firm-level forms, which must be filled out once during each submission period and are applicable to all firm proposal submissions:

1. Firm Certifications (3.4.8)
2. Audit Information (3.4.9)
3. Prior Awards Addendum (3.4.10)
4. Commercial Metrics Survey (3.4.11)

Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: The EHB will not allow the upload of relevant technical papers, product samples, videotapes, slides, or other ancillary items, and they will not be considered during the review process.

3.4.3 Forms

All form submissions shall be done electronically and do not count toward the 46-page limit.

3.4.3.1 Contact Information

A sample Contact Information form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each contact person and submit the form as required in section 6.

Note: Contact Information is public information and may be disclosed.

3.4.3.2 Proposal Certifications

A sample Proposal Certifications form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

3.4.3.3 Proposal Summary

A sample Proposal Summary form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror shall provide complete information for each item and submit the form as required in section 6.

Note: The Proposal Summary, including the Technical Abstract, is public information and may be disclosed. Do not include proprietary information in this form.

3.4.3.4 Proposal Budget

A sample of the Proposal Budget form is provided in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. The offeror must complete the Budget Summary following the instructions provided with the sample form. The total requested funding for the Phase II effort shall not exceed $750,000. Contextual help is provided on the electronic budget form for additional explanation. Information shall be submitted to explain the offeror's plans for use of the requested funds to enable NASA to determine whether the proposed price is fair and reasonable.

Note: The Government is not responsible for any monies expended by the firm before award of any contract. Successful offerors are responsible for reimbursing NASA for resources utilized in performance of the effort, and the cost of such resources will be included in their contract values (not to exceed capped amounts).

In addition, the following uploads must be submitted in the Proposal Budget form, as applicable:

Proposal Requirements for Use of Government Resources

In cases where an offeror seeks to use NASA or another Federal department or agency laboratory services, equipment, or facilities (collectively, "resources"), the offeror shall provide the following:

1. Statement, signed by the appropriate Government official at the affected Federal department or agency laboratory, verifying that the resources should be available during the proposed period of performance. Offerors must upload this letter in the Proposal Budget form.
2. Signed letter on company letterhead from the contractor's Small Business Official explaining why the SBIR/STTR research project requires the use of Government resources, including data that verifies the absence of non-Federal facilities or personnel capable of supporting the research effort, and the associated cost estimate. Offerors must upload this letter in the Proposal Budget form.

See Part 8 of the Technical Proposal instructions for additional information on use of Government Resources.

Use of Subcontractors and Consultants

Subject to the restrictions set forth below, the SBC may establish business arrangements with other entities or individuals to participate in performance of the proposed R/R&D effort.

Note:

1. ***Offerors should list consultants by name and specify, for each, the number of hours and hourly costs.***
2. ***Breakdown of subcontractor budget should mirror the SBC's own breakdown in the Proposal Budget form and include breakdowns of direct labor, other direct costs, and profit, as well as indirect rate agreements.***
3. ***A signed letter of commitment is required for each subcontractor and/or consultant. For educational institutions, the letter must be from the institution's office of sponsored programs.***

> ***STTR: The RI's budget must be submitted at the time of proposal submission, and if the RI is an educational institution, the RI must submit a letter from the institution's Office of Sponsored Programs.***

Subcontractors' and consultants' work has the same place-of-performance restrictions as stated in section 1.5.2.

The following restrictions apply to the use of subcontractors/consultants, and the formula below must be used in preparing budgets with subcontractors/consultants:

SBIR Phase II Subcontractors/Consultants	**STTR Phase II Subcontractors/Consultants**
The proposed subcontracted business arrangements, including consultants, must not exceed 50 percent of the research and/or analytical work [as determined by the total cost of the proposed subcontracting effort (to include the appropriate overhead (OH) and general and administrative expense (G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit, if any)]. Occasionally, deviations from these SBIR requirements may occur, and must be approved in writing by the Funding Agreement officer after consultation with the Agency SBIR/STTR Program Manager.	A minimum of 40 percent of the research or analytical work must be performed by the proposing SBC, and a minimum of 30 percent must be performed by the RI. Any subcontracted business effort other than that performed by the RI shall not exceed 30 percent of the research and/or analytical work [(as determined by the total cost of the subcontracting effort (to include the appropriate overhead (OH) and general and administrative expense (G&A) in comparison to the total effort (total contract price including cost sharing, if any, less profit, if any)]. Deviations from these STTR requirements are not allowed, as the performance-of-work requirements are specified in statute at 15 U.S.C. 638(e).

Example:	Total price to include profit	$725,000
	Profit	$21,750
	Total price less profit	$725,000 – $21,750 = $703,250
	Subcontractor cost	$250,000
	G&A	5%
	G&A on subcontractor cost	$250,000 × 5% = $12,500
	Subcontractor cost plus G&A	$250,000 + $12,500 = $262,500
	Percentage of subcontracting effort*	**$262,500/$703,250 = 37.3%**
	***Subcontractor cost plus G&A/total price less profit**	

- For an SBIR Phase II, this is acceptable because it is below the limitation of 50 percent.
- For an STTR Phase II, where there is a subcontract with a company other than the RI, this is unacceptable because it is above 30 percent limitation.

See Part 9 of the Technical Proposal for additional information on the use of subcontractors and consultants.

Milestone Plan

For Phase II, offerors shall submit a proposed quarterly milestone plan with the Proposal Budget form. The milestone plan shall be in accordance with the proposed work plan, outlining the work to be accomplished each quarter and the cost proposed associated with each of the quarterly milestones. The cost breakdown shall be similar to the Proposal Budget form for each of the proposed quarterly milestones (i.e., each milestone should include the labor, supplies, travel, and profit associated with those tasks to be accomplished that quarter). The proposed cost associated with each quarterly milestone must be realistic for the work to be accomplished but is not required to be equally distributed across each quarter.

3.4.4 Technical Proposal

This part of the submission shall not contain any budget data and must consist of all 10 parts listed below in the given order. All 10 parts of the technical proposal must be numbered and titled. Parts that are not applicable must be included and marked “Not applicable.” A proposal omitting any part will be considered nonresponsive to this solicitation and may be rejected during administrative screening. The required table of contents is provided below:

Phase II Table of Contents

Part 1: Table of Contents *(Suggested page limit – 0.5 page)*

The technical proposal shall begin with a brief table of contents indicating the page numbers of each of the parts of the proposal (see above).

Part 2: Identification and Significance of the Innovation and Results of the Phase I Award *(Suggested page limit – 15 pages)*

Please provide a summary of your Phase I results and, building on those results, succinctly describe the Phase II proposed work, including

- The proposed innovation.
- The relevance and significance of the proposed innovation to an interest, need, or needs within the subtopic.
- The proposed innovation relative to the state of the market, the state of the art, and its feasibility.

Please be advised that the evaluators may review the Phase I final technical report to verify accuracy of this summary. However, proposers should not rely on this and should include relevant results in the Phase II proposal.

Part 3: Technical Objectives *(Suggested page limit – 2 pages)*

State the specific objectives of the Phase I R/R&D effort as it relates to the problem statement(s) posed in the subtopic description and the types of innovations being requested by the subtopic manager(s).

> **Proposed Deliverables:** Indicate the proposed deliverables at the end of the Phase II effort and how they match up to the subtopic. These may include, but are not limited to, required contract deliverables, test reports, and software or hardware.

Note: All offerors submitting proposals who are planning to use NASA IP must describe their planned developments with the IP. The NASA Evaluation License Application should be added as an attachment under Proposal Certifications (see section 1.6).

Part 4: Work Plan *(Suggested page limit – 10 pages)*

Include a detailed description of the Phase II R/R&D plan to meet the technical objectives. The plan should indicate what will be done, where it will be done, and how the R/R&D will be carried out. Discuss in detail the methods planned to achieve each task or objective. Task descriptions, schedules, resource allocations, estimated task hours for each key personnel, and planned accomplishments, including project milestones, shall be included. Offerors should ensure that the estimated task hours provided in the work plan for key personnel are consistent with the hours reported in the Proposal Budget form. If the offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed, and charged should be included in the proposal.

STTR: In addition, the work plan will specifically address the percentage and type of work to be performed by the SBC and the RI. The plan will provide evidence that the SBC will exercise management direction and control of the performance of the STTR effort, including situations in which the PI may be an employee of the RI.

Part 5: Related R/R&D *(Suggested page limit – 1 page)*

Describe significant current and/or previous R/R&D that is directly related to the proposal, including any conducted by the PI or by the offeror. Describe how it relates to the proposed effort and any planned coordination with outside sources. The offeror must persuade reviewers of his or her awareness of key recent R/R&D conducted by others in the specific subject area.

Part 6: Key Personnel and Bibliography of Directly Related Work *(Suggested page limit – 5 pages)*

Identify all key personnel involved in Phase II activities whose expertise and functions are essential to the success of the project. Provide biographical information, including directly related education and experience. Where resume/vitae are extensive, summaries that focus on the most relevant experience or publications are desired and may be necessary to meet proposal size limitation.

The PI is considered key to the success of the effort and must make a substantial commitment to the project. The following requirements are applicable:

Functions: The functions of the PI are planning and directing the project, leading it technically and making substantial personal contributions during its implementation, serving as the primary contact with NASA on the project, and ensuring that the work proceeds according to contract agreements. Competent management of PI functions is essential to project success. The Phase II proposal shall describe the nature of the PI's activities and the amount of time that the PI will personally apply to the project. The amount of time the PI proposes to spend on the project must be acceptable to the Contracting Officer.

Qualifications: The qualifications and capabilities of the proposed PI and the basis for PI selection are to be clearly presented in the proposal. NASA has the sole right to accept or reject a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.

Eligibility: This part shall also establish and confirm the eligibility of the PI and shall indicate the extent to which existing projects and other proposals recently submitted or planned for submission in the year commit the time of the PI concurrently with this proposed activity. Any attempt to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI will result in rejection of the proposal. However, for an STTR the PI can be primarily employed by either the SBC or the RI. Please see section 1.5.3 for further explanation.

Note: If the Phase II PI is different than the PI proposed under Phase I, please provide rationale for the change.

Part 7: Commercialization and Business Planning *(Required minimum of 2 pages; no more than 8 pages)*

***NASA is requiring Phase II offerors to provide commercialization and business planning information in the proposal and is enforcing a requirement that firms provide a minimum and a maximum amount of information as required by page length. Firms that do not meet this requirement may be considered nonresponsive to this requirement and the proposal may not receive a score under Section 4.4.2: Factor 4: Commercialization and Business Planning, which could result in an overall lower score for the proposal*.**

The Commercialization Plan should provide the following information to communicate and validate that the firm has the knowledge and ability to commercialize the innovation being proposed and to validate the company's future viability and financial viability.

Below are a minimum set of specific requests for information that firms should provide in the Commercialization Plan. The Commercialization Plan should validate that a quantitative market analysis has been completed and that the innovation has a convincing value proposition. The Commercialization Plan should demonstrate that pro forma financial projections for the firm have been developed and validated to confirm the stability of the company. The Commercialization Plan should also address how to protect intellectual property (IP) that results from the innovation and whether the firm plans to receive any assistance and mentoring. Lastly, if the firm has any financial letters of commitment, these can be uploaded in the Capital Commitments Addendum and will not count against your page limit.

Commercial Potential—Quantitative Market Analysis

1. Describe the market segment and potential commercial total addressable market (TAM) that is appropriate to the proposed innovation.
    a. Indicate how the market was validated and what assumptions were used in the analysis.
    b. Indicate the market size by providing the scope in dollars if possible.
    c. Indicate market segmentation and/or TAM in dollars if possible.
    d. Indicate the projected percentage of the offeror's market share in 2 to 3 years after entry into the identified market.
2. Describe the proposed innovation in terms of target customers (e.g., NASA, other Federal agency, or commercial enterprise).
3. Describe the competitive landscape by identifying potential competitors.
    a. Indicate potential competitors by company name within the identified market.
    b. Discuss the barriers to entry and how many years it would take a competitor to enter this segment in terms of capitalization, technology, and people.
    c. Describe how the proposed innovation is different from current and future competitors.

Commercial Intent—Value Proposition

1. Describe the commercial development.
    a. Include the development timeline to bring the innovation to market.
    b. Describe the applicable business model (spin-out, license, original equipment manufacturer (OEM), etc.) the offeror would use to bring the innovation to market.

c. Indicate the channels of distribution (direct sales, distributors, etc.) that would be used in bringing the innovation into the identified market.
d. Indicate the pro forma 2- to 3-year revenue dollar projections based on the proposed innovation's penetration of the identified market.
e. Describe any follow-on development (long term > 5 years) plans to expand your proposed innovation's market presence.

2. Describe the risks to the commercial development plan and what mitigations, if any, can be taken over a reasonable period of time to lessen the risks.

Commercial Capability—How Will the Innovation Enter into a Market?

1. Describe the current and future company capitalization efforts.
   a. Provide a pro forma forecast based on income statements, balance sheet(s), and statement of cash flows. These forecasts should indicate current and projected revenues, expenses, and other items that are calculated as a percentage of future sales.
   b. Discuss the operations/manufacturing and business staff conducting the project and how they will be utilized to achieve commercialization.
   c. Describe the physical plant, including facilities and the capital equipment, tooling, and test equipment used to conduct the investigation and how they will be utilized to achieve commercialization.
   d. Discuss consultants, incubators, and research institutions that will be utilized to achieve commercialization.
   e. Indicate how the innovation will enter into production (i.e., in house or through a licensee or other means) and what changes (if any) will be made to company capitalization for commercialization.
2. As applicable, describe the approach, path to market, and revenues from past commercialization(s) resulting from SBIR/STTR awards disclosed in the Commercial Metrics Survey (CMS). (Companies with no SBIR/STTR awards or only fairly recent SBIR/STTR awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.)

Intellectual Property (IP)

1. Describe how you will protect the IP that results from your innovation.
   a. Note any actions you may consider to attain at least a temporary competitive advantage.
   b. Describe your company's prior IP record.
   c. Comment on the company's strategy to build a sustainable business through protection of IP.

Assistance and Mentoring

1. Describe the existing and future business relationships in terms of any formal partnerships, joint ventures, or licensing agreements with other companies/organizations.
2. Describe the plans for securing needed technical or business assistance through mentoring, partnering, or through arrangements with state assistance programs, Small Business Development Centers (SBDCs), Federally-funded research laboratories, Manufacturing Extension Partnership centers, Federal programs, or other assistance providers.
   - Identify if any assistance and mentoring is being requested under your TABA needs assessment and provide details in this section of the Commercialization Plan. The TABA needs assessment is reviewed separately from the Commercialization Plan.

Show you have a plan for this funding in one or more of the following ways:

1. A letter of commitment* for follow-on funding and/or product sales.
2. A letter of commitment* for matching funding to be provided for a future Phase II-E application.
3. A letter of capital commitment, signed by the proper authority (CEO, CFO, etc.), that indicates a commitment to provide funding and/or product sales, should the Phase II project be successful and the market need still exists.
4. A specific plan to secure Phase III funding.

****Note: Letters of funding support commitments should be submitted as part of the Capital Commitments Addendum found in section 3.4.6 and will be considered only under Factor 4: Commercial Potential and Feasibility (section 4). Any formal letters of commitment or intent submitted in the Capital Commitments Addendum will not count toward the page limits of the application*.***

Part 8: Facilities/Equipment *(Suggested page limit – 2 pages)*

If an offeror requests to use Government-furnished laboratory equipment, facilities, or services (collectively, "Government resources") the offeror shall describe in this part why the use of such Government resources is necessary and not reasonably available from the private sector. See sections 3.4.3.4 and 5.14 for additional requirements when proposing use of such Government resources. The narrative description of resources should support the proposed approach and documentation in the Proposal Budget form.

Part 9: Subcontractors and Consultants *(Suggested page limit – 2 pages)*

The offeror must describe all subcontracting or other business arrangements and identify the relevant organizations and/or individuals with whom arrangements are planned. The expertise to be provided by the entities must be described in detail, as well as the functions, services, number of hours, and labor rates. Offerors are responsible for ensuring that all organizations and individuals proposed to be utilized are actually available for the time periods proposed. Subcontract costs shall be documented in the Subcontractors/Consultants section of the Proposal Budget form, and supporting documentation should be uploaded for each (appropriate documentation is specified in the form). The narrative description of subcontractors and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards *(Suggested page limit – 0.5 page)*

WARNING: While it is permissible with proper notification to submit identical proposals or proposals containing a significant amount of essentially equivalent work for consideration under numerous Federal program solicitations, it is unlawful to enter into funding agreements requiring essentially equivalent work.

If an applicant elects to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other Federal program solicitations, a statement must be included in each such proposal indicating the following:

1. The name and address of the agencies to which proposals were submitted or from which awards were received.
2. Date of proposal submission or date of award.
3. Title, number, and date of solicitations under which proposals were submitted or awards received.
4. The specific applicable research topics for each proposal submitted for award received.
5. Titles of research projects.
6. Name and title of principal investigator or project manager for each proposal submitted or award received.

Offerors are at risk for submitting essentially equivalent proposals and therefore are strongly encouraged to disclose these issues to the soliciting agency to resolve the matter prior to award.

A summary of essentially equivalent work information, as well as related research and development on proposals and awards, is also required on the Proposal Certifications form (if applicable).

3.4.5 Research Agreement (Applicable for STTR proposals only)

STTR: The Research Agreement (different from the Allocation of Rights Agreement; see http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions) is a single-page document electronically submitted and endorsed by the SBC and RI. A model agreement is provided, or firms can create their own custom agreement. The Research Agreement shall be submitted as required in section 6.

All STTR Phase II proposals must provide sufficient information to convince NASA that the proposed SBC/RI cooperative effort represents a sound approach for converting technical information residing at the RI into a product or service that meets a need described in a solicitation research topic.

3.4.6 Capital Commitments Addendum Supporting Phase II and Phase III

Letters of capital commitment act as an indication of market validation for the proposed innovation and add significant credibility to the proposed effort. Although NASA can be a future stakeholder and could possibly issue a Phase III contract for the innovation to be infused in a future mission, it should be understood that NASA's goal under the SBIR/STTR program is for small businesses to commercialize innovations in markets that are larger than just NASA. Letters of capital commitment should demonstrate that the company has initiated dialogue with relevant non-NASA stakeholders (potential customers, end users, strategic partners, investors, etc.) for the proposed innovation and that a legitimate business opportunity may exist should the innovation prove feasible outside of NASA. Additionally, NASA offers a Phase II/E program where a funded Phase II company can obtain additional NASA funding for the innovation. A Phase II/E application requires matching funding from an outside source in order to qualify. Applicants are encouraged to provide letters of capital commitment that can provide matching funds for a future Phase II/E application and should start this process at the onset of the first Phase II project.

The letter(s) must not exceed 2 pages in length; should come directly from potential customers, end users, strategic partners, investors, etc.; and must contain affiliation information and contact information for the signatory stakeholder. Letters and supporting documents that only support the development of the innovation with no capital funding commitment as described above will not be reviewed. Letters and supporting documents from state, local, and Congressional representatives are NOT considered letters of capital commitment. They should not be submitted as part of the application and will not be reviewed.

If letters of capital commitment are not appropriate for this stage of an innovation due to business considerations, then the applicant must clearly justify why letters of capital commitment are not being included in the application. The justification should relate to the technical and commercial considerations of the innovation proposed in the application.

3.4.7 Briefing Chart

A one-page briefing chart is required to assist in the ranking and advocacy of proposals prior to selection and contains the following sections:

- Identification and Significance of Innovation
- Technical Objectives
- Proposed Deliverables
- NASA Applications
- Non-NASA Applications
- Graphic

The briefing chart shall not contain any proprietary data or ITAR-restricted data. An electronic form will be provided during the submissions process.

Note: The briefing chart is public information and may be disclosed. Do not include proprietary information in this form.

3.4.8 Firm Certifications

Firm certifications that are applicable across all proposal submissions submitted to this solicitation must be completed via the Firm Certifications section of the Proposal Submissions EHB. The offeror shall answer “Yes” or “No” as applicable. An example of the certification can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the certifications.

3.4.9 Audit Information

Although firms are not required to have an approved accounting system, knowledge that a firm has an approved accounting system facilitates NASA’s determination that rates are fair and reasonable. To assist NASA, the SBC shall complete the questions in the Audit Information form regarding the firm’s rates and upload the Federal agency audit report or related information that is available from the last audit. There is a separate Audit Information section in the Proposal Budget form that shall also be completed. If your firm has never been audited by a Federal agency, then answer "No" to the first question and you do not need to complete the remainder of the form. An electronic form will be provided during the submissions process.

The Contracting Officer will use this Audit Information to assist with negotiations if the proposal is selected for award. The Contracting Officer will advise offerors what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate to support the necessary determination on rates.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the audit information.

3.4.10 Prior Awards Addendum

If the SBC has received more than 15 Phase II awards in the prior 5 fiscal years, submit the name of the awarding agency, solicitation year, phase, date of award, funding agreement/contract number, and topic or subtopic title for each Phase II. If your firm has received any SBIR or STTR Phase II awards, even if it has received fewer than 15 in the last 5 years, it is still recommended that you complete this form for those Phase II awards your firm did receive. This information will be useful when completing the Commercialization Metrics Survey (CMS) and in tracking the overall success of the SBIR and STTR programs. Any NASA Phase II awards your firm has received will be automatically populated in the electronic form, as are any Phase II awards previously entered by the SBC during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the addendum information.

3.4.11 Commercial Metrics Survey (CMS)

NASA has instituted a comprehensive commercialization survey/data gathering process for firms with prior NASA SBIR/STTR awards. If the SBC has received any Phase III awards resulting from work on any NASA SBIR or STTR awards, provide the related Phase I or Phase II contract number, name of Phase III awarding agency, date of award, Funding Agreement number, amount, project title, and period of performance. The survey will also ask for firm financial, sales, and ownership information, as well as any commercialization success the firm has had as a result of SBIR or STTR awards. This information must be updated annually during proposal submission via the EHB. This information will allow firms to demonstrate their ability to carry SBIR/STTR research through to achieve commercial success and allows agencies to track the overall commercialization success of their SBIR and STTR programs. The survey should be limited to information requested above. An electronic form will be provided during the submissions process.

Note: Information received from SBIR/STTR awardees completing the survey is kept confidential and will not be made public except in broad aggregate, with no firm-specific attribution.

The CMS is a required part of the proposal submissions process and must be completed via the Proposal Submissions EHB. Companies with no SBIR/STTR awards or only fairly recent SBIR/STTR awards will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

3.4.12 Contractor Responsibility Information

No later than 10 business days after the notification of selection for negotiations, the offeror shall provide a signed statement from the firm’s financial institution(s), on the financial institution’s letterhead, stating whether or not the firm is in good standing and how long the firm has been with the institution.

3.4.13 Allocation of Rights Agreement (STTR awards only)

An SBC, before receiving an STTR award, must negotiate a written agreement between the SBC and the partnering Research Institution (RI), allocating intellectual property (IP) rights, if any, to carry out follow-on research, development, or commercialization. This written agreement must be signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable. A sample Allocation of Rights Agreement is available in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

The SBC must submit this agreement with the proposal by uploading it in the Proposal Budget form. This will help to expedite contract negotiations.

3.4.14 Phase II Request for Use of Technical and Business Assistance (TABA) Funds

Offerors are not required to request TABA at Phase II, and there is no prerequisite that an offeror must request and use Phase I TABA funding in order to obtain TABA under a Phase II award.

If an offeror decides to request TABA at Phase II, the offeror must request TABA authority from NASA in the Phase II proposal submission. Requests for TABA funding are not reviewed under the technical evaluation of the proposal, and the request for TABA will not be part of the decision to make a Phase II award. All TABA requests will be reviewed after a proposal is selected for award and during the contract negotiation process.

If an offeror chooses to request up to $50,000 for TABA at Phase II, the offeror will be required to provide a TABA plan and coordinate with the selected vendors to obtain the vendor qualification statement(s) and submit these via the Electronic Handbook (EHB). Below is an example of the type of information that will be requested under each.

TABA Plan

- Name, contact information, and company information including DUNS number for TABA vendor(s) that will provide the TABA services.
    - Note: All TABA vendors must be a legal business in the United States, and NASA will review the U.S. Government-wide System for Award Management (SAM) excluded parties list to ensure the proposed TABA vendor can receive Federal funds. NASA will consider TABA requests that are missing any requested TABA information (e.g., DUNS number, Vendor Qualification Statements, etc.) as incomplete and will not review the TABA request or provide TABA approval under the award.
- Description of TABA vendor(s) expertise and knowledge of providing technical and business assistance services.
- Itemized list of services and costs.
- Expected metric and outcome for each service to be provided.
- Plan to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- TABA costs reflected in the budget forms.

Vendor Qualification Statement(s)—A 3-page qualification statement for each of the selected vendors(s) that provides the following:

- Statement on the selected vendor(s) letterhead and signed by an authorizing entity within the vendors' organization that can attest to the services being provided.
- Documentation that the vendor is a legal business in the United States.
- A capabilities statement that
    - Indicates the qualifications, expertise, and knowledge to provide the TABA services requested by the offeror.
    - Indicates the level of expertise and knowledge of the Federal SBIR/STTR program and specifically any prior support provided to Phase I or II awardees.
    - Describes the overall metrics of success for the services requested by the offeror.
    - Describes the plans to report to the offeror so the offeror can report back to NASA as a deliverable on the outcomes and success of the TABA services and what information will be provided to validate the results.

NASA reserves the right to withhold funds requested for TABA until a formal review and approval of the requested vendor(s) is completed. If the project is selected for award and the offeror demonstrates this requirement sufficiently as determined by the Government, NASA will permit the awardee to acquire the requested assistance, in an amount up to $50,000 for the Phase II project, as an allowable cost of the SBIR/STTR award. Approval or denial of TABA funding will be provided during the contract negotiation period and before award. **The amount will be in addition to the Phase II award value, is not subject to any profit or fee by the requesting firm, and cannot be used in the calculation of indirect cost rates or General and Administrative Expenses (G&A).** The amount is based on the original period of performance. Requests for TABA funding outside of the Phase II period of performance will not be considered.

Schedule of Deliverables and Payments for TABA—Offerors that are approved to receive TABA under a Phase II award will be reimbursed for TABA expenses. Firms may request TABA reimbursement at the midpoint of the contract when submitting the midterm report and/or at the end of the contract when submitting the final report. Awardees requesting reimbursement will be required to submit invoices for services received when submitting the contract reports.

4. Method of Selection and Evaluation Criteria

4.1. Access to Proprietary Data by Non-NASA Personnel

4.1.1 Non-NASA Reviewers

In addition to utilizing Government personnel in the proposal review process, NASA, at its discretion and in accordance with 1815.207-71 of the NASA FAR Supplement, may utilize individuals from outside the Government with highly specialized expertise not found in the Government. Any decision to obtain an outside evaluation shall take into consideration requirements for the avoidance of organizational or personal conflicts of interest and any competitive relationship between the prospective contractor or subcontractor(s) and the prospective outside evaluator. Any such evaluation will be under agreement with the evaluator that the information (data) contained in the proposal will be used only for evaluation purposes and will not be further disclosed.

4.1.2 Non-NASA Access to Confidential Business Information

In the conduct of proposal processing and potential contract administration, the Agency may find it necessary to provide proposal access to other NASA contractor and subcontractor personnel. NASA will provide access to such data only under contracts that contain an appropriate NFS 1852.237-72 Access to Sensitive Information clause that requires the contractors to fully protect the information from unauthorized use or disclosure.

4.2 Phase I Proposals

NASA conducts a three-stage review process of all proposals to determine if the proposal can be moved forward to be evaluated and ranked on a competitive basis as follows:

1. All proposals received by the published deadline will undergo an administrative review to determine if the proposal meets the requirements found in section 3, Proposal Preparation Instructions and Requirements. A proposal that is found to be noncompliant with the requirements in section 3 will be declined and no further evaluations will occur. The offeror will be notified of NASA's decision to eliminate the proposal from consideration and the reasons for elimination.
2. Proposals that pass the administrative review will be screened to determine technical responsiveness to the subtopic of this solicitation. Proposals that are determined to be nonresponsive to the subtopic will be declined and no further evaluations will occur. The offeror will be notified that NASA declined the proposal and will receive written feedback.
    - ***Note: Offerors are advised to be thoughtful in selecting a subtopic to ensure the proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR/STTR program will NOT evaluate a proposal under a different subtopic not selected by the firm.***
3. Proposals determined to be responsive to the administrative requirements and technically responsive to the subtopic of this solicitation, as evidenced by the technical abstract and technical proposal, will be fully evaluated to determine the most promising technical and scientific approaches. Each proposal will be reviewed on its own merit.

NASA is under no obligation to fund any proposal or any specific number of proposals in a given subtopic. NASA also may elect to fund several, all, or none of the proposed approaches to the same subtopic.

4.2.1 Evaluation Process

Proposals shall provide all information needed for a complete evaluation. Evaluators will not seek additional information. NASA scientists and engineers will perform evaluations. Also, qualified experts outside of NASA (including industry, academia, and other Government agencies) may assist in performing evaluations as required to determine or verify the merit of a proposal. Offerors should not assume that evaluators are acquainted with the offeror, key individuals, or with any experiments or other information. Any pertinent references or publications should be noted in Part 5 of the technical proposal.

4.2.2 Phase I Evaluation Criteria

NASA intends to select for award those proposals that offer the most advantageous research and development and delivers a technological innovation that contributes to NASA's missions, provides societal benefit, and grows the U.S. economy. NASA will give primary consideration to the scientific and technical merit and feasibility of the proposal and its benefit to NASA interests. Each proposal will be evaluated and scored on its own merits using the factors described below:

Factor 1: Scientific/Technical Merit and Feasibility

The proposed R/R&D effort will be evaluated on whether it offers a clearly innovative and feasible technical approach to the described NASA problem area. Proposals must clearly demonstrate relevance to the subtopic as well as to one or more NASA mission and/or programmatic needs. Specific objectives, approaches, and plans for developing and verifying the innovation must demonstrate a clear understanding of the problem and the current state of the art. The degree of understanding and significance of the risks involved in the proposed innovation must be presented.

Factor 2: Experience, Qualifications, and Facilities

The technical capabilities and experience of the PI, project manager, key personnel, staff, and consultants and subcontractors, if any, are evaluated for consistency with the research effort and their degree of commitment and availability. The necessary instrumentation or facilities required must be shown to be adequate and any reliance on external sources, such as Government-furnished equipment or facilities, addressed (section 3.3.4, part 8).

Factor 3: Effectiveness of the Proposed Work Plan

The work plan will be reviewed for its comprehensiveness, effective use of available resources, labor distribution, and the proposed schedule for meeting the Phase I objectives. The methods planned to achieve each objective or task should be discussed in detail. Please see Factor 5 for price evaluation criteria.

STTR: The clear delineation of responsibilities of the SBC and RI for the success of the proposed cooperative R/R&D effort will be evaluated. The offeror must demonstrate the ability to organize for effective conversion of intellectual property into products and services of value to NASA and the commercial marketplace.

Factor 4: Commercial Potential and Feasibility

The evaluation of this factor will consider if the offeror has demonstrated their knowledge of NASA mission programs, other Government agencies and non-Government markets that could be applied to the proposed innovation. If known, offerors should indicate if there are any existing and projected commitments for funding of the innovation beyond Phase I and II. This can include investment, sales, licensing, and other indicators of commercial potential.

Factor 5: Price Reasonableness

The offeror's cost proposal will be evaluated for price reasonableness based on the information provided in the Proposal Budget form. NASA will comply with the FAR and NASA FAR Supplement (NFS) to evaluate the fairness and reasonableness of the proposed price/cost.

The Contracting Officer shall submit a recommendation for award to the Source Selection Official (SSO) after completion of evaluation for price reasonableness and determination of responsibility.

Scoring of Factors and Weighting

Factors 1, 2, and 3 will be scored numerically, with Factor 1 worth 50 percent and Factors 2 and 3 each worth 25 percent. The sum of the scores for Factors 1, 2, and 3 will constitute the Technical Merit score. The evaluation for Factor 4, Commercial Potential and Feasibility, will be in the form of an adjectival rating (Excellent, Very Good, Good, Fair, or Poor). For Phase I proposals, Technical Merit is more important than Commercial Merit. Factors 1 to 4 will be evaluated and used in the selection of proposals for negotiation. Factor 5 will be evaluated and used in the award decision, i.e., NASA will only make an award when the price is fair and reasonable.

4.2.3 Prioritization

In prioritizing proposals recommended for negotiations, NASA will also consider other factors, including recommendations from the program, centers, and mission directorates regarding such things as overall NASA priorities, program balance, and available funding. Programmatic balance considerations may include first-time awardees/participants, historically underrepresented communities, geographic distribution, balance across ideation/point solutions/market stimulation, and mission directorate/center balance.

4.2.4 Selection

Proposals recommended for negotiations will be forwarded to the SBIR/STTR PMO for analysis and presented to the Source Selection Official (SSO) and mission directorate representatives. The SSO has the final authority for choosing the specific proposals for contract negotiation. Each proposal selected for negotiation will be evaluated for cost/price reasonableness, the terms and conditions of the contract will be negotiated, and a responsibility determination made. The Contracting Officer will advise the SSO on matters pertaining to cost reasonableness, responsibility, and known past performance issues.

The list of proposals selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All firms will receive a formal notification letter. A Contracting Officer will negotiate an appropriate contract to be signed by both parties before work begins.

4.2.5 I-Corps

For awardees invited to submit an I-Corps proposal pursuant to section 3.3.6.2, NASA will provide a programmatic assessment of firms based on the following criteria:

- Proposed team members demonstrate a commitment to the requirements of the I-Corps program.
- The proposed team includes the proper composition and roles as described in the proposal requirements.

- The proposal defines that the small business is at a stage that fits the goals of the program and aligns with the NASA SBIR/STTR program goals.
- The proposal demonstrates that there is potential for commercialization in both NASA and non-NASA markets.

Based on these assessments, STTR offerors will be selected to participate in phone interviews conducted by the NASA SBIR/STTR PMO and the NSF-provided I-Corps instructors to determine the dynamics of the teams and gauge their level of commitment to meeting requirements for the full I-Corps cohort. NASA will make the final selections for I-Corps based upon its initial assessments of the I-Corps proposals for the SBIR boot camps and the assessments of the phone interviews for the STTR cohorts.

NASA anticipates a total of approximately 35 SBIR/STTR firms will be selected for participation in the I-Corps program for Phase I.

4.2.6 Technical and Business Assistance (TABA)

NASA conducts a separate review of all Phase I offeror requests for TABA after the SSO makes the final selection of projects to enter into negotiation for a Phase I contract. The SBIR/STTR PMO conducts the initial evaluation of the TABA request to determine if the request meets the requirements found in section 3.3.13 and the statute. The Contracting Officer makes the final determination to allow TABA funding under the contract.

The review of Phase I TABA requests will include the following:

- A review to determine if the awardee will use the funding to develop a Phase II TABA Needs Assessment and a Phase II Commercialization and Business Plan and/or if there are additional services being requested.
- A review of the vendor(s) expertise and knowledge of providing technical and business assistance services to develop and complete a TABA Needs Assessment, a Commercialization and Business Plan, or other proposed TABA services.
- A review of the costs to be provided to the TABA vendor(s).
- Proposed plans to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- Verification that TABA costs are reflected in the budget forms.

4.3 Phase II Proposals

NASA conducts a two-stage review process of all Phase II proposals to determine if the proposal can be moved forward to be evaluated and ranked on a competitive basis as follows:

1. All proposals received by the published deadline will undergo an administrative review to determine if the proposal meets the requirements found in section 3, Proposal Preparation Instructions and Requirements. Proposals that are found to be noncompliant with the requirements in section 3 will be eliminated from consideration. NASA will notify the offeror that their proposal has been eliminated and will provide the reason.
2. Proposals determined to be responsive to the administrative requirements will be technically evaluated to determine the most promising technical and scientific approaches.

Each proposal will be reviewed on its own merit. NASA is under no obligation to fund any proposal or any specific number of proposals in a given subtopic. It also may elect to fund several, all, or none of the proposed approaches to the same subtopic.

4.3.1 Evaluation Process

Proposals shall provide all information needed for a complete evaluation. Evaluators will not seek additional information. NASA scientists and engineers will perform evaluations. Also, qualified experts outside of NASA (including industry, academia, and other Government agencies) may assist in performing evaluations as required to determine or verify the merit of a proposal. Offerors should not assume that evaluators are acquainted with the offeror, key individuals, or with any experiments or other information. Any pertinent references or publications should be noted in Part 5 of the technical proposal.

4.3.2 Phase II Evaluation Criteria

NASA intends to select for award those proposals that offer the most advantageous research and development and deliver technological innovations that contributes to NASA's missions, provides societal benefit, and grows the U.S. economy. NASA will give primary consideration to the scientific and technical merit and feasibility of the proposal and its benefit to NASA interests. Each proposal will be evaluated and scored on its own merits using the factors described below:

Note: Past performance will not be a separate evaluation factor but will be evaluated under Factors 1 (with respect to performance in Phase I) and 4 (with respect to commercialization past performance, as applicable) below.

Factor 1: Scientific/Technical Merit and Feasibility

The proposed R/R&D effort will be evaluated on its originality, the feasibility of the innovation, and potential technical value. In addition, past performance of Phase I will be evaluated to determine the degree to which Phase I objectives were met, and whether the Phase I results indicate a Phase II project is appropriate. The evaluators may review the Phase I final technical report to verify the Phase I results.

Factor 2: Experience, Qualifications, and Facilities

The technical capabilities and experience of the PI or project manager, key personnel, staff, and consultants and subcontractors, if any, are evaluated for consistency with the research effort and their degree of commitment and availability. The necessary instrumentation or facilities required must be shown to be adequate and any reliance on external sources, such as Government-furnished equipment or facilities, addressed (section 3.4.4, Part 8).

Factor 3: Effectiveness of the Proposed Work Plan

The work plan will be reviewed for its comprehensiveness, effective use of available resources, labor distribution, and the proposed schedule for meeting the Phase II objectives. The methods planned to achieve each objective or task should be discussed in detail. The proposed path beyond Phase II for further development and infusion into a NASA mission or program will also be reviewed. Please see Factor 5 for price evaluation criteria.

STTR: The clear delineation of responsibilities of the SBC and RI for the success of the proposed cooperative R/R&D effort will be evaluated. The offeror must demonstrate the ability to organize for effective conversion of intellectual property into products and services of value to NASA and the commercial marketplace.

Factor 4: Commercialization and Business Planning: The proposal will be evaluated for the commercial potential and feasibility of the proposed innovation and associated products and services as described in Part 7. Evaluation of the commercialization and business plan and the overall proposal will include consideration of the following areas:

1. **Commercial Potential—Quantitative Market Analysis:** This includes assessment of
    a. The market segmentation and the commercial Total Addressable Market (TAM).
    b. The proposed innovation in terms of target customers (e.g., NASA, other Federal agency, commercial enterprise).
    c. The competitive landscape, by identifying potential competitors.

2. **Commercial Intent—Value Proposition:** This includes assessing
    a. The commercial development plan by providing a development timeline to bring the innovation to market.
    b. The applicable business model (spin-out, license, OEM, etc.) the offeror would use to bring the innovation to market.
    c. The risks to the commercial development plan and what mitigations, if any, can be taken over a reasonable period of time to lessen the risks.

3. **Commercial Capability—Pro Forma Financial Projections:** This includes assessment of
    a. The current and future company capitalization efforts.
    b. As applicable, the description of the approach, path to market, and revenues from past commercialization(s) resulting from SBIR/STTR awards disclosed in the CMS.

4. **Intellectual Property (IP):** This includes assessment of
    a. How the offeror will protect the IP that results from the innovation.

5. **Assistance and Mentoring:** This includes assessment of
    a. The existing and future business relationships in terms of any formal partnerships, joint ventures, or licensing agreements with other companies/organizations.
    b. The plans for securing needed technical or business assistance through mentoring, partnering, or through arrangements with state assistance programs, SBDCs, Federally-funded research laboratories, Manufacturing Extension Partnership centers, Federal programs, or other assistance providers.

6. **Capital Commitments Addendum:** This includes assessment of
    a. Any letters of commitment describing follow-on funding, product sales, or matching funding to be provided for a future Phase II/E application.
    b. Letter of intent or evidence of negotiations to provide funding should the Phase II project be successful and the market need still exists.
    c. A specific plan to secure Phase III funding.

Factor 5: Price Reasonableness

The offeror's cost proposal will be evaluated for price reasonableness based on the information provided in the Proposal Budget form. NASA will comply with the FAR and NASA FAR Supplement (NFS) to evaluate the proposed price/cost to be fair and reasonable.

The Contracting Officer shall submit a recommendation for award to the SSO after completion of evaluation for price reasonableness and determination of responsibility.

Scoring of Factors and Weighting

Factors 1, 2, 3, and 4 will be scored numerically, with Factor 1 worth 45 percent, Factors 2 and 3 each worth 25 percent, and Factor 4 worth five percent. The sum of the scores for Factors 1, 2, 3, and 4 will constitute the Technical Merit score. Factors 1 to 4 will be evaluated and used in the selection of proposals for negotiation. Factor 5 will be evaluated as part of the award decision, i.e., NASA will only make award when the price is fair and reasonable.

4.3.3 Prioritization

In prioritizing proposals recommended for negotiations, NASA will also consider other factors, including recommendations from the program, centers, and mission directorates regarding such things as overall NASA priorities, program balance, and available funding. Programmatic balance considerations may include first-time awardees/participants, historically underrepresented communities, geographic distribution, balance across ideation/point solutions/market stimulation, and mission directorate/center balance.

4.3.4 Selection

Proposals recommended for negotiations will be forwarded to the SBIR/STTR PMO for analysis and presented to the SSO and mission directorate representatives. The SSO has the final authority for choosing the specific proposals for contract negotiation. Each proposal selected for negotiation will be evaluated for cost/price reasonableness. After completion of evaluation for cost/price reasonableness and a determination of responsibility, the Contracting Officer will submit a recommendation for award to the SSO.

The list of proposals selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All firms will receive a formal notification letter. A Contracting Officer will negotiate an appropriate contract to be signed by both parties before work begins.

4.3.5 Technical and Business Assistance (TABA)

NASA conducts a separate review of all requests for TABA after the SSO makes the final selection of projects to enter into negotiation for a Phase II contract. This process consists of the SBIR/STTR PMO conducting the initial evaluation of the TABA request to determine if the request meets the requirements found in section 3.4.14 and the statute. The Contracting Officer makes the final determination to allow TABA funding to be used under the contract.

The review of Phase II TABA requests will include the following:

- A review to determine if the awardee provided a Phase II TABA Needs Assessment that describes the specific services being requested.
- A review of the vendor(s) expertise and knowledge of providing technical and business assistance services as described in TABA Needs Assessment and the vendor qualification statements.
- A review of the costs to be provided to the TABA vendor(s).
- Proposed plans to submit the two required deliverables summarizing the outcome of the TABA services with expected supporting information.
- Verification that TABA costs are reflected in the budget forms.

4.4 Notification and Feedback to Unsuccessful Offerors

After Phase I and Phase II selections for negotiation have been announced, a notification will be sent to the Small Business Official designated in the proposal according to the processes described below.

Note: Due to the competitive nature of the program and limited funding, recommendations to fund or not fund a proposal will be final, and the decision cannot be contested by the offeror. Any notification or feedback provided to the offeror is not an opportunity to reopen selection decisions or obtain additional information regarding the final decision. Applicants are encouraged to use the written feedback as a way to understand the outcome of their proposal review and to develop plans to strengthen future proposals.

Unsuccessful Phase II offerors cannot resubmit their unsuccessful Phase II proposal to a future Phase II solicitation.

4.4.1 Phase I Feedback

For Phase I, NASA uses a two-stage process to notify offerors of the outcome of their proposal.

1. At the time of the public selection announcement, the Small Business Official will receive an email indicating the outcome of the proposal.
2. NASA will automatically email proposal feedback to the designated Small Business Official within 60 days of the announcement of selection for negotiation. If you have not received your feedback by this time, contact the NASA SBIR/STTR Program Support Office at sbir@reisystems.com.

4.4.2 Phase II Feedback

For Phase II, NASA uses a two-stage process to notify offerors of the outcome of their proposal.

1. At the time of the public selection announcement, the Small Business Official will receive an email indicating the outcome of the proposal.
2. Per the requirements in the email notification and this solicitation, offerors must send a feedback request via email to the NASA SBIR/STTR Program Support Office at sbir@reisystems.com within 60 days after the selection announcement. ***Late requests will not be honored.***

5. Considerations

5.1 Requirement for Contracting

Upon award of a Funding Agreement, the awardee will be required to make certain legal commitments through acceptance of numerous clauses in both Phase I and Phase II Funding Agreements. Copies of complete terms and conditions are available upon request.

To simplify making contract awards and to reduce processing time, all contractors selected for Phase I and Phase II contracts will ensure that:

1. All information in your proposal is current (e.g., your address has not changed, the proposed PI is the same, etc.). If changes have occurred since submittal of your proposal, notify the Contracting Officer immediately.
2. Your firm is registered with System for Award Management (SAM) (section 2.2).
3. Your firm is in compliance with the VETS-4212 requirement (section 2.3.1). Confirmation that a VETS-4212 report has been submitted to the Department of Labor, and is current, shall be provided to the Contracting Officer within 10 business days of the notification of selection for negotiation.
4. Your firm HAS NOT proposed a Co-Principal Investigator.
5. For STTR, the proposal contains the Allocation of Rights Agreement (ARA) which has been signed by authorized representatives of the SBC, RI, and subcontractors and consultants, as applicable.
6. Your firm is required to provide timely responses to all communications from the NSSC Contracting Officer.
7. All proposed cost is supported with documentation, such as a quote, previous purchase order, published price lists, etc. All letters of commitment are dated and signed by the appropriate person with contact information. If a university is proposed as a subcontractor or a RI, the signed letter shall be on the university letterhead from the Office of Sponsored Programs. If an independent consultant is proposed, the signed letter should not be on a university letterhead. If the use of Government facilities or equipment is proposed, your firm shall submit a signed letter from the Government facility authorizing the use of the facility and stating the availability and the cost, if any, together with a signed letter from your firm justifying the need to use the facility.

From the time of proposal notification of selection for negotiation until the award of a contract, all communications shall be submitted electronically to NSSC-SBIR-STTR@nasa.gov.

Note: Costs incurred prior to and in anticipation of award of a contract are entirely the risk of the contractor in the event that a contract is not subsequently awarded. A notification of selection for negotiation is not to be misconstrued as an award notification to commence work.

5.2 Awards

5.2.1 Award Conditions

NASA awards are electronically signed by a NASA Contracting Officer and transmitted electronically to the organization via email. NSSC will distribute the NASA SBIR/STTR award with the following items for each phase.

Phase I:

- SF26—Contract Cover Sheet
- Contract Terms and Conditions—to include reference to the proposal and budget

- Attachment 1: Contract Distribution List
- Attachment 2: Example of the Final Summary Chart
- Attachment 3: IT Security Management Plan Template
- Attachment 4: Applicable Documents List
- Negotiation Confirmation
- Phase I Frequently Asked Questions (FAQs)

Phase II:

- SF26—Contract Cover Sheet
- Contract Terms and Conditions—to include reference to the proposal and budget
- Attachment 1: Contract Distribution List
- Attachment 2: Final Summary Chart and Instructions
- Attachment 3: IT Security Management Plan
- Attachment 4: Applicable Documents List
- Phase II Frequently Asked Questions (FAQs)

5.2.2 Type of Contract

NASA SBIR/STTR Phase I and Phase II awards are made as firm fixed price contracts.

5.2.3 Model Contracts

Examples of the Phase I and II contracts can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note: Model contracts are subject to change.

5.3 Reporting and Required Deliverables

An IT Security Management Plan is required at the beginning of the contract. Contractors interested in doing business with NASA and/or providing IT services or solutions to NASA should use the list found at the website of the Office of the Chief Information Officer (OCIO) as a reference for information security requirements: https://www.nasa.gov/content/security-requirements-policies. An example of the IT Security Management Plan can be found in the NASA SBIR/STTR Firm Library: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. For more information, see NASA FAR Supplement clause 1852.204-76

All contracts shall require the delivery of technical reports that present (1) the work and results accomplished; (2) the scientific, technical, and commercial merit and feasibility of the proposed innovation and project results; (3) the proposed innovation's relevance and significance to one or more NASA interests (section 9); and (4) the strategy for development and transition of the proposed innovation and project results into products and services for NASA mission programs and other potential customers. Deliverables may also include the demonstration of the proposed innovation and/or the delivery of a prototype or test unit, product, or service for NASA testing and utilization.

The technical reports and other deliverables are required as described in the contract and are to be provided to NASA. These reports shall document progress made on the project and activities required for completion. Periodic certification for payment will be required as stated in the contract. A final report must be submitted to NASA upon completion of the Phase I or Phase II R/R&D effort in accordance with applicable contract provisions.

A final New Technology Summary Report (NTSR) is due at the end of the contract, and New Technology Report(s) (NTR) are required if technology(ies) are developed under the award prior to submission of the final invoice. For additional information on NTSR and NTR requirements and definitions, see sections 1.12 and 5.8.

If TABA is requested, both Phase I and Phase II contracts will require TABA deliverables that summarize the outcome of the TABA services with expected supporting information.

Report deliverables shall be submitted electronically via the EHB. For any reports that require an upload, NASA requests the submission in PDF or Microsoft Word format.

Note: To access contract management in the EHB, you will be required to have an identity in the NASA Access Management System (NAMS). This is the Agency's centralized system for requesting and maintaining accounts for NASA IT systems and applications. The system contains user account information, access requests, and account maintenance processes for NASA employees, contractors, and remote users such as educators and foreign users. A basic background check is required for this account. Instructions will be provided during contract negotiations.

It is recommended that you begin this process immediately upon notification, as this access will be required to submit deliverables and invoices.

5.4 Payment Schedule

All NASA SBIR and STTR contracts are firm-fixed-price contracts. The exact payment terms will be included in the contract.

Although invoices are submitted electronically through the Department of Treasury's Invoice Processing Platform (IPP), as a condition for payment, invoice certifications shall be completed in the EHB for each individual invoice. The certification is preset in the EHB, and it shall be completed before uploading each invoice in IPP. Upon completion of the certification, a link to IPP is automatically provided in the EHB.

If TABA is requested, both Phase I and II awardees will be required to submit TABA vendor invoices for reimbursement per the payment schedule in sections 3.3.13 for Phase I and 3.4.14 for Phase II.

5.5 Profit or Fee

Contracts may include a reasonable profit. The reasonableness of proposed profit is determined by the Contracting Officer during contract negotiations. Reference FAR 15.404-4.

5.6 Cost Sharing

Cost sharing is permitted for proposals under this program solicitation; however, cost sharing is not required. Cost sharing will not be an evaluation factor in consideration of your proposal.

5.7 Rights in Data Developed Under SBIR Funding Agreements

The SBIR/STTR Protection Period begins with award of an SBIR/STTR Funding Agreement and ends 20 years, or longer at the discretion of the Participating Agency, from the date of award of an SBIR/STTR Funding Agreement (either Phase I, Phase II, or Federally-funded SBIR/STTR Phase III) unless subsequent to the award, the Agency and the SBC negotiate for some other protection period for the SBIR/STTR Data.

SBIR/STTR Data Rights Clause

(a) Definitions.

(1) Computer Software. Computer programs, source code, source code listings, object code listings, design details, algorithms, processes, flow charts, formulae, and related material that would enable the software to be reproduced, recreated, or recompiled. Computer Software does not include Computer Databases or Computer Software Documentation.

(2) Data. All recorded information, regardless of the form or method of recording or the media on which it may be recorded. The term does not include information incidental to contract or grant administration, such as financial, administrative, cost or pricing, or management information.

(3) Form, Fit, and Function Data. Data relating to items, components, or processes that are sufficient to enable physical and functional interchangeability, and data identifying source, size, configuration, mating and attachment characteristics, functional characteristics, and performance requirements. For Computer Software it means data identifying source, functional characteristics, and performance requirements, but specifically excludes the source code, algorithms, processes, formulas, and flow charts of the software.

(4) Government Purpose. Any activity in which the United States Government is a party, including cooperative agreements with international or multi-national defense organizations or sales or transfers by the United States Government to foreign governments or international organizations. Government Purposes include competitive procurement, but do not include the rights to use, modify, reproduce, release, perform, display, or disclose Technical Data or Computer Software for commercial purposes or authorize others to do so.

(5) Operations, Maintenance, Installation, or Training Purposes (OMIT) Data. Data that is necessary for operation, maintenance, installation, or training purposes (but not including detailed manufacturing or process data).

(6) SBIR/STTR Computer Software Rights. The Federal Government's rights during the SBIR/STTR Protection Period in specific types of SBIR/STTR Data that are Computer Software.

(A) The Federal Government may use, modify, reproduce, release, perform, display, or disclose SBIR/STTR Data that are Computer Software within the Government. The Federal Government may exercise SBIR/STTR Computer Software Rights within the Government for:

(1) Use in Federal Government computers;

(2) Modification, adaptation, or combination with other Computer Software, provided that the Data incorporated into any derivative software are subject to the rights in § 3(ee) of the SBIR/STTR Policy Directive and that the derivative software is marked as containing SBIR/STTR Data;

(3) Archive or backup; or

(4) Distribution of a computer program to another Federal agency, without further permission of the Awardee, if the Awardee is notified of the distribution and the identity of the recipient prior to the distribution, and a copy of the SBIR/STTR Computer Software Rights included in the Funding Agreement is provided to the recipient.

(B) The Federal Government shall not release, disclose, or permit access to SBIR/STTR Data that is Computer Software for commercial, manufacturing, or procurement purposes without the written permission of the Awardee. The Federal Government shall not release, disclose, or permit access to SBIR/STTR Data outside the Government without the written permission of the Awardee unless:

(i) The non-Governmental entity has entered into a non-disclosure agreement with the Government that complies with the terms for such agreements outlined in § 8 of the SBIR/STTR Policy Directive; and

(ii) The release or disclosure is—

(I) To a Federal Government support service contractor or their subcontractor for purposes of supporting Government internal use or activities, including evaluation, diagnosis and correction of deficiencies, and adaptation, combination, or integration with other Computer Software provided that SBIR/STTR Data incorporated into any derivative software are subject to the rights in § 3(ee) of the SBIR/STTR Policy Directive; or

(II) Necessary to support certain narrowly-tailored essential Government activities for which law or regulation permits access of a non-Government entity to a contractors' data developed exclusively at private expense, non-SBIR/STTR Data, such as for emergency repair and overhaul.

(7) SBIR/STTR Data. All Data developed or generated in the performance of an SBIR or STTR award, including Technical Data and Computer Software developed or generated in the performance of an SBIR or STTR award. The term does not include information incidental to contract or grant administration, such as financial, administrative, cost or pricing or management information.

(8) SBIR/STTR Data Rights. The Federal Government's license rights in properly marked SBIR/STTR Data during the SBIR/STTR Protection Period are as follows: SBIR/STTR Technical Data Rights in SBIR/STTR Data that are Technical Data or any other type of Data other than Computer Software; and SBIR/STTR Computer Software Rights in SBIR/STTR Data that is Computer Software. Upon expiration of the protection period for SBIR/STTR Data, the Federal Government has a royalty-free license to use, and to authorize others to use on its behalf, these data for Government Purposes, and is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties, except that any such data that is also protected under a subsequent SBIR/STTR award shall remain protected through the protection period of that subsequent award. The Federal Government receives Unlimited Rights in Form Fit, and Function Data, OMIT Data, and all unmarked SBIR/STTR Data.

(9) SBIR/STTR Protection Period. The period of time during which the Federal Government is obligated to protect SBIR/STTR Data against unauthorized use and disclosure in accordance with SBIR/STTR Data Rights. The SBIR/STTR Protection Period begins at award of an SBIR/STTR Funding Agreement and ends not less than twenty years from that date (See § 8(b)(4) of the SBIR/STTR Policy Directive).

(10) SBIR/STTR Technical Data Rights. The Federal Government's rights during the SBIR/STTR Protection Period in SBIR/STTR Data that are Technical Data or any other type of Data other than Computer Software.

(A) The Federal Government may, use, modify, reproduce, perform, display, release, or disclose SBIR/STTR Data that are Technical Data within the Government; however, the Government shall not use, release, or disclose the data for procurement, manufacturing, or commercial purposes; or release or disclose the SBIR/STTR Data outside the Government except as permitted by paragraph (B) below or by written permission of the Awardee.

(B) SBIR/STTR Data that are Technical Data may be released outside the Federal Government without any additional written permission of the Awardee only if the non-Governmental entity or foreign government has entered into a non-disclosure agreement with the Federal Government that complies with the terms for such agreements outlined in § 8 of the SBIR/STTR Policy Directive and the release is:

(i) Necessary to support certain narrowly tailored essential Government activities for which law or regulation permits access of a non-Government entity to a contractors' data developed exclusively at private expense, non-SBIR/STTR Data, such as for emergency repair and overhaul;

(ii) To a Government support services contractor in the performance of a Government support services contract for internal Government use or activities, including evaluation, diagnosis or modification, provided that SBIR/STTR Technical Data incorporated into any derivative Data are subject to the rights in § 3(ii) of the SBIR/STTR Policy Directive, and the release is not for commercial purposes or manufacture;

(iii) To a foreign government for purposes of information and evaluation if required to serve the interests of the U.S. Government; or

(iv) To non-Government entities or individuals for purposes of evaluation.

(11) Technical Data. Recorded information, regardless of the form or method of the recording, of a scientific or technical nature (including Computer Software Documentation and Computer Databases). The term does not include Computer Software or financial, administrative, cost or pricing, or management information, or other data incidental to contract or grant administration. The term includes recorded Data of a scientific or technical nature that is included in Computer Databases.

(12) Unlimited Rights. The Government's rights to access, use, modify, prepare derivative works, reproduce, release, perform, display, disclose, or distribute Data in whole or in part, in any manner and for any purpose whatsoever, and to have or authorize others to do so.

(b) Allocation of SBIR/STTR Data Rights.

(1) An SBC retains ownership of all SBIR/STTR Data it develops or generates in the performance of an SBIR/STTR award. The SBC retains all rights in SBIR/STTR Data that are not granted to the Federal Government in accordance with the SBIR/STTR Policy Directive. These rights of the SBC do not expire.

(2) During the SBIR/STTR Protection Period, the Federal Government receives SBIR/STTR Technical Data Rights in appropriately marked SBIR/STTR Data that is Technical Data or any other type of Data other than Computer Software; and SBIR/STTR Computer Software Rights in appropriately marked SBIR/STTR Data that is Computer Software.

(3) After the protection period, the Federal Government may use, and authorize others to use on its behalf, for Government Purposes, SBIR/STTR Data that was protected during the SBIR/STTR Protection Period. Awards issued by the U.S. Department of Energy are subject to Unlimited Rights after the expiration of the SBIR/STTR Protection Period.

(4) The Federal Government receives Unlimited Rights in Form, Fit, and Function Data, OMIT Data, and all unmarked SBIR/STTR Data

(c) Identification and Delivery of SBIR/STTR Data. Any SBIR/STTR Data delivered by the Awardee, and in which the Awardee intends to limit the Federal Government's rights to SBIR/STTR Data Rights, must be delivered with restrictive markings. The Federal Government assumes no liability for the access, use, modification, reproduction, release, performance, display, disclosure, or distribution of SBIR/STTR Data without markings. The Awardee or its subcontractors or suppliers shall conspicuously and legibly mark all such SBIR/STTR Data with the appropriate legend.

(1) The authorized legend shall be placed on each page of the SBIR/STTR Data. If only portions of a page are subject to the asserted restrictions, the SBIR/STTR Awardee shall identify the restricted portions (e.g., by circling or underscoring with a note or other appropriate identifier). With respect to SBIR/STTR Data embodied in Computer Software, the legend shall be placed on: (1) the printed material or media containing the Computer Software; or (2) the transmittal document or storage container. The legend shall read as follows:

"SBIR/STTR DATA RIGHTS
Funding Agreement No.
Award Date

SBIR/STTR Protection Period
SBIR/STTR Awardee
SBIR/STTR Awardee Address

This is SBIR/STTR Data (or is Computer Software or a Prototype that embodies or includes SBIR/STTR Data) to which the SBIR/STTR Awardee has SBIR/STTR Data Rights and to which the Federal Government has received SBIR/STTR Technical Data Rights (or SBIR/STTR Computer Software Rights) during the SBIR/STTR Protection Period and rights of use for Government Purposes after the SBIR/STTR Protection Period, as those terms are defined in the SBIR/STTR Funding Agreement. Awards issued by the U.S. Department of Energy are subject to Unlimited Rights after the SBIR/STTR Protection Period, as that term is defined in the SBIR/STTR Funding Agreement. Any reproduction of SBIR/STTR Data or portions of such data marked with this legend must also reproduce the markings."

(End of Legend)

(2) Data submitted without correct or appropriate markings may be corrected within 6 months from the date the data is delivered.

d) Relation to patents. Nothing regarding SBIR/STTR Data Rights in this clause shall imply a license to or imply a requirement to license to the Federal Government any patent to a Subject Invention (as defined under the Bayh-Dole Act implemented at 37 CFR 401) made under an SBIR/STTR award.

5.8 Copyrights

The contractor may copyright and publish (consistent with appropriate national security considerations, if any) material developed with NASA support. NASA receives a royalty-free license for the Federal Government and requires that each publication contain an appropriate acknowledgment and disclaimer statement.

5.9 Invention Reporting, Election of Title, Patent Application Filing, and Patents

Consistent with the SBIR/STTR program requirements, the Contractor shall complete electronic submission of the New Technology Report (NTR) for any new subject inventions, and the New Technology Summary Report (NTSR) for the interim and final contract periods, via the SBIR/STTR EHB at http://sbir.nasa.gov under the Handbooks section.

NASA SBIR and STTR contracts will include FAR 52.227-11 Patent Rights – Ownership by the Contractor and NFS 1852.227-11 Patent Rights – Ownership by the Contractor (APR 2015), which requires SBIR/STTR contractors to disclose all subject inventions to NASA within 2 months of the inventor's report to the contractor. A subject invention means any invention of the contractor made in the performance of work under this contract. Once the contractor discloses a subject invention, the contractor has up to 2 years to notify the Government whether it elects to retain title to the subject invention. If the contractor elects to retain title, a patent application covering the subject invention must be initiated within the 1-year statutory period. If the contractor fails to do any of these within time-specified periods, the Government has the right to obtain title.

SBCs normally may elect to retain ownership of any subject invention. In such circumstances, the Government shall have a nonexclusive, nontransferable, irrevocable, royalty-free license for Federal Government use. Further, the Government reserves the right to require the patent holder to license others in certain circumstances and may require that anyone exclusively licensed to sell the invention in the United States must normally manufacture it domestically. To the extent authorized by 35 U.S.C. 205, the Government will not make public any information disclosing a Government-supported invention for a minimum 4-year period (which may be extended by subsequent SBIR funding agreements) to allow the contractor a reasonable time to pursue a patent.

5.10 1852.225-70 Export Licenses

The contractor shall comply with all U.S. export control laws, including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). Offerors are responsible for ensuring that all employees who will work on this contract are eligible under export control laws, EAR, and ITAR. Any employee who is not a U.S. citizen or a permanent resident may be restricted from working on this contract if the technology is restricted under export control laws, ITAR, or EAR unless the prior approval of the Department of State or the Department of Commerce is obtained via a technical assistance agreement or an export license. Violations of these regulations can result in criminal or civil penalties.

For additional information on ITAR, please visit the Code of Federal Regulations (CFR) at https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title22/22cfr120_main_02.tpl. For additional information on EAR, please visit https://www.bis.doc.gov/index.php/regulations/export-administration-regulations-ear. For additional training, refer to http://sbir.gsfc.nasa.gov/content/training-resources. For additional assistance, contact the NASA SBIR helpdesk at sbir@reisystems.com.

5.11 Government-Furnished and Contractor-Acquired Property

In accordance with the SBIR/STTR Policy Directive, the Federal Government may transfer title to property provided by the SBIR/STTR Participating Agency to the awardee, or acquired by the awardee for the purpose of fulfilling the contract, where such transfer would be more cost effective than recovery of the property.

5.12 Essentially Equivalent Awards and Prior Work

If an award is made pursuant to a proposal submitted under either SBIR or STTR solicitations, the firm will be required to certify with every invoice that it has not previously been paid nor is currently being paid for essentially equivalent work by any agency of the Federal Government. **Failure to report essentially equivalent or duplicate efforts can lead to the termination of contracts and/or civil or criminal penalties.**

5.13 Additional Information

5.13.1 Precedence of Contract Over Solicitation

This program solicitation reflects current planning. If there is any inconsistency between the information contained herein and the terms of any resulting SBIR/STTR contract, the terms of the contract take precedence over the solicitation.

5.13.2 Evidence of Contractor Responsibility

In addition to the information required to be submitted for Phase II proposals as stated in in section 3.4.12, before award of an SBIR or STTR contract, the Government may request the offeror to submit certain organizational, management, personnel, and financial information to establish responsibility of the offeror. Contractor responsibility includes all resources required for contractor performance (e.g., financial capability, workforce, and facilities).

5.14 Use of Government Resources

Federal Departments and Agencies

Use of SBIR funding for unique Federal/non-NASA resources from a Federal department or agency that does not meet the definition of a Federal laboratory as defined by U.S. law and in the SBA Policy Directive on the SBIR/STTR program requires a waiver from the SBA. Proposals requiring waivers must include an explanation of why the waiver is appropriate. NASA will provide the offeror's request, along with an explanation to SBA, during the negotiation process. NASA cannot guarantee that a waiver can be obtained from SBA. Specific proposal instructions to request use of Government Resources are in sections 3.3 and 3.4 of the solicitation.

Note: NASA facilities qualify as Federal laboratories.

Support Agreements for Use of Government Resources

All offerors selected for award who require the use of any Federal facility shall, within 20 business days of notification of selection for negotiations, provide to the NSSC Contracting Officer an agreement by and between the Contractor and the appropriate Federal facility/laboratory, executed by the Government official authorized to approve such use. The agreement must delineate the terms of use, associated costs, and facility responsibilities and liabilities. Having a signed agreement for use of Government resources is a requirement for award.

For proposed use of NASA resources, a SBA SBIR/STTR Support Agreement template is available in the Firm Library (http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html) and must be executed before a contractor can use NASA resources. Offerors shall only include a signed letter of commitment from an authorized NASA point of contact in the proposals. NASA expects selected offerors to finalize and execute their SBA SBIR/STTR Support Agreement during the negotiation period with the NSSC.

Contractor Responsibilities for Costs

In accordance with FAR Part 45, it is NASA's policy not to provide services, equipment, or facilities (resources) (capital equipment, tooling, test, and computer facilities, etc.) for the performance of work under SBIR/STTR contracts. Generally, any contractor will furnish its own resources to perform the proposed work on the contract.

In all cases, the contractor shall be responsible for any costs associated with services, equipment, or facilities provided by NASA or another Federal department or agency, and such costs shall result in no increase in the price of this contract.

Note: The SBIR/STTR Support Agreement has been updated to include additional requirements related to NASA IT Security. The new additions are found under Section C. Part 3 of the Terms and Conditions (of the Support Agreement) and are below.

> 3. If Contractor's use of NASA resources includes use of or access to NASA Information Technology (IT) resources, the Contractor will at all times remain in compliance with and adhere to all NASA IT security requirements and processes, including those set forth in the Contractor's IT Security Plan. The Contractor's failure to do so may result in NASA's unilateral termination of this Use Agreement.

6. Submission of Proposals

6.1 Submission Requirements

NASA uses electronically supported business processes for the SBIR/STTR programs. An offeror must have internet access and an email address. Paper submissions are not accepted.

The Electronic Handbook (EHB) for submitting proposals is located at http://sbir.nasa.gov under the Handbooks section. The Proposal Submissions EHB guides firms through the steps for submitting an SBIR/STTR proposal. All EHB submissions are through a secure connection. Communication between NASA's SBIR/STTR programs and the firm is primarily through a combination of EHB and email.

6.2 Submission Process

New SBCs must register in the EHB to begin the submission process. Returning firms can use the same account they have used for previous submissions. Firms are encouraged to start the proposal process early to allow sufficient time to complete the submissions process. It is recommended that the Small Business Official, or an authorized representative designated by the Small Business Official, be the first person to register for the SBC. The SBC's Employer Identification Number (EIN)/Taxpayer Identification Number is required during registration.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update and change the firm-level forms.

For successful proposal submission, SBCs shall complete all forms online, upload their technical proposal in an acceptable format, and have the Small Business Official and Principal Investigator (PI) electronically endorse the proposal. Electronic endorsement of the proposal is handled online with no additional software requirements. The term "technical proposal" refers to the part of the submission as described in section 3.3.4 for Phase I proposals or 3.4.4 for Phase II proposals.

STTR: The Research Institution is required to electronically endorse the Research Agreement prior to the SBC endorsement of the completed proposal submission.

6.2.1 What Needs to Be Submitted

A complete proposal package must be submitted via the Proposal Submissions EHB, located on the NASA SBIR/STTR website, at the published due date and time.

Note: Other forms of submissions are not acceptable.

The complete Phase I proposal package includes the following:

1. Proposal Contact Information
2. Proposal Certifications
3. Proposal Summary
4. Proposal Budget
5. Technical Proposal (upload) (see Section 3.3.4)
6. Research Agreement (STTR only)
7. Briefing Chart
8. NASA Evaluation License Application (only if TAV is being proposed)

9. I-Corps Interest Form
10. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercial Metrics Survey (CMS)
11. Technical and Business Assistance (TABA) Request, if applicable
12. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)
13. For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.

The complete Phase II proposal package includes the following:

1. Proposal Contact Information
2. Proposal Certifications
3. Proposal Summary
4. Proposal Budget
5. Technical Proposal
6. Research Agreement (STTR only)
7. Briefing Chart
8. NASA Evaluation License Application, only if TAV is being proposed
9. Capital Commitments Addendum, if applicable
10. Technical and Business Assistance (TABA) Request, if applicable
11. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercialization Metrics Survey (CMS)
12. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)
13. For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.

6.2.2 Technical Proposal Submissions

NASA converts all technical proposal files to PDF format for evaluation. Therefore, NASA requests that technical proposals be submitted in PDF format.

Note: Embedded animation or video, as well as reference technical papers for "further reading," will not be considered for evaluation.

Virus Check

The offeror is responsible for performing a virus check on each submitted technical proposal. As a standard part of entering the proposal into processing, NASA will scan each submitted electronic technical proposal for viruses.

Note: The detection by NASA of a virus on any electronically submitted technical proposal may cause rejection of the proposal.

6.2.3 Technical Proposal Uploads

Firms will upload their technical proposal using the Proposal Submissions EHB. Directions will be provided to assist users. All transactions via the EHB are encrypted for security. Firms cannot submit security/password-protected technical proposals and/or supporting documentation, as reviewers may not be able to open and read the files.

You may upload the technical proposal multiple times, with each new upload replacing the previous version, but only the final uploaded and electronically endorsed version will be considered for review. Before you can submit the proposal package, you must download the entire proposal package and certify that you have reviewed it to ensure that you have uploaded the correct materials.

6.3 Deadline for Phase I Proposal Receipt

A complete Phase I proposal package shall be received no later than 5:00 p.m. EST on Friday, January 8, 2021, via the NASA SBIR/STTR website (http://sbir.nasa.gov), under the Handbooks section.

An offeror who waits to submit a proposal package near the deadline is at risk of not completing the required uploads and endorsements of their proposal. The Electronic Handbook (EHB) will terminate any active submissions at the published deadline of 5:00 p.m. ET on Friday, January 8, 2021. This termination will result in the offeror receiving an error message, and any remaining parts of the proposal will not be uploaded. If a complete proposal package is not received by the 5 p.m. EST deadline, the proposal package will be determined to be incomplete and will not be evaluated.

As stated in section 4.2, NASA conducts a three-stage review process of all proposals to determine if the proposal can be evaluated and ranked on a competitive basis. Proposals that are found to be noncompliant with the requirements in section 3 of this solicitation will be declined and no further evaluations will occur. The offeror will be notified of NASA’s decision to decline the proposal and that the decision is final.

Note: Offerors are strongly encouraged to start the submission process early to allow sufficient time for completing their complete proposal package.

6.4 Deadline for Phase II Proposal Receipt

A Phase II proposal package shall be received no later than 5:00 p.m. ET the last day of the Phase I contract original period of performance via the NASA SBIR/STTR website (http://sbir.nasa.gov) under the Handbooks section.

The EHB will be available for submissions approximately 6 weeks prior to completion date of Phase I contracts.

An offeror who waits to submit a proposal package near the deadline is at risk of not completing the required uploads and endorsements of their proposal. The Electronic Handbook (EHB) will terminate any active submissions at the published deadline of 5:00 p.m. ET on the last day of the Phase I original contract period of performance. This termination will result in the offeror receiving an error message, and any remaining parts of the proposal will not be uploaded. If a complete proposal package is not received by the 5 p.m. EST deadline, the proposal package will be determined to be late and will not be evaluated.

As stated in section 4.3, NASA conducts a two-stage review process of all proposals to determine if the proposal can be evaluated and ranked on a competitive basis. Proposals that are found to be noncompliant with the requirements in section 3 of this solicitation will be declined, and no further evaluations will occur. The offeror will be notified of NASA’s decision to decline the proposal and that the decision is final.

6.5 Acknowledgment of Proposal Receipt

NASA will acknowledge receipt of electronically submitted proposals upon endorsement by the Small Business Official to the Small Business Official's email address as provided on the proposal cover sheet, as well as to the user who created the proposal, if different. ***If a proposal acknowledgment is not received after submission, the offeror should immediately contact the NASA SBIR/STTR Program Support Office at 301-937-0888 or sbir@reisystems.com***.

6.6 Withdrawal of Proposals

Prior to the close of submissions, proposals may be withdrawn via the Proposal Submissions EHB hosted on the NASA SBIR/STTR website (http://sbir.nasa.gov) under the Handbooks section. In order to withdraw a proposal after the deadline, the designated Small Business Official must send written notification via email to sbir@reisystems.com.

6.7 Service of Protests

For any concerns or disagreements, see Section 1.11.

Copies of any protests, as defined in section 33.101 of the FAR, shall be served on the Contracting Officer by obtaining written and dated acknowledgement of receipt from the NASA SBIR/STTR program contact listed below:

Theresa Stanley
NASA Shared Services Center
Building 1111, Jerry Hlass Road
Stennis Space Center, MS 39529
Agency-SBIR-STTRSolicitation@mail.nasa.gov

The copy of any protest shall be received within one calendar day of filing a protest with the U.S. Government Accountability Office (GAO).

7. Proposal, Scientific and Technical Information Sources

7.1 NASA Websites

General sources relating to organizational and programmatic information at NASA is available via the following websites:

NASA Budget Documents, Strategic Plans, and Performance Reports:
http://www.nasa.gov/about/budget/index.html
NASA Organizational Structure: http://www.nasa.gov/centers/hq/organization/index.html
NASA SBIR/STTR Programs: http://sbir.nasa.gov

Information regarding 2020 NASA Technology Taxonomy and the NASA Strategic Integration Framework can be obtained at the following websites:

Office of the Chief Technologist	
2020 NASA Technology Taxonomy	https://www.nasa.gov/offices/oct/taxonomy/index.html

NASA Mission Directorates	
Aeronautics Research	http://www.aeronautics.nasa.gov/
Human Exploration and Operations	http://www.nasa.gov/directorates/heo/home/
Science	http://nasascience.nasa.gov
Space Technology	http://www.nasa.gov/directorates/spacetech/home/index.html

NASA Centers	
Ames Research Center (ARC)	http://www.nasa.gov/centers/ames/home/index.html
Armstrong Flight Research Center (AFRC)	http://www.nasa.gov/centers/armstrong/home/index.html
Glenn Research Center (GRC)	http://www.nasa.gov/centers/glenn/home/index.html
Goddard Space Flight Center (GSFC)	http://www.nasa.gov/centers/goddard/home/index.html
Jet Propulsion Laboratory (JPL)	http://www.nasa.gov/centers/jpl/home/index.html
Johnson Space Center (JSC)	http://www.nasa.gov/centers/johnson/home/index.html
Kennedy Space Center (KSC)	http://www.nasa.gov/centers/kennedy/home/index.html
Langley Research Center (LaRC)	http://www.nasa.gov/centers/langley/home/index.html
Marshall Space Flight Center (MSFC)	http://www.nasa.gov/centers/marshall/home/index.html
Stennis Space Center (SSC)	http://www.nasa.gov/centers/stennis/home/index.html
NASA Shared Services Center (NSSC)	https://www.nssc.nasa.gov/

7.2 United States Small Business Administration (SBA)

The Policy Directives for the SBIR/STTR programs may be obtained from the SBA at the following address:

U.S. Small Business Administration
Office of Technology – Mail Code 6470
409 Third Street, S.W.
Washington, DC 20416
Phone: 202-205-6450

SBA information can also be obtained at http://www.sbir.gov.

7.3 National Technical Information Service

The National Technical Information Service (NTIS) is an agency of the Department of Commerce and is the Federal Government's largest central resource for Government-funded scientific, technical, engineering, and business-related information. For information regarding various NTIS services and fees, call or write:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Phone: 703-605-6000
URL: http://www.ntis.gov

7.4 Other Sources of Assistance

The U.S. Government invests in a wide variety of resources designed to aid and assist small business owners and their employees. A variety of websites containing these resources and links to additional resources can be found at http://sbir.nasa.gov/content/additional-sources-assistance.

8. Submission Forms

Note: Previews of all forms and certifications are available via the NASA SBIR/STTR Firm Library, located at http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

8.1 SBIR Phase I Checklist

For assistance in completing your Phase I proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.3.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Briefing Chart
    g. NASA Evaluation License Application (only if TAV is being proposed)I-Corps Interest Form
    h. Technical and Business Assistance (TABA) Request, if applicable
    i. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey (CMS)
    j. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)
3. **The technical proposal shall not exceed a total of 19 standard 8.5- by 11-inch pages and shall follow the format requirements (section 3.3.2).**
4. The technical proposal contains all 10 parts in order (section 3.3.4).
5. Any additional required letters/documentation.
    a. A letter of commitment from the appropriate Government official if the research or R&D effort requires use of Government resources (section 3.3.3.4).
    b. Letters of commitment from subcontractors/consultants.
    c. If the firm is an eligible joint venture or a limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    d. NASA Evaluation License Application if proposing the use of NASA technology (TAV).
    e. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $125,000 (section 1.3), and if requesting TABA, the cost for TABA does not exceed $6,500 (section 3.3.13).
7. Proposed project duration does not exceed 6 months (section 1.3).
8. Proposal package electronically endorsed by the Small Business Official and the Principal Investigator (PI) at the published deadline.

9. **Complete proposal packages and all endorsements shall be received no later than 5:00 p.m. ET on January 8, 2021 (section 6.3).**

8.2 STTR Phase I Checklist

For assistance in completing your Phase I proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.3.
   a. Proposal Contact Information
   b. Proposal Certifications
   c. Proposal Summary
   d. Proposal Budget
   e. Technical Proposal
   f. Research Agreement (STTR only)
   g. Briefing Chart
   h. NASA Evaluation License Application (only if TAV is being proposed)I-Corps Interest Form
   i. Technical and Business Assistance (TABA) Request, if applicable
   j. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
      i. Firm Certifications
      ii. Audit Information
      iii. Prior Awards Addendum
      iv. Commercialization Metrics Survey (CMS)
   k. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)
      For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.
3. **The technical proposal shall not exceed a total of 19 standard 8.5- by 11-inch pages and shall follow the format requirements (section 3.3.2).**
4. The technical proposal contains all 10 parts in order (section 3.3.4).
5. Any additional required letters/documentation.
   a. A letter of commitment from the facility manager if the research or R&D effort requires use of Federal facilities (section 3.3.3.4).
   b. Letters of commitment from subcontractors/consultants.
   c. If the firm is an eligible joint venture or limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
   d. NASA Evaluation License Application if proposing the use of NASA technology (TAV).
   e. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $125,000 (section 1.3) and if requesting TABA, the cost for TABA does not exceed $6,500 (section 3.3.13).
7. Proposed project duration does not exceed 13 months (section 1.3).
8. Research Agreement electronically endorsed by both the Small Business Official and the Research Institution (RI) (section 3.3.5, 6.2).

9. Proposal package electronically endorsed by the Small Business Official and the Principal Investigator (PI) at the published deadline.
10. Signed Allocation of Rights Agreement.
11. **Complete proposal packages and all endorsements shall be received no later than 5:00 p.m. ET on January 8, 2021 (section 6.3).**

8.3 SBIR Phase II Checklist

For assistance in completing your Phase II proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).

2. The entire proposal package is submitted consistently with the requirements outlined in section 3.4.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Briefing Chart
    g. NASA Evaluation License Application, only if TAV is being proposed
    h. Capital Commitments Addendum, if applicableTechnical and Business Assistance (TABA) Request, if applicableFirm-Level Forms (completed once for all proposals submitted to a single solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey (CMS)
    i. Electronic Endorsement by the Small Business Official and Principle Investigator (PI)

3. **The technical proposal shall not exceed a total of 46 8.5- by 11-inch pages and shall follow the format requirements (section 3.4.2).**

4. The technical proposal contains all 10 parts in order (section 3.4.4).

5. Any additional required letters/documentation.
    a. A letter of commitment from the facility manager if the research or R&D effort requires use of Federal facilities (section 3.4.4).
    b. Letters of commitment from subcontractors/consultants.
    c. Letters in support of Capital Commitments Addendum.
    d. If the firm is an eligible joint venture or limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    e. NASA Evaluation License Application if proposing the use of NASA technology (TAV).
    f. Supporting documentation of budgeted costs.

6. Proposed funding does not exceed $750,000 (section 1.8), and if requesting TABA, the cost for TABA does not exceed $50,000 (section 3.4.14).

7. Proposed project duration does not exceed 24 months (section 1.3).

8. Proposal package electronically endorsed by the Small Business Official and the Principal Investigator (PI) at the required deadline.

9. **Complete Phase II proposal packages and all endorsements shall be <u>received</u> no later than 5 p.m. ET on the last day of the Phase I contract period of performance (section 6.4).**

8.4 STTR Phase II Checklist

For assistance in completing your Phase II proposal, use the following checklist to ensure your submission is complete.

1. The proposal and innovation is submitted for one subtopic only (section 3.1).
2. The entire proposal package is submitted consistently with the requirements outlined in section 3.4.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
    e. Technical Proposal
    f. Research Agreement
    g. Briefing Chart
    h. Capital Commitments Addendum, if applicable
    i. NASA Evaluation License Application, only if TAV is being proposed
    j. Technical and Business Assistance (TABA) Request, if applicable
    k. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey (CMS)
    l. Electronic Endorsement by the Small Business Official and Principle Investigator (PI) For STTR submissions, it also includes the Research Agreement and endorsement of this agreement by the Research Institution (RI) official.
3. **The technical proposal shall not exceed a total of 46 8.5- by 11-inch pages and shall follow the format requirements (section 3.4.2).**
4. The technical proposal contains all 10 parts in order (section 3.4.4).
5. Any additional required letters/documentation.
    a. A letter of commitment from the facility manager if the research or R&D effort requires use of Federal facilities (section 3.4.4).
    b. Letters of commitment from subcontractors/consultants.
    c. Letter in support of Capital Commitments Addendum.
    d. If the firm is an eligible joint venture or limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.
    e. NASA Evaluation License Application if proposing the use of NASA Technology (TAV).
    f. Supporting documentation of budgeted costs.
6. Proposed funding does not exceed $750,000 (section 1.8), and if requesting TABA, the cost for TABA does not exceed $50,000 (section 3.4.14).
7. Proposed project duration does not exceed 24 months (section 1.3).
8. Research Agreement electronically endorsed by both the Small Business Official and the Research Institution (RI) (section 3.4.5, 6.2).
9. Proposal package electronically endorsed by the Small Business Official and the Principal Investigator (PI) at the required deadline.

10. Signed Allocation of Rights Agreement.
11. **Complete Phase II proposal packages and all endorsements shall be <u>received</u> no later than 5:00 p.m. ET on the last day of the Phase I contract (section 6.4).**

9. Research Topics for SBIR and STTR

Introduction

The SBIR and STTR subtopics are organized into groupings called Focus Areas. Focus Areas are a way of grouping NASA interests and related technologies with the intent of making it easier for proposers to understand related needs across the Agency and thus identify subtopics where their research and development capabilities may be a good match.

<u>Notes:</u>
Offerors are advised to be thoughtful in selecting a subtopic to ensure the proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR/STTR program will NOT move a proposal between subtopics.

The SBIR and STTR subtopics will appear in one combined listing. The STTR subtopics will begin with a "T" and will be clearly marked so that offerors will know that the additional Research Institution (RI) partnership is required before submitting a proposal.

The NASA SBIR/STTR program does not allow switching from STTR to SBIR, or vice versa, during the proposal review process or after an award. The NASA SBIR/STTR program does not allow switching between Phase I and Phase II.

Subtopic numbering conventions from previous years' solicitations have been maintained for traceability of like subtopics from previous solicitations. The mapping is as follows:

A – Aeronautics Research Mission Directorate (ARMD)
H – Human Exploration and Operations Mission Directorate (HEOMD)
S – Science Mission Directorate (SMD)
Z – Space Technology Mission Directorate (STMD)
T – Small Business Technology Transfer (STTR)

Proposers should think of the subtopic lead mission directorates and lead/participating centers as potential customers for their proposals. Multiple mission directorates and centers may have interests across the subtopics within a Focus Area.

Related subtopic pointers are identified in the subtopic headers when applicable to assist proposers with identifying related subtopics that also potentially seek related technologies for different customers or applications. As stated in section 3.1, an offeror shall not submit the same (or substantially equivalent) proposal to more than one subtopic. It is the offeror's responsibility to select which subtopic to propose to.

Potential Transition and Infusion Opportunities

The NASA SBIR/STTR program has over the years helped small businesses transition or "infuse" their innovations into NASA programs and missions. The subtopics that are provided in this solicitation are developed by the mission directorates and centers to address a variety of technology needs. The opportunities listed below and in Appendix C are only a few examples of NASA programs where transition and infusion can take place. It should be noted that there are many other opportunities across NASA that are of equal importance to the Agency and the Nation. These include, but are not limited to, Aeronautics, Earth and Planetary (beyond Moon and Mars) Science, Heliophysics, and Astrophysics.

Refer to Appendix C for a listing of all the subtopics by focus area and a designation if these following opportunities that exist within each subtopic. Proposers should think of this as a guide while understanding that NASA is not placing any priority on subtopics or awards that fall under these specific opportunities. Proposers that submit a proposal under a subtopic that is aligned with these opportunities do not increase their chance for an award.

Moon to Mars Campaign

NASA is implementing the Moon to Mars campaign, a program for the exploration and utilization of the Moon followed by missions to Mars and other destinations (see https://www.nasa.gov/topics/moon-to-mars/overview). Working with U.S. companies and international partners, NASA will push the boundaries of human exploration forward to the Moon and on to Mars. NASA is working to establish a permanent human presence on the Moon within the next decade to uncover new scientific discoveries and lay the foundation for private companies to build a lunar economy.

Commercial Lunar Payload Services (CLPS)

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services.

NASA Flight Opportunities

Flight Opportunities facilitates rapid demonstration of promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital testing with industry flight providers. The program matures capabilities needed for NASA missions and commercial applications while strategically investing in the growth of the U.S. commercial spaceflight industry. These flight tests take technologies from ground-based laboratories into relevant environments to increase technology readiness and validate feasibility while reducing the costs and technical risks of future missions. Awards and agreements for flight test are open to researchers from industry, academia, non-profit research institutes, and government organizations. These investments help advance technologies of interest to NASA while supporting commercial flight providers and expanding space-based applications and commerce. For more information on how to apply for a flight test, see https://www.nasa.gov/directorates/spacetech/flightopportunities/opportunities.

International Space Station (ISS) Utilization

Flying experiments on Station is a unique opportunity to eliminate gravity as a variable, provide exposure to vacuum and radiation, and have a clear view of the Earth and space. For more information on ISS opportunities, see https://www.nasa.gov/mission_pages/station/research/research_information.html.

Focus Area 1 In-Space Propulsion Technologies

Lead MD: **STMD**

Participating MD(s): **STTR**

NASA is interested in technologies for advanced in-space propulsion systems to reduce travel time, increase payload mass, reduce acquisition costs, reduce operational costs, and enable new science capabilities for exploration and science spacecraft. The future will require demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. This focus area seeks innovations for NASA propulsion systems in chemical, electric, nuclear thermal and advanced propulsion systems related to human exploration and science missions. Propulsion technologies will focus on a number of mission applications including ascent, descent, orbit transfer, rendezvous, station keeping, proximity operations and deep space exploration.

Z10.01 Cryogenic Fluid Management (SBIR)

Lead Center: **GRC**

Participating Center(s): **JSC, MSFC**

Scope Title:

Cryogenic Fluid Management (CFM)

Scope Description:

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, methane) storage and transfer to support NASA's space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include, but are not limited to, upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in situ resource utilization (ISRU). Anticipated outcome of Phase I proposals is expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II.

- Integrated refrigeration cycles for a combination of hydrogen and oxygen liquefaction on the lunar surface. Cycles should be initially sized for at least 11.7 metric tons per year (3.3 kg/hr of oxygen and 0.4 kg/hr of hydrogen). It is desired to minimize the mass and power of the system. Proposals should compare total input power and mass to liquefaction of fluids separately. The main contaminate is water; while the final contamination level is not known, some sensitivity should be explored in the 10s of ppm range in each stream. For Phase I, the main product should be cycle analysis and configuration, including the key sensitivities of the cycle. Phase II should include some level of buildup and test/demonstration of system.
- Subgrid computational fluid dynamics (CFD) of the film condensation process for 1g and low-gravity (lunar or martian) to be implemented into commercial industry standard CFD codes. The

subgrid model should capture the formation and growth of the liquid layer as well as its movement along a wall boundary. The condensation subgrid model should be validated against experimental data (with a target accuracy of 25%), with emphasis on cryogenic fluid-based condensation data. The subgrid model and implementation scheme should be a deliverable. Phase I should be focused on simplified geometries (vertical plates/walls), while Phase II should be focused on complicated geometries (full propellant cylindrical).

- Integrated cryogenic propellant gas generation system for lander vehicles and supporting architecture: Design and develop concepts to enable integrated cryogenic propellant gas generation for lander vehicle reactor coolant system (RCS) gas accumulators. Proposers shall consider vehicle designs that use either liquid hydrogen/liquid oxygen or liquid methane/liquid oxygen main propellant combinations. Designs shall be capable of outputting a minimum 3,000-psia storage press at 300-K storage temperature and meeting the following minimum mass gasification rates: 0.1 g/sec hydrogen, 0.3 g/sec methane, and/or 0.5 g/sec oxygen. The gas generation system shall demonstrate novel integration into alternate vehicle heat sources such as thermal control systems, active CFM cooling systems, fuel cells, internal combustion (I/C) engines, electrical power systems, pumps, etc. Proposed gas generation system shall not couple to vehicle main engines or RCS thruster during firing operations. Proposers should consider integration into vehicle system architectures, mass efficiency, and minimization of propellant waste. Phase I effort should include vehicle integration concept design, design of autogenous pressurization hardware, and test demonstration of autogenous pressurization hardware using liquid cryogens. Phase II should focus on system refinement and a scale test demonstration using liquid propellants.
- Develop cryogenic mass flow meters applicable to liquid oxygen and methane, having a volumetric flow measurement capacity of 1 to 20 L/min (fluid line size of approximately ½ in.), of rugged design that is able to withstand launch-load vibrations (e.g., 20g rms), with remote powered electronics (not attached to the flowmeter), able to function accurately in microgravity and vacuum environment, and having measurement error less than +/- 0.5% of the mass flow rate reading. Ability to measure bidirectional flow, compatibility with liquid hydrogen, and ability to measure mass flow rate during two-phase flows is also desired. Designs that can tolerate gas flow without damage to the flowmeter are also desired. Goal is proof of concept end of Phase I, working flowmeter end of Phase II.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.1 Cryogenic Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:

Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment, preferably with hardware deliverable to NASA.

State of the Art and Critical Gaps:

CFM is a crosscutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU-produced propellants. The Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA's exploration plans for multiple architectures, whether it is hydrogen/oxygen or methane/oxygen systems, including chemical propulsion and nuclear thermal propulsion. Several recent Phase IIs have resulted from CFM subtopics, most notably for advanced insulation, cryocoolers, and liquid acquisition devices.

Relevance / Science Traceability:

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Artemis as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, oxygen will have to be produced, liquefied, and stored, the latter two of which are CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed.

References:

1. Johnson, et al. "Comparison of oxygen liquefaction methods for use on the Martian surface." Cryogenics 90, 60-69, 2018.
2. Green, R. and Kleinhenz, J. "In-Situ Resource Utilization (ISRU) Living off the Land on the Moon and Mars." American Chemical Society National Meeting & Exposition; March 31, 2019 - April 04, 2019; Orlando, FL; United States.
3. Stochl, R., et al. "Autogenous pressurization of cryogenic vessels using submerged vapor injection." NASA-TM-104516, 1991.

Z10.03 Space Nuclear Propulsion (SBIR)

Lead Center: **MSFC**

Participating Center(s): **GRC, SSC**

Scope Title:

Reactor and Fuel System for Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP)

Scope Description:

The focus is on highly stable materials for nuclear fuels and nonfuel reactor components (insulator, moderator, etc.) that can heat the working fluid to high temperatures, be compatible with the working fluid, minimize dimensional deformation during operation, and be easy to manufacture to meet the design requirements.

NEP relies on reactor systems capable of achieving 5-yr life with a working fluid exit temperature of at least 927 °C and a thermal power of at least 5 MW. Innovative concepts for enhancing reactor reliability, fabricability, and testability while still enabling an acceptable power system specific mass (typically <15 kg/kWe) are sought. Projected use for human missions to Mars will require continuous run times ~2 yr.

NTP uses hydrogen as the working fluid (propellant). Fuel temperatures required to achieve a specific impulse (Isp) of 900 sec can exceed 2,600 °C. Projected use for human missions to Mars will require cumulative run times ~3.5 hr and 5 to 6 restarts. Current technology hurdles with ceramic and carbide fuels include embedding nitride or carbide kernels with coatings in a carbide matrix with potential for total fission product containment and high fuel burnup, and simple modern manufacturing of complex geometries with high uniform density.

Specific technologies being sought include:

- Innovative ultrahigh-temperature material property testing and performance evaluation above 2,000 °C in a vacuum and hot hydrogen environment. The materials used in the reactor core will reach temperatures up to 2,700 °C. No current material property data and performance characteristics above 2,000 °C exist, and the subtopic wishes to solicit innovations in this area to start filling those data gaps, thus reducing technical risk of material choices within the reactor, and begin optimization of material choices. The key materials to be evaluated are the fuel element matrix materials, such as refractory ceramics. These materials are highly sensitive to oxygen and must be tested in a vacuum, inert atmosphere, or reducing (hydrogen) atmosphere. Some of the key parameters to gather at 2,000+ °C temperatures include (but are not limited to) static modulus, modulus of rupture, tension and compression flow curves, tension and compression creep, fatigue and hardness with measurement absolute accuracies ±0.5%. In addition to those key parameters, contact and noncontact strain measurement techniques with absolute accuracies of ±0.5% at these ultrahigh temperatures are also sought.
- Innovative fuel element designs and propellant flow configurations that facilitate achieving propellant exit temperatures in excess of 2,500 °C.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

Desired deliverables for this technology would include research that can be conducted to determine technical feasibility of the proposed concept during Phase I and show a path toward a Phase II hardware demonstration. Testing the technology in a simulated (as close as possible) NTP environment as part of Phase II is preferred. Delivery of a prototype test unit at the completion of Phase II allows for followup testing by NASA.

Phase I Deliverables: Feasibility analysis and/or small-scale experiments proving the proposed technology to develop a given product (Technology Readiness Level (TRL) 2 to 3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables: A full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 3 to 5). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for NTP application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology. Unique government facilities can be used as part of Phase II.

State of the Art and Critical Gaps:

The state of the art is reactor fuel developed for the Rover/NERVA program in the 1960s and early 1970s. The fuel was carbon based and had what is known as "midband" corrosion, which affected the fuel endurance. Switching over to cermet (metal and ceramics) or advance carbide fuels shows promise but has fabrication challenges. Limited property data for most materials at ultrahigh temperatures considered makes the material performance analysis to meet the engine operating requirements riskier.

Focus is on a range of modern technologies associated with NTP using solid-core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf with an Isp goal of 900 sec (using hydrogen) and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple startups (>5) with cumulative run time >200 min in a single mission, which can be no more than 2-yr round trip, according to a recent NASA study. The Rover/NERVA program ground tested a variety of engine sizes for a variety of burn durations and startups.

Relevance / Science Traceability:

By closing these ultrahigh-temperature data gaps, the Space Nuclear Propulsion (SNP) project intends to infuse the results into design considerations/optimizations for risk reduction. In addition to directly benefiting SNP by closing the current material data gaps, the technology improvements in high-temperature materials would also benefit the following:

- Department of Defense (DOD) Defense Advanced Research Projects Agency (DARPA) NTP program.
- Wing leading-edge systems, due to their use of refractory alloy base structures to 2,000 °C.
- Fission surface power, due to the use of materials in long-term high-temperature environments.
- Refractory reaction control systems (RCSs) that reach up to 2,000 °C temperatures.
- Refractory rocket nozzles for upper stages and landers that reach ~2,200+ °C.

STMD (Space Technology Mission Directorate) is supporting the SNP project.

Future mission applications:

- Human missions to Mars.
- Science missions to the outer planets.
- Planetary defense.

Some technologies may have applications for fission surface power systems.

References:

Solid-core NTP has been identified as an advanced propulsion concept that could provide the fastest trip times for human missions to Mars over a variety of mission years. NTP had major technical work done between 1955 and 1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed, including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990s. The NTP concept is like a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber and exposes the engine components and surrounding structures to a radiation environment.

1. Durham, F. P., “Nuclear Engine Definition Study Preliminary Report”, LA-5044-MS Vol I, Informal Los Alamos Report, 1972.
2. Altseimer, J. H., Mader, G. F., Stewart, J. J., “Operating Characteristics and Requirements for the NERVA Flight Engine,” Paper 70-676, AIAA 6th Propulsion Joint Specialist Conference, June 1970.
3. Angelo, J. A., Buden, D., “Space Nuclear Power”, OrbitBook Company 1985.
4. Koenig, D. R., “Experience Gained from the Space Nuclear Rocket Program (Rover)”, LA-10062-H, Los Alamos Document, 1986.

5. Walton, J. T., “An Overview of Tested and Analyzed NTP Concepts”, AIAA-91-3503.
6. Finseth, J. L., “Overview of Rover Engine Tests- Final Report”, NAS 8-37814, 1991.
7. Bhattacharyya, S.K. et al, “Space Exploration Initiative Fuels, Materials and Related Technologies – Nuclear Propulsion Technology Panel Final Report”, NASA Technical Memorandum 105706, September 1993.
8. Haslett, R. A., “Space Nuclear Thermal Propulsion Program Final Report”, PL-TR-95-1064, Phillips Laboratory Air Force Report, 1995.

Z10.04 Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters (SBIR)

Lead Center: **GRC**

Participating Center(s):

Scope Title:

Structurally Robust Magnetic Circuit Materials for Hall-Effect Thrusters

Scope Description:

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

To shape the magnetic fields needed for operations, Hall-effect thrusters utilize a magnetic circuit that also forms the thruster structure. The magnetic circuit components direct magnetic flux (typically produced by electromagnetic coils) and may experience operational temperatures in excess of 500 °C due to coil self-heating and the close proximity of plasma-wetted surfaces. Both low-carbon magnetic iron and cobalt-iron (Co-Fe) soft ferromagnetic alloys have been traditionally used in the role; low-carbon magnetic iron is typically cheaper with larger billet size availability, whereas Co-Fe soft ferromagnetic alloys are attractive due to high magnetic saturation and Curie temperature properties. As Hall-effect thrusters become larger to support future high-power applications, thruster components also experience and must survive increased inertial launch loads. To address this issue, prospective magnetic circuit materials are desired with improved structural strength compared to SOA options while retaining comparable or better magnetic and thermal properties. Prospective materials capable of being produced in machinable, large-diameter (i.e., >400 mm) solid billets—or that can be additively manufactured to achieve comparable sizes—are of particular interest. This solicitation seeks such prospective magnetic circuit materials suitable for Hall-effect thruster applications with the following properties:

- Mechanical: Meets or exceeds yield stress properties in Table X2.4 of ASTM Standard A801-14.
- Magnetic: Meets or exceeds properties in Appendix X1 of ASTM Standard A848-17.
- Thermal: Meets or exceeds Curie temperature of 770 °C.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing test data characterizing key material properties as well as an assessment of material size scalability for future production.
3. Material samples that can be utilized for independent verification of claimed improvements over SOA materials.

Phase II:

1. Kickoff meeting with NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
2. A final report with test data either characterizing key material properties for produced large billets or demonstrating the functionality of one or more thruster components integrated with operating thruster hardware (in which partnering with electric propulsion developers may be necessary).

State of the Art and Critical Gaps:

SOA magnetic circuit materials used for Hall-effect thrusters are typically in two families: low-carbon magnetic iron or cobalt-iron (Co-Fe) soft ferromagnetic alloys (e.g., Hiperco®). While Co-Fe alloys are frequently preferred because of their magnetic and thermal properties, their available billet sizes do not readily accommodate larger thruster components needed for future high-power (i.e., >50 kW) electric propulsion applications. Low-carbon magnetic iron does come in large billet sizes, but past NASA high-power thruster development efforts (e.g., NASA-457Mv2 thruster) have identified potential risks regarding the survivability of components when subjected to launch loads. A magnetic circuit material that retains or exceeds the magnetic and thermal properties of SOA options while providing improved structural strength and scalability to large billet sizes is highly desirable to mitigate the risk.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- D.M. Goebel and I. Katz, "Chapter 7: Hall Thrusters," Fundamentals of Electric Propulsion: Ion and Hall Thrusters, https://descanso.jpl.nasa.gov/SciTechBook/SciTechBook.html
- ASTM Standard A801-14, "Standard Specification for Wrought Iron-Cobalt High Magnetic Saturation Alloys (UNS R30005 and K92650)."
- ASTM Standard A848-17, "Standard Specification for Low-Carbon Magnetic Iron."
- D.F. Susan, et al., "Equal Channel Angular Extrusion for Bulk Processing of Fe-Co-2V Soft Magnetic Alloys, Part I: Processing and Mechanical Properties," Journal of Materials Research, 33.15 (2018): 2168-2175.
- A.B. Kustas, et al., "Equal Channel Angular Extrusion for Bulk Processing of Fe-Co-2V Soft Magnetic Alloys, Part II: Texture Analysis and Magnetic Properties," Journal of Materials Research, 33.15 (2018): 2176-2188.
- Z. Turgut, et al., "High Strength Bulk Fe-Co Alloys Produced by Powder Metallurgy," Journal of Applied Physics, 103.7 (2008): 07E724.
- M.S. Masteller, J.W. Bowman, and L. Li, "High Temperature Aging Behavior of High Strength 49% Co-1.9% V-0.3% Nb-Fe Soft Magnetic Alloy," IEEE Transactions on Magnetics, 32.5 (1996): 4839-4841.
- Decadal surveys for each of the SMD divisions, https://science.nasa.gov/about-us/science-strategy/decadal-surveys
- 2020 NASA Technology Taxonomy, https://www.nasa.gov/offices/oct/taxonomy/index.html
- 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies), https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf

Scope Title:

High-Efficiency, Long-Life Hollow Cathodes

Scope Description:

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. Critical NASA electric propulsion needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Hollow cathodes in electric propulsion systems are utilized for generating discharge plasma and effecting plume neutralization in gridded-ion and Hall-effect thrusters. In SOA hollow cathodes, operating temperatures can range from 1,000 to 1,700 °C, and the cathode assembly may need to survive in excess of 10,000 operational hours and 10,000 thermal on-off cycles without failure. Critical NASA needs for hollow cathodes are:

1. High-current hollow cathodes with reduced power consumption. While SOA hollow cathodes can provide up to 25-A direct current necessary for electric propulsion applications, future interest in 100-kW electric propulsion systems will require a substantial increase in cathode current output to the range of 100 to 200 ADC. Scaling of current cathode architectures using various emitter technologies have achieved cathodes operating at >100-ADC emission current; however, these results typically require substantial increases in electrical power needed to drive plasma generation in the cathode and/or in an associated heating element for impregnate-based emission sources. Size increases for emitter and cathode, including heating elements, can also be significant to maintain the necessary thermal conditions for stable cathode life; the resultant larger sized cathodes can stress heater elements and limit their cyclic life—a concern facing cathodes utilizing LaB6 emitters. This solicitation seeks stable-performance, long-life cathode architectures that reduce power consumption (i.e., improve electrical efficiency) for >100-ADC emission current via improved heater design and operation, emitter material selection and configuration, lower plasma generation costs, reduced cathode thermal losses via conduction or radiation, etc.
2. Reduced-flow hollow cathodes in Hall-effect thrusters. Hollow cathodes used in Hall-effect thrusters are frequently operated with a fixed flow fraction relative to the anode flow; this approach is commonly utilized to reduce the cost and complexity of the propellant feed system. To promote efficient discharge plasma generation, these cathodes are typically operated with a higher than necessary propellant flow, which reduces specific impulse and may have negative impacts on cathode lifetime due to pressure-driven emission behavior. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode operation while reducing the total cathode (i.e., non-anode) flow fraction to less than 7% to 10% of the anode flow rate typically used in thruster operations. Being able to sustain thruster operations at such low total cathode flow fractions can result in significant propellant savings, particularly for high-power Hall-effect thrusters. This solicitation seeks readily adaptable methods to reduce cathode propellant flow needs (i.e., improve propellant utilization) without adversely affecting cathode and Hall-effect thruster stability and life.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Virtual kickoff meeting with the NASA Technical Monitor and potential stakeholders within the first month of the period of performance.
2. A final report containing quantitative analysis, modeling, or proof-of-concept test data addressing key risk factors associated with the technical approach and comparisons to SOA cathodes.

3. A cathode subsystem design that is compatible with high-power Hall-effect thruster concepts.

Phase II:

1. Kickoff meeting with the NASA Contracting Officer Representative (COR) and potential stakeholders within the first month of the period of performance.
2. A final report with test data supporting cathode performance, stability, and lifetime claims.
3. Cathode assembly hardware that can be utilized for independent verification of claimed improvements over SOA cathode assemblies.

State of the Art and Critical Gaps:

Future interest in 100-kW electric propulsion systems will require cathode current outputs in the range of 100 to 200 ADC. Experience to date with scaling current cathode architectures has resulted in cathodes that consume several kilowatts of power during operations. Such cathodes pose significant thermal management challenges for the thruster and concerns about the cathode's cyclic lifetime. Alternative cathode architectures that can significantly reduce power consumption are highly desirable to reduce risk for high-power electric propulsion applications.

Typical Hall-effect thrusters utilize a cathode flow fraction between 7% and 10% of the anode flow, with past studies of 50-kW-class thrusters at times requiring >10% cathode flow fraction to promote thruster stability at certain throttle points. For high-power electric propulsion systems utilizing Hall-effect thrusters, reducing cathode propellant flow needs can result in significant propellant savings on the order of hundreds of kilograms for typical NASA mission lifetimes. Past efforts to bifurcate the cathode flow between the cathode and an external (i.e., keeper or downstream region) contribution have demonstrated some success in providing stable and efficient cathode and thruster operations while achieving <7% total cathode flow fraction. Approaches for reducing cathode flow needs that can be readily adapted to SOA thruster architectures are highly desirable to improve system efficiency and lifetime.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power electric propulsion is a key element in supporting sustained human exploration of cislunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy, with archival information contained in the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

References:

- V.J. Friedly and P.J. Wilbur, “High Current Hollow Cathode Phenomena,” AIAA 90-2587.
- M.A. Mantenieks and R.M. Myers, “Preliminary Test Results of a Hollow Cathode MPD Thruster,” IEPC 91-076.
- D.M. Goebel and E. Chu, “High Current Lanthanum Hexaboride Hollow Cathodes for High Power Hall Thrusters,” IEPC-2011-053.

- H. Kamhawi and J. Van Noord, "Development and Testing of High Current Hollow Cathodes for High Power Hall Thrusters," AIAA-2012-4080.
- M.L. Plasek, et al., "Experimental Investigation of a Large-Diameter Cathode," AIAA-2014-3825.
- D.M. Goebel, K.K. Jameson, and R.R. Hofer, "Hall Thruster Cathode Flow Impact on Coupling Voltage and Cathode Life," Journal of Propulsion and Power, Vol. 28, No. 2, March-April 2012.
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- 2020 NASA Technology Taxonomy, https://www.nasa.gov/offices/oct/taxonomy/index.html
- 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies), https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_2_in-space_propulsion_final.pdf

Focus Area 2 Power, Energy and Storage

Lead MD: **STMD**

Participating MD(s): **SMD**

Power is a ubiquitous technology need across many NASA missions including human exploration, space science, and space technology. New technologies are sought to better generate electrical power and distribute it efficiently to both human and robotic power mission users. In space power, mission applications include planetary surface power, large-scale spacecraft prime power, and small-scale robotic probe power. Applicable technology development is sought for: 1) megawatt-class dynamic power conversion from a nuclear heat source to electricity, 2) efficient means of transmitting, connecting, and managing kilowatt-class power over long distances on planetary surfaces, and 3) high-voltage, radiation tolerant switches and components that are needed to optimize mass and efficiency for new high power missions. An overarching objective is to mature technologies from analytical or experimental proof-of-concept (TRL3) to breadboard demonstration in a relevant environment (TRL5). Successful efforts will transition into NASA Projects where the SBIR/STTR deliverables will be incorporated into ground testbeds or flight demonstrations. Note that there are similar power technology development needs at higher power levels for electrified aircraft propulsion which is covered in Focus Area 18 – Air Vehicle Technologies.

S3.01 Power Generation and Conversion (SBIR)

Lead Center: **GRC**

Participating Center(s): **JPL**

Scope Title:

Photovoltaic Energy Conversion

Scope Description:

This subtopic is seeking photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance for missions in areas of scientific interest including high-intensity, high-temperature (HIHT); low-intensity, low-temperature (LILT); and high-radiation environments. Additionally sought are solar power systems that can provide high power in compactly stowed volumes for small spacecraft.

These improvements may be achieved by optimizing the cell technology to operate in HIHT/LILT, increasing end of life (EOL) performance, increasing photovoltaic cell efficiency above 35% at 1 AU, and decreasing solar cell module/blanket stowed volume. Missions at distances of greater than 1 AU may include an inner planetary flyby, as such technologies that optimize solar cell string length to account for the changes in power generation are also of interest.

Photovoltaic energy conversion: advances in, but not limited to, the following: (1) Photovoltaic cell and blanket technologies capable of LILT operation applicable to outer planetary (low solar intensity) missions; (2) Photovoltaic cell and blanket technologies capable of HIHT operation applicable to inner planetary missions; (3) Photovoltaic cell and blanket technologies that enhance and extend performance in lunar applications including orbital, surface, and transfer; and (4) Solar cell and blanket technologies to support missions in high-radiation, LILT environments near Jupiter and its moons.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables include detailed reports with proof of concept and key metrics of components tested and verified.

Phase II deliverables include detailed reports with relevant test data along with proof-of-concept hardware and components developed.

State of the Art and Critical Gaps:

State-of-the-art (SOA) photovoltaic array technology consists of high-efficiency, multijunction cell technology on thick honeycomb panels and, as of late, lightweight blanket system deployable systems. There are very limited demonstrated technology for HIHT and LILT missions. A current solution for high-radiation intensity involves adding thick cover glass to the cells, which increases the overall system mass.

Significant improvements in overall performance are needed to address the current gaps between SOA and many mission requirements for photovoltaic cell efficiency >30%, array mass specific power >200 W/kg, decreased stowed volume, long-term operation in radiation environments, high-power arrays, and a wide range of environmental operating conditions.

Relevance / Science Traceability:

These technologies are relevant to any space science, Earth science, planetary surface, or other science mission that requires affordable high-efficiency photovoltaic power production for orbiters, flyby craft, landers, and rovers.
Specific requirements can be found in the References, but include many future Science Mission Directorate (SMD) missions. Specific requirements for orbiters and flybys to Outer planets include: LILT capability (>38% at 10 AU and <140 °C), radiation tolerance (6×10^{15} 1 MeV e/cm^2), high power (>50 kW at 1 AU), low mass (3× lower than the standard operating procedure (SOP)), low volume (3× lower than SOP), long life (>15 years), and high reliability.

These technologies are relevant and align with any Space Technology Mission Directorate (STMD) or Human Exploration and Operations Mission Directorate (HEOMD) mission that requires affordable high-efficiency photovoltaic power production.
NASA outlines New Lunar Science, Human Exploration Missions: https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions

NASA Science Missions: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951

References:

- Solar Power Technologies for Future Planetary Science Missions: https://solarsystem.nasa.gov/resources/548/solar-power-technologies-for-future-planetary-science-missions/
- NASA outlines New Lunar Science, Human Exploration Missions: https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions
- NASA Science Missions: https://science.nasa.gov/missions-page

S3.02 Dynamic Power Conversion (SBIR)

Lead Center: **GRC**

Participating Center(s):

Scope Title:

Dynamic Power Conversion

Scope Description:

NASA is developing dynamic radioisotope power systems (DRPSs) for unmanned robotic missions to the Moon and other solar system bodies of interest. This technology directly aligns with the Science Mission Directorate (SMD) strategic technology investment plan for space power and energy storage and could be infused into a highly efficient RPS for missions to dark, dusty, or distant destinations where solar power is not practical. Current work in DRPSs is focused on novel Stirling, Brayton, or Rankine convertors that would be integrated with one or more 250-W_{th} general-purpose heat source (GPHS) modules or 1-W_{th} lightweight radioisotope heater unit (RHU) to provide high thermal-to-electric efficiency, low mass, long life, and high reliability for planetary spacecraft, landers, and rovers. Heat is transferred from the radioisotope heat source assembly to the power convertor hot end using conductive or radiative coupling. Power convertor hot-end temperatures would generally range from 300 to 500 °C for RHU applications and 500 to 800 °C for GPHS applications. Waste heat is removed from the cold end of the power convertor at temperatures ranging from 20 to 175 °C, depending on the application, using conductive coupling to radiator panels. The NASA projects target power systems able to produce a range of electrical power output levels based on the available form factors of space-rated fuel sources. These include a very low range of 0.5 to 2.0 W_e that would utilize one or more RHU, a moderate range of 40 to 70 W_e that would utilize a single GPHS Step-2 module, and a high range of 100 to 500 W_e that would utilize multiple GPHS Step-2 modules. For these power ranges, one or more power convertors could be used to improve overall system reliability. The current solicitation is focused on innovations that enable efficient and robust power conversion systems. Areas of interest include:

1. Robust, efficient, highly reliable, and long-life thermal-to-electric dynamic power convertors that would be used to populate a generator of a prescribed electric power output ranges.
2. Electronic controllers applicable to Stirling, Brayton, or Rankine power convertors.
3. Multilayered metal insulation (MLMI) for minimizing environmental heat losses and maximizing heat transfer from the radioisotope heat source assembly to the power convertor.
4. Advanced dynamic power conversion components and RPS integration components, including efficient alternators able to survive extended exposure to 200 °C, robust high-temperature-tolerant Stirling regenerators, robust highly effective recuperators, integrated heat pipes, and radiators that improve system performance, and improve the margin, reliability, and fault tolerance for existing components.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study and analysis, as described in a final report.

Phase II deliverables: prototype hardware that has demonstrated basic functionality in a laboratory environment, the appropriate research and analysis used to develop the hardware, and maturation options for flight designs.

State of the Art and Critical Gaps:

Radioisotope power systems are critical for long-duration NASA missions in dark, dusty, or harsh environments. Thermoelectric systems have been used on the very successful RPSs flown in the past, but are limited in efficiency. Dynamic thermal energy conversion provides significantly higher efficiency, and through proper engineering of the noncontact moving components, can eliminate wear mechanisms and provide long life. Although high-efficiency performance of dynamic power convertors has been proven, reliable and robust systems tolerant of off-nominal operation are needed. In addition to convertors appropriate for GPHS RPSs, advances in much smaller and lower power dynamic power conversion systems are sought that can utilize RHUs for applications such as distributed sensor systems, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on icy moons and other bodies of interest. Although the power convertor advances are essential, to develop reliable and robust systems for future flight advances in convertor components as well as RPS integration components are also needed. These would include efficient alternators able to survive 200 °C, robust high-temperature-tolerant regenerators, robust high-efficiency recuperators, heat pipes, radiators, and controllers applicable to Stirling flexure-bearing, Stirling gas-bearing, or Brayton convertors.

Relevance / Science Traceability:

This technology directly aligns with the Science Mission Directorate - Planetary Science Division for space power and energy storage. Investments in more mature technologies through the Radioisotope Power System Program is ongoing. This SBIR subtopic scope provides a lower TRL technology pipeline for advances in this important power capability that improves performance, reliability, and robustness.

References:

- Radioisotope Power Systems (RPS): https://rps.nasa.gov/about-rps/overview/
- Oriti, Salvatore: "Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center," *AIAA Propulsion and Energy (P&E)* 2018, AIAA 2018-4498.
- Wilson, Scott D.: "NASA Low Power Stirling Convertor for Small Landers, Probes, and Rovers Operating in Darkness," *AIAA P&E* 2018, AIAA 2018-4499.
- Wong, Wayne: "Advanced Stirling Convertor (ASC) Technology Maturation," *AIAA P&E* 2015, AIAA 2015-3806.

Scope Title:

Additive Manufacturing Microfabrication of Stirling Heat Engine Regenerators

Scope Description:

In space applications where solar power is not practical, dynamic power conversion is an effective alternative. Of the several technologies used for dynamic power conversion, free-piston Stirling heat engines, coupled with alternators, offer high thermal-to-electric conversion efficiency, low mass, and long life. One component of Stirling heat engines that contributes to their excellent efficiency is the regenerator, which acts as a heat exchanger/storage for the working fluid as it passes from the heat acceptor to the rejector and again as it returns to the acceptor to repeat the cycle. The current state of the art in the construction of regenerators results in a cylindrical annulus made up of heat- and corrosion-resistant, short metallic fibers in diameters of 20 to 40 µm, packed to form an annulus with a porosity of 80% to 90% (solid fraction 10% to 20%), and sintered to achieve structural stability.

In some instances, these random fiber regenerators have released small particle debris due to less-than-complete sintering of the fiber matrix, presenting a risk of interference in the very small running clearance gaps of the displacer and power pistons, and potentially negatively affecting the performance and robustness of the heat engine. NASA has engaged in initial studies to determine the feasibility of producing continuous regenerator matrices through additive manufacturing (AM), and while these studies show promise, it has been determined that limitations of selective laser melting in the minimum achievable feature size and spacing between features prevents realization of performance goals. Sought are advances in AM microfabrication that demonstrate:

1. Applicability to high-temperature, corrosion-resistant metal alloys (Inconel, FeCrAlY, etc.).
2. Capability of creating ligaments in diameters as small as 20 µm, with spacing between ligaments as small as 100 µm.

3. Capability of producing cylindrical annuli on the order of 5.5 cm O.D. and 4.0 cm I.D. in axial lengths of up to 5 cm. Axial length may be achieved by stacking multiple components of shorter lengths.
4. Reasonable build time to support on-demand production.
5. Ability to create regenerator matrices that are stable and robust in the anticipated vibro-acoustic environments associated with space missions (launch, pyroshock, entry/descent/landing, etc.).

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study and analysis, as described in a final report.

Phase II deliverables: prototype hardware that has demonstrated basic functionality in a laboratory environment, the appropriate research and analysis used to develop the hardware, and maturation options .

State of the Art and Critical Gaps:

Radioisotope power Systems (RPS) are critical for long duration NASA missions to destinations sufficiently far from the Sun that solar power is impractical, and for missions to permanently shadowed areas of planetary bodies and their moons. Thermoelectric power systems (RTG) have enjoyed much success in past missions, but their efficiency is limited. Dynamic RPS offer significantly higher efficiency, resulting in lower system mass and reduced radioisotope inventory for a given power output. Advances in microfabrication of regenerators are needed for reduction of risk associated with stability of the regenerator matrix and improvements in reliability and robustness to support long mission durations.

Relevance / Science Traceability:

The technology described here aligns with the Science Mission Directorate Planetary Science Division (SMD/PSD) requirements for space power and energy storage and provides a low-TRL pathway for technologies that may contribute to a reduction of risk and improvements in reliability and robustness of Stirling heat engines in space-power applications.

References:

- Ibrahim, et al: “A Microfabricated Segmented-Involute-Foil Regenerator for Enhancing Reliability and Performance of Stirling Engines,” NASA Contractor Report 2007-215006, 2007.
- Ibrahim, M.B. and Tew, R.C.: *Stirling Convertor Regenerators*, CRC Press, Boca Raton, FL, 2017.

S3.03 Energy Storage for Extreme Environments (SBIR)

Lead Center: **GRC**

Participating Center(s): **JPL**

Scope Title:

Energy Storage for Extreme Environments

Scope Description:

NASA's Planetary Science Division is working to implement a balanced portfolio within the available budget and based on a decadal survey that will continue to make exciting scientific discoveries about our solar system. This balanced suite of missions shows the need for low mass/volume energy storage that can effectively operate in extreme environments for future NASA Science Missions.

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes from -200 °C for outer planet missions to 400 to 500 °C for Venus missions, and a span of -230 to +120 °C for missions to the lunar surface. Operational durations of 30 to 60 days for Venus; 30 to 60 days for deep-space environments such as Europa, Enceladus, and Titan; and 14-day eclipses for lunar night survival and operations on the Moon are of interest. Advancements to battery energy storage capabilities that address operation for one of the listed missions (Venus, deep space, or lunar) combined with high specific energy and energy density (>250 Wh/kg and >500 Wh/L for rechargeable or >800 Wh/kg and >1000 Wh/L for nonrechargeable at the cell level) are of interest in this solicitation. Novel battery-pack-level designs and technologies that enhance battery reliability and safety and support improved thermal management are also of interest. Combinations of cell-level improvements and/or battery-system-level improvement for enhanced temperature capability will be considered.

Furthermore, missions that incorporate nonrechargeable (primary) batteries will benefit from instrumentation or modeling that can effectively determine state of charge to a high degree of accuracy and/or state of health, particularly those missions that use cell chemistries with discharge voltage profiles that are a weak function of state of charge or state of health such as lithium carbon monofluoride (Li-CFx) cells. Technologies of interest include: radiation-hardened (to 1 Mrad total ionizing dose) coulomb integration application-specific integrated circuits (ASIC) or hybrid circuits, with >1% accuracy over 1 to 20 A, operating over 24 to 36 V; computational models that can predict state of charge/state of health for primary cells; nondestructive instrumentation that can detect state of charge/state of health for primary and secondary cells.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward a Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase II emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

State of the Art and Critical Gaps:

State-of-the-art primary and rechargeable cells are limited in both capacity and temperature range. Typical primary Li-SO_2 and Li-$SOCl_2$ operate within a maximum temperature range of -40 to 80 °C but suffer from capacity loss, especially at low temperatures. At -40 °C, the cells will provide roughly half the capacity available at room temperature. Similarly, rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and also suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended through the use of low-temperature electrolytes, but with limited rate capability and concerns over lithium plating on charge. There is currently a gap that exists for high-temperature batteries, primary and rechargeable, that can operate at Venus atmospheric temperatures. In addition, there is a gap in the ability to accurately predict or measure the amount of usable capacity of primary battery cells, particularly after a long mission cruise with exposure to varying temperatures and ionizing radiation dose. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures to minimize or eliminate the need for strict thermal management of the batteries (which adds complexity and mass to the spacecraft) as well as instrumentation or modeling to predict state of charge/state of health of primary batteries for deep-space missions.

Relevance / Science Traceability:

These batteries are applicable over a broad range of science missions. Low-temperature batteries are needed for potential NASA decadal missions to ocean worlds (Europa, Enceladus, and Titan) and the icy giants (Neptune, Uranus). These batteries are also needed for science missions on the lunar surface. Low-temperature batteries developed under this subtopic would enhance these missions and could be potentially enabling if the missions are mass or volume limited. There is also significant interest in a Venus surface mission that will require primary and/or rechargeable batteries that can operate for 60+ days on the surface of Venus. A high-temperature battery that can meet these requirements is enabling for this class of missions.

References:

NASA Science: https://science.nasa.gov/

Solar Electric Propulsion: https://www1.grc.nasa.gov/space/sep/

Z1.05 Lunar and Planetary Surface Power Management and Distribution (SBIR)

Lead Center: **GRC**

Participating Center(s): **GSFC, JSC**

Scope Title:

Innovative Ways to Transmit Power Over Long Distances for Lunar and Mars Missions

Scope Description:

The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA's plans for future human-rated space missions. A major component of these plans involves establishing bases on the lunar surface for sustained presence and a new transportation capability and surface assets for a human exploration mission to Mars. Surface power generation on planetary surfaces is envisioned to require 10 to 50 kW to be efficiently transmitted distances greater than 1 km to remotely located mission elements such as habitat modules, landers, ascent vehicles, etc. While current state-of-the-art space power systems are similar in power level (e.g., the International Space Station), the transmission distances are only 10s of meters, so new high-power, high-voltage and/or new power-beaming technologies are sought to enable surface power transmission over long distances. Examples of the innovative technologies sought are lower mass/higher efficiency power electronic regulators, switchgear, cabling, connectors, wireless sensors, power beaming, power scavenging, and power management control. The technologies of interest would need to operate in extreme-temperature environments, including lunar night, and could experience temperature changes from -153 to 123 °C for lunar applications, and -125 to 80 °C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation levels.

In addition, new human Mars transportation capabilities are expected to require multiple channels of 100 kW or more to be efficiently transmitted 100s of meters from an alternating current (AC) power generator to multiple electric thrusters requiring high-voltage direct-current (DC) power. Technologies sought include high-performance rotary alternators, high-performance transformers, rectifiers, and cabling.

While this subtopic would directly address the lunar and Mars base initiatives, technologies developed could also benefit other NASA Mission Directorates, including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects that could find value in the technologies developed herein include Gateway, In Situ Resource Utilization (ISRU), Advanced Modular Power Systems (AMPS), In-Space Electric Propulsion, Planetary Exploration, and Hybrid Gas-Electric Propulsion. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes and the need for electronics with higher power density and efficiency.

Specific technologies of interest would include:

- Application of wide band-gap electronics in DC-DC isolating converters with wide temperature (-70 to 150 °C), high power density (>2 kW/kg), high-efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Low-mass, highly conductive wires and terminations that provide reliable small gauges for long-distance power transmission in the 1 to 10 kW range, low-mass insulation materials with increased dielectric breakdown strength and void reductions with 1,000 V or greater ratings, and low-loss/low-mass shielding.
- Power-beaming concepts to enable highly efficient flexible/mobile power transfer in the 100 to 1,000 W range, including the fusion of power, communication, and navigation.
- Power generation and distribution components of a 3-phase/1,200-Hz permanent magnet alternator, 480 VAC to 650 VDC power management, and distribution with direct drive to Hall thrusters. Key components of the distribution include high-performance rotary alternators and AC transmission technologies, including alternator voltage, step-up/step-down transformers, rectifiers, and power cabling.

Note: to propose power connection/termination-related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically enabled high-voltage connectors and/or near-field wireless power transfer in the 1 to 10 kW range, see subtopic titled Dust-Tolerant Mechanisms.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

- Prototype
- Hardware

Desired Deliverables Description:

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report usually suffices in summarizing the work, but a prototype is preferred. Phase II hardware prototypes will have opportunities for infusion into NASA technology testbeds and commercial landers.

State of the Art and Critical Gaps:

While high-power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes that will be encountered. The temperature swings will be a critical requirement on any technology developed, from power converters to cabling or power-beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms. To enable a new Mars transportation capability for human exploration, new technology development must be started soon to address the very unique needs of a mixed AC/DC space-rated power system to prove feasibility and provide realistic performance metrics for detailed vehicle design concepts and mission trade studies.

Relevance / Science Traceability:

This subtopic would directly address a remaining technology gap in the lunar and Mars surface mission concepts and Mars human transportation needs. There are potential infusion opportunities with SMD (Science Mission Directorate) Commercial Lander Payload Services (CLPS) and HEOMD (Human Exploration and Operations Mission Directorate) Flexible Lunar Exploration (FLEx) Landers. In addition, technologies developed could benefit other NASA missions, including Gateway. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes.

References:

The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf

Space Policy Directive-1, Reinvigorating America's Human Space Exploration Program, December 11, 2017: https://www.federalregister.gov/documents/2017/12/14/2017-27160/reinvigorating-americas-human-space-exploration-program

Z1.06 Radiation-Tolerant High-Voltage, High-Power Electronics (SBIR)

Lead Center: **GSFC**

Participating Center(s): **GRC, JPL, LaRC**

Scope Title:

Radiation-Tolerant High-Voltage, High-Power Electronics

Scope Description:

NASA's directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural galactic cosmic ray space radiation environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion-radiation-induced single-event-effect (SEE) degradation and catastrophic failure of wide bandgap (WBG) power transistors and diodes. This subtopic seeks to facilitate movement of this understanding into the successful development of radiation-hardened high-voltage transistors and rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- High-voltage, high-power solutions: Taxonomy Area (TX) 03.3.4, Power Management and Distribution (PMAD) - Advanced Electronic Parts, calls out the need for development of radiation-hardened high-voltage components for power systems. NASA has a core need for diodes and transistors that meet the following specifications:
    - Diodes: minimum 1200 V, 40 A, with fast recovery <50 ns. Forward voltage drop should not exceed 150% of that in state-of-the-art unhardened diodes.
    - Transistors: minimum 650 V, 40 A, with <24-mohm on-state drain-source resistance.
- High-voltage, low-power solutions: In support of TX 8.1.2 (Sensors and Instruments - Electronics), radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
    - Transistors: minimum 1000 V, <40-ns rise and fall times
    - Diodes: 2 kV to 5 kV, <50-ns recovery time. Forward voltage drop should not exceed 150% of that in state-of-the-art unhardened diodes.
- High-voltage, low- to medium-power solutions: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
    - Transistors: minimum 600 V, <50-ns rise and fall times, current ranging from low to >20 A.

Successful proposal concepts should result in the fabrication of transistors and/or diodes that meet or exceed the above performance specifications without susceptibility to damage due to the galactic cosmic ray heavy-ion space radiation environment (SEEs resulting in permanent degradation or catastrophic failure). These diodes and/or transistors will form the basis of innovative high-efficiency, low-mass and low-volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion SEE radiation-tolerant devices.

Other innovative heavy-ion SEE radiation-tolerant, high-power, high-voltage discrete device technologies will be considered that offer significant electrical performance improvement over state-of-the-art heavy-ion SEE radiation-tolerant power devices.

Expected TRL or TRL Range at completion of the Project: **4 to 5**

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype

- Analysis

Desired Deliverables Description:

Phase I deliverables must state the initial state of the art for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle:

- For vertical-field power devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV-cm2/mg and sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident LET of 75 MeV-cm2/mg and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value (Bragg peak).

Deliverables in Phase II shall include prototype and/or production-ready semiconductor devices (diodes and/or transistors); and device electrical and radiation performance characterization (device electrical performance specifications, heavy-ion SEE radiation test results, and total-dose radiation analyses).

State of the Art and Critical Gaps:

High-voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial WBG power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed that they are very susceptible to damage from the high-energy, heavy-ion space radiation environment (galactic cosmic rays) that cannot be shielded against. Higher voltage devices are more susceptible to these effects; as a result, to date, there are space-qualified GaN transistors now available, but these are limited to 300 V. Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas have been identified for spacecraft power management and distribution (PMAD), and science instrument power applications and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current PPUs (power processing units) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), and its lunar/planetary habitation objectives requiring tens to 100 kW power production, the technology sought by this subtopic is truly enabling.

State-of-the-art, currently available heavy-ion SEE-tolerant silicon power devices include a Schottky diode capable of 600 V, 30 A, and 27-ns recovery time, and a power MOSFET capable of 650 V, 8 A, with on-state resistance of 450 mohm. Commercial (non-SEE tolerant) SiC and GaN offerings are available that meet the electrical performance needs indicated in this subtopic, but that cannot meet the heavy-ion SEE requirements indicated. At this time, there are no publicly available data on the heavy-ion SEE performance of Ga_2O_3 or diamond power devices.

Relevance / Science Traceability:

Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science instrument applications. This subtopic therefore feeds a broad array of space technology hardware development activities by providing SEE (heavy-ion) radiation-hardened state-of-the-art device technologies that achieve higher voltages with lower power consumption and greater efficiency than presently available.

Taxonomy Area (TX) 03.3.4, Power Management and Distribution (PMAD) - Advanced Electronic Parts, calls out the need for development of radiation-hardened high-voltage components for power systems. This subtopic serves as a feeder to the subtopic Lunar and Planetary Surface Power Distribution, in which WBG circuits for PMAD applications are solicited. The solicited developments in this subtopic will also feed systems development for the NASA Kilopower project due to the savings in size/mass combined with radiation hardness.

TX 08.1.2, Sensors and Instruments - Electronics: Radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. These applications are aligned with science objectives including Earth science LIDAR needs, Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid research and in the search for life on other planets such as Mars require high-voltage power systems and will thus benefit from mass and power savings from this subtopic's innovations.

References:

Partial listing of relevant references:

1. E. Mizuta, et al., "Single-Event Damage Observed in GaN-on-Si HEMTs for Power Control Applications," *IEEE Transactions on Nuclear Science,* vol. 65, pp. 1956-1963, 2018.
2. M. Zerarka, et al., "TCAD Simulation of the Single Event Effects in Normally-OFF GaN Transistors After Heavy Ion Radiation," *IEEE Transactions on Nuclear Science,* vol. 64, pp. 2242-2249, 2017.
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Z1.07 Dynamic Energy Conversion for Space Nuclear Power and Propulsion (SBIR)

Lead Center: **GRC**

Participating Center(s): **MSFC**

Scope Title:

Megawatt-Class Nuclear Power System

Scope Description:

Recent Mars transportation assessments identify megawatt-class nuclear electric propulsion (NEP) systems as a reasonable approach for use in a crewed mission to Mars. A critical subcomponent of the reference NEP concept is a dynamic thermal-to-electric power convertor. Dynamic power convertors are needed that address the following technical challenges:

- Robust, efficient, high-reliability, long-life thermal-to-electric power conversion and controller technology in the minimum range of 100 to 500 kWe. Brayton, Rankine, and Stirling convertors are of primary interest. Multiple parallel/redundant convertors may be used to achieve the megawatt-class power level.
    - Includes subcomponents such as efficient turbomachinery, bearings, alternators, recuperators, and heat exchangers.
- Convertors must be capable of interfacing with pumped liquid-metal loops: one for thermal energy input and one for heat rejection.

In addition, liquid metal pumps that address the following technical challenges are also needed:

- Can operate for long periods of time (years) at relevant in-space (in vacuum and zero g) reactor/power generation temperatures.
- Can withstand liquid metal freeze-thaw transition during initial reactor startup in zero g.
- Low mass and high efficiency at fluid throughputs that are relevant for in-space nuclear power generation.
- Wetted surfaces of the pump composed of materials that are compatible with liquid metals under consideration for in-space nuclear power generation (NaK, Li, etc.).

The desired deliverables are primarily prototype hardware, research, and analysis to demonstrate concept feasibility and a Technology Readiness Level (TRL) range of 3 to 5. There is a strong desire for hardware that can operate or has a clear path for operation in the relevant space environment. The specified higher power levels are of priority, but demonstrations at lower power levels may be considered as long as the scaling to higher power levels is straightforward and does not require significant new technology or configuration change. The prototype hardware may include one (or more) of the following:

- Power convertor (hot-end temperature = 850 ºC, cold-end temperature = 100 to 200 ºC).
- Controller electronics.
- Convertor subcomponent(s).
- Liquid metal pump and/or subcomponent(s).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

The desired deliverables for Phase I include monthly progress reports and a comprehensive final report.

For Phase II, the primary interest is component and/or breadboard hardware that demonstrates concept feasibility in a laboratory or relevant environment. The appropriate research and analysis required to develop the hardware are also desired. The Phase II deliverables should include hardware, monthly progress reports, and a comprehensive final report.

State of the Art and Critical Gaps:

Multikilowatt electric propulsion systems are well developed and have been used on commercial and military satellites for several years. Higher power electric propulsion systems are currently being considered to support crewed missions to near-Earth asteroids and as cargo transport for sustained lunar or Mars exploration, and for very high power crewed missions to Mars and the outer planets. One of the key technologies required in a NEP system is the power convertor. A recent Mars Transportation Assessment Study was completed that included Brayton, Stirling, Rankine, thermoelectric, and thermionic technologies in the trade space. The study identified HeXe Brayton as the baseline dynamic power convertor in the reference NEP concept, with supercritical CO_2 Brayton and K-Rankine as the primary options. Current state-of-the-art Brayton technology has been demonstrated in a relevant space environment (ground test) in the 10s of kWe range. Convertor scaleup to the 100s of kWe per unit is required.

Relevance / Science Traceability:

This technology directly aligns with the Space Technology Mission Directorate (STMD) roadmap for space power and energy storage.

References:

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Focus Area 3 Autonomous Systems for Space Exploration

Lead MD: **HEOMD**

Participating MD(s): **SMD, STTR**

The exploration of space requires the best of the nation's technical community to provide the technologies that will enable human and robotic exploration beyond Low Earth Orbit (LEO): to establish a lunar presence, to visit asteroids, to extend human reach to Mars, and for increasingly ambitious robotic missions such as a Europa Lander. Autonomous Systems technologies provide the means of migrating mission control from Earth to spacecraft, habitats, and robotic explorers. This is enhancing for missions in the Earth-Lunar neighborhood and enabling for deep space missions. Long light-time delays, for example up to 42 minutes round-trip between Earth and Mars, require time-critical control decisions to be closed on-board autonomously, rather than through round-trip communication to Earth mission control. For robotic explorers this will be done through automation, while for human missions this will be done through astronaut-automation teaming.

Long-term crewed spacecraft and habitats, such as the International Space Station, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low-Earth orbit, while still requiring significant real-time support from Earth. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to on-board automation that teams with astronauts to autonomously manage spacecraft and habitats. For outer planet robotic explorers, the opportunity is to autonomously and rapidly respond to dynamic environments in a timely fashion.

The “Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition” subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms onboard a spacecraft to optimize and automate operations. Neuromorphic processors can enable a spacecraft to sense, adapt, act, and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team.

The “Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration“ subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, and learn in a manner that the performance of the system is assured and improves over time. Building upon the success of the previous solicitations, this extended scope will enable small businesses to develop both the learning technology and the necessary assurance technology within the scope of cognitive agents that forward base mission control to spacecraft and habitats, and multiply the cognitive assets available to the crew.

The “Fault Management Technologies” subtopic has interest in onboard fault management capabilities (viz. onboard sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), with the goal of providing a system capability for management of future spacecraft. Offboard components such as modeling techniques and tools, development environments, and verification and validation (V&V) technologies are also relevant, provided they contribute to novel or capable on-board fault management.

The “Integrated Data Uncertainty Management & Representation for Trustworthy and Trusted Autonomy in Space” subtopic is seeking to improve autonomous systems performance within Multi-agent Cyber-Physical-Human (CPH) teams. This effort concentrates on increasing autonomous systems performance towards the point where they may function as teammates with specified independence, but under the ultimate human direction, or alternatively, where they can exercise complete independence in decision-making and operations in pursuit of given mission goals; for instance, for control of uncrewed missions for planetary infrastructure development in preparation for human presence, or maintenance and operation of crew habitats during the crew’s absence.

The “Coordination and Control of Swarms of Space Vehicles” subtopic addresses technologies for control and coordination of planetary rovers, flyers, and in-space vehicles in dynamic environments. Coordinated swarms can provide a more robust and sensor-rich approach to space missions, allowing simultaneous recording of sensor data from dispersed vehicles and co-ordination especially in challenging environments such as cave exploration. Primary interest is in technologies appropriate for low-cardinality (4- to 15-vehicle) swarms of small spacecraft, as well as planetary rovers and flyers (e.g., Mars helicopter).

Please refer to the description and references of each subtopic for further detail to guide development of proposals within this technically diverse focus area.

H6.22 Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition (SBIR)

Lead Center: **GRC**

Participating Center(s): **ARC**

Scope Title:

Neuromorphic Capabilities

Scope Description:

This subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms onboard a spacecraft to optimize and automate operations. This includes enabling cognitive systems to improve mission communication and data-processing capabilities, enhance computing performance, and reduce memory requirements. Neuromorphic processors can enable a spacecraft to sense, adapt, act, and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team. Additionally, this processing architecture shows promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.

The goal of this program is to develop neuromorphic processing software, hardware, algorithms, architectures, simulators, and techniques as enabling capability for autonomous space operations. Emerging memristor and other radiation-tolerant devices, which show potential for addressing the need for energy-efficient neuromorphic processors and improved signal processing capability, are of particular interest due to their resistance to the effects of radiation.

Additional areas of interest for research and/or technology development include: (a) spiking algorithms that learn from the environment and improve operations, (b) neuromorphic processing approaches to enhance data processing, computing performance, and memory conservation, and (c) new brain-inspired chips and breakthroughs in machine understanding/intelligence. Novel memristor approaches that show promise for space applications are also sought.

This subtopic seeks innovations focusing on low-size, -weight, and -power (-SWaP) applications suitable to lunar orbital or surface operations, thus enabling efficient onboard processing at lunar distances. Focusing on SWaP-constrained platforms opens up the potential for applying neuromorphic processors in spacecraft or robotic control situations traditionally reserved for power-hungry general-purpose processors. This technology will allow for increased speed, energy efficiency, and higher performance for computing in unknown and uncharacterized space environments including the Moon and Mars. Proposed innovations should justify their SWaP advantages and target metrics over the comparable relevant state of the art.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I will emphasize research aspects for technical feasibility and show a path toward a Phase II proposal. Phase I deliverables include concept of operations of the research topic, simulations, and preliminary results. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware and/or software development with delivery of specific hardware and/or software products for NASA, targeting demonstration operations on a low-SWaP platform. Phase II deliverables include a working prototype of the proposed product and/or software, along with documentation and tools necessary for NASA to use the product and/or modify and use the software. In order to enable mission deployment, proposed prototypes should include a path, preferably demonstrated, for fault and mission tolerances. Phase II deliverables should include hardware/software necessary to show how the advances made in the development can be applied to a CubeSat, SmallSat, and rover flight demonstration.

State of the Art and Critical Gaps:

The current state of the art (SOA) for in-space processing is the High Performance Spaceflight Computing (HPSC) processor being developed by Boeing for NASA Goddard Space Flight Center (GSFC). The HPSC, called the Chiplet, contains 8 general purpose processing cores in a dual quad-core configuration. Delivery is expected by December 2022. In a submission to the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program, the highest computational capability required by a typical space mission is 35 to 70 GFLOPS (billion fast logical operations per second).

The current SOA does not address the capabilities required for artificial intelligence and machine learning applications in the space environment. These applications require significant amounts of multiply and accumulate operations, in addition to a substantial amount of memory to store data and retain intermediate states in a neural network computation. Terrestrially, these operations require general-purpose graphics processing units (GP-GPUs), which are capable of teraflops (TFLOPS) each—approximately 3 orders of magnitude above the anticipated capabilities of the HPSC.

Neuromorphic processing offers the potential to bridge this gap through a novel hardware approach. Existing research in the area shows neuromorphic processors to be up to 1,000 times more energy efficient than GP-GPUs in artificial intelligence applications. Obviously, the true performance depends on the application, but nevertheless the architecture has demonstrated characteristics that make it well-adapted to the space environment.

Relevance / Science Traceability:

The Cognitive Communications Project, through the Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program, is one potential customer of work from this subtopic area. Neuromorphic processors are a key enabler to the cognitive radio and system architecture envisioned by this project. As communications become more complex, cognition and automation will play a larger role to mitigate complexity and reduce operations costs. Machine learning will choose radio configurations and adjust for impairments and failures. Neuromorphic processors will address the power requirements that traditional computing architectures now struggle to meet and are of relevance to Lunar return and Mars for autonomous operations, as well as of interest to HEOMD and Science Mission Directorate (SMD) for in situ avionics capabilities.

References:

Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com.

H6.23 Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration (SBIR)

Lead Center: **ARC**

Participating Center(s): **JSC**

Scope Title:

Learning and Adaptation for Space Cognitive Agents

Scope Description:

This subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, and learn in a manner that the performance of the system is assured and improves over time. Cognitive agents for space applications need to adapt and learn from observation, instruction, and interaction as missions proceed. The value of preprogrammed agents that do not adapt over time will diminish in extended missions. Building upon the success of the previous solicitations, this extended scope will enable small businesses to develop both the learning technology and the necessary assurance technology within the scope of cognitive agents that forward base mission control to spacecraft and habitats, and multiply the cognitive assets available to the crew.
It should be feasible for cognitive agents based on these architectures to be certified or licensed for use on deep space missions to act as liaisons that interact both with the mission control operators, the crew, and most, if not all, of the spacecraft subsystems. With such a cognitive agent that has access to all onboard data and communications, the agent could continually integrate this dynamic information and advise the crew and mission control accordingly by multiple modes of interaction including text, speech, and animated images. This agent could respond to queries and recommend to the crew courses of action and direct activities that consider all known constraints, the state of the subsystems, available resources, risk analyses, and goal priorities.

Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable to provide crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true requiring this NASA investment. Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations, and address learning and adaptation during mission scenarios of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

For Phase I, a preliminary cognitive architecture, preliminary feasibility study, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. A preliminary demonstration prototype of the proposed cognitive architecture is highly encouraged.

For Phase II, the Phase I proposed detailed feasibility study plan is executed generating a comprehensive cognitive architecture, comprehensive feasibility study report including design artifacts such as System Modeling Language/Unified Modeling Language (SysML/UML) diagrams, a demonstration of an extended prototype of an agent that instantiates the architecture interacting with a spacecraft simulator and humans executing a plausible Human Exploration and Operations Mission Directorate (HEOMD) design reference mission beyond cislunar orbit (e.g., Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf), and a detailed plan to develop a comprehensive cognitive architecture feasibility study suitable for proposing to organizations interested in funding this flight capability is expected. A Phase II prototype suitable for a compelling flight experiment on the ISS is encouraged.

State of the Art and Critical Gaps:

Long-term crewed spacecraft, such as the International Space Station, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low-Earth orbit and still require significant real-time support from Earth. Autonomous agents performing cognitive computing can provide crew support for future missions beyond cislunar by providing them robust, accurate, and timely information, and perform tasks enabling the crew more time to perform the mission science. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to onboard agents that team with flight crews to autonomously manage a space-flight mission.

The majority of Apollo missions required the timely guidance of mission control for success, typically within seconds of an off-nominal situation. Outside of cislunar space, the time delays will become untenable for Earth to manage time-critical decisions as was done for Apollo. The emerging field of cognitive computing is a vast improvement on previous information retrieval and integration technology, and is likely capable to provide this essential capability.
Investments continue to be made in a wide variety of cognitive agents. However, a critical gap that this subtopic addresses is assured learning for cognitive agents enabling it to appropriately adapt to the crew it interacts with in a manner that assures performance improves and not degrades over time mitigating risks related to learning systems.

Relevance / Science Traceability:

This subtopic is directly relevant to the HEOMD Advanced Exploration Systems (AES) domain: Foundational Systems - Autonomous Systems and Operations.

There is growing interest in NASA to support long-term human exploration missions to the Moon and eventually to Mars. Human exploration up to this point has relied on continuous communication with short delays. To enable missions with intermittent communication with long delays, new artificially intelligent technologies must be developed in order to keep the crew sizes small. Technologies developed under this subtopic are expected to be suitable for testing on Earth analogues of deep space spacecraft as well as the Deep Space Gateway envisioned by NASA.

References:

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2. COGNITIVE 2020 : The Twelfth International Conference on Advanced Cognitive Technologies and Applications: https://www.iaria.org/conferences2020/COGNITIVE20.html
3. ACC'20 - The 4th International Conference on Applied Cognitive Computing:https://americancse.org/events/csce2020/conferences/acc20
4. 2020 International Conference on Cognitive Computing: http://thecognitivecomputing.org/2020/
5. C. Gkiokas, "Cognitive agents and machine learning by example: Representation with conceptual graphs", Computational Intelligence Vol. 34 Issue 2 May 2018.
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S5.05 Fault Management Technologies (SBIR)

Lead Center: **JPL**

Participating Center(s): **ARC, MSFC**

Scope Title:

Development, Design, and Implementation of Fault Management Technologies

Scope Description:

NASA's science program has well over 100 spacecraft in operation, formulation, or development, generating science data accessible to researchers everywhere. As science missions have increasingly complex goals—often on compressed timetables—and have more pressure to reduce operations costs, system autonomy must increase in response.

Fault Management (FM) is a key component of system autonomy, serving to detect, interpret, and mitigate failures that threaten mission success. Robust FM must address the full range of hardware failures, and also must consider failure of sensors or the flow of sensor data, harmful or unexpected system interaction with the environment, and problems due to faults in software or incorrect control inputs—including failure of autonomy components themselves. Despite lessons learned from past missions, spacecraft failures are still not uncommon and reuse of FM approaches is limited, illustrating deficiencies in our approach to handling faults in all phases of the flight project lifecycle.

While this subtopic addresses particular interest in onboard FM capabilities (viz. onboard sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), the goal is to provide a *system capability* for management of future spacecraft. Offboard components such as modeling techniques and tools, development environments, and verification and validation (V&V) technologies are also relevant, provided they contribute to novel or capable on-board fault management.

Needed innovations in FM can be grouped into the following two categories:

1. Fault Management Operations Approaches: This category encompasses FM "in-the-loop," including algorithms, computing, state estimation/classification, machine learning, and model-based reasoning. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of unrecoverable faults is needed to realize greater system autonomy.
2. Fault Management Design and Implementation Tools: Also sought are methods to formalize and optimize onboard FM, such as model-based system engineering (MBSE). New technologies to improve or guarantee fault coverage, manage and streamline complex FM, and system modeling and analysis significantly contribute to the quality of FM design and may prove decisive in trades of new versus traditional FM approaches. Automated test case development, false positive/false negative test tools, model V&V tools, and test coverage risk assessments are examples of contributing technologies.

Specific algorithms and sensor technologies are in scope, provided their impact is not limited to a particular subsystem, mission goal, or failure mechanism. Novel artificial-intelligence-inspired algorithms, machine learning, etc., should apply to *this and only this subtopic* if their design or application is specific to detection, classification, or mitigation of system faults and off-nominal system behavior. While the core interests of this subtopic are spacecraft resilience and enabling spacecraft autonomy, closed-loop FM for other high-value systems such as launch vehicles and test stands is also in scope, particularly if techniques can be easily adapted to spacecraft.

Related technologies, but without a primary focus on resolution of system faults, such as machine-learning approaches to spacecraft characterization or science data preprocessing, autonomy architectures, or generalized system modeling and design tools, should be directed to other subtopics such as S5.03, Accelerating NASA Science and Engineering through the Application of Artificial Intelligence, or S5.04, Integrated Science Mission Modeling.

Expected outcomes and objectives of this subtopic are to mature the practice of FM, leading to better estimation and control of FM complexity and development costs, more flexible and effective FM designs, and accelerated infusion into future missions through advanced tools and techniques. Specific objectives include the following:

- Increased spacecraft resilience against faults and failures.
- Increased spacecraft autonomy through greater onboard fault estimation and response capability.
- Increase collection and quality of science data through mitigation of interruptions and fault tolerance.
- Enable cost-effective FM design architectures and operations.
- Determine completeness and appropriateness of FM designs and implementations.
- Decrease the labor and time required to develop and test FM models and algorithms.
- Improve visualization of the full FM design across hardware, software, and operations procedures.
- Determine extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage.

- Increase data integrity between multidiscipline tools.
- Standardize metrics and calculations across FM, systems engineering (SE), safety and mission assurance (S&MA), and operations disciplines.
- Bound and improve costs and implementation risks of FM while improving capability, such that benefits demonstrably outweigh the risks, leading to mission infusion.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Software

Desired Deliverables Description:

The aim of the Phase I project should be to demonstrate the technical feasibility of the proposed innovation and thereby bring the innovation closer to commercialization. Note, however, the research and development (R&D) undertaken in Phase I is intended to have high technical risk, and so it is expected that not all projects will achieve the desired technical outcomes.

The required deliverable at the end of an SBIR Phase I contract is a report that summarizes the project's technical accomplishments. As noted above, it is intended that proposed efforts conduct an initial proof of concept, after which successful efforts would be considered for follow-on funding by Science Mission Directorate (SMD) missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

The Final Report should thoroughly document the innovation, its status at the end of the effort, and as much objective evaluation of its strengths and weaknesses as is practical. The report should include a description of the approach, foundational concepts and operating theory, mathematical basis, and requirements for application. Results should include strengths and weaknesses found, measured performance in tests where possible.

Additional deliverables may significantly clarify the value and feasibility of the innovation. These deliverables should be planned to demonstrate retirement of development risk, increasing maturity, and targeted applications of particular interest. Although the wide range of innovations precludes a specific list, some possible deliverables are listed below:

- For innovations that are algorithmic in nature this could include development code or prototype applications, demonstrations of capability, and results of algorithm stress-testing.
- For innovations that are procedural in nature, this may include sample artifacts such as workflows, model prototypes and schema, functional diagrams, examples, or tutorial applications.
- Where a suitable test problem can be found, documentation of the test problem and a report on test results, illustrating the nature of the innovation in a quantifiable and reproducible way. Test reports should discuss maturation of the technology, implementation difficulties encountered and overcome, and results and interpretation.

Phase II proposals require at minimum a report describing the technical accomplishments of the Phase I award and how these results support the underlying commercial opportunity. Describing the commercial potential is best done through experiment: Ideally the Phase II report should describe results of a prototype implementation to a relevant problem, along with lessons learned and future work expected to adapt the technology to other applications. Further demonstration of commercial value and advantage of the technology can be accomplished through steps such as the following:

- Delivery of the technology in software form, as a reference application, or through providence of trial or evaluation materials to future customers.
- Technical manuals, such as functional descriptions, specifications, and users guides.
- Conference papers or other publications.
- Establishment of a preliminary performance model describing technology metrics and requirements.

Each of these measures represents a step taken to mature the technology and further reduce the difficulty in reducing it to practice. Although it is established that further development and customization will continue beyond Phase II, ideally at the conclusion of Phase II a potential customer should have access to sufficient materials and evidence to make informed project decisions about technology suitability, benefits, and risks.

State of the Art and Critical Gaps:

Many recent SMD missions have encountered major cost overruns and schedule slips due to difficulty in implementing, testing, and verifying FM functions. These overruns are invariably caused by a lack of understanding of FM functions at early stages in mission development and by FM architectures that are not sufficiently transparent, verifiable, or flexible enough to provide needed isolation capability or coverage. In addition, a substantial fraction of SMD missions continue to experience failures with significant mission impact, highlighting the need for better FM understanding early in the design cycle, more comprehensive and more accurate FM techniques, and more operational flexibility in response to failures provided by better visibility into failures and system performance. Furthermore, SMD increasingly selects missions with significant operations challenges, setting expectations for FM to evolve into more capable, faster-reacting, and more reliable onboard systems.

The SBIR program is an appropriate venue because of the following factors:

- Traditional FM design has plateaued, and new technology is needed to address emerging challenges. There is a clear need for collaboration and incorporation of research from outside the spaceflight community, as fielded FM technology is well behind the state of the art and failing to keep pace with desired performance and capability.
- The need for new FM approaches spans a wide range of missions, from improving operations for relatively simple orbiters to enabling entirely new concepts in challenging environments. Development of new FM technologies by SMD missions themselves is likely to produce point solutions with little opportunity for reuse and will be inefficient at best compared to a focused, disciplined research effort external to missions.
- SBIR level of effort is appropriately sized to perform intensive studies of new algorithms, new approaches, and new tools. The approach of this subtopic is to seek the right balance between sufficient reliability and cost appropriate to each mission type and associated risk posture. This is best achieved with small and targeted investigations, enabled by captured data and lessons learned from past or current missions, or through examination of knowledge capture and models of missions in formulation. Following this initial proof of concept, successful technology development efforts under this subtopic would be considered for follow-on funding by SMD missions as risk-reduction and infusion activities. Research should be conducted to demonstrate

technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Relevance / Science Traceability:

FM technologies are applicable to all SMD missions, albeit with different emphases. Medium-to-large missions have very low tolerance for risk of mission failure, leading to a need for sophisticated and comprehensive FM. Small missions, on the other hand, have a higher tolerance for risks to mission success but must be highly efficient, and are increasingly adopting autonomy and FM as a risk mitigation strategy.

A few examples are provided below, although these may be generalized to a broad class of missions:

- Lunar Flashlight (currently in assembly, test, and launch operations (ATLO), as an example of many similar future missions): Enable very low-cost operations and high science return from a 6U CubeSat through onboard error detection and mitigation, streamlining mission operations. Provide autonomous resilience to onboard errors and disturbances that interrupt or interfere with science observations.
- Europa Lander: Provide onboard capability to detect and correct radiation-induced execution errors. Provide reliable reasoning capability to restart observations after interruptions without requiring ground in-the-loop. Provide MBSE tools to model and analyze FM capabilities in support of design trades, V&V of FM capabilities, and coordinated development with flight software. Maximize science data collection during an expected short mission lifetime due to environmental challenges.
- Rovers and Rotorcraft (Mars Sample Return, Dragonfly): Provide onboard capability for systems checkout, enabling lengthy drives/flights between Earth contacts and mobility after environmentally induced anomalies (e.g., unexpected terrain interaction). Improve reliability of complex activities (e.g., navigation to features, drilling and sample capture, capsule pickup and remote launch).
- Search for Extrasolar Planets (observation): Provide sufficient system reliability through onboard detection, reasoning, and response to enable long-period, stable observations. Provide onboard or onground analysis capabilities to predict system response and optimize observation schedule. Enable reliable operations while out of direct contact (e.g., deliberately occluded from Earth to reduce photon, thermal, and radio-frequency background).

References:

- NASA's approach to FM and the various needs are summarized in the NASA FM Handbook: https://www.nasa.gov/pdf/636372main_NASA-HDBK-1002_Draft.pdf
- Additional information is included in the talks presented at the 2012 FM Workshop:
  - https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html
  - particularly https://www.nasa.gov/pdf/637595main_day_1-brian_muirhead.pdf
- Another resource is the NASA Technical Memorandum "Introduction to System Health Engineering and Management for Aerospace (ISHEM)," https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf
  - This is greatly expanded on in the following publication: Johnson, S. (ed): *System Health Management with Aerospace Applications*, Wiley, 2011, https://www.wiley.com/en-us/System+Health+Management%3A+with+Aerospace+Applications-p-9781119998730
- FM technologies are strongly associated with autonomous systems as a key component of situational awareness and system resilience. A useful overview was presented at the 2018 SMD

Autonomy Workshop, archiving a number of talks on mission challenges and design concepts: https://science.nasa.gov/technology/2018-autonomy-workshop

T10.03 Coordination and Control of Swarms of Space Vehicles (STTR)

Lead Center: **JPL**

Participating Center(s): **LaRC**

Scope Title:

Enabling Technologies for Swarm of Space Vehicles

Scope Description:

This subtopic is focused on developing and demonstrating technologies that enable cooperative operation of swarms of space vehicles in a dynamic environment. Primary interest is in technologies appropriate for low-cardinality (4- to 15-vehicle) swarms of small spacecraft, as well as planetary rovers and flyers (e.g., Mars helicopter). Large swarms and other platforms are of interest if well motivated in connection to NASA's Strategic Plan and needs identified in decadal surveys.

The proposed technology must be motivated by a well-defined "design reference mission" presented in the proposal with clear connection to the needs identified in decadal surveys. The proposed design reference mission is used to derive the high-level requirements for the technology development effort.

Areas of high interest are:

- Distributed estimation for exploration and inspection of a target object or phenomena by various assets with heterogenous sensors and from various vantage points.
- High-precision relative localization and time synchronization in orbit and on planet surface.
- Operations concepts and tools that provide situational awareness and commanding capability for a team of spacecraft or swarm of robots on another planet.
- Coordinated task recognition and planning, operation, and execution with realistic communication limitations.
- Communicationless coordination by observing and estimating the actions of other agents in the multiagent system.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I awards will be expected to develop theoretical frameworks, algorithms, and software simulation and demonstrate feasibility (TRL 3). Phase II awards will be expected to demonstrate capability on a hardware testbed (TRL 4 to 6).

- Phase I and Phase II: Algorithms and research results clearly depicting metrics and performance of the developed technology in comparison to state of the art (SOA). Software implementation of the developed solution along with simulation platform must be included as a deliverable.
- Phase II only: Prototype of the sensor or similar if proposal is to develop such subsystem.

State of the Art and Critical Gaps:

Technologies developed under this subtopic enable and are critical for multi-robot missions for collaborative planetary exploration. Distributed task recognition, allocation, and execution, collaborative motion planning for larger science return, and distributed estimation and shared common operational picture are examples of technology needs in this area.

These technologies also enable successful formation flying spacecraft missions, robust distributed GNC, precision relative navigation, distributed tasking and execution, and distributed estimation of the swarm state as well as the science target are examples of the technology gaps in this area.

Relevance / Science Traceability:

Subtopic technology directly supports NASA Space Technology Roadmap TA4 (4.5.4 Multi-Agent Coordination, 4.2.7 Collaborative Mobility, and 4.3.5 Collaborative Manipulation) and Strategic Space Technology Investment Plan (Robotic and Autonomous Systems: Relative GNC and Supervisory control of an S/C team), and is relevant to the following concepts:

- Multi-robot follow-on to the Mars 2020 and Mars helicopter programs are likely to necessitate close collaboration among flying robots as advanced scouts and rovers.
- PUFFERs are being developed at the Jet Propulsion Laboratory (JPL) and promise a low-cost swarm of networked robots that can collaboratively explore lava tubes and other hard-to-reach areas on planet surfaces.
- A convoy of spacecraft is being considered, in which the lead spacecraft triggers detailed measurement of a very dynamic event by the following spacecraft.

Multiple concepts for distributed space telescopes and distributed synthetic apertures are proposed that rely heavily on coordination and control technologies developed under this subtopic.

References:

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[3] Evan Ackerman, "PUFFER: JPL's Pop-Up Exploring Robot; This little robot can go where other robots fear to roll," https://spectrum.ieee.org/automaton/robotics/space-robots/puffer-jpl-popup-exploring-robot(link is external).

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[5] "Mars Helicopter to Fly on NASA's Next Red Planet Rover Mission," https://www.nasa.gov/press-release/mars-helicopter-to-fly-on-nasa-s-next-red-planet-rover-mission/.

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[7] S. Bandyopadhyay, R. Foust, G. P. Subramanian, S.-J. Chung and F. Y. Hadaegh, "Review of Formation Flying and Constellation Missions Using Nanosatellites," Journal of Spacecraft and Rockets, vol. 53, no. 3, 2016, pp. 567-578.

[8] S. Kidder, J. Kankiewicz and T. Vonder Haar. "The A-Train: How Formation Flying is Transforming Remote Sensing," https://atrain.nasa.gov/publications.php.

[9] T. Huntsberger, A. Trebi-Ollennu, H. Aghazarian, P. Schenker, P. Pirjanian and H. Nayar. "Distributed Control of Multi-Robot Systems Engaged in Tightly Coupled Tasks," Autonomous Robots 17, 79–92, 2004.

[10] Space Studies Board, "Achieving Science with CubeSats: Thinking Inside the Box," National Academies of Sciences, Engineering, and Medicine, 2016, http://sites.nationalacademies.org/SSB/CompletedProjects/SSB_160539.

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[12] Astro2010: The Astronomy and Astrophysics Decadal Survey, https://science.nasa.gov/astrophysics/special-events/astro2010-astronomy-and-astrophysics-decadal-survey.

[13] Astro2020: Decadal Survey on Astronomy and Astrophysics 2020, https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020.

[14] Decadal Survey for Earth Science and Applications from Space 2018, https://www.nationalacademies.org/our-work-decadal-survey-for-earth-science-and-applications-from-space.

T10.04 Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway (STTR)

Lead Center: **ARC**

Participating Center(s): **JSC, KSC, SSC**

Scope Title:

Artificial Intelligence for the Gateway Lunar Orbital Platform

Scope Description:

Gateway is a planned lunar-orbit spacecraft that will have a power and propulsion system, a small habitat for the crew, a docking capability, an airlock, and logistics modules. Gateway is expected to serve as an intermediate way station between the Orion crew capsule and lunar landers as well as a platform for both crewed and uncrewed experiments. Gateway is also intended to test technologies and operational procedures for suitability on long-duration space missions such as a mission to Mars. As such, it will require new technologies such as autonomous systems to run scientific experiments onboard, including biological experiments; perform system health management, including caution and warning; autonomous data management; and other functions. In contrast to the International Space Station, Gateway is much more representative of lunar and deep space missions—for example, the radiation environment.

This subtopic solicits autonomy, artificial intelligence, and machine learning technologies to manage and operate engineered systems to facilitate long-duration space missions, with the goal of testing proposed technologies on Gateway. The current concept of operations for Gateway anticipates uncrewed (dormant) periods of up to 9 months. Technologies need to be capable of or enable long-term, mostly unsupervised autonomous operation. While crew are present, technologies need to augment the crew's abilities, allow more autonomy from Earth-based Mission Control, and learn how to perform or improve their performance of autonomous operations by observing the crew. Additionally, the technologies may need to allow for coordination with the Orion crew capsule, lunar landers, Earth, and their various systems and subsystems.

Examples of needs include but are not limited to:

1. Autonomous operations and tending of science payloads, including environmental monitoring and support for live biological samples, and in situ automated analysis of science experiments.
2. Prioritizing data for transmission from Gateway. Given communications limitations, it may be necessary to determine what data can be stored for transmission when greater bandwidth is available, and what data can be eliminated as it will turn out to be useless, based on criteria relevant to the conduct of science and/or maintenance of the physical assets. Alternatively, it may be useful to adaptively compress data for transmission from the Gateway, which could include scientific experiment data and status, voice communications, scientific experiment data and status, and/or systems health management data.
3. Autonomous operations and health management of Gateway. When Gateway is unoccupied, unexpected events or faults may require immediate autonomous detection and response, demonstrating this capability in the absence of support from Mission Control (which is enabling for future Mars missions and time-critical responses in lunar environment as well). Efforts to develop smart habitats will allow long-term human presence on the Moon and Mars such as the Space Technology Research Institutes (https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-habitats) are relevant.

The deliverables range from research results to prototypes demonstrating various ways that autonomy and artificial intelligence (e.g., automated reasoning, machine learning, and discrete control) can be applied to aspects of Gateway operations and health management individually and/or jointly. As one example, for autonomous biological science experiments, the prototype could include hardware to host live samples for a minimum of 30 days that provide monitoring and environmental maintenance, as well as software to autonomously remedy issues with live science experiments. As another example, software that monitors the Gateway habitat while uncrewed, automatically notifies of any off-nominal conditions, and then, when crew arrive, transitions Gateway from quiescent status to a status capable of providing the crew with life support.

As another example, machine learning from the data stream of Gateway sensors to determine anomalous versus nominal conditions and prioritize and compress data communications to Earth.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I deliverables minimally include a detailed concept for autonomy technology to support Gateway operations such as experiments. Prototypes of software and/or hardware are strongly encouraged.

Phase II deliverables will be full technology prototypes that could be subsequently matured for deployment on Gateway.

State of the Art and Critical Gaps:

The current state of the art in human spaceflight allows for autonomous operations of systems of relatively limited scope, involving only a fixed level of autonomy (e.g., amount of human involvement needed), and learning at most one type of function (e.g., navigation). Gateway will require all operations and health management to be autonomous at different levels (almost fully autonomous when no astronauts are on board versus limited autonomy when astronauts are present), the autonomy to learn from human operations, and the autonomy across all functions. The autonomy will also need to adapt to new missions and new technologies. Proposers should be aware of and consider potential interfaces and interactions such as those between Gateway and smart habitats. Proposers may want to be aware of pertinent related efforts such as those being conducted by the Space Technology Research Institutes.

As NASA continues to expand with the eventual goal of Mars missions, the need for autonomous tending of science payloads will grow substantially. In order to address the primary health concerns for crew on these missions, it is necessary to conduct science in the most relevant environment. Acquisition of this type of data will be challenging while the Gateway and Artemis missions are being performed due to limited crewed missions and limited crew time.

Relevance / Science Traceability:

Gateway and other space-station-like assets in the future will need the ability to execute an increasingly large number of autonomous operations over longer durations with higher degrees of complexity and less ability to have human intervention due to increasing duration space missions such as missions to Mars.

References:

- Basic Moon to Mars Background: https://www.nasa.gov/topics/moon-to-mars/lunar-outpost.
- Basic Gateway Background: https://www.nasa.gov/topics/moon-to-mars/lunar-gateway.

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- Conducting Autonomous Experiments in Space: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180004314.pdf.
- Space Technology Research Institutes https://www.nasa.gov/press-release/nasa-selects-two-new-space-tech-research-institutes-for-smart-habitats

T10.05 Integrated Data Uncertainty Management and Representation for Trustworthy and Trusted Autonomy in Space (STTR)

Lead Center: **LaRC**

Participating Center(s): **GSFC, JPL**

Scope Title:

Integrated Data Uncertainty Management and Representation for Trustworthy and Trusted Autonomy in Space

Scope Description:

Multi-agent Cyber-Physical-Human (CPH) teams in future space missions must include machine agents with a high degree of autonomy. In the context of this subtopic, by "autonomy" we mean the capacity and authority of an agent (human or machine) for independent decision-making and execution in a specified context. We refer to machine agents with these attributes as autonomous systems (AS). In multi-agent CPH teams, humans may serve as remote mission supervisors or as immediate mission teammates, along with AS. AS may function as teammates with specified independence, but under the ultimate human direction. Alternatively, AS may exercise complete independence in decision-making and operations in pursuit of given mission goals; for instance, for control of uncrewed missions for planetary infrastructure development in preparation for human presence, or maintenance and operation of crew habitats during the crew's absence.

In all cases, trustworthiness and trust are essential in CPH teams. The term "trustworthiness" denotes the degree to which the system performs as intended and does not perform prohibited actions in a specified context. "Trust" denotes the degree of readiness by an agent (human or machine) to accept direction or advice from another agent (human or machine), also in a specified context. In common sense terms, trust is a confidence in a system's trustworthiness, which in turn, is the ability to perform actions with desired outcomes.

Because behind every action lies a decision-making problem, trustworthiness of a system can be viewed in terms of the soundness of decision-making by the system participants. Accurate and relevant information forms the basis of sound decision-making. In this subtopic, we focus on data that inform CPH team decision-making, both in human-machine and machine-machine interactions, from two perspectives: the quality of the data and the representation of the data in support of trusted human-machine and machine-machine interactions.

We consider data exchanges in multi-agent CPH teams that include AS. Data exchanges in multi-agent teams must be subject to the following conditions:

- Known data accuracy, noise characteristics, and resolution, as a function of the physical sensors in relevant environments.
- Known data accuracy, noise characteristics, and resolution as a function of data interpretation if the contributing sensors have a perception component or if data are delivered to an agent via another perception engine (e.g., visual recognition based on deep learning).
- Known data provenance and integrity.
- Dynamic anomaly detection in data streams during operations.
- Comprehensive uncertainty quantification (UQ) of data from a single source.
- Data fusion and combined UQ, if multiple sources of data are used for decision-making.
- If data from either a single source or fused data from multiple sources are used for decision-making by an agent (human or machine), the data and the attendant UQ must be transformed into a representation conducive to and productive for decision-making. This may include data filtering, compression, or expansion, among other approaches.
- UQ must be accompanied by a sensitivity analysis of the mission/operation/action goals with respect to uncertainties in various data, to enable appropriate risk estimation and risk-based decision-making by relevant agents, human or machine.
- Tools for real-time, a priori, and a posteriori data analysis, with explanations relevant to participating agents. For instance, if machine learning is used for visual data perception in decision-making by humans, methods of interpretable or explainable AI (XAI) may be in order.

We note that deep learning and machine learning, in general, are not the chief focus of this subtopic. The techniques are mentioned as an example of tools that may participate in data processing. If such tools are used, the representation of the results to decision-makers (human or machine) must be suitably interpretable and equipped with UQ.

Addressing the entire set of the conditions listed above would likely be impractical in a single proposal. Therefore, proposers may offer methods and tools for addressing a subset of conditions.

Proposers should offer both a general approach to achieving a chosen subset of the listed conditions and a specific application of the general approach to appropriate data types. The future orbiting or surface stations are potential example platforms, because the environment would include a variety of autonomous systems used for habitat maintenance when the station is uninhabited, continual system health management, crew health, robotic assembly, and cyber security, among other functions. However, the proposers may choose any relevant design reference mission for demonstration of proposed approaches to integrated data uncertainty management and representation, subject to a convincing substantiation of the generalizability and scalability of the approach to relevant practical systems, missions, and environments.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Software

Desired Deliverables Description:

Since UQ and management in data is an overarching theme in this subtopic, an analysis of uncertainties in the processes and data must be present in all final deliverables, both in Phases I and II.

Phase I: For the areas selected in the proposal, the following deliverables would be in order:

1. Thorough but succinct analysis of the state of the art in the proposed area under investigation.
2. Detailed description of the problem used as the context for algorithm development, including substantiation for why this is a representative problem for a set of applications relevant to NASA missions.
3. Detailed description of the approach, including pseudocode, and the attendant design of experiments for testing and evaluation.
4. Hypotheses about the scalability and generalizability of the proposed approach to realistic problems relevant to NASA missions.
5. Preliminary software and process implementation.
6. Preliminary demonstration of the software.
7. Thorough analysis of performance and gaps.
8. Detailed plan for Phase II, including the design reference mission and the attendant technical problem.
9. Items 1 to 8 documented in a final report for Phase I

Phase II:

1. Detailed description and analysis of the design reference mission and the technical problem selected in Phase I, in collaboration with NASA Contracting Officer Representative (COR)/Technical Monitor (TM).
2. Detailed description of the approach/algorithms developed further for application to the Phase II design reference mission and problem, including pseudocode, and the design of experiments for testing and evaluation.
3. Demonstration of the algorithms, software, methods, and processes.
4. Thorough analysis of performance and gaps, including scalability and applicability to NASA missions.
5. Resulting code.
6. Detailed plan for potential Phase III.
7. Items 1 to 5 documented in a final report for Phase II.

State of the Art and Critical Gaps:

Despite progress in real-time data analytics, serious gaps remain that will present an obstacle to the operation of systems in NASA missions that require heavy participation of autonomous systems, both in human-machine teams and in uncrewed environments, whether temporary or permanent. The gaps come under two main categories:

1. Quality of the information based on various data sources—Trustworthiness of the data is essential in making decisions with desired outcomes. This gap can be summarized as the lack of reliable and actionable UQ associated with data, as well as the difficulty of detecting anomalies in data and combining data from disparate sources, ensuring appropriate quality of the result.
2. Representation of the data to decision-makers (human or machine) that is conducive to trustworthy decision-making—We distinguish raw data from useful information of appropriate complexity and form. Transforming data, single-source or fused, into information productive for decision-making, especially by humans, is a challenge.

Specific gaps are listed under the Scope Description as conditions the subsets of which must be addressed by proposers.

Relevance / Science Traceability:

The technologies developed as a result of this subtopic would be directly applicable to the Space Technology Mission Directorate (STMD), Science Mission Directorate (SMD), Human Exploration and Operations Mission Directorate (HEOMD), and Aeronautics Research Mission Directorate (ARMD), as all of these mission directorates are heavy users of data and growing users of autonomous systems. For instance, the Gateway mission will need a significant presence of autonomous systems, as well as human-machine team operations that rely on autonomous systems for habitat maintenance when the station is uninhabited, continual system health management, crew health, robotic assembly, among other functions. Human presence on the Moon surface will require similar functions, as well as future missions to Mars. All trustworthy decision-making relies on trustworthy data. This topic addresses gaps in data trustworthiness, as well as productive data representation to human-machine teams for sound decision-making.

The subtopic is also directly applicable to ARMD missions and goals, because future airspace will heavily rely on autonomous systems. Thus, the subtopic is applicable to such projects as Airspace Operations and Safety Program (AOSP)/Advanced Air Mobility (AAM) and Air Traffic Management—eXploration ATM-X. The technologies developed as a result of this subtopic would be applicable to the National Airspace System (NAS) in the near future as well, because of the need to process data related to vehicle and system performance.

References:

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Focus Area 4 Robotic Systems for Space Exploration

Lead MD: **STMD**

Participating MD(s): **SMD, STTR**

This focus area includes development of robotic systems technologies (hardware and software) that will enable and enhance future space exploration missions. In the coming decades, robotic systems will continue to change the way space is explored. Robots will be used in all mission phases: as independent explorers operating in environments too distant or hostile for humans, as precursor systems operating before crewed missions, as crew helpers working alongside and supporting humans, and as caretakers of assets left behind. As humans continue to work and live in space, they will increasingly rely on intelligent and versatile robots to perform mundane activities, freeing human and ground control teams to tend to more challenging tasks that call for human cognition and judgment. Technologies are needed for robotic systems to improve transport of crew, instruments, and payloads on planetary surfaces, on and around small bodies, and in-space. This includes hazard detection, sensing/perception, active suspension, grappling/anchoring, legged locomotion, robot navigation, end-effectors, propulsion, and user interfaces.

Innovative robot technologies provide a critical capability for space exploration. Multiple forms of mobility, manipulation and human-robot interaction offer great promise in exploring planetary bodies for science investigations and to support human missions. Enhancements and potentially new forms of robotic systems can be realized through advances in component technologies, such as actuation and structures (e.g. 3D printing). Mobility provides a critical capability for space exploration. Multiple forms of mobility offer great promise in exploring planetary bodies for science investigations and to support human missions. Manipulation provides a critical capability for positioning crew members and instruments in space and on planetary bodies. Robotic manipulation allows for the handling of tools, interfaces, and materials not specifically designed for robots, and it provides a capability for drilling, extracting, handling, and processing samples of multiple forms and scales. This increases the range of beneficial tasks robots can perform and allows for improved efficiency of operations across mission scenarios. Furthermore, manipulation is important for human missions, human precursor missions, and unmanned science missions. Moreover, sampling, sample handling, transport, and distribution to instruments, or instrument placement directly on in-place rock or regolith, is important for robotic missions to locales too distant or dangerous for human exploration.

Future space missions may rely on co-located and distributed teams of humans and robots that have complementary capabilities. Tasks that are considered "dull, dirty, or dangerous" can be transferred to robots, thus relieving human crew members to perform more complex tasks or those requiring real-time modifications due to contingencies. Additionally, due to the limited number of astronauts anticipated to crew planetary exploration missions, as well as their constrained schedules, ground control will need to remotely supervise and assist robots using time-delayed and limited bandwidth communications. Advanced methods of human-robot interaction over time delay will enable more productive robotic exploration of the more distant reaches of the solar system. This includes improved visualization of alternative future states of the robot and the terrain, as well as intuitive means of communicating the intent of the human to the robotic system.

S4.02 Robotic Mobility, Manipulation and Sampling (SBIR)

Lead Center: **JPL**

Participating Center(s): **ARC, GRC, GSFC**

Scope Title:

Robotic Mobility, Manipulation, and Sampling

Scope Description:

Technologies for robotic mobility, manipulation, and sampling are needed to enable access to sites of interest as well as acquisition and handling of samples for in situ analysis or return to Earth from planets and other planetary bodies including the moon, Mars, Venus, Ceres, Europa, Titan, Enceladus, comets, and asteroids.

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as Earth's Moon and Mars. Wheeled, legged, and aerial solutions are of interest. Wheel concepts with good tractive performance in loose sand while being robust to harsh rocky terrain are of interest. Technologies to enable mobility on small bodies and access to liquid below the surface (e.g., in conduits or deep oceans) are desired, as well as the associated sampling technologies.

Manipulation technologies are needed to deploy sampling tools to the surface, transfer samples to in situ instruments and sample storage containers, and hermetically seal sample chambers. Sample acquisition tools are needed to acquire samples on planetary and small bodies through soft and hard materials, including ice. Minimization of mass and ability to work reliably in the harsh mission environment are important characteristics for the tools. Finally, design for planetary protection and contamination control is important for sample acquisition and handling systems.

Component technologies for low-mass and low-power systems tolerant to the in situ environment (e.g., temperature, radiation, and dust) are of particular interest. Technical feasibility and value should be demonstrated during Phase I via analysis or prototype demonstration, and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan (to include a discussion of challenges and appropriate testing) to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following (order does not reflect priority):

- Surface mobility and sampling systems for planets, small bodies, and moons.
- Near-subsurface sampling tools such as icy-surface drills to 30 cm depth deployed from a manipulator.
- Subsurface ocean access such as via a deep drill system.
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples.
- Pneumatic sample transfer systems and particle flow measurement sensors.
- Low-mass/power vision systems and processing capabilities that enable fast surface traverse.
- Active lighting stereo systems for landers and rovers.
- Force-torque sensors that can operate in cryogenic and high-radiation environments such as Europa.
- Electromechanical connectors enabling tool change-out in dirty environments.
- Tethers and tether play-out and retrieval system.
- Miniaturized flight motor controllers.
- Cryogenic operation actuators.

- Robotic arms for low-gravity environments.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Hardware, software, and designs for component robotic systems.

- Phase I: proof of concept to include research and analysis along with design in a final report.
- Phase II: prototype for further testing.

State of the Art and Critical Gaps:

Scoops, powder drills, and rock core drills and their corresponding handling systems have been developed for sample acquisition on Mars and asteroids. Non-flight systems have been developed for sampling on comets, Venus, and Earth's Moon. Some of these environments still present risk and have gaps that need to be addressed (i.e. Venus).

Ocean worlds exploration presents new environments and unique challenges not met by existing mobility and sampling systems. New mobility, manipulation, and sampling technologies are needed to enable new types of missions and missions to different and challenging environments.

Relevance / Science Traceability:

The subtopic supports multiple programs within Science Mission Directorate (SMD). The Mars program has had infusion of technologies such as a force-torque sensor in the Mars 2020 mission. Recent awards would support the Ocean Worlds program with surface and deep drills for Europa, and future awards could include technologies to support missions to Enceladus, Titan, and other planetary bodies with subsurface oceans. Sample-return missions could be supported such as from Ceres, comets, and asteroids. Products from this subtopic have been proposed for New Frontiers program missions. With renewed interest in return to Earth's Moon, the mobility and sampling technologies could support future robotic missions to the Moon.

References:

- Mars Exploration/Program & Missions, https://mars.nasa.gov/programmissions/
- Solar System Exploration, https://solarsystem.nasa.gov/
- Ocean Worlds website: https://www.nasa.gov/specials/ocean-worlds/
- Ocean Worlds article: https://science.nasa.gov/news-articles/ocean-worlds

T7.04 Surface Construction (STTR)

Lead Center: **KSC**

Participating Center(s): **GRC, MSFC**

Scope Title:

Surface Construction

Scope Description:

Surface construction technologies must be developed to support long-term sustainable human presence on the lunar and eventually Martian surfaces. To enable a sustained human presence on the Moon, multiple assets are likely to be landed proximal to each other. While the Apollo landers demonstrated that it is possible to land on an unprepared surface, landing multiple proximal assets under Artemis will pose an unacceptable risk to nearby hardware.

For this reason, launch and landing pads are a high initial priority due to significant risks associated with these operations. When a lander vehicle launches or lands on an extraterrestrial body, the rocket engine exhaust plume impinges on the surface and interacts with the regolith, and blast ejecta is created along with associated cratering of the surface. Lunar regolith blast ejecta travels at high velocities (>2,000 m/s) for long distances (kilometers) in a vacuum environment creating hazards for surrounding assets. Ejecta can also impact the bottom of the lander vehicle, risking damage to the engines, thermal insulation, and sensors. Regolith ejecta can enter cislunar space as debris if the ejecta is sufficiently energetic to achieve orbit. The cratering can affect the stability of the landing gear and expose subsurface hazards.

As a part of a Launch and Landing Pad (LLP) system, concepts for construction of blast ejecta barriers such as berms, walls, curtains, deflectors, or other solutions are also sought. These blast ejecta barriers will protect the lunar base in the vicinity of the LLP during routine launches and landings and will also provide protection in the event of an anomalous energy release in the lander.

Upon the completion of an LLP system, follow-on surface construction projects will reduce risk to other parts of the lunar infrastructure and are expected to include:

- Stabilized roads and pads to mitigate trafficability and operational risks.
- Radiation shielding for nuclear power plants.
- Trenching for cables and other below-grade operations.
- Site preparation including establishing grade, leveling, compaction, and rock clearing.
- Unpressurized structures for radiation, thermal, and micrometeoroid protection.
- Pressurized structures.

This subtopic is focused on applied research to enable the design, testing, and verification of civil engineering products suitable for use in lunar surface architecture. New analysis methods and specialized construction equipment will be required to meet the unique lunar environment. The desired outcome of this work is the definition of feasible civil engineering system solutions with associated methods, analysis, structural designs, construction equipment concept prototypes, and concepts of operations.

The construction operations shall be robotically competed using indigenous lunar resources to the highest degree possible to minimize crew interaction and minimize the transportation mass from Earth to the Moon.

Proposers need to consider operations and hardware designs in a Global Positioning System (GPS-) denied environment for positioning, leveling, and control. In selecting and developing procedures and materials for surface stabilization and landing pad construction, proposers should consider the ability to perform maintenance and repair for long-term operations.

For hardware, processes, and operations that require mobility, proposers should define the interface and operation requirements, but may refrain from designing specific mobility units as these may be available through other development activities. Proposers should also specify the interfaces to other lunar systems that might be required such as power, regolith size sorting, beneficiation, etc., and include the source of all feedstocks for construction materials and associated processing required.

Proposed techniques can utilize Earth-supplied consumables (such as binders, water, purge gases, etc.) but need to quantify the types and amounts needed for the proposed construction operations. Emphasis should be given to consumables that can eventually be extracted or produced from in situ resources. The proposed lunar methods, materials, and technologies shall be traceable to Mars applications to the highest degree possible. The lunar construction technologies proposed should also contain methodologies for verification of the as-built or finished construction to ensure it will perform as required.

Research institute partnering is anticipated to provide analytical, research, and engineering support to the proposers. Examples may include helping apply civil engineering principles and planning methods, identification and development of needed standards or specifications for lunar operations, or the development of analytical and verification methods for the design and prototyping of structures, hardware, and associated software.

Specific figures of merit for proposed solutions include the following for Commercial Lunar Payload Services (CLPS) and human-class landers:

- Performance of infrastructure in intended applications (e.g., under launch/landing conditions).
- Performance under lunar surface environmental conditions (e.g., thermal cycling, ultraviolet (UV), vacuum, and radiation).
- Required payload mass.
- Estimated power requirements.
- Feedstock sources and requirements.
- Construction time.
- Surface preparation/analysis requirements.
- Strategy for verification of as-built structural performance.
- Concepts of operation.
- Expected life of infrastructure.

All proposals need to identify the state-of-the-art of applicable technologies and processes. Prototypes to be delivered at the conclusion of Phase II will be required to operate under lunar equivalent vacuum, temperature, and dust conditions, so thermal management and dust mitigation strategies utilized during the operation of the proposed technology will need to be specified in the Phase I proposal. The Phase I proposals should at least result in a Technology Readiness Level (TRL) of 2 to 4.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I must include the design and test of critical attributes or high risk areas associated with the proposed surface construction technology or process used to achieve the objectives of the Phase II delivered prototype as described in a final report.

By the end of Phase II, the prototype hardware should be advanced by appropriately justified demonstration(s) to TRL 4 to 6, and be capable of further testing in more relevant environments (TRL 7 to 8) beyond Phase II.

State of the Art and Critical Gaps:

The state of the art for robotic construction on the lunar surface includes regolith excavation and manipulation systems such as the Regolith Advanced Surface Systems Operations Robot (RASSOR). Sintered regolith interlocking pavers and emplacement systems were jointly developed and tested by NASA and the Pacific International Space Center for Exploration Systems (PISCES). Robotic construction of blast ejecta barriers was completed by NASA where a lunar teleoperated robotic bulldozer was able to clear and level an area of 100 by 100 m and then build a 2-m-high berm in the sand dunes of Moses Lake in Washington. Sintered basalt and ablative polymer concrete materials that have been tested at high plasma temperatures in the Arc Jet facility at NASA Ames Research Center performed well as a heat shield material. Specialized concrete formulations and emplacement systems have been developed by Marshall Space Flight Center and others.

Relevance / Science Traceability:

Surface construction of infrastructure directly addresses the STMD Strategic Thrust, “Land: Increase Access to Planetary Surfaces.” It also addresses the strategic thrust of “Explore: Expand Capabilities Through Robotic Exploration and Discovery.” The risks of landing on the Moon were demonstrated in the lunar Surveyor and Apollo missions. The robotic Surveyor spacecraft had difficulty landing safely, and during Apollo, five of six landings had close calls such as avoiding hazardous terrain, dust obscuration during landing, and slopes that tipped the lander as far as 11°, which happened on Apollo 15. The need for trafficability risk mitigation is highlighted by Spirit rover becoming immobilized in Martian regolith. Lunar dust and radiation mitigations are considered major risks for long-term lunar operations.

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Z5.04 Technologies for Intravehicular Activity Robotics (SBIR)

Lead Center: **ARC**

Participating Center(s): **JSC**

Scope Title:

Improve the Capability or Performance of Intravehicular Activity Robots

Scope Description:

To support human exploration beyond Earth orbit, NASA is developing Gateway, which will be an orbiting facility near the Moon. This facility will serve as a starting point for missions to cislunar space and beyond. It could enable assembly and servicing of telescopes and deep space exploration vehicles. It could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.

In contrast to the International Space Station (ISS), which is continuously manned, Gateway is expected to be occupied by humans only intermittently—perhaps only 1 month per year. Consequently, there is a significant need for Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking, particularly when astronauts are not present. Similar capabilities are needed for future lunar or planetary surface habitats. Intravehicular activity (IVA) robots can potentially perform a wide variety of tasks, including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and operations.

The objective of this subtopic is to develop technologies that can improve the capability or performance of IVA robots to perform payload operations and spacecraft caretaking. Proposals are specifically sought to create technologies that can be integrated and tested with the NASA Astrobee, Robonaut 2, or other NASA robots in the following areas:

- Sensors and perception systems for performing contact tasks; manipulation; and/or interior environment monitoring, inspection, modeling, and navigation.
- Robotic tools for manipulating logistics and stowage or performing maintenance, housekeeping, or emergency management operations (e.g., fire detection and suppression in multiple constrained locations or cleaning lunar dust out of air filters).
- Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.); increase robot autonomy via computationally efficient methods (planning, scheduling, and task execution); or improve human-robot interaction between IVA robots and human teams on the ground under communications constraints, including low bandwidth and extended loss-of-signal periods (software architecture, remote operations methods, etc.).

This subtopic also seeks to advance technologies that will enable the next generation of IVA robots to operate in lunar surface habitats, including:

- Novel robotic end effectors capable of reliably performing fine grasping tasks, such as plugging and unplugging MIL-STD-38999 electrical connectors and fluid quick-disconnect connectors.
- Compact, reliable, modular robotic actuators and controllers for IVA robots.
- Software that enables autonomous management of robot operational and hardware faults such that the robot can “fail operational.” For example, the software may use algorithms to determine how to automatically respond to a failure in a motion planner for move to a commanded location by taking into account a projected collision and replanning to the next closest point not in collision.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.X Other Robotic Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Proposals must describe how the technology will make a significant improvement over the current state of the art, rather than just an incremental enhancement, for a specific IVA robot application.

Deliverables should focus on prototype components, subsystems, and the demonstration thereof. Specifically, Phase I awards shall deliver an interim and final report discussing these results. Phase II awards shall deliver demonstration reports along with supporting software, design information, and documentation.

State of the Art and Critical Gaps:

The technology developed by this subtopic would both enable and enhance the Astrobee free-flying robot and Robonaut 2 humanoid robot, which are the state of the art for IVA robots. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVA tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2021 SBIR awards could potentially be tested with these, or other, robots in ground testbeds at Ames Research Center (ARC) and Johnson Space Center (JSC) in follow-on awards. Likewise, on-orbit testing on ISS may be possible during follow-on awards.

The technology developed by this subtopic would also fill technical gaps identified by the proposed Game Changing Development (GCD) Integrated System for Autonomous and Adaptive Caretaking (ISAAC) project, which will mature autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability:

This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

- Astrobee freeflying robot, GCD
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC), GCD
- Smart Deep Space Habitats (SmartHabs), Space Technology Research Institutes (STRI)

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:

- SPHERES (Synchronized Position Hold, Engage, Reorient, Experimental Satellite)/Astrobee facility, ISS
- Robonaut 2 humanoid robot, ISS
- Gateway program, Advanced Exploration Systems (AES)
- Logistics Reduction project, AES
- Autonomous Systems Operations project, AES

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Focus Area 5 Communications and Navigation

Lead MD: **HEOMD**

Participating MD(s): **SMD, STTR**

NASA seeks proposals to produce novel, innovative technologies in the communications and navigation discipline to support Exploration, Science and Space Technology missions, including the eventual return of humans to the Lunar surface. Missions are generating ever-increasing data volumes that require increased performance from communications systems while minimizing spacecraft impact. This requires higher peak throughput from the communications systems with lower flight communication system cost, mass, and power per bit transmitted. Long range, deep-space optical communications systems are needed to support data-intensive missions to Mars and beyond. Reliable, secure communications on a non-interference basis are also required in complex radio frequency (RF) environments such as inside a launch vehicle fairing or spacecraft cavity, where new analysis methods are needed for predicting the RF environment. Future missions that perform rendezvous and docking; on-orbit servicing, assembly, and manufacturing; or precision landing need increased autonomy to reduce dependence on ground-based tracking, orbit determination and maneuver planning.

This requires new and more efficient trajectory planning methods, robust autonomous onboard navigation, and improved precision of onboard instrumentation while minimizing cost, mass, and power. This focus area supports the development of innovative technologies for optical and quantum communications systems, cognitive communications, flight dynamics and navigation, transformational communications approaches, electric and magnetic field prediction methods, positioning and timing, guidance, navigation, and control that will provide a significant improvement over the current state of the art.

H9.01 Long-Range Optical Telecommunications (SBIR)

Lead Center: **JPL**

Participating Center(s): **GRC, GSFC**

Scope Title:

Free-Space Optical Communications Technologies

Scope Description:

This subtopic seeks innovative technologies for advancing free-space optical communications by pushing future data volume returns to and from space missions in multiple domains with return data rates >100 Gbps (cislunar, i.e., Earth or lunar orbit to ground), >10 Gbps (Earth-Sun L1 and L2), >1 Gbps/AU^2 (deep space), and >1 Gbps (planetary lander to orbiter and/or inter-spacecraft). Ground-to-space forward data rates >25 Mbps at ranges extending to farthest Mars ranges are targeted. Optical metrology (optimetrics) services, including high-precision ranging, Doppler, and astrometric measurements derived from the optical communications signal, are sought as well.

Innovative technologies offering low size, weight, and power (SWaP) with improved efficiency, reliability, robustness, are sought for novel state-of-the-art spaceflight laser communication systems, with supporting ground technologies.

Photon-counting sensitivity, near infrared (NIR), spaceflight worthy detectors/detector arrays for supporting laser ranging for potential navigation and science are of particular interest. Ground-based technologies that support operations of large-aperture daytime light collectors are needed to transition deep space optical communications to operational status. High-power, NIR, intensity-modulated lasers with fast rise times and low-timing jitter (subnanosecond) are needed to support high forward data rates and laser ranging.

Proposals are sought in the following specific areas:

Flight Laser Transceivers:

Low-mass, high-effective isotropic radiated power (EIRP) laser transceivers for links over planetary distances with:

- 30- to 50-cm clear aperture diameter telescopes for laser communications.
- Targeted mass of optomechanical assembly per aperture area, less than 200 kg/m^2.
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and flight temperatures by the optics and structure, at least -20 to 70 °C operational range.
- Design to mitigate stray light while pointing transceivers 3° from edge of Sun.
- Survive direct Sun pointing for extended duration (few hours to days).
- Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, light-weighted thermally stable structural properties are sought.
- Acquisition, tracking, and pointing architectures that can operate with dim laser beacons (irradiance of few pW/m^2 as entrance of flight aperture) from Mars farthest ranges.
- Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%).
- Receiver field-of-view (FOV) of at least 1 mrad angular radius for beacon assisted acquisition, tracking, and pointing.
- As a goal, additional focal plane with wider FOV (>10 mrad) to support onboard astrometry is desired.
- Beaconless pointing subsystems for space-to-ground operations beyond 3 AU.
- Assume integrated spacecraft microvibration angular disturbance of 150 µrad (<0.1 Hz to ~500 Hz).
- Low-complexity small-footprint agile laser transceivers for bidirectional optical links (>1 to 10 Gbps at a nominal link range of 1,000 to 20,000 km) for planetary lander/rover-to-orbiter and/or space-to-space cross links.
- Disruptive low-SWaP technologies that can operate reliably in space over extended mission duration.
- Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high frequency base disturbance by at least 50 dB.
- Desire integrated launch locks and latching mechanism.
- Robust for spaceflight.
- Should afford limited +/-5 to +/-12 mrad actuated field-of-regard for the optical line of sight of the transceiver.

Flight Laser Transmitters:

- High-Gbps laser transmitters.

- 1,550-nm wavelength.
- Lasers, electronics, and optical components ruggedized for extended space operations.
- High rate 10 to 100 Gbps for cislunar.
- 1 Gbps for deep space.
- Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the Consultative Committee for Space Data Systems (CCSDS).
- High peak-to-average power laser transmitters for regular or augmented M-ary pulse-position modulation (M-PPM) with M = 4, 8, 16, 32, 64, 128, and 256 operating at NIR wavelengths, preferably 1,550 nm, with average powers from 5 to 50 W.
- Subnanosecond pulse.
- Low-pulse jitter.
- Long lifetime and reliability operating in space environment (>5 and as long as 20 yr).
- High-modulation and polarization extinction ratio with 1 to 10 GHz line width.
- Space-qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power >20 W per channel; peak-to-average power ratios >200; >10 Gbps channel modulation capability.
- >20% wall-plug efficiency (direct current- (DC-) to-optical, including support electronics) with description of approach for stated efficiency of space-qualifiable lasers.
- Multiwatt Erbium-doped fiber amplifier (EDFA), or alternatives, with high-gain bandwidth (>30 nm, 0.5 dB flatness) concepts will be considered.
- Radiation tolerance better than 50 krad is required (including resilience to photodarkening).

Receivers/Sensors:

- Space-qualifiable high-speed receivers and low-light-level sensitive acquisition, tracking, pointing, detectors, and detector arrays.
- NIR wavelengths: 1,064 and/or 1,550 nm.
- Sensitive to low-irradiance incident at flight transceiver aperture (~ fW/m^2 to pW/m^2) detection.
- Low subnanosecond timing jitter and fast rise time.
- Novel hybridization of optics and electronic readout schemes with in-built preprocessing capability.
- Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high-precision range and range rate measurements.
- Tolerant to space radiation effects, total dose >50 krad, displacement damage and single event effects.

Novel technologies and accessories:

- Narrow bandpass optical filters.
- Space-qualifiable, subnanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~40 dB).

- NIR wavelengths from 1,064- to 1,550-nm region, with high transmission through Earth's atmosphere.
- Reliable tuning over limited range.
- Novel photonics integrated circuit (PIC) devices targeting space applications with objective of reducing SWaP of modulators, without sacrificing performance.
- Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.
- Concepts for offering redundancy to laser transmitters in space.
- Optical fiber routing of high-average powers (10s of watts) and high-peak powers (1 to 10 kW).
- Redundancy in actuators and optical components.
- Reliable optical switching.

Ground assets for optical communication:

Low-cost, large aperture receivers for faint optical communication signals from deep-space subsystem technologies:

- Demonstrate innovative subsystem technologies for >10-m-diameter deep-space ground collector.
- Capable of operating to within 3° of solar limb.
- Better than 10-μrad spot size (excluding atmospheric seeing contribution).
- Desire demonstration of low-cost, primary-mirror segment fabrication to meet a cost goal of less than $35K per square meter.
- Low-cost techniques for segment alignment and control, including daytime operations.
- Partial adaptive correction techniques for reducing the FOV required to collect signal photons under daytime atmospheric "seeing" conditions.
- Innovative adaptive techniques not requiring a wave-front sensor and deformable mirror of particular interest.
- Mirror cleanliness monitor and control systems.
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics.
- Large-core-diameter multimode fibers with low temporal dispersion for coupling large optics to detectors remote (30 to 50 m) from the large optics.
- 1,550-nm sensitive photon counting detector arrays compatible with large-aperture ground collectors with a means of coupling light from large-aperture diameters to reasonably sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion.
- Integrated time tagging readout electronics for >5 gigaphotons/sec incident rate.
- Time resolution <50 ps at 1-sigma.
- Highest possible single photon detection efficiency, at least 50% at highest incident photon-flux rates.
- Total detector active area >0.3 to 1 mm^2

- Integrated dark rate <3 megacount/sec.
- Optical filters.
- Subnanometer noise equivalent bandwidths.
- Tunable in a limited range in the 1,550-nm spectral region.
- Transmission losses <0.5 dB.
- Clear aperture >25 mm, and acceptance angle >40 mrad or similar etendue.
- Out-of-band rejection of >50 dB from 0.7 to 1.8 µm.
- Multikilowatt laser transmitters for use as ground beacon and uplink laser transmitters.
- NIR wavelengths in 1.0- or 1.55-µm spectral region.
- Capable of modulating with narrow nanosecond and subnanosecond rise times.
- Low-timing jitter and stable operation.
- High-speed real-time signal processing of serially concatenated PPM operating at a few bits per photon with user interface outputs.
- 15- to 60-MHz repetition rates.

Examples of potential outcomes are, prototype hardware with embedded software and/or firmware of components or assemblies for free-space optical communications (FSOC) optical transceivers, flight and ground laser transmitters, high-sensitivity space-worthy detectors, and novel FSOC photonics targeting near-earth and deep-space applications.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.1 Optical Communications

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

For all technologies lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly prove technical feasibility (proof of concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

State of the Art and Critical Gaps:

The state of the art (SOA) for FSOC can be subdivided into near-Earth (extending to cislunar and translunar distances) and planetary ranges with the Lagrange points falling in between.

Near-Earth FSOC technology has matured through a number of completed and upcoming technology demonstrations from space. Transition from technology demonstration to an operational service demands low-SWaP, novel high-speed (10 to 100 Gbps) space-qualified laser transmitters and receivers. Transmitters and receivers servicing near-Earth applications can possibly be repurposed for deep-space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5,000 to 100,000 km or inter-satellite links. Innovative light-weight space-qualified modems for handling multiple optical-modulation schemes. Emerging photonics technologies that can benefit space FSOC applications are sought.

Deep space FSOC is motivated by NASA's initiative to send humans to Mars. Critical gaps following a successful technology demonstration will be light-weighted 30- to 50-cm optical transceivers with a wide operational temperature range -20 to 50 °C over which wave-front error and focus is stable; high peak-to-average power space qualified lasers with average powers of 20 to 50 W; and single photon-sensitive radiation-hardened flight detectors with high-detection efficiency, fast rise times, and low-timing jitter. The detector size should be able to cover 1 mrad FOV with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from Earth or use celestial beacon sources. For Deep Space Optical Communications (DSOC) ground laser transmitters with high-average power (kW class) but narrow line-widths (<0.25 nm) and high-variable repetition rates are required. Innovative optical coatings for large aperture mirrors that are compatible with near-Sun pointing applications for efficiently collecting the signal and lowering background and stray light. Reliability through space-qualified materials and component selection and implementation of redundancy are highly sought after to enable sending humans to planetary destinations, as well as enable higher resolution science instruments. Deriving auxiliary optimetrics from the FSOC signals to support laser ranging and time transfer will also be critical for providing services to future human missions to Mars. High-rate uplink from the ground to Mars with high-modulation rate high-power lasers are also currently lacking.

Relevance / Science Traceability:

A number of FSOC-related NASA projects are ongoing with launch expected in the 2019-2022 time frame. The Laser Communication Relay Demonstration (LCRD) is an Earth-to-geostationary satellite relay demonstration to launch in 2021. The Illuma-T Project will follow to extend the relay demonstration to include a low Earth orbit (LEO) node on the International Space Station (ISS). In 2023, the Optical to Orion (O2O), Artemis II, demonstration will transmit data from the Orion crewed capsule as it performs a translunar trajectory and return to Earth.

In 2022, the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to AU distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstrations Mission (TDM) program and Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.

Of the 6 technologies recently identified by NASA for sending humans to Mars, laser communications was identified (https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars)

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https://www.nasa.gov/mission_pages/tdm/dsoc/index.html

H9.03 Flight Dynamics and Navigation Technologies (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JSC, MSFC**

Scope Title:

Advanced Techniques for Trajectory Design and Optimization

Scope Description:

NASA seeks innovative advancements in trajectory design and optimization for Earth orbit, cislunar, and interplanetary missions, including:

- Low-thrust trajectories in a multibody dynamical environment.
- Small-body (moons, asteroids, and comets) exploration.
- Distributed space systems (swarms, constellations, or formations).

In particular, NASA is seeking innovative techniques for optimization of trajectories that account for:

- System uncertainties (i.e., navigation errors, maneuver execution errors, etc.).
- Spacecraft and operational constraints (power, communications, thermal, etc.).
- Trajectory impacts on ability to make required navigational and/or science observations.

Furthermore, innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoon/multibody tours; low thrust, multispiral Earth orbits), apply novel artificial intelligence/machine learning (AI/ML) algorithms or provide unique methods for visualizing and manipulating trajectory designs are sought.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT), Collocation Stand Alone Library and Toolkit (CSALT), Copernicus, Evolutionary Mission Trajectory Generator (EMTG), Mission Analysis Low-Thrust Optimization (MALTO), Mission Analysis, Operations, and Navigation (MONTE), and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.2 Flight Mechanics

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:

Algorithms and software for optimizing trajectories while considering system uncertainties, spacecraft and operational constraints, and trajectory impacts on making navigational or science observations, do not currently exist. In addition, designing trajectories for complex missions, such as low-thrust cislunar or multibody tour missions rely heavily on hands-on work by very experienced people. That works reasonably well for designing a single-reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

Relevance / Science Traceability:

Relevant missions include:

- Artemis - Lunar Gateway.
- Europa Clipper.
- Lucy.
- Psyche.
- Dragonfly.
- Lunar IceCube.
- Roman Space Telescope.

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to more fully explore trade spaces and more quickly respond to changes in the mission.

References:

1. General Mission Analysis Tool (GMAT): https://software.nasa.gov/software/GSC-18094-1, https://gmat.atlassian.net/wiki/spaces/GW/overview?mode=global.
2. Collocation Stand Alone Library and Toolkit (CSALT): https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003690.pdf
3. Evolutionary Mission Trajectory Generator (EMTG): https://software.nasa.gov/software/GSC-16824-1, https://github.com/nasa/EMTG.
4. Copernicus: https://software.nasa.gov/software/MSC-26673-1, https://www.nasa.gov/centers/johnson/copernicus/index.html.
5. Mission Analysis Low-Thrust Optimization (MALTO): https://software.nasa.gov/software/NPO-43625-1
6. Mission Analysis, Operations, and Navigation (MONTE): https://montepy.jpl.nasa.gov/

Scope Title:

Autonomous Onboard Spacecraft Navigation, Guidance, and Control

Scope Description:

Future NASA missions require precision landing, rendezvous, formation flying, proximity operations (e.g., servicing and assembly), noncooperative object capture, and coordinated platform operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous, onboard spacecraft navigation and maneuver planning and execution technologies for applications in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning, including:

- Onboard relative and proximity navigation, multiplatform relative navigation (relative position, velocity and attitude, or pose), which support cooperative and collaborative space operations such as On-orbit Servicing, Assembly, and Manufacturing (OSAM).
- Advanced filtering techniques that address rendezvous and proximity operations as a multisensor, multitarget tracking problem; handle nonGaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, terrain relative navigation, and small body proximity operations.
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations in low and variable lighting conditions, including artificial intelligence/machine learning (AI/ML) algorithms.
- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission resequencing, onboard computation of large divert maneuvers, primitive body/lunar proximity operations, and pinpoint landing, including robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS), Navigator NavCube, core Flight System (cFS), or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration. For proposals that include hardware development, delivery of a prototype under the Phase I contract is preferred, but not necessary.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:

Currently navigation, guidance, and control functions rely heavily on the ground for tracking data, data processing, and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round trip communication time delays make it necessary to reduce reliance on Earth for navigation solutions and maneuver planning. Spacecraft that arrive at a near-Earth asteroid (NEA) or a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids, and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently does not have the navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

Relevance / Science Traceability:

Relevant missions include:

- Artemis (Lunar Gateway, Orion Multi-Purpose Crew Vehicle, Human Landing Systems).
- On-orbit Servicing, Assembly and Manufacturing (OSAM).
- LunaNet.
- autonomous Navigation, Guidance and Control (autoNGC).
- Roman Space Telescope.
- Europa Clipper.
- Lucy.
- Psyche.

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time replanning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

References:

1. Goddard Enhanced Onboard Navigation System (GEONS): (https://software.nasa.gov/software/GSC-14687-1), (https://goo.gl/TbVZ7G)
2. Navigator: (http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf)
3. NavCube: (https://goo.gl/bdobb9)
4. core Flight System (cFS): https://cfs.gsfc.nasa.gov/
5. On-orbit Servicing, Assembly, and Manufacturing (OSAM): https://nexis.gsfc.nasa.gov/osam/index.html
6. LunaNet: https://esc.gsfc.nasa.gov/news/_LunaNetConcept
7. autonomous Navigation, Guidance and Control (autoNGC): https://techport.nasa.gov/view/94817

Scope Title:

Conjunction Assessment Risk Analysis (CARA)

Scope Description:

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 cm and the number of objects in orbit is steadily increasing, which causes an increasing threat to human spaceflight and robotic missions in the near-Earth environment. The NASA CARA team receives screening data from the 18th Space Control Squadron concerning predicted close approaches between NASA satellites and other space objects. CARA determines the risk posed by those events and recommends risk mitigation strategies, including collision avoidance maneuvers, to protect NASA non-human-spaceflight assets in Earth orbit. The ability to perform CARA more accurately and rapidly will improve space safety for all near-Earth operations. This subtopic seeks innovative technologies to improve the CARA process including:

- Improved conjunction assessment (CA) event evolution prediction methods, models, and algorithms with improved ability to predict characteristics for single and ensemble risk assessment, especially using artificial intelligence/machine learning (AI/ML).
- AI/ML applied to CA risk assessment parameters.
- Middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions).
- Methods for combining commercial data (observations or ephemerides) with 18th Space Control Squadron (18 SPCS) derived solutions (available as Vector Covariance Messages, Conjunction Data Messages, or Astrodynamics Support Workstation output) to create a single improved orbit determination solution including more data sources.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:

Current state of the art has been adequate in performing CA and collision mitigation for space objects that fall under the high interest events (HIE). With the incorporation of the Space Fence and the deployment of large constellations, the number of objects tracked and assessed for conjunctions is expected to greatly increase. This presents a critical gap in which current approaches may not suffice. Thus, smarter ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), improved CA event evolution prediction, and AI/ML applied to CA risk assessment parameters and/or event evolution are needed. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for CA.

Collision avoidance maneuver decisions are based on predicted close approach distance and probability of collision. The accuracy of these numbers depend on underlying measurements and mathematics used in estimation. Current methods assume Gaussian distributions for errors and that all objects are shaped like cannon balls for nongravitational force computations. These assumptions and others cause inaccurate estimates that can lead decision makers to perform unnecessary collision avoidance maneuvers, thus wasting propellant. Better techniques are needed for orbit prediction and covariance characterization and propagation. Better modeling of nongravitational force effects is needed to improve orbit prediction. Modeling of nongravitational forces relies on knowledge of individual object characteristics.

Relevance / Science Traceability:

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth, cislunar, and lunar environments. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer term predictions, and reduce propellant usage for collision avoidance maneuvers.

References:

1. NASA Conjunction Assessment Risk Analysis (CARA) Office: https://satellitesafety.gsfc.nasa.gov/cara.html.
2. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/.
3. Newman, Lauri, K., "The NASA robotic conjunction assessment process: Overview and operational experiences," Acta Astronautica, Vol. 66, Issues 7-8, Apr-May 2010, pp. 1253-1261, https://www.sciencedirect.com/science/article/pii/S0094576509004913.
4. Newman, Lauri K., et al. "Evolution and Implementation of the NASA Robotic Conjunction Assessment Risk Analysis Concept of Operations." (2014). https://ntrs.nasa.gov/search.jsp?R=20150000159.
5. Newman, Lauri K., and Matthew D. Hejduk. "NASA Conjunction Assessment Organizational Approach and the Associated Determination of Screening Volume Sizes." (2015). https://ntrs.nasa.gov/search.jsp?R=20150011461.
6. Office of Safety and Mission Assurance, “NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments”, NPR 8715.6B, https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=6B.

H9.05 Transformational Communications Technology (SBIR)

Lead Center: **GRC**

Participating Center(s): **GSFC**

Scope Title:

Revolutionary Concepts

Scope Description:

NASA seeks revolutionary transformational communications technologies, for lunar exploration and beyond, that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. The proposer is expected to identify new ideas, create novel solutions, and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (≈10 yr) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program. The transformational communications technology development will focus research in the following areas:

- Systems optimized for energy efficiency (information bits per unit energy).
- Hybridization of communications and sensing systems to maximize performance and minimize size, weight, and power (SWaP), especially for harsh environments.
- Advanced materials; smart materials; electronics embedded in structures; functional materials; graphene-based electronics/detectors.
- Techniques to overcome traditional analog-to-digital converter speed and power consumption limitations.
- Technologies that address flexible, scalable digital/optical core processing topologies to support both radio-frequency (RF) and optical communications in a single terminal.
- Nanoelectronics and nanomagnetics; quantum logic gates; single electron computing; superconducting devices; technologies to leapfrog Moore’s law.
- Energy harvesting technologies to enhance space communication system efficiency.
- Human/machine and brain-machine interfacing to enable new communications paradigms; the convergence of electronic engineering and bioengineering; neural signal interfacing.
- Quantum communications, methods for probing quantum phenomenon, methods for exploiting exotic aspects of quantum theory.

The research should be conducted to demonstrate theoretical and technical feasibility during the Phase I and Phase II development cycles and be able to demonstrate an evolutionary path to insertion within approximately 10 years. Delivery of a prototype of the most critically enabling element of the technology for NASA testing at the completion of the Phase II contract is expected.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I deliverables shall include a final report describing theoretical analysis and prototyping concepts. The technology should have eventual commercialization potential.

For Phase II consideration, the final report should include a detailed path towards Phase II prototype hardware.

State of the Art and Critical Gaps:

While according to the Business R&D and Innovation Survey of the $323 billion of research and development performed by companies in the United States in 2013, Information and Computing Technology industries accounted for 41%. But it must be understood that the majority of these investments seek short-term returns and that most of the investment is in computer technology, cloud computing and networking, semiconductor manufacturing, etc.—not new and futuristic "over-the-horizon" technologies with uncertain returns on investment. As a concrete example, deep-space mission modeling indicates a need for a 10× improvement in data rate per decade out to 2040. How will that be achieved? To some extent that goal will be achieved by moving to Ka-band and optical communications and perhaps antenna arraying on a massive scale. But given the ambitiousness of the goal, disruptive technologies like what is being sought here, will be required.

Relevance / Science Traceability:

NASA seeks revolutionary, transformational communications technologies that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. This is a broad subtopic expected to identify new ideas, create novel solutions, and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (≈10 yr) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program.

References:

NASA Space Communication and Navigation (SCaN) Network Architecture Definition Document Executive Summary

https://www.nasa.gov/sites/default/files/files/SCaN_ADD_Vol1Rev4.pdf

H9.07 Cognitive Communication (SBIR)

Lead Center: **GRC**

Participating Center(s): **GSFC, JPL**

Scope Title:

Lunar Cognitive Capabilities

Scope Description:

NASA's Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks, and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by onboard data processing and modern space networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden. Examples of these cognitive capabilities include:

- Link technologies—reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference.
- Network technologies—robust intersatellite links, data storage/forwarding, multinode routing in unpredictable environments.
- System technologies—optimal scheduling techniques for satellite and surface relays in distributed and real-time environments.

Through Space Policy Directive-1, NASA is committed to landing American astronauts on the Moon by 2024. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling. Examples of research and/or technology development include:

- Onboard processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft.
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics.
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment.
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems.
- Flexible communication platforms with novel signal processing technology to support cognitive approaches.
- Other innovative, related areas of interest to the field of cognitive communications.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, and surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low-size, -weight, and -power (-SWaP) attributes suitable for small satellite (e.g., 50 kg) or CubeSat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of onboard resources, such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits, and show a path towards a Phase II implementation. Phase I deliverables include a feasibility assessment and concept of operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3 to 4) and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting demonstration operations on a small satellite or CubeSat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools, as necessary, for NASA to modify and use the cognitive software capability or hardware component(s). Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Algorithms must be implemented in software. Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software defined radio platforms shall be compliant with the latest NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009, and NASA-HNBK-4009. The deliverable shall be demonstrated in a relevant emulated environment and have a clear path to Phase III flight implementation on a SWaP-constrained platform.

State of the Art and Critical Gaps:

To summarize NASA Technology Roadmap TA5: "As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks.... Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data.... Reconfigurable radio systems...could autonomously optimize the RF [radio-frequency] links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system in order to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance."

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc.
- Data routing between lunar relay satellites, as necessary, to conserve power, route data to Earth, and meet quality of service requirements.
- Efficient use of lunar communication spectrum while coexisting with future/current interference sources.
- On-demand communication resource scheduling.
- Multihop, delay tolerant routing.

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms.

- Integrated wide-band sensing and narrow-band communication on the same radio terminal.
- Intersatellite networking and routing, especially in unpredictable and unscheduled environments.
- On-demand scheduling technology for communication links.
- Cross-layer optimization approaches for optimum communication efficiency at a system level.

Relevance / Science Traceability:

Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short- and long-term performance for improvements.

References:

Several related reference papers and articles include:

- "NASA Explores Artificial Intelligence for Space Communications"
    - https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications
- "Implementation of a Space Communications Cognitive Engine"
    - https://ntrs.nasa.gov/search.jsp?R=20180002166
- "Reinforcement Learning for Satellite Communications: From LEO to Deep Space Operations"
    - https://ieeexplore.ieee.org/document/8713802
- "Cognitive Communications and Networking Technology Infusion Study Report"
    - https://ntrs.nasa.gov/search.jsp?R=20190011723
- "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications"
    - https://ntrs.nasa.gov/search.jsp?R=20170009153
- "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits"
    - https://ntrs.nasa.gov/search.jsp?R=20170009386
- "Architecture for Cognitive Networking within NASAs Future Space Communications Infrastructure"
    - https://ntrs.nasa.gov/search.jsp?R=20170001295
- "Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks"
    - https://ntrs.nasa.gov/search.jsp?R=20170006541

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: http://ieee-ccaa.com/

S3.04 Guidance, Navigation, and Control (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL, MSFC**

Scope Title:

Guidance, Navigation, and Control

Scope Description:

NASA seeks innovative, groundbreaking, and high-impact developments in spacecraft guidance, navigation, and control technologies in support of future science and exploration mission requirements. This subtopic covers mission-enabling technologies that have significant size, weight and power, cost, and performance (SWaP-CP) improvements over the state-of-the-art commercial off-the-shelf (COTS) capabilities in the areas of S, Absolute and Relative Navigation Systems, and Pointing Control Systems, and Radiation-Hardened Guidance, Navigation, and Control (GNC) Hardware.

Component technology developments are sought for the range of flight sensors, actuators, and associated algorithms and software required to provide these improved capabilities. Technologies that apply to most spacecraft platform sizes will be considered.

Advances in the following areas are sought:

- Spacecraft Attitude Determination and Control Systems: Sensors and actuators that enable <0.1 arcsecond-level pointing knowledge and arcsecond-level control capabilities for large space telescopes, with improvements in size, weight, and power requirements.
- Absolute and Relative Navigation Systems: Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. For relative navigation, machine vision technologies apply. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, robotic servicing and sample return capabilities, and other GNC techniques for enabling the collection of distributed science measurements. In addition, flight sensors and algorithms that support onboard terrain relative navigation are of interest.
- Pointing Control Systems: Mechanisms that enable milliarcsecond-class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technology that can be used to enable other areas within this subtopic applies.
- Radiation-Hardened Hardware: GNC sensors that could operate in a high radiation environment, such as the Jovian environment.
- Increasing the fundamental precision of gyroscopes and accelerometers that utilize optical cavities could benefit autonomous navigation and open up new science possibilities. Two strategies may be pursued to increase the precision. First, can the scale factor be increased without a concomitant increase in the quantum noise? Possible approaches include but are not limited to: (a) the use of fiber optics to increase cavity length without increasing SWaP and (b) exploitation of the degeneracies known as exceptional points (EPs) that occur in non-Hermitian systems. Prominent examples of such systems include parity-time symmetric systems and cavities containing a fast-light medium. It remains to be seen, however, whether the boost in scale factor near an EP can result in increased precision or is entirely counteracted by additional quantum noise. Proposals are

sought that seek to answer this question through theoretical or experimental means in passive and active systems, including continuous-wave and pulsed lasers. Second, can the quantum noise be reduced without a concomitant reduction in scale factor? The frequency measurement in a laser gyro or accelerometer only involves the uncertainty in phase. Therefore, the relevant quantum noise might be reduced by squeezing. Proposals are sought that investigate and utilize squeezing, for example via the propagation of quantum solitons, for the improvement of inertial sensors.

Proposals should show an understanding of one or more relevant science or exploration needs and present a feasible plan to fully develop a technology and infuse it into a NASA program.

This subtopic is for all mission-enabling GNC technology in support of Science Mission Directorate (SMD) missions and future mission concepts. Proposals for the development of hardware, software, and/or algorithms are all welcome. The specific applications could range from CubeSats/SmallSats, to ISS payloads, to flagship missions.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.X Other Guidance, Navigation, and Control

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Prototype hardware/software, documented evidence of delivered TRL (test report, data, etc.), summary analysis, supporting documentation.

- Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment as described in a final report.
- Phase II technology development efforts shall deliver a component/prototype at the TRL 5 to 6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) Descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

State of the Art and Critical Gaps:

Capability area gaps:

- Spacecraft GNC Sensors—highly integrated, low-power, low-weight, radiation-hard component sensor technologies, and multifunctional components.
- Spacecraft GNC Estimation and Control Algorithms—sensor fusion, autonomous proximity operations algorithm, robust distributed vehicle formation sensing and control algorithms.

Relevance / Science Traceability:

Science areas: Heliophysics, Earth Science, Astrophysics, and Planetary missions’ capability requirement areas:

- Spacecraft GNC Sensors—optical, radio-frequency (RF), inertial, and advanced concepts for onboard sensing of spacecraft attitude and orbit states

- Spacecraft GNC Estimation and Control Algorithms—innovative concepts for onboard algorithms for attitude/orbit determination and control for single spacecraft, spacecraft rendezvous and docking, and spacecraft formations.

References:

- 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
- 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE

T5.04 Quantum Communications (STTR)

Lead Center: **GRC**

Participating Center(s): **GSFC, JPL**

Scope Title:

Quantum Communications

Scope Description:

NASA seeks to develop quantum networks to support the transmission of quantum information for aerospace applications. This distribution of quantum information could potentially be utilized in secure communication, sensor arrays, and quantum computer networks. Quantum communication may provide new ways to improve sensing the entangling of distributed sensor networks to provide extreme sensitivity for applications such as astrophysics, planetary science, and Earth science. Also of interest are ideas or concepts to support the communication of quantum information between quantum computers over significant free-space distances (greater than 10 km up to geosynchronous equatorial orbit (GEO)) for space applications or supporting linkages between terrestrial fiber-optic quantum networks. Technologies that are needed include quantum memory, quantum entanglement distribution systems, quantum repeaters, high-efficiency detectors, quantum processors, and quantum sensors that make use of quantum communication for distributed arrays and integrated systems that bring several of these aspects together using Integrated Quantum Photonics. A key need for all of these are technologies with low size, weight, and power that can be utilized in aerospace applications. Some examples (not all inclusive) of requested innovation include:

- High-rate free-space quantum entanglement distribution systems.
- Photonic waveguide integrated circuits for quantum information processing and manipulation of entangled quantum states; requires phase stability, low propagation loss, that is, <0.1 dB/cm, and efficient fiber coupling, that is, coupling loss <1.5 dB.
- Waveguide-integrated single-photon detectors for >100 MHz incidence rate, 1-sigma time resolution of <25 ps, dark count rate <100 Hz, and single-photon detection efficiency >50% at highest incidence rate.
- Integrated sensors that support arrays of distributed sensors, such as an entangled interferometric imaging array.
- Integrated photonic circuit quantum memory.
- Quantum entanglement fidelity measurement capabilities.
- Scalable quantum memory.

Quantum sensor-focused proposals that do not include an aspect of quantum communication should propose to the Quantum Sensing and Measurement subtopic as individual quantum sensors are not covered by this subtopic.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Hardware
- Analysis
- Research
- Prototype

Desired Deliverables Description:

Phase I research should (highly encouraged) be conducted to demonstrate technical feasibility with preliminary hardware (i.e., beyond architecture approach/theory; a proof-of-concept) being delivered for NASA testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 4 to 6 level with mature hardware and preliminary integration and testing in an operational environment. Deliverables are desired that substantiate the quantum communication technology utility for positively impacting the NASA mission. The quantum communication technology should impact one of three key areas: information security, sensor networks, and networks of quantum computers. Deliverables that substantiate technology efficacy include reports of key experimental demonstrations that show significant capabilities, but in general it is desired that the deliverable include some hardware that shows the demonstrated capability.

State of the Art and Critical Gaps:

There is a critical gap between the United States and other countries, such as Japan, Singapore, Austria, and China, in quantum communications in space. Quantum communications is called for in the 2018 National Quantum Initiative (NQI) Act, which directs the National Institute of Standards and Technology (NIST), National Science Foundation (NSF), and Department of Energy (DOE) to pursue research, development, and education activities related to Quantum Information Science. Applications in quantum communication, networking, and sensing, all proposed in this subtopic, are the contributions being pursued by NASA to integrate the advancements being made through the NQI.

Relevance / Science Traceability:

This technology would benefit NASA communications infrastructure as well as enable new capabilities that support its core missions. For instance, advances in quantum communication would provide capabilities for added information security for spacecraft assets as well as provide a capability for linking quantum computers on the ground and in orbit. In terms of quantum sensing arrays, there are a number of sensing applications that could be supported through the use of quantum sensing arrays for dramatically improved sensitivity.

References:

- Evan Katz, Benjamin Child, Ian Nemitz, Brian Vyhnalek, Tony Roberts, Andrew Hohne, Bertram Floyd, Jonathan Dietz, and John Lekki: “Studies on a Time-Energy Entangled Photon Pair Source and Superconducting Nanowire Single-Photon Detectors for Increased Quantum System Efficiency,” SPIE Photonics West, San Francisco, California (Feb. 6, 2019).

- M. Kitagawa and M.Ueda: “Squeezed Spin States," Phys. Rev. A 47, 5138–5143 (1993).
- Daniel Gottesman, Thomas Jennewein, and Sarah Croke: “Longer-Baseline Telescopes Using Quantum Repeaters,” Phys. Rev. Lett. 109 (Aug. 16, 2012).
- Nicolas Gisin and Rob Thew: “Quantum Communication,” Nature Photonics, volume 1, pp. 165–171 (2007).
- H. J. Kimble: “The Quantum Internet,” Nature, volume 453, pp. 1023–1030 (June 19, 2008).
- C. L. Degen, F. Reinhard, and P. Cappellaro: “Quantum Sensing,” Rev. Mod. Phys. 89 (July 25, 2017).
- Ian, Nemitz, Jonathan Dietz, Evan Katz, Brian Vyhnalek, and Benjamin Child: “Bell Inequality Experiment for a High Brightness Time-Energy Entangled Source,” SPIE Photonics West, San Francisco, CA, (March 1, 2019).

Focus Area 6 Life Support and Habitation Systems

Lead MD: **HEOMD**

Participating MD(s): **STTR**

The Life Support and Habitation Systems Focus Area seeks key capabilities and technology needs encompassing a diverse set of engineering and scientific disciplines, all of which provide technology solutions that enable extended human presence in deep space and on planetary surfaces such as Moon and Mars, including Orion, ISS, Gateway, Artemis and Human Landing Systems. The focus is on systems and elements that directly support human missions and astronaut crews, such as Environmental Control and Life Support Systems (ECLSS), Extravehicular Activity (EVA) systems, crew provisioning, plant growth for bioregenerative food production, and tools for systems engineering. Because spacecraft and their systems may involve multiple partnerships, with institutional, corporate, and governmental involvement, Model Based Systems Engineering approaches may enable and improve their distributed development.

For future crewed missions beyond low-Earth orbit (LEO) and into the solar system, regular resupply of consumables and emergency or quick-return options will not be feasible. New technologies must be compatible with attributes of the environments expected, including microgravity or partial gravity, varying atmospheric pressure and composition, space radiation, and the presence of planetary dust. Technologies of interest are those that enable long-duration, safe, economical, and sustainable deep-space human exploration. Special emphasis is placed on developing technologies that will fill existing gaps as described in this solicitation, that reduce requirements for consumables and other resources, including mass, power, volume and crew time, and which will increase safety and reliability with respect to the state-of-the-art. Spacecraft may be untended by crew for long periods, therefore systems must be operable after these intervals of dormancy.

Environmental Control and Life Support Systems encompass process technologies and monitoring functions necessary to provide and maintain a livable environment within the pressurized cabin of crewed spacecraft, including environmental monitoring, water recycling, and atmosphere revitalization. Of special note for this solicitation, these processes and functions include non-genetic methods for assessing the microbial burden within spacecraft, monitoring systems for identifying and quantifying a wide spectrum of inorganic and organic constituents in spacecraft wastewater and potable water, and use of novel additive manufacturing methods to print sorbent beds for removal of atmospheric contaminants. Novel methods for microbial assessment may also be useful assessing previously dormant spacecraft before crew entry and supporting planetary protection compliance.

Unique needs exist for the Exploration Extra-vehicular Mobility Unit (EMU), including innovations to improve the system to supply feed water to the Portable Life Support System (PLSS), and new technologies for the spacesuit's Pressure Garment Bladder. For intra-vehicular activity (IVA), new flame retardant textiles are needed for crew apparel fabrics to be used in high oxygen environments expected during lunar and planetary exploration.

Future human missions may include an in-situ capability to produce supplemental fresh food. Advanced technologies for remotely sensing the health status and performance of crop plants within space-based controlled environment production systems are sought. In addition, tailoring the rhizosphere with beneficial microbial consortia, through biopriming seeds or other methods, could potentially promote growth and yield or confer resistance against biotic and abiotic stresses.

The current collaborative environment between government, commercial and international sectors will result in the distributed development of human spacecraft elements and systems for human missions of the future such as Gateway and lunar surface missions including Artemis. Their integration may benefit from advances in model-based systems engineering approaches.

Please refer to the description and references of each subtopic for further detail to guide development of proposals within this technically diverse focus area.

H3.02 Microbial Monitoring for Spacecraft Cabins (SBIR)

Lead Center: **JPL**

Participating Center(s): **GRC, JSC, KSC, MSFC**

Scope Title:

Spacecraft Microbial Monitoring for Long Duration Human Missions

Scope Description:

With the advent of molecular methods, emphasis is now being placed on nucleic acids to rapidly detect microorganisms. However, the sensitivity of current gene-based microbial detection systems is low (~100 gene copies per reaction), requires elaborate sample process steps, involves destructive analyses, and requires fluids to be transferred and detection systems are relatively large size. Recent advancements in the metabolomics field have potential to substitute (or augment) current gene-based microbial detection technologies that are multistepped, destructive, and labor intensive (e.g., significant crew time). NASA is soliciting nongene-based microbial detection technologies and systems that target microbial metabolites and that quantify the microbial burden of surfaces, air, and water inside for long-duration deep-space habitats.

Potable water:

A simple integrated, microbial sensor system that enables sample collection, processing, and detection of microbes or microbial activity of the crew potable water supply is sought. A system that is fully-automated and can be in-line in an Environmental Control and Life Support System- (ECLSS-) like water system is preferred.

Habitat surfaces:

Future crewed habitats in cislunar space will be crew-tended and thus unoccupied for many months at a time. When crew reoccupies the habitat they will want to quickly, efficiently, and accurately assess the microbial status of the habitat surfaces. A microbial assessment/monitoring system or hand-held device that requires little to no consumables is sought.

Airborne contamination:

Future human spacecraft, such as Gateway and Mars vehicles, may be required to be dormant while crew is absent from the vehicle, for periods that could last from 1 to 3 years. Before crews can return, these environments must be verified prior to crew return. These novel methods have the potential to enable remote autonomous microbial monitoring that does not require manual sample collection, preparation, or processing.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.4 Environmental Monitoring, Safety, and Emergency Response

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data, and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps:

The state of the art on the International Space Station (ISS) for microbial monitoring is culturing and counting, as well as grab samples that are returned to Earth. NASA has invested in DNA-based polymerase chain reaction (PCR) systems, partially robotic in some cases, to eliminate the need for on-orbit culturing. However, a fully automated system is still not ready and there is still a gap for a low- or no-crew time detection system.

Relevance / Science Traceability:

The technologies requested could be proven on the ISS and would be useful to long-duration human exploration missions away from Earth, where sample return was not possible. The technologies are applicable to Gateway, Lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support Systems (LSS) Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of ECLSS. The LSS Project is under the Advanced Exploration Systems (AES) Program, Human Exploration and Operations Mission Directorate (HEOMD).

References:

1. A list of targeted contaminants for environmental monitoring can be found at "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at: https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs

2. Advanced Exploration Systems Program, Life Support Systems Project: https://www.nasa.gov/content/life-support-systems
3. NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview", 49th International Conference on Environmental Systems, ICES-2019-297 https://ttu-ir.tdl.org/bitstream/handle/2346/84496/ICES-2019-297.pdf
4. National Aeronautics and Space Administration, 2020 NASA Technology Taxonomy, https://www.nasa.gov/offices/oct/taxonomy/index.html
5. NASA Standard 3001 - Requirements: https://www.nasa.gov/hhp/standards

H3.05 Additive Manufacturing for Adsorbent Bed Fabrication (SBIR)

Lead Center: **ARC**

Participating Center(s): **JSC, MSFC**

Scope Title:

Additive Manufacturing for Adsorbent Bed Fabrication

Scope Description:

Current state-of-the-art (SOA) Air Revitalization System (ARS) contaminant-removal systems utilize packed beds. Packed beds have high pressure drop, large void volumes, poor heat management, and poor mechanical stability. Some alternate sorbent technologies (e.g., structural sorbent and monolith) have been proposed previously, but they are at a low TRL and require additional research and development to prove the concepts and resolve scale-up issues. Using robocasting techniques, a type of 3D paste printing, sorbent pastes are used to print sorbent beds with custom flow paths and rod size. With this approach, sorbent beds can be designed and fabricated with controlled pressure drop, tailored flow path, minimized void spaces, good heat management, high mechanical and chemical stability, and optimized structures with high mass transfer. In addition, having the ability to formulate one's own sorbent paste materials allows variability in binders and co-binder selections for optimal contaminant removal and thermal performance. Previous studies have been completed for a variety of sorbent pastes (activated carbon [Ref. 1], zeolite 13X [Ref. 2], 5A, 4A, polymer, amine functionalized zeolite [Ref. 3], etc.). However, these works did not focus on optimizing the printed structure for cyclic operation and addressing scale-up issues.

NASA aims to use the 3D-printed sorbent beds as drop-in replacements for packed sorbent beds such as those found in the Carbon Dioxide Removal Assembly (CDRA) on the International Space Station (ISS). Using robocasting techniques to print scale-up sorbent beds is also at a low TRL and requires additional development. However, it is the preferred technique over other options (e.g., structured sorbents) because, if successful, the resulting technology will yield equivalent system mass reduction due to better thermal and fluid management and mass transfer properties. Technology solutions could include, but not be limited to, SOA solid sorbent materials such as zeolite 13X, zeolite 5A, silica gel, metal-organic-frameworks (MOFs), and activated carbon. All proposed technologies should address issues related to scale-up, paste formulation, printability, mechanical and hydrothermal stability, system design, and heaters integration. The components used in the paste formulation must abide by spacecraft chemical safety standards. This subtopic is open for novel ideas that address any of the numerous technical challenges listed below for the design and fabrication of printed sorbent beds for humidity and/or CO_2 removal. This subtopic does not seek new sorbent chemistries, instead, zeolite paste formulation and paste printing are desired.

- Innovative concepts on how to make silica gel paste for use in removing water from air, either in a cabin humidity control system or as part of a CO_2 removal process requiring desiccation.
- Choosing the correct paste formulation for optimal and mechanical stability.
- Designing the lattice structures to minimize pressure drop, provide large surface area for mass transfer, and prevent channeling.
- Designing a heater system for thermal regeneration of the sorbent that would minimize contact resistance between heater and sorbent and minimize mass while providing a uniform temperature throughout the bed. Heaters could be commercial-off-the-shelf (COTS) types (e.g. cartridge or Kapton® heaters) or they could be 3D printed.

NASA is especially interested in technologies that can be incorporated into closed-loop life-support systems. Three life-support functions of particular Interest are CO_2 removal, cabin humidity control, and trace contaminant control, as solid sorbents are particularly suited to these applications. Technologies targeting other NASA life-support functions are also of interest.

Proposals targeting CO_2 removal applications should consider the following:

- Improvements in sorbent CO_2 capacity and selectivity leading to smaller, more efficient components, lower energy consumption, and operation at lower CO_2 partial pressures are highly desirable.
- Increases in the robustness of sorbent materials to mechanical stresses and temperature and humidity changes/cycling.
- Full-scale systems must achieve the following performance targets:
    - CO_2 removal rate of 4.16 kg/day (a 4-crew load).
    - System must maintain an environment with 3.0 mmHg $ppCO_2$ for cabin applications (based on the daily average $ppCO_2$).
    - System size ≤0.3 m^3 for a 4-crew system.
    - Average system power ≤500 W of power for a 4-crew system.
    - System mass of ≤450 kg for the 4-person load.
    - System must effectively separate out water vapor from cabin air (less than 100 ppm water vapor in the CO_2 product is desired).

System must effectively separate out oxygen and nitrogen from cabin air (less than 1% O_2 and 2% N_2 by volume in the CO_2 product is desired).

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Research

Desired Deliverables Description:

Phase I deliverables: Detailed sorbent paste formulation and analysis, proof-of-concept test data, and predicted performance (mass, volume, and thermal performance) for contaminant removal (e.g., carbon dioxide, water, or trace contaminants). Deliverables should clearly describe and predict performance over the SOA with an estimated scaled-up design for a 4-person crew.

Phase II deliverables: Delivery of technologically mature components/subsystems that demonstrate functional performance with appropriate interfaces. Prototypes should be at least at a 4-crew-member scale.

State of the Art and Critical Gaps:

Current and future human exploration missions require an optimized ARS that can reduce the system mass, volume, and power, and increase reliability. The SOA systems (CDRA, the Carbon Dioxide Reduction Assembly (CRA), and the Trace Contaminant Control System (TCCS) are adsorbent-based or catalyst-based and their performances are limited because they use COTS sorbent materials. COTS sorbent pellets/beads have fixed performance parameters (e.g., mass transfer capability), which limit the ability to tailor the sorbents to meet specific needs. Spacecraft system design requirements differ from those used in industry. For example, one industrial application focuses on removing carbon dioxide at a relatively high concentration (12% from flue gas), whereas CDRA focuses on removing carbon dioxide at low partial pressure (3 mmHg). Therefore, having the ability to tailor a sorbent to NASA objectives would lead to more efficient adsorbent systems not just for the ARS but also other life support systems that utilize sorbents (e.g., the multifiltration beds). In addition, often times COTS sorbents are sold in bulk (impractical for NASA-scale systems) and become obsolete when manufacturers cease production. Instead of having to reevaluate and redesign systems for new COTS materials to address obsolescence, NASA can use a well-characterized 3D-printed sorbent formulation to remake or even to improve SOA systems. Here, having control over the formulation of these materials could mean continuity in the use of the materials as well and an ability to optimize and tailor the materials for spacecraft use. In addition, as new materials are available for use, (e.g., MOFs), these materials can be adapted using the same 3D-printed design. That is, once the lattice and heater designs are completed, the backbone may be used for other sorbent materials. Moreover, the 3D printing can be done commercially once an acceptable paste formulation has been established. Sorbent paste printing techniques need additional technology investment to reach a level of maturity necessary for consideration for use in a flight Environmental Control and Life Support System (ECLSS). This approach offers high returns and is a paradigm shift from the SOA, as it offers the ability to control flow paths, thermal management, and mass transfer properties.

Relevance / Science Traceability:

This technology could be a drop-in replacement for the current CO_2 adsorption beds and can be proven on the ISS with potential for application in long-duration human exploration missions, including Gateway, Lunar surface, and Mars, including surface and transit. It is imperative that CO_2 be removed to support human life during space missions. This subtopic is supported by the Advanced Exploration Systems (AES) Program in an effort to improve the SOA ARS in the ECLSS.

References:

1. Wójtowicz, Marek A., Joseph E. Cosgrove, Michael A. Serio, Andrew E. Carlson, and Cinda Chullen. "Monolithic Trace-Contaminant Sorbents Fabricated from 3D-printed Polymer Precursors." (2019). https://ntrs.nasa.gov/citations/20190028890
2. Thakkar, Harshul, Stephen Eastman, Amit Hajari, Ali A. Rownaghi, James C. Knox, and Fateme Rezaei. "3D-printed zeolite monoliths for CO2 removal from enclosed environments." *ACS applied materials & interfaces* 8, no. 41 (2016): 27753-27761.

3. Lawson, Shane, Connor Griffin, Kambria Rapp, Ali A. Rownaghi, and Fateme Rezaei. "Amine-functionalized MIL-101 monoliths for CO2 removal from enclosed environments." *Energy & Fuels* 33, no. 3 (2019): 2399-2407.

H3.07 Flame-Retardant Textiles for Intravehicular Activities (IVA) (SBIR)

Lead Center: **JSC**

Participating Center(s): **GRC**

Scope Title:

Flame-Retardant Textiles for Crew Clothing and for Use in Spacecraft Cabins

Scope Description:

There is a textile technology gap for apparel fabrics for lunar and planetary human exploration. While there are industrial fabrics that are flame retardant in oxygen-enriched atmospheres up to 100% at ambient pressure, there is no apparel or furnishing fabric that is flame retardant in enriched atmosphere of 36% oxygen at a pressure of 8.2 psi (56.5 kPa). The challenge for developing next-to-the-skin flame-retardant fabrics comes from the many other requirements these fabrics must satisfy. They must be comfortable. This means they must have high drape, be soft to the touch, and have no inherent unpleasant smell. In addition, they cannot be toxic through the skin or outgas toxic chemicals. These fabrics must be washable and durable over a period of up to three years of repeated use. In other words, these fabrics must have physical and mechanical properties (no static cling, color fastness, tensile strength and elongation dry and wet, tear resistance, bending stiffness, torsional stiffness, abrasion resistance, etc.) that make them suitable for use in T-shirts and pants to be worn in an atmosphere containing 36% oxygen. NASA needs such new fabrics to send astronauts to the Moon in order to later establish a sustainable human presence beyond low Earth orbit (LEO) or on the Moon, and in preparation for a future trip to Mars.

The gap in textile technology that affects IVA results from the need to protect astronauts inside space vehicles and space habitats with atmosphere of 34 ± 2% oxygen at a pressure of 8.2 psi (56.5 kPa). During the period the astronauts reside in the Lunar Lander, they will need fire protection provided by their clothing as they will not continuously wear their space suits during the entire period the lander is on the Moon.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

In Phase I, the deliverable should be a report demonstrating the feasibility to produce new flame-retardant, nontoxic apparel fibers and/or finishing treatments on existing fibers that do not support combustion in an atmosphere of 36% oxygen at a pressure of 8.2 psi. The chemical process for developing a synthetic fiber or a finishing treatment, including any test results, should be fully described to understand any toxicity issue related to processing. Furthermore, the researchers should describe the rheological, physical, and mechanical properties of the new fiber or finishing treatment and explain how these properties will make these fibers suitable for apparel applications.

In Phase II, the deliverable should be a fiber that can withstand the production processes used in the textile industry. The researchers should therefore process the new fiber and experiment with different processing conditions to determine which conditions will lead to consistent results that will enable scaling-up production. In other words, the researchers must demonstrate that they can make fine yarns that will not break or produce excessive lint when woven into fabrics. It is highly desirable that samples of fabrics be developed and evaluated.

State of the Art and Critical Gaps:

The state of the art in flame-retardant apparel fibers and fabrics for use next to the skin is mostly represented by meta-aramids, modacrylic, and flame-retardant (FR) fibers (FR rayon, FR wool, etc.). These fibers will not support combustion in air, but they burn in an atmosphere of 36% oxygen.

The critical gap is the absence of an inherently strong, flame-retardant (in 36% oxygen), nontoxic, and comfortable fiber to use for next-to-the-skin clothing.

Relevance / Science Traceability:

This work will benefit several space programs, namely the lunar Human Landing System (HLS), Orion, Gateway, and Artemis, enabling the astronauts to function in habitats, pressurized rovers, and other space vehicles with enriched oxygen atmospheres and to shorten prebreathe times prior to extravehicular activities (EVAs).

References:

NASA imagery collection of crew clothing in the Skylab Project. Nonflammable clothing development program, Richard Johnston and Matthew I. Radnofsky, Fire Technology 4, 88-102 (1968) https://airandspace.si.edu/collection-objects/jacket-skylab-2-kerwin/nasm_A19772817000

H4.05 Advancements in Water and Air Bladder Assemblies and Technology (SBIR)

Lead Center: **JSC**

Participating Center(s):

Scope Title:

Advancements in Feedwater Supply Assembly Technology

Scope Description:

The current technology for the Feedwater Supply Assembly (FSA) has many challenges to overcome including material durability and water capacity. Therefore, new innovative ideas and solutions are sought. The FSA will be integrated into the Exploration Extravehicular Mobility Unit (xEMU) Portable Life Support System (PLSS) and contained in the suit hatch compartment. The hatch volume is not a uniform shape and the current design uses cylindrical bladders which are not capable of optimizing water volume quantities. Additionally, many challenges exist in the material currently used for the FSA bladders. This material is known for its ability to maintain cleanliness and sterility; however, when made into these particular bladders, material failure and leakages are common at low cycle counts when tested as a pressurized system. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements as well.

The FSA shall be a sterile compliant bladder, capable of storing ultrapure feedwater with a relatively high-cycle life when pressurized. In order for the thermal control loop to operate properly, a water source is needed. A volumetrically adaptable, sterile, and durable feedwater bladder is essential. The suit pressure acts on this bladder and as water evaporates, the bladder resupplies the loop. The bladder must be clean and not leak particulates or polymer chains into the water over long periods of quiescence. The maximum design pressure (MDP) for the system will be 35 psid with a nominal operating pressure of 15 psid. These bladders will be reused in a fill-drain-refill = 1 cycle environment. The current cycle life requirement is 696 cycles per bladder. Additional requirements are captured in the reference located at the following link: https://ntrs.nasa.gov/search.jsp?R=20190033446. Having a bladder with these qualities not only buys down the safety risk of rupture, it promotes reliability at higher pressures and provides an avenue to extend Extravehicular Activity (EVA) length.

This subtopic is relevant to the xEMU, International Space Station (ISS), as well as commercial space companies. The goal is to have proposed solutions to be designed, built, integrated, and tested at the Johnson Space Center and integrated into the xEMU. These solutions have the potential for a direct infusion path as the PLSS is matured to meet the design and performance goals.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the Exploration Portable Life Support System (xPLSS). Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xPLSS or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps:

As the design for the new xEMU is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. The FSA is at a stall in technology development and requires new innovative ideas. This solicitation is an attempt to seek new technologies for the FSA. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements.

Relevance / Science Traceability:

This technology may be relevant to the xEMU, ISS, as well as commercial space companies. As a new Space Suit xPLSS is being designed, built, integrated, and tested at the Johnson Space Center and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured to meet the design and performance goals.

References:

Feedwater Supply Assembly Requirements are located at the following links:

1. Feedwater Supply Assembly (FSA 431) requirements are located at the following link: https://ntrs.nasa.gov/search.jsp?R=20190033446
2. Auxiliary Feedwater Supply Assembly (FSA 531) requirements are located at the following link: https://ntrs.nasa.gov/search.jsp?R=20190033446

Note to offeror: The following two drawings referenced in the requirements shall be provided if offeror is selected for award.

1. Feedwater Supply Assembly (FSA 431) Drawing SLN 13102397
2. Auxiliary Feedwater Supply Assembly (FSA 531) Drawing SLN 13102398

Scope Title:

Advanced Pressure Garment Bladder Materials

Scope Description:

The current pressure garment bladder in the legacy space suit is a urethane-coated Oxford-weave nylon. This bladder material serves as the gas bladder of the space suit and, along with the restraint material, comprises the pressure garment bladder/restraint assembly which is sized and patterned to accommodate both anatomical movement and a range of sizing. The bladder is patterned using heat sealing or radio-frequency (RF) welding techniques. While this material has been acceptable for many years, there are known deficits. The urethane coating has high tack and can result in excessive friction against the skin. Embossing or flocking of the bladder, while not significantly increasing weight, may be viable solutions to this issue, although there may be others.

In addition, the current bladder needs to be manually wiped with biocide after each Extravehicular Activity (EVA) to prevent microbial growth. This contributes to crew overhead time and may be challenging with advanced suit architectures on the Moon which inhibit routine access to all bladder locations. An antimicrobial treatment or coating on the air-tight side of the pressure bladder will improve long-term performance of the Pressure Garment System (PGS) and reduce crew time and consumables.
Lastly, while the bladder material is sufficiently strong to contain the pressurization loads of the suit in the event that the restraint layer experiences catastrophic failure, it is not impervious to damage itself through puncture from a sharp edge/corner or from an incoming micrometeorite, impacting mission success and/or crew safety. As such, a self-healing bladder could mitigate this risk and provide a more robust bladder/restraint system in the next-generation suit assembly.
In addition to one or more of the aforementioned design goals, a successful solution should also meet all of the following requirements:

1. The bladder material is capable of being bonded together into gore or convolute patterns without the use of an adhesive;
2. The bladder material bonded seams shall have a bond strength of at least 85 lb/in;
3. The bladder material shall not leak more than 3.9×10^{-8} lbm/hr-in^2 of oxygen at 4.3 psid.

This subtopic is relevant to the Exploration Extravehicular Mobility Unit (xEMU), International Space Station (ISS), as well as commercial space companies. The goal is to have proposed solutions to be designed, built, integrated, and tested at the Johnson Space Center (JSC) and integrated into the xEMU. These solutions have the potential for a direct infusion path as the xEMU is matured to meet the design and performance goals.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the xEMU. Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xEMU or specific to Pressure Garment Bladder is desired.

State of the Art and Critical Gaps:

As the design for the new xEMU is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. This solicitation is an attempt to seek new technologies for the Pressure Garment Bladder. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, durability and extensibility will become some of the most important requirements.

Relevance / Science Traceability:

This may be relevant to the xEMU, ISS, as well as commercial space companies. As a new xEMU PGS is being designed, built, and tested at JSC, solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References:

Note to offeror:

Sample drawings of patterned gore and/or convolute bladder assemblies shall be provided if offeror is selected for award.

T6.06 Enabling Spacecraft Water Monitoring through Nanotechnology (STTR)

Lead Center: **JSC**

Participating Center(s): **ARC, GRC, JPL, KSC, MSFC**

Scope Title:

Monitoring Systems for Inorganic and Organic Analytes in Spacecraft Water Streams

Scope Description:

This subtopic solicits for technologies that fill specific gaps in capabilities needed for spacecraft water management in the area of environmental monitoring. Its focus is on technologies that identify and quantify inorganic and organic species in water for use during long-duration human missions away from Earth. This subtopic is aligned with the thrust "Enabling Next-Generation Water Monitoring Systems with Nanotechnology," described within a white paper of the Nanotechnology Signature Initiative (NSI) "Water Sustainability through Nanotechnology."

NASA is seeking miniature analytical systems to measure mineral and organic constituents in potable water and wastewater. NASA is interested in sensor suites capable of simultaneous measurement of inorganic or organic species. There is interest in the capability for monitoring species within wastewater, regenerated potable water, thermal control system cooling water, and samples generated from science activities and biomedical operations. Potential wastewater streams, both current and possible in the future, include urine, urine brines, humidity condensate, Sabatier and Bosch product water, wastewater from hygiene, and wastewater from laundry. Multispecies analyte measurement capability is of interest that would provide a similar capability to that available from standard water monitoring instruments such as ion-chromatography, inductively coupled plasma spectroscopy, and high-performance liquid chromatography. Components that enable the miniaturization of these monitoring systems, such as microfluidics and small scale detectors, will also be considered.

Technologies should be targeted to have >3-year service life and at least >50% size reduction compared to current state of the art. Ideally, monitoring systems should require no hazardous reagents, have long-term calibration stability, can be recalibrated in flight, require few consumables, and require very little crew time to operate and maintain. The proposed analytical instrument should be compact, require minimal sample preparation, be compatible with microgravity and partial gravity, and be power efficient. Sample volumes should be minimized and should be identified within the proposal.

Monitoring capability is of interest for both identification and quantification of organic and inorganic contaminants, including polyatomic ions and unknowns. Examples of species of interest and their levels for measurement are specified in Spacecraft Water Exposure Guidelines (SWEGs), released as JSC 63414 (last revised July 2017). Targeted inorganic compounds identified in the SWEGs for human exploration missions include ammonium, antimony, barium, cadmium, manganese, nickel, silver, and zinc. But there is also interest in measurement of other cations and anions including iron, copper, aluminum, chromium, calcium, magnesium, sodium, potassium, arsenic, lead, molybdenum, fluoride, bromide, boron, silicon, lithium, phosphates, sulfates, chloride, iodine, nitrate, and nitrite. Examples of organics include benzene, caprolactam, chloroform, phthalates, dichloromethane, dimethylsilanediol, glycols, aldehydes, formate, 2-mercaptobenzothiozole, alcohols, ketones, and phenol, N-phenyl-beta-naphthylamine.

Please see references for additional information, including NASA's water quality requirements and guidelines, and the current state of the art in spacecraft water management, including recycling wastewater.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.4 Environmental Monitoring, Safety, and Emergency Response

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables—Reports demonstrating proof of concept, including test data from proof-of-concept studies, and concepts and designs for Phase II. In addition, Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables—Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps:

There is limited capability for water quality analysis onboard current spacecraft. Simple measurements of water composition are made on the ISS during flight, and these are limited to conductivity, total organic carbon and iodine concentration. For identification and characterization of ionic or organic species in water and wastewater, samples currently must be returned to Earth.

Water recovery from wastewater sources is considered enabling to long-duration human exploration missions away from Earth. Without substantial water recovery, life support system launch weights are prohibitively large. Regenerative systems are utilized on the International Space Station (ISS) to recycle water from humidity condensate, Sabatier product water, and urine into potable water (see ICES-2019-36 for more information). Several hardware failures have occurred onboard the ISS, which demonstrate the need for in situ measurement of inorganic and organic contaminants (for examples, see ICES-2018-123 and ICES-2018-87). This will be especially important for human exploration missions in deep space where return of samples to Earth for analysis on the ground will be impossible. Spacecraft water analysis capability will also benefit onboard science, biomedical, and spacecraft maintenance operations. It will be necessary to confirm that potable water systems are safe for human use following periods of spacecraft dormancy (ICES-2017-43).

NASA has unique water needs in space that have analogous applications on Earth. NASA’s goal is zero-discharge water treatment, targeting 100% water recycling and reuse. NASA’s wastewater collection differs from systems used on Earth in that it is highly concentrated with respect to urine, uses minimal flush water, is separated from solid wastes, and contains highly acidic and toxic pretreatment chemicals. NASA is interested in recovery of potable water from wastewater, low toxicity residual disinfection, antifouling treatments for plumbing lines and tanks, "microbial check valves" that prevent microbial cross-contamination where water treatment and potable water systems share connections, and miniaturized sensors and monitoring systems for contaminants in potable water and wastewater. Only the last gap, technologies to monitor contaminants in water, is requested in this subtopic. Spacecraft traveling away from Earth require the capability of a fully functional water analysis laboratory, including identification and quantification of known and unknown inorganic ions, organics, and microbes, as well as pH, conductivity, total organic carbon, and other typical measurements. SWEGs have been published for selected contaminants. Nanotechnology may offer solutions in all of these application areas.

Relevance / Science Traceability:

Technologies developed under this subtopic could be proven on the ISS and would be enabling to long-duration human exploration missions away from Earth, including Gateway and exploration of the Moon and Mars, including both surface and transit.

This subtopic is directed at needs identified by the Environmental Control and Life Support—Crew Health and Performance Systems Leadership Team (ECLS-CHP SLT) in areas of water management and environmental monitoring.

This subtopic is directed at meeting NASA's commitments as a collaborating agency with the National Nanotechnology Signature Initiative: "Water Sustainability through Nanotechnology." This initiative was established under the NTSC Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology.

References:

- NASA is a collaborating agency with the NTSC Committee on Technology Subcommittee on Nanoscale Science, Engineering and Technology's Nanotechnology Signature Initiative (NSI): "Water Sustainability through Nanotechnology" (Water NSI). For a white paper on the NSI, see https://www.nano.gov/node/1580
- A high-level overview of NASA's spacecraft water management was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: A Federal Perspective, October 19, 2016" https://www.nano.gov/publicwebinars
- A general overview of the state of the art of spacecraft water monitoring and technology needs was presented at a webinar sponsored by the Water NSI: "Water Sustainability through Nanotechnology: Enabling Next-Generation Water Monitoring Systems, January 18, 2017" located at https://www.nano.gov/publicwebinars
- For a list of targeted contaminants and constituents for water monitoring, see "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants, JSC 63414" located at https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs
- 2020 NASA Technology Taxonomy, TX06: Human Health, Life Support, and Habitation Systems, TX06.4.1, Sensors: Air, Water, Microbial, and Acoustic https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy.pdf
- Layne Carter, Jill Williamson, Daniel Gazda, Chris Brown, Ryan Schaezler, Frank Thomas, Jesse Bazley, Sunday Molina “Status of ISS Water Management and Recovery,” 49th International Conference on Environmental Systems, ICES-2019-36 https://ttu-ir.tdl.org/handle/2346/84720
- Molly S. Anderson, Ariel V. Macatangay, Melissa K. McKinley, Miriam J. Sargusingh, Laura A. Shaw, Jay L. Perry, Walter F. Schneider, Nikzad Toomarian, Robyn L. Gatens "NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview," 49th International Conference on Environmental Systems, ICES-2019-297 https://ttu-ir.tdl.org/handle/2346/84496
- Dean Muirhead, Layne Carter, Jill Williamson, Antja Chambers "Preventing Precipitation in the ISS Urine Processor," 47th International Conference on Environmental Systems, ICES-2018-87 https://ttu-ir.tdl.org/handle/2346/74086
- Dean L. Muirhead, Layne Carter “Dimethylsilanediol (DMSD) Source Assessment and Mitigation on ISS: Estimated Contributions from Personal Hygiene Products Containing Volatile Methyl Siloxanes (VMS)” 48th International Conference on Environmental Systems, ICES-2018-123 https://ttu-ir.tdl.org/handle/2346/74112
- Donald Layne Carter, David Tabb, Molly Anderson "Water Recovery System Architecture and Operational Concepts to Accommodate Dormancy," 47th International Conference on Environmental Systems, Paper ICES-2017-43 https://ttu-ir.tdl.org/handle/2346/72884

Several of the references may also be available at https://ntrs.nasa.gov

T6.07 Space Exploration Plant Growth (STTR)

Lead Center: **KSC**

Participating Center(s): **ARC, JSC**

Scope Title:

Remote Sensing Technologies for Monitoring Plants

Scope Description:

Plant (crop) systems envisioned for future space travel could provide supplemental fresh food for the human crews during early missions and increased amounts of food along with oxygen and carbon dioxide removal for future longer-term missions. This latter concept has been referred to as bioregenerative life support. To do this will require controlled environments for growing the crops, perhaps using techniques similar to recirculating hydroponics used on Earth. But this will require careful monitoring of the environment and the plants themselves to assess their health and performance. In addition, crew time will likely be limited in many space settings, so having the monitoring systems operate autonomously or with little human intervention would be beneficial.

This subtopic solicits advanced technologies for remotely sensing the status of plants in controlled environments of space. These environments are typically small in volume, often use narrow band lighting from light-emitting diodes (LEDs), and are subject to reduced gravity. Example methods might include multispectral and hyperspectral sensing of crops, use of bio-indicators in the crops themselves, or other innovative, noninvasive means. Technologies could focus on approaches for (1) monitoring the morphology and growth of plants and possibly standing biomass and/or (2) monitoring stress to the plants, including water stress, nutrient stress, and plant pathogens. Sensing of volatile compounds produced by the plants is not solicited for this subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables—Reports demonstrating proof of concept, including test data from proof-of-concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables—Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness should be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps:

NASA's Advanced Plant Habitat (APH) growth chamber on the International Space Station (ISS) provides a controlled environment with about 0.2 m^2 growing area. Within the APH, environmental control includes light from LEDs, temperature, humidity, and carbon dioxide concentration, along with water delivery to a solid medium used to support root systems. The APH is used primarily for plant research on the ISS, and the environmental parameters are logged regularly. Plants in the APH chamber can be monitored with visible imagery and infrared sensing for canopy temperatures. The APH is closed atmospherically to allow condensate recovery and water recycling and to also track plant carbon dioxide uptake and evapotranspiration. Larger plant chambers used for crop production on future missions would build on these capabilities, but may or may not be atmospherically closed to the crew cabin.

Relevance / Science Traceability:

This technology could be proven on the ISS and would be useful to long-duration human exploration missions, including Gateway, lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support and Habitation Systems Capability Leadership Team (CLT) in areas of in situ production of fresh foods.

References:

Askim, J. R.; Mahmoudi, M.; Suslick, K. S. 2013. Optical sensor arrays for chemical sensing: The optoelectronic nose. Chem. Soc. Rev. 42 (22): 8649-8682.

Chaerle, L.; Hagenbeek, D.; De Bruyne, E.; Valcke, R.; Van Der Straeten, D. 2004. Thermal and chlorophyll-fluorescence imaging distinguish plant-pathogen interactions at an early stage. Plant and Cell Physiology 45 (7): 887-896.

Clevers, J. G.; Kooistra, L.; Schaepman, M. E. 2010. Estimating canopy water content using hyperspectral remote sensing data. Int. J. Appl. Earth Obs. Geoinformation 12: 119-125.

Fahlgren, N.; Gehan, M. A.; Baxter, I. 2015. Lights, camera, action: high-throughput plant phenotyping is ready for a close-up. Cur. Opin. Plant Biol. 24:93-99.

Loreto, F.; Barta, C.; Brilli, F.; Nogues, I. 2006. On the induction of volatile organic compound emissions by plants as consequence of wounding or fluctuations of light and temperature. Plant Cell Environ 29 (9): 1820-1828.

Richards, J. R.; Schuerger, A. C.; Capelle, G.; Guikema, J. A. 2003. Laser-induced fluorescence spectroscopy of dark- and light-adapted bean (*Phaseolus vulgaris* L) and wheat (*Triticum aestivum* L) plants grown under three irradiances levels and subjected to fluctuating lighting conditions. Remote Sensing of Environment 84:323-341.

Schuerger, A. C.; Copenhaver, K. L.; Lewis, D.; Kincaid, R.; May, G. 2007. Canopy structure and imaging geometry may create unique problems during spectral reflectance measurements of crop canopies in bioregenerative advanced life support systems. Intl. J. Astrobiology 6 (2): 109-121.

Serbin, S. P.; Singh, A.; Desai, A. R.; Dubois, S. G.; Jablonski, A. D.; Kingdon, C. C.; Kruger, E. L.; Townsend, P. A. 2015. Remotely estimating photosynthetic capacity, and its response to temperature, in vegetation canopies using imaging spectroscopy. Remote Sens. Environ. 167: 78-87.

Ustin, S. L. 2013. Remote sensing of canopy chemistry. Proc. Natl. Acad. Sci. 110: 804-805.

Zeidler, C.; Zabel, P.; Vrakking, V.; Dorn, M.; Bamsey, M.; Schubert, D.; Ceriello, A.; Fortezza, R.; De Simone, D.; Stanghellini, C.; Kempkes, F.; Meinen, E.; Mencarelli, A.; Swinkels, G-J.; Paul, A-L.; Ferl, R. J. 2019. The plant health monitoring system of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase. Front. Plant Sci. 10:1457 (doi: 10.3389/fpls.2019.01457).

Scope Title:

Biopriming of Plant Microbiome to Promote Crop Health and Growth

Scope Description:

This subtopic solicits advanced technologies for identifying, selecting, developing, or designing microbes that can promote plant growth in controlled environment crop production systems for space. In the terrestrial environment, the microbiome of the roots (rhizosphere) and the above ground plant (phyllosphere) act as a genetic extension of the plant. The rhizosphere consortia metabolizes precursor compounds that can be further metabolized by the plants and in turn promote growth. This consortia can also produce secondary metabolites that exhibit antimicrobial activity and further protect the plant. Currently, space-bound seeds are surface sterilized, and growth substrates are sterilized, which does away with most microbially conferred advantages—think of a human without its own healthy gut microbes. Therefore, NASA is interested in tailoring a rhizosphere for space crops and “biopriming” plant seeds with a beneficial, probiotic microbial assemblage that is amenable to containment and presents no human health risk. Approaches should consider one or a few organisms that have demonstrated beneficial effects on crops rather than whole communities. These organisms could be applied to seeds or be transferred endophytically (inside the seed or plant material). Crops for these systems would be grown hydroponically or in solid media watered with nutrient solution, or using water along with controlled-release fertilizer. As examples, microbes that confer resistance to stresses such as root zone hypoxia, root zone drought stress, and plant pathogens could be considered. Target crops should focus on leafy greens, such as lettuce, leafy Brassica species, leafy Chenopod species, or small fruiting crops such as pepper and tomato. The ability to put organisms into stasis and then reactivate them in a relevant, operational mode should be considered.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.3 Human Health and Performance

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

Desired Deliverables Description:

Phase I Deliverables—Reports demonstrating proof of concept, including test data from proof-of-concept studies, and concepts and approaches for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

a. Identification of microbes of interest from literature accounts or current experimentation from existing libraries, including Veggie or the International Space Station (ISS).
b. Obtain full genomic profiling to scan for unfavorable genomic components and triage candidates for beneficial effects.

Phase II Deliverables—Delivery of isolated microorganisms and/or microbial communities for testing on candidate crops. Preliminary assessment on the safety for use with food crops should be included. Scientific publications and presentations at relevant professional societies.

a. Apply to candidate crop seedlings and conduct growth evaluations.
b. Assess growth and metabolite content of treated crops.
c. Perform toxicity and biofilm tests for candidate microbes both in isolation and in combination. Toxicity screen will be against relevant human cell lines.

State of the Art and Critical Gaps:

NASA's Advanced Plant Habitat (APH) and Veggie plant growth chambers on the ISS provide controlled environments with about 0.2 m^2 growing area. Plants are grown in a solid medium (arcillite or calcined clay) that is sterilized prior to launch, and plants are typically propagated using surface sterilized seeds. But neither system is sterile in its operations and are open to the cabin environment (Veggie) or occasionally opened and accessed by the crew for horticultural operations (APH). For one Veggie study, a Fusarium fungus was noted growing on zinnia plants, likely due to a malfunction in the air circulation resulting in very high humidity. Similar environmental anomalies (environmental control failures, too little or too much water in the root zone, nutrient stress) can occur in any controlled environment, including those envisioned for future space crop production systems. Having a microbiome that can confer resistance to such perturbations and generally promote healthier growth can reduce the risk of crop failures for these systems. Biocontainment measures are not typically required for probiotic consortia in field settings, but may be an issue in confined environments of space. Introducing a tailored microbiome into a controlled environment such as Veggie aboard the ISS will undoubtedly rule out classes of microbes due to their propensity to become opportunistic pathogens. Therefore, there is a large knowledge gap when it comes to the types of strains that will be beneficial for crop production not only in space, but in closed environments. Storage and handling of these tailored microbiomes for long-duration space exploration also presents a unique challenge.

Relevance / Science Traceability:

This technology could be proven on the ISS and would be useful to long-duration human exploration missions, including Gateway, lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support and Habitation Systems Capability Leadership Team (CLT) in areas of in situ production of fresh foods. The research is also applicable to the rapidly expanding controlled environment agriculture (CEA) industry on Earth.

References:

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Cha, J-Y., Han, S.; Hong, H-J., et al. 2016. Microbial and biochemical basis of a *Fusarium* wilt-suppressive soil. The ISME Journal 10: 119-129.

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Mahnert, A., Moissl-Eichinger, C., Berg, G. 2015. Microbiome interplay: plants alter microbial abundance and diversity within the built environment. Front. Microbiol. 6:887 (doi:10.3389/fmicb.2015.00887).

Marasco, R.; Rolli, E.; Ettoumi, B.; Vigani, G.; Mapelli, F., et al. 2012. A drought resistance-promoting microbiome is selected by root system under desert farming. PLOS ONE 7(10): e48479 (doi:10.1371/journal.pone.0048479).

Mayaka, S.; Tirosh, T.; Glick, B.R. 2004. Plant growth-promoting bacteria that confer resistance to water stress in tomatoes and peppers. Plant Science 166: 525-530.

Quiza, L.; St-Arnaud, M.; Yergeau, E. 2015. Harnessing phytomicrobiome signaling for rhizosphere microbiome engineering. Front. Plant Sci. 14 (https://doi.org/10.3389/fpls.2015.00507).

Rosenblueth, M.; Martínez-Romero, E. 2006. Bacterial endophytes and their interactions with hosts. MPMI Vol. 19, No. 8: 827-837 (DOI: 10.1094/ MPMI -19-0827).

Focus Area 7 Human Research and Health Maintenance

Lead MD: **HEOMD**

Participating MD(s): **N/A**

NASA's Human Research Program (HRP) investigates and mitigates the highest risks to astronaut health and performance for exploration missions. HRP achieves this through a focused program of basic, applied and operational research leading to the development and delivery of:

- Human health, performance, and habitability standards.
- Countermeasures and other risk mitigation solutions.
- Advanced habitability and medical support technologies.

HRP has developed an Integrated Research Plan (IRP) to describe the requirements and notional approach to understanding and reducing the human health and performance risks. The IRP describes the Program's research activities that are intended to address the needs of human space exploration and serve HRP customers. The Human Research Roadmap (http://humanresearchroadmap.nasa.gov) is a web-based version of the IRP that allows users to search HRP risks, gaps, and tasks.

The HRP is organized into several research Elements:

- Human Health Countermeasures.
- Human Factors and Behavioral Performance.
- Exploration Medical Capability.
- Space Radiation.

Each of the HRP Elements address a subset of the risks. A fifth Element, Research Operations and Integration (ROI), is responsible for the implementation of the research on various space and ground analog platforms. HRP subtopics are aligned with the Elements and solicit technologies identified in their respective research plans.

H12.01 Radioprotectors and Mitigators of Space Radiation-Induced Health Risks (SBIR)

Lead Center: **JSC**

Participating Center(s):

Scope Title:

Radioprotectors and Mitigators of Space Radiation-Induced Health Risks

Scope Description:

Space radiation is a significant obstacle when sending humans on long-duration missions beyond low Earth orbit. Although various forms for radiation exist in space, astronauts during Lunar or Mars missions will be exposed constantly to galactic cosmic radiation (GCR), which consists of high-energy particles ranging from protons to extremely heavy ions. Astronaut health risks from space radiation exposure are categorized into cancer, late and early central nervous systems (CNS) effects, and degenerative risks, which include cardiovascular diseases (CVD) and premature aging. With the current gender and age-specific exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions without countermeasures.

This subtopic solicits proposals to develop biological countermeasures that mitigate one or several of the radiation risks associated with space travel. Compounds that target common pathways (e.g., inflammation) across aging, cancer, cardiovascular disease, and neurodegeneration would be preferred. Most of the countermeasure developments in the medical arena have focused on mitigating the effects of X- or gamma rays. The proposed project should focus on repurposing of technology and compounds for high-energy charged-particle applications. Compounds that are under current development or have been proven effective for other applications are both suitable for this subtopic.

Expected TRL or TRL Range at completion of the Project: 5 to 8

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.5 Radiation

Desired Deliverables of Phase I and Phase II:

- Analysis

Desired Deliverables Description:

Deliverables for Phase I of the project will be data generated in testing the proposed radioprotectors with high energy protons. The company should test the proposed radioprotectors using high energy protons or other charged particles at space relevant doses. This testing can be performed with cell models at an accelerator facility of choice. After contract award, the company should immediately coordinate with the NASA technical monitor for any special considerations for the testing.

In Phase II of the project, the company should conduct in vivo evaluation of the radioprotectors using appropriate animal models, which may include humanized mouse models. Testing in Phase II of the project should be performed with a combination of different particle types and energies that simulate the space radiation environment. NASA will make the accelerator facility at the Brookhaven National Laboratory available for both Phase I and II of the project. Demonstration of the effectiveness in reducing proton-induced biological impacts is needed for a successful Phase II proposal. Deliverables for Phase II of the project will be data generated using animal models and a combination of charged particle types and energies.

State of the Art and Critical Gaps:

Exposure of crew members to space radiation during Lunar and Mars missions can potentially impact the success of the missions and cause long-term diseases. Space radiation risks include cancer, late and early CNS effects, CVD, and accelerated aging. Abiding by the current exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions. Mitigation of space radiation risks can be achieved with physical (shielding) and biomedical means. This subtopic addresses development of drugs that mitigate one or several of the identified space radiation risks. Development of countermeasures for adverse health effects from radiation exposure is also actively supported by the Department of Defense (DOD), Department of Homeland Security (DHS), and the National Institute of Health (NIH). However, some of the radioprotectors used in radiotherapy might have toxic levels that are unacceptable for astronauts. Some of the countermeasures developed for DOD/DHS are aimed at mitigating acute radiation syndromes, but not cancer risks. Furthermore, these radioprotectors are mostly for exposure to X- or gamma rays. This SBIR subtopic solicits specifically proposals to evaluate the radioprotectors that have been proven effective in mitigating biological impacts of X- or gamma rays for space radiation applications.

Relevance / Science Traceability:

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

References:

The following references discuss the different health effects NASA has identified in regard to space radiation exposure:

- Evidence report on central nervous systems effects: https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf.
- Evidence report on degenerative tissue effects: https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf.
- Evidence report on carcinogenesis: https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf.

H12.03 Portable Spatial Disorientation Simulator - Trainer (SBIR)

Lead Center: **JSC**

Participating Center(s):

Scope Title:

Portable Spatial Disorientation Simulator - Trainer

Scope Description:

Astronauts are at risk of spatial disorientation due to vestibular alterations during and following g-level transitions, such as landing on Earth. This disorientation has previously been simulated using a bilateral bipolar Galvanic vestibular stimulation (GVS) delivered in a suprathreshold range (2 to 5 mA) over the mastoid processes independent of head orientation. NASA needs a portable GVS-based system that can be coupled to head orientation and movements to enhance the simulation of the g-transition induced spatial disorientation effect astronauts experience.

This system will be used for astronaut crewmembers to simulate performing landing and recovery type tasks while experiencing head-tilt contingent vertigo due to vestibular alterations. This simulator will also be used by recovery operations personnel to validate nominal and contingency procedures with a simulated deconditioned crewmember. Finally, this disorientation simulator will be used experimentally to develop sensorimotor standards related to fitness to perform critical mission tasks.

The requirements include:

- Phase 1A head-worn inertial measurement unit (IMU) sensor that can measure natural head rotation (position and velocity) and linear acceleration in all three planes.

- A GVS that is head-coupled and proportional to head tilt orientation as well as pitch and roll velocity, with the ability to adjust the algorithms to alter the IMU sensor combinations that drive the GVS signal.
- The system should also allow a user-adjustable manual gain to allow for individual sensitivity, with minimal two-fault current limit at 5 mA and emergency on/off switch.
- The system should allow a two-channel multiple electrode configuration that can provide illusory motion in both head roll and pitch axes.
- The system should be self-powered for minimally 1 hr with user switchable rechargeable batteries.
- The system should include nonvolatile memory (onboard data storage) to record IMU sensor data, GVS current delivery, and external trigger and/or manual synch event push-button timing.
- This system should be able to be worn while performing nonsuited crew landing and egress type activities without interfering with other crew-worn equipment.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.6 Human Systems Integration

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:

Phase I deliverable is a laboratory version of the disorientation trainer that successfully demonstrates the proof of concept for the requirements listed under scope description have been met.

Phase II deliverable is a portable wearable version of the disorientation trainer that can be deployed in field settings.

State of the Art and Critical Gaps:

While there are GVS available, there are no GVS devices on the market that are portable or that can be coupled to head movement. This capability would provide the ability to train astronauts on what to expect with regards to spatial disorientation in a realistic mission simulation.

Relevance / Science Traceability:

This is relevant to Human Exploration and Operations Mission Directorate (HEOMD), because of its applicability in human research and exploration. For example, this technology would assist in the success of the sensorimotor standards project, sponsored by NASA's Human Research Program.

References:

Moore ST, Dilda V, MacDougall HG. Galvanic vestibular stimulation as an analogue of spatial disorientation after spaceflight. Aviat Space Environ Med. 2011;82(5):535-542. (download from https://www.ingentaconnect.com/content/asma/asem/2011/00000082/00000005/art00006)

Focus Area 8 In-Situ Resource Utilization

Lead MD: **STMD**

Participating MD(s): **STTR**

In-Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural and discarded) to create products and services for robotic and human exploration. Local resources include 'natural' resources found on extraterrestrial bodies such as water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.), vast quantities of metals in mineral rocks and soils, and atmospheric constituents, as well as human-made resources such as trash and waste from human crew, and discarded hardware that has completed its primary purpose. The most useful products from ISRU are propellants, fuel cell reactants, life support commodities (such as water, oxygen, and buffer gases), and feedstock for manufacturing and construction. ISRU products and services can be used to i) reduce Earth launch mass or lander mass by not bringing everything from Earth, ii) reduce risks to the crew and/or mission by reducing logistics, increasing shielding, and providing increased self-sufficiency, and/or iii) reducing costs by either needing less launch vehicles to complete the mission or through the reuse of hardware and lander/space transportation vehicles. Since ISRU systems must operate wherever the resource of interest exists, technologies and hardware will need to be designed to operate in harsh environments, reduced gravity, and potential non-homogeneous resource physical, mineral, and ice/volatile characteristics. This year's solicitation will focus on critical technologies needed in the areas of Resource Acquisition and Consumable Production for the Moon and Mars. The ISRU focus area is seeking innovative technology for:

- Large, Lightweight, Deployable Solar Concentrators and Thermal Energy Transmission
- Critical Components/Subsystems for Oxygen Extraction from Lunar Regolith
- Lunar Ice Mining via In Situ Subsurface Heating, Sublimation, and Capture

As appropriate, the specific needs and metrics of each of these specific technologies are described in the subtopic descriptions.

T14.01 Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage (STTR)

Lead Center: **GRC**

Participating Center(s): **JSC**

Scope Title:

Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage

Scope Description:

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, and methane) production, storage, transfer, and usage to support NASA's in-situ resource utilization (ISRU) goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions to the Moon and Mars. Anticipated outcome of Phase I proposals are expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II. Solicited topics are as follows:

- A piecewise-smooth set of correlations for use in lumped node codes that models the complete cryogenic pool boiling curve for heat transfer between fluid and wall encountered in cryogenic storage (e.g., hot spots along the tank wall) or transfer systems. Six submodels should be developed, including (1) onset of nucleate boiling, (2) nucleate boiling heat transfer coefficient (HTC), (3) critical heat flux (CHF), (4) transition boiling HTC, (5) Leidenfrost point, and (6) film boiling HTC. There should be seamless coupling between all five submodels such that the boiling curve is a smooth function (heat flux as a function of wall superheat). Both quenching and heating configurations must be modeled. The model must be anchored to experimental cryogenic pool boiling data for helium, hydrogen, argon, nitrogen, oxygen, and methane. The complete cryogenic pool boiling model should be validated against cryogenic experimental data across the range of fluids, with a target accuracy of 25%. The quenching and heating pool boiling models and implementation scheme should be a deliverable. Phase I should have an emphasis on developing the CHF model for all cryogens while Phase II should include the remaining five models as well as microgravity applications.

- Develop and demonstrate methodologies for recovering propellant from lunar and Martian descent stages that have low fill levels (<5%) of liquid oxygen, hydrogen, and/or methane mixed with helium. Methodologies can assume liquid extraction (for a short amount of time) or vapor extraction. Possible uses of the fluids could include fuel cells, life support/breathing air, or other applications. Methodologies should focus on the amount of propellant that might be extractable at different purities (prop/helium). Phase I should focus on defining and refining the methodologies for scavenging, as well as defining what should be done to the landers to enable or facilitate later access for scavenging. Phase II should include some sort of a demonstration, perhaps using simulant or similar fluids.
- Advance nonliquid electrolyte technologies for chemical flow cells (e.g., fuel cells, electrolyzers, flow batteries, etc.) that generate electrical power from a chemical reaction or reconstitute a reaction byproduct into fuels and oxidizer for such a chemical flow cell. These electrolytes are required to be cycled through very low temperatures (<150 K) during storage to survive a lunar night or cislunar travel and recover completely (>98%) mechanical, electrical, and chemical performance. Ideally, these electrolytes would be able to process propellants (hydrogen, oxygen, methane, kerosene, etc.) and either tolerate or recover from exposure to standard propellant contaminants with minimal/no performance loss. Due to the potential for high fluid pressures and vibration loads, any proposal will illustrate how the electrolyte could be mechanically supported to operate hermetically under these conditions. To demonstrate that the electrolyte exceeds the state of the art, the deliverable test article will support an electrical current density of at least 300 mA/cm^2 for at least 500 hr, support transient currents >750 mA/cm^2 for at least 30 sec, and support slew rates >50 A/cm^2/s. Providing test data for the electrolyte performance degradation rate when operated as intended is required with test times >5,000 hr significantly strengthening the proposal. It would be beneficial if the electrolyte operated reversibly with equal efficiently. Liquid electrolytes, loose or contained within a support structure, are excluded from this scope due to the complications that liquid electrolytes pose for an eventual system during launch.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.1 Cryogenic Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Prototype

Desired Deliverables Description:

Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment preferably with hardware (or model subroutines) deliverable to NASA.

Electrolyte technologies for chemical cell product deliverables would be an operational electrochemical test article demonstrating the capability of the electrolyte to support the listed current density by processing the intended propellants when packaged as a flow cell. This test article will have an active area of at least 50 cm^2 and would ideally contain multiple cells to demonstrate extensibility to existing stack designs. It would be favorable to include empirical electrochemical performance data of the electrolyte over as much of the pressure range from 5 to 3,015 psia as possible to illustrate the potential viability range for lunar applications.

State of the Art and Critical Gaps:

Cryogenic Fluid Management (CFM) is a cross-cutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU-produced propellants. Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA's exploration plans for multiple architectures, whether it is hydrogen/oxygen or methane/oxygen systems including chemical propulsion and nuclear thermal propulsion. There are no complete cryogenic data-based pool boiling curves for propellants of interest.

Existing electrolytes for space applications are limited to a polymeric membrane based on perfluorinated teflon and ceramic electrolyte. While it has the necessary electrochemical and mechanical properties, the polymeric membrane has very tight thermal constraints due to a high moisture content, which complicates thermal system designs for lunar systems during transit. It is also very sensitive to chemical contamination. The ceramic electrolyte has significant mechanical and slew rate limitations, but is more resilient to chemical contamination and has a much larger thermal range, which allows storage in very cold environments. Once operational and at temperature, either existing electrolyte technology operates in cold lunar regions. Should an off-nominal event occur during the lunar night that results in a cold-soak, neither existing electrolyte technology has a meaningful chance of recovering from the exposure to the low temperatures.

Relevance / Science Traceability:

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Human Exploration and Operations Mission Directorate (HEOMD) as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, cryogens will have to be produced, liquefied, and stored, the latter two of which are CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed on the Moon or Mars.

NASA already has proton-exchange-membrane- (PEM-) based electrochemical hardware in the International Space Station (ISS) Oxygen Generator Assembly and is developing electrochemical systems for space applications through the Evolved Regenerative Fuel Cell. These system designs could be readily adapted to a solid electrolyte with capabilities beyond the existing state of the art for specific applications such as ISRU, lunar fuel cell power systems, or regenerative fuel cell energy storage systems. As CLPS companies have identified primary fuel cell power systems as a required technology, it would be helpful to ensure that there are options available that could survive the lunar night when offline without active thermal control. This would enable a longer period between missions to refuel and recover the electrochemical system.

References:

1. Kartuzova, O., and Kassemi, M., "Modeling K-Site LH2 Tank Chilldown and no Vent Fill in Normal Gravity" AIAA-2017-4662

2. Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration (https://arc.aiaa.org/doi/abs/10.2514/6.2017-5368(link is external))

3. NASA Technology roadmap (https://gameon.nasa.gov/about/space-technology-roadmap/), §TA03.2.2.1.2. Chemical Power Generation and §TA03.2.2.2.3. Regenerative Fuel Cell Energy Storage (NOTE: This may be a dated link as this Roadmap still references ETDP/ETDD.)

4. Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production (https://doi.org/10.1016/j.reach.2019.100026(link is external))

Z12.01 Extraction of Oxygen and Water from Lunar Regolith (SBIR)

Lead Center: **JSC**

Participating Center(s): **GRC, JPL, KSC, MSFC**

Scope Title:

Solar Concentrator Technologies for Oxygen Extraction and In Situ Construction

Scope Description:

Solar concentrators have been used to successfully demonstrate multiple in situ resource utilization (ISRU) technologies, including hydrogen and carbothermal reduction, sintering of regolith to produce launch/landing pads, and production of blocks for construction. Terrestrial state-of-the-art solar concentrators are heavy, not designed for easy packaging/shipping and assembly/installation, and can be maintained and cleaned on a periodic basis to maintain performance. For ISRU space applications, NASA is interested in solar concentrators that are able to be packaged into small volumes, are lightweight, easily deployed and set up, can autonomously track the Sun, and can perform self-cleaning operations to remove accumulated dust. Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface in temperatures of up to 110 °C (230 °F) during sunlit periods and as as low as -170 °C (-274 °F) during periods of darkness. Systems must also be able to operate for at least 1 year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that regolith mining operations will be tens of meters away from the solar concentrators, but that regolith processing systems and solar concentrators will be co-located on a single lander. Phase I efforts can be demonstrated at any scale; Phase II efforts must be scalable up to 11.1 kW of delivered solar energy, assuming an incoming solar flux of ~1,350 W/m^2 while also considering volumetric constraints for launch and landing. Each of the following specific areas of technology interest may be developed as a standalone technology.

- Lightweight mirrors/lenses: Proposals must clearly state the estimated W/kg for the proposed technology. Phase II deliverables must be deployed and supported in Earth 1g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability, and cost.
- Efficient transmission of energy for oxygen/metal extraction: While the solar concentrator will need to move to track the Sun, reactors requiring direct thermal energy for oxygen extraction will be in a fixed position and orientation. Concentrated sunlight must be directed to a single or multiple spots to effectively heat or melt the regolith. Proposals must define the expected transition losses from collection to delivery and should capture any assumptions made regarding the distance from collection to delivery.
- Sintering end effector: Solar concentrators have been used to demonstrate the fabrication of 3D printed components using regolith as the only feedstock. Proposals responding to this specific technology area must produce and maintain a focal point temperature between 1,000 and 1,100 ^{o}C for the purpose of sintering lunar regolith. Proposals should assume that the focal point can move along the regolith at a speed between 1 and 10 mm/sec.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I deliverables may be a conceptual design with analysis to show feasibility at relevant scales and/or a small demonstration of the concept.

Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

State of the Art and Critical Gaps:

The 2011 paper "Thermal Energy for Lunar In Situ Resource Utilization: Technical Challenges and Technology Opportunities" [Ref. 1] summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques (dust mitigation is addressed in another subtopic).

The last solar concentrator system developed for ISRU had an overall efficiency of ~33%. The performance of the system is captured in the 2011 paper "Solar Thermal System for Lunar ISRU Applications: Development and Field Operation at Mauna Kea, HI" [Ref. 6].

Relevance / Science Traceability:

NASA Strategic Knowledge Gap (SKG) 1-F, "Determine the likely efficiency of ISRU processes using lunar simulants in relevant environments," as well as NASA SKG 1-G, "Measure the actual efficiency of ISRU processes in the lunar environment," are both important for the development of future ISRU systems. There are multiple ISRU processes that involve the use of solar concentrators, and determining their efficiency through technology development efforts may address NASA SKGs.

References:

1. Gordon, P. E., Colozza, A. J., Hepp, A. F., Heller, R. S., Gustafson, R., Stern, T., & Nakamura, T. (2011). Thermal energy for lunar in situ resource utilization: Technical challenges and technology opportunities. https://ntrs.nasa.gov/citations/20110023752
2. Gustafson, R., White, B., Fidler, M., & Muscatello, A. (2010). Demonstrating the solar carbothermal reduction of lunar regolith to produce oxygen. In 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition (p. 1163).
3. Mueller, R. P., Sibille, L., Hintze, P. E., Lippitt, T. C., Mantovani, J. G., Nugent, M. W., & Townsend, I. I. (2014). Additive construction using basalt regolith fines. In *Earth and Space 2014* (pp. 394-403). https://ntrs.nasa.gov/citations/20150000305
4. Muscatello, A., & Gustafson, R. B. (2010). The 2010 Field Demonstration of the Solar Carbothermal Reduction of Regolith to Produce Oxygen. https://ntrs.nasa.gov/citations/20110006938
5. Muscatello, T. (2017). Oxygen Extraction from Minerals. https://ntrs.nasa.gov/citations/20170001458
6. Nakamura, T., & Smith, B. (2011, January). Solar thermal system for lunar ISRU applications: Development and field operation at Mauna Kea, HI. In 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (p. 433).

Scope Title:

Novel Oxygen Extraction Concepts

Scope Description:

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from silicates using various techniques. The target production rates are 1,000 kg of O_2 per year for a lunar pilot plant, and 10,000 kg of O_2 per year for a lunar full-scale plant. Each of the following specific areas of technology interest may be proposed as individual efforts to support existing oxygen extraction development projects.

- Contaminant Removal: Proposed concepts should be capable of removing 0.36 g of HCl, 0.68 g of HF, and 0.1 g of H_2S per kg of processed regolith from a mixed gas stream of CO, CO_2, and H_2 in a way that minimizes the use of consumables. Phase I efforts should provide an estimated mass/power as a function of contaminant quantities. Phase II efforts should demonstrate the technology using actual gases.
- Regolith Inlet/Outlet Valves: Proposed concepts should be capable of passing abrasive granular material through the valve for at least 1,000 cycles and should be actuated with a type of motor that has flight heritage (e.g., brushless direct current (BLDC) motors or stepper motors). Phase I efforts should provide an estimated mass and power for the concept through analysis and/or demonstration. Phase II efforts should demonstrate the technology using lunar regolith simulant and collect data to predict leak rates for up to 10,000 cycles.
- Contamination-Tolerant Vacuum Pump: Some in situ resource utilization (ISRU) processes may require a pressurized volume to be evacuated in order to prevent the loss of products and

consumables to the vacuum of space when regolith either enters or exits the volume. The pump may be exposed to corrosive substances such as HCl, HF, and H_2S. Proposed concepts should be capable of evacuating a volume of 50 L with an initial pressure of 5 psia down to a pressure of <5 torr at the pump inlet in <2 min while compressing the gases to 1 atm at the pump outlet. Phase I efforts should provide an estimated mass, power, and life for the concept. Phase II efforts should demonstrate the technology using actual gases.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

See Scope Description for definitions of Phase I and II deliverables for each technology.

State of the Art and Critical Gaps:

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. Multiple efforts are underway to bring carbothermal reduction technology to TRL6. Other techniques that use ionic liquids, molten salts, and molten regolith electrolysis have been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Many of these processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

Relevance / Science Traceability:

The Space Technology Mission Directorate (STMD) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to begin mining it at a useful scale. A lunar water prospecting mission is required to properly assess the utilization potential of water on the lunar surface. Until water prospecting data becomes available, NASA recognizes the need to make progress on the technology needed to extract oxygen from dry lunar regolith.

References:

1. Fox, E. T. (2019). Ionic Liquid and In Situ Resource Utilization. https://ntrs.nasa.gov/citations/20190027398
2. Gustafson, R. J., White, B. C., & Fidler, M. J. (2009). Oxygen production via carbothermal reduction of lunar regolith. *SAE International Journal of Aerospace*, *4*(2009-01-2442), 311-316.
3. Gustafson, R. J., White, B. C., Fidler, M. J., & Muscatello, A. C. (2010). The 2010 Field Demonstration of the Solar Carbothermal Reduction of Regolith to Produce Oxygen. https://ntrs.nasa.gov/citations/20110005526

4. Gustafson, R., White, B., & Fidler, M. (2011, January). 2010 field demonstration of the solar carbothermal regolith reduction process to produce oxygen. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 434).
5. Muscatello, A., & Gustafson, R. B. (2010). The 2010 Field Demonstration of the Solar Carbothermal Reduction of Regolith to Produce Oxygen. https://ntrs.nasa.gov/citations/20110006938
6. Muscatello, T. (2017). Oxygen Extraction from Minerals. https://ntrs.nasa.gov/citations/20170001458
7. Paley, M. S., Karr, L. J., & Curreri, P. (2009). Oxygen Production from Lunar Regolith using Ionic Liquids. https://ntrs.nasa.gov/citations/20090017882
8. Sibille, L., Sadoway, D. R., Sirk, A., Tripathy, P., Melendez, O., Standish, E., ... & Poizeau, S. (2009). Production of Oxygen from Lunar Regolith using Molten Oxide Electrolysis. https://ntrs.nasa.gov/citations/20090018064

Scope Title:

Lunar Ice Mining

Scope Description:

We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in permanently shadowed regions (PSRs), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 K. The inverse challenge exists with water collection. Unless the water vapor is under pressure, extremely cold temperatures will be necessary to capture it. NASA is seeking methods to acquire lunar water ice from PSRs. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 and 100 K and 10-9 torr vacuum.

- Phase I demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 2.78 kg H_2O/hr (15 metric tons of water in 225 days).
- Phase II demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 2.78 kg H_2O/hr.
- Proposals should state expected energy requirements (both electrical and thermal).
- Proposers should assume a mobile platform is considered to be available, but should not be necessary for technology demonstration.
- Proposers should state their assumptions about water ice concentration.
- Proposals should describe a tolerance for a trace amount of organics or volatiles that may accumulate on collection surfaces.
- Proposers should estimate Wh/kg H_20 for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address the ability of a concept to be able to operate for at least 1 year, with a goal of 5 years without substantial maintenance.

Estimates for mass and volume of the final expected hardware should be specified.

In addition, each of the following specific areas of technology interest may be proposed to support existing efforts related to lunar ice mining.

- Regolith/Ice Excavation: Proposed concepts should be able to excavate frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the excavation concept as well as an estimate for any temperature increase in the frozen regolith caused by the excavation technique. Phase II efforts should demonstrate the technique with lunar simulant at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time.
- Regolith/Ice Crushing: Proposed concepts should be able to crush frozen regolith simulant with a water ice content of at least 5% by mass while minimizing a temperature increase in the excavated material. Phase I efforts should provide an estimated mass/power for the crusher concept as well as an estimate for any temperature increase in the frozen regolith caused by the crushing technique. Phase II efforts should demonstrate the technique with lunar simulant mixed with ice having an initial unconfined compressive strength of 10 MPa at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time.
- Subsurface Volatile Extraction: Proposed concepts should be able to release volatiles at a depth of 50 cm below the surface with a water ice content of at least 5% by mass. Phase I efforts should provide an estimated mass/power for the concept. Phase II efforts should demonstrate the technique with lunar simulant at a target production rate of 0.28 kg H_20/hr and collect data to predict the estimated wear over time if applicable.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

See Scope Description for definitions of Phase I and II deliverables for each technology.

State of the Art and Critical Gaps:

Scoops and bucket-wheel excavators have been demonstrated for the collection of unconsolidated material but may not be effective at excavating consolidated regolith-ice composites. The Planetary Volatiles Extractor (PVEx) developed by Honeybee Robotics is the state of the art for heated core drills, but life testing is required to determine the rate of wear due to repeated excavation. Multiple groups have investigated the use of thermal mining methods to separate water from regolith, but the depth of water removed is relatively shallow. Very little work has been performed on the ability to capture water in a lunar environment after it has been released from the surface.

Relevance / Science Traceability:

The current NASA Administrator has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. STMD has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References:

1. Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. *Science*, *330*(6003), 463-468.
2. Hibbitts, C. A., Grieves, G. A., Poston, M. J., Dyar, M. D., Alexandrov, A. B., Johnson, M. A., & Orlando, T. M. (2011). Thermal stability of water and hydroxyl on the surface of the Moon from temperature-programmed desorption measurements of lunar analog materials. *Icarus*, *213*(1), 64-72.
3. Poston, M. J., Grieves, G. A., Aleksandrov, A. B., Hibbitts, C. A., Darby Dyar, M., & Orlando, T. M. (2013). Water interactions with micronized lunar surrogates JSC-1A and albite under ultra-high vacuum with application to lunar observations. *Journal of Geophysical Research: Planets*, *118*(1), 105-115.
4. Andreas, E. L. (2007). New estimates for the sublimation rate for ice on the Moon. *Icarus*, *186*(1), 24-30.

Focus Area 9 Sensors, Detectors, and Instruments

Lead MD: **SMD**

Participating MD(s): **STTR**

NASA's Science Mission Directorate (SMD) (https://science.nasa.gov/) encompasses research in the areas of Astrophysics, Earth Science, Heliophysics and Planetary Science. The National Academy of Science has provided NASA with recently updated Decadal surveys that are useful to identify technologies that are of interest to the above science divisions. Those documents are available at https://sites.nationalacademies.org/SSB/SSB_052297.

A major objective of SMD instrument development programs is to implement science measurement capabilities with smaller or more affordable aerospace platforms so development programs can meet multiple mission needs and therefore make the best use of limited resources. The rapid development of small, low-cost remote sensing and in-situ instruments capable of making measurements across the electromagnetic spectrum is essential to achieving this objective. For Earth Science needs, in particular, the subtopics reflect a focus on instrument development for airborne and uninhabited aerial vehicle (UAV) platforms. Astrophysics has a critical need for sensitive detector arrays with imaging, spectroscopy, and polarimetric capabilities, which can be demonstrated on ground, airborne, balloon, or suborbital rocket instruments. Heliophysics, which focuses on measurements of the sun and its interaction with the Earth and the other planets in the solar system, needs a significant reduction in the size, mass, power, and cost for instruments to fly on smaller spacecraft. Planetary Science has a critical need for miniaturized instruments with in-situ sensors that can be deployed on surface landers, rovers, and airborne platforms. For the 2021 program year, we are continuing to update the Sensors, Detectors and Instruments Topic, adding new, rotating out, and retiring some of the subtopics. Please read each subtopic of interest carefully. We continue to emphasize Ocean Worlds and solicit development of in-situ instrument technologies and components to advance the maturity of science instruments focused on the detection of evidence of life, especially extant of life, in the Ocean Worlds. The microwave technologies continue as two subtopics, one focused on active microwave remote sensing and the second on passive systems such as radiometers and microwave spectrometers. NASA has additional interest in advancing quantum sensing technologies to enable wholly new quantum sensing and measurement techniques focused on the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties. Furthermore, photonic integrated circuit technology is sought to enable size, weight, power, and cost reductions, as well as improved performance of science instruments, subsystems, and components which is particularly critical for enabling use of affordable small spacecraft platforms.

A key objective of this SBIR topic is to develop and demonstrate instrument component and subsystem technologies that reduce the risk, cost, size, and development time of SMD observing instruments and to enable new measurements. Proposals are sought for development of components, subsystems and systems that can be used in planned missions or a current technology program. Research should be conducted to demonstrate feasibility during Phase I and show a path towards a Phase II prototype demonstration. The following subtopics are concomitant with these objectives and are organized by technology.

S1.01 Lidar Remote-Sensing Technologies (SBIR)

Lead Center: **LaRC**

Participating Center(s): **GSFC**

Scope Title:

Lidar Remote-Sensing Technologies

Scope Description:

NASA recognizes the potential of lidar technology to meet many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric, geophysical, and topographic parameters from ground, airborne, and space-based platforms. To meet NASA's requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface features of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as unmanned aerial vehicles, SmallSats, and CubeSats are also considered and encouraged. Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- Backscatter: Measures beam reflection from aerosols and clouds to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures laser absorption by trace gases from atmospheric or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve concentration of gas within measurement volume.
- Ranging: Measures the return beam's time of flight to retrieve distance.
- Doppler: Measures wavelength changes in the return beam to retrieve relative velocity

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. A typical Phase I deliverable could be a technical report demonstrating the feasibility of the technology and a design that is to be built under a Phase II program. In some instances where a small subsystem is under investigation, a prototype deliverable under the Phase I is acceptable.

Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer. Higher fidelity Phase II prototypes that are fielded in harsh environments such as aircraft often require follow on programs such as Phase III SBIR to evaluate and optimize performance in relevant environment.

State of the Art and Critical Gaps:

- Compact, efficient, and rugged narrow-linewidth continuous-wave and pulsed lasers operating between ultraviolet and infrared wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 290 to 320 nm (ozone absorption), 450 to 490 nm (ocean sensing), 532 nm, 817 nm (water vapor line), 935 nm (water vapor line), 1064 nm, 1550 nm (Doppler wind), 1645 to 1650 nm (methane line), and 3000 to 4000 nm (hydrocarbon lines and ice measurement). Architectures involving new developments in high-efficiency diode laser, quantum cascade laser, and fiber laser technologies are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1 to 10 kHz with pulse energy greater than 1 mJ and from 20 to 100 Hz with pulse energy greater than 100 mJ. For laser spectral spectral absorption applications such as Differential Absorption Lidar or Integrated Path Absorption Lidar a frequency-agile source is required to tune >100 pm on a shot-by-shot basis while maintaining high spectral purity of >1000:1. Laser sources of wavelength at or around 780 nm are <u>not</u> sought this year. Also, laser sources of wavelength at or near 2050 nm are <u>not</u> sought this year. Laser sources for lidar measurements of carbon dioxide are <u>not</u> sought this year.
- Novel approaches and components for lidar receivers such as: integrated optical/photonic circuitry, frequency-agile ultra-narrow-band solar blocking filters at 817 and/or 935 nm, and phased-array or electro-optical beam scanners for large (>10 cm) apertures. Development of telescopes should be submitted to a different subtopic within S2 “Advanced Telescope Technologies,” unless the design is specifically a lidar component, such as a telescope integrated with other optics. Infrared photodetectors involving new semiconductor materials/architectures should be submitted to a different subtopic, S1.04 “Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter,” unless the design is specifically a lidar component, such as a photodetector combined with electronics or optics for lidar application that match wavelength ranges listed for lasers in the above bullet. Receivers for direct-detection wind lidar are <u>not</u> sought this year.
- New 3D mapping and hazard detection lidar with compact and high-efficiency diode and fiber lasers to measure range and surface reflectance of planets or asteroids from >100 km altitude during mapping to <1 m during landing or sample collection, within size, weight, and power fit into a 4U CubeSat or smaller. New lidar technologies are sought that allow system reconfiguration in

orbit, single photon sensitivities and single beam for long distance measurement, and variable dynamic range and multiple beams for near-range measurements.

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments. Advances are needed in generation of high-efficiency and high-pulse energy (>>1 mJ) from compact (SmallSat to CubeSat size) packages, avoiding the long cavity lengths associated with current solid-state laser transmitter designs. Mass-producible laser designs, perhaps by a hybrid diode/fiber/crystal architecture, are desirable for affordable sensor solutions and reducing parts count. Heat removal from lasers is a persistent problem, requiring new technologies for thermal management of laser transmitters. New materials concepts could be of interest for the reduction of weight for optical benches and subcomponents. Novel low-SWaP (size, weight, and power) electrical systems are of interest for data acquisition from multipixel linear mode photon detector arrays in future multichannel lidar receivers, capable of fast waveform capturing, onboard signal processing, and data compression.

Relevance / Science Traceability:

The proposed subtopic addresses missions, programs, and projects identified by the Science Mission Directorate, including:

- Atmospheric Water Vapor—Profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosols processes.
- Aerosols—Profiling of atmospheric aerosols and how aerosols relate to clouds and precipitation.
- Atmospheric Winds—Profiling of wind fields to support studies in weather and atmospheric dynamics on Earth and atmospheric structure of planets.
- Topography—Altimetry to support studies of vegetation and the cryosphere of Earth, as well as the surface of planets and solar system bodies.
- Greenhouse Gases—Column measurements of atmospheric gases, such as methane, that affect climate variability.
- Hydrocarbons—Measurements of planetary atmospheres.
- Gases Related to Air Quality—Sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects in atmospheric chemistry and health effects.
- Automated Landing, Hazard Avoidance, and Docking—Technologies to aid spacecraft and lander maneuvering and safe operations.

References:

- NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on earth science published in 2018 under the title "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space": http://sites.nationalacademies.org/DEPS/esas2017/index.htm
- For planetary science, NASA missions are aligned with the National Research Council decadal survey titled "Planetary Science and Astrobiology Decadal Survey 2023-2032": https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032
- Description of NASA lidar instruments and applications can be found at:
    - https://science.larc.nasa.gov/lidar/
    - https://science.gsfc.nasa.gov/sci/

S1.02 Technologies for Active Microwave Remote Sensing (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

High-Efficiency Solid-State Power Amplifiers

Scope Description:

This subtopic supports technologies to aid NASA in its active microwave sensing missions. Specifically, we are seeking L- and/or S-band solid-state power amplifiers (SSPAs) to achieve a power-added efficiency (PAE) of >50% for 1 kW peak transmit power, through the use of efficient multidevice power combining techniques or other efficiency improvements. There is also a need for high-efficiency ultra-high-frequency (335 to 535 MHz) monolithic microwave integrated circuit (MMIC) power amplifiers, with saturated output power greater than 20 W, high efficiency of >70%, and gain flatness of 1 dB over the band.

Solid-state amplifiers that meet high efficiency (>50% PAE) requirements and have small form factors would be suitable for SmallSats, support single satellite missions (such as RainCube), and enable future swarm techniques. No such devices at these high frequencies, high powers, and efficiencies are currently available. We expect a power amplifier with TRL 2 to 4 at the completion of the project.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Provide research and analysis to advance scope concept as a final report.

Phase II: Design and simulation of 1-kW S-/L-band amplifiers with >50% PAE, with prototype.

State of the Art and Critical Gaps:

Surface Deformation and Change is strongly desired for Earth remote sensing, for land use, natural hazards, and disaster response. NASA-ISRO Synthetic Aperture Radar (NISAR) is a Flagship-class mission, but only able to revisit locations on ~weekly basis, whereas future constellation concepts, using SmallSats would decrease revisit time to less than 1 day, which is game changing for studying earthquake precursors and postrelaxation. For natural hazards and disaster response, faster revisit times are critical. MMIC devices with high saturated output power in the few to several watts range and with high PAE (>50%) are desired.

Relevance / Science Traceability:

Surface Deformation and Change science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR mission are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments.

References:

- NISAR follow-on for Surface Deformation: https://science.nasa.gov/earth-science/decadal-sdc
- Radar in a CubeSat (RainCube): https://www.jpl.nasa.gov/cubesat/missions/raincube.php
- Global Atmospheric Composition Mission: https://www.nap.edu/read/11952/chapter/9
- Global Precipitation Measurement Mission: https://www.nasa.gov/mission_pages/GPM/overview/index.html

Scope Title:

Deployable Antenna Technologies

Scope Description:

Low-frequency deployable antennas for Earth and planetary radar sounders: antennas capable of being hosted by SmallSat/CubeSat platforms are required for missions to icy worlds, large/small body interiors (i.e., comets, asteroids), and for Earth at center frequencies from 5 to 100 MHz, with fractional bandwidths >=10%. Dual-frequency solutions or even tri-frequency solutions are desired; for example, an approximately 5- to 6-MHz band, with an approximately 85- to 95-MHz band. Designs need to be temperature tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band) deployable antennas for SmallSats and CubeSats: Small format, deployable antennas are desired (for 65 to 70 GHz) with an aperture size of ~1 m^2 that when stowed, fit into form factors suitable for SmallSats—with a desire for similar on the more-challenging CubeSat format. Concepts that remove, reduce, or control creases/seams in the resulting surface, on the order of a fraction of a wavelength at 70 GHz are highly desired.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

For both antenna types (low and high frequency) a paper design is desired for Phase I, and a prototype for Phase II. Concepts and prototypes for targeted advances in deployment technologies are welcome and do not need to address every need for mission-ready hardware.

State of the Art and Critical Gaps:

Low-frequency antennas, per physics, are large, and so are deployable, even for large spacecraft. For Small/CubeSats the challenges are to get enough of an antenna aperture with the proper length to achieve relatively high bandwidths. No such 10% fractional antenna exists for the Small/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1-m^2-diameter antenna on a Small/CubeSat is required to be deployable. Specific challenge for high-frequency deployable antennas is to deploy the aperture with enough accuracy such that the imperfections (i.e., residual folds, support ribs, etc.) are flat enough for antenna performance.

Relevance / Science Traceability:

Low-frequency-band antennas are of great interest to subsurface studies, such as those completed by MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) and SHARAD (Shallow Radar) for Mars, and planned for Europa by the REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) on the Europa Clipper. Studies of the subsurfaces of other icy worlds is of great interest to planetary science, as is tomography of small bodies such as comets and asteroids. Because of the impact of the ionosphere, low-frequency sounding of Earth is very challenging from space, but there is great interest in solutions to make this a reality. Lastly, such low-frequency bands are also of interest to radio-astronomy, such as that being done for OLFAR, https://research.utwente.nl/files/5412596/OLFAR.pdf

V-band deployable antennas are mission enabling for pressure sounding from space.

References:

For low-frequency deployables, see similar missions (on much larger platforms):

- REASON: https://www.jpl.nasa.gov/missions/europa-clipper/
- MARSIS: https://mars.nasa.gov/express/mission/sc_science_marsis01.html

For high-frequency deployable, see similar, but lower frequency mission:

- RainCube: https://www.jpl.nasa.gov/cubesat/missions/raincube.php

Scope Title:

Steerable Aperture Technologies

Scope Description:

Technologies enabling low-mass steerable technologies, especially for L or S bands—including, but not limited to—antenna or radio-frequency (RF) electronics, enabling steering: cross track +/-7° and along track +/-15°. This would enable a complete antenna system with a mass density of 10 kg/m^2 (or less) with a minimum aperture of 12 m^2.

Examples of different electronics solutions include completely integrated TR (transmit/receive) modules, with all control features for steering included; or alternatively, an ultra-compact TR module controller, which can control N modules, thus allowing reduction in size and complexity of the TR modules themselves.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I: A paper study with analysis.

Phase II: Prototype of subcomponent.

State of the Art and Critical Gaps:

No technology currently exists for such low mass density for steerable arrays.

Relevance / Science Traceability:

Surface Deformation and Change science is a key Earth Science Decadal Survey topic.

References:

NISAR follow-on and Surface Deformation:

- https://nisar.jpl.nasa.gov/
- https://science.nasa.gov/earth-science/decadal-sdc

Scope Title:

Low-Power W-Band Transceiver

Scope Description:

Require a low-power compact W-band (monolithic integrated circuit or application-specific integrated circuit (ASIC) preferred) transceiver with up/down converters with excellent cancellers to use the same antenna for transmit and receive. Application is in space landing radar altimetry and velocimetry. Wide-temperature-tolerant technologies are encouraged to reduce thermal control mass, either through designs insensitive to temperature changes or active compensation through feedback. Electronics must be tolerant to a high-radiation environment through design (rather than excessive shielding). In the early phases of this work, radiation tolerance must be considered in the semiconductor/materials choices, but it is not necessary to demonstrate radiation tolerance until later. For ocean worlds around Jupiter, bounding (worse case) radiation rates are expected to be at less than 50 rad(Si)/sec—with minimal shielding—during the period of performance (landing or altimeter flyby), but overall total dose is expected to be in the hundreds of krad total ionizing dose (TID). Most cases will be less extreme in radiation.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

- Prototype

Desired Deliverables Description:

Phase I: Paper study/design.

Phase II: Prototype.

State of the Art and Critical Gaps:

Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Such transceivers currently do not exist.

Relevance / Science Traceability:

- https://solarsystem.nasa.gov/missions/ace/in-depth/
- https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf

References:

Missions for atmospheric science and altimetry applications:

- https://solarsystem.nasa.gov/missions/ace/in-depth/
- https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter8--141029.pdf

S1.03 Technologies for Passive Microwave Remote Sensing (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL**

Scope Title:

Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers

Scope Description:

NASA requires novel solutions to challenges of developing stable, sensitive, and high-resolution radiometers and spectrometers operating from microwave frequencies to 1 THz. Novel technologies are requested to address challenges in the current state of the art of passive microwave remote sensing. Technologies could improve the sensitivity, calibration, or resolution of remote-sensing systems or reduce the size, weight, and power (SWaP). Companies are invited to provide unique solutions to problems in this area. Possible technologies could include:

- Low-noise receivers at frequencies up to 1 THz.
- Solutions to reduce system 1/f noise over time periods greater than 1 sec.
- Internal calibration systems or methods to improve calibration repeatability over time periods greater than days or weeks.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description:

Research, analysis, software, or hardware prototyping of novel components or methods to improve the performance of passive microwave remote sensing.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:

Depending on frequency, current passive microwave remote-sensing instrumentation is limited in sensitivity (as through system noise, 1/f noise, or calibration uncertainty), resolution, or in SWaP. Critical gaps depend on specific frequency and application.

Relevance / Science Traceability:

Critical need: Creative solutions to improve the performance of future Earth-observing, planetary, and astrophysics missions. The wide range of frequencies in this scope are used for numerous science measurements such as Earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

References:

- Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.

Scope Title:

Photonic Systems for Microwave Remote Sensing

Scope Description:

Photonic systems are an emerging technology for passive microwave remote sensing. This topic solicits photonic systems and subsystems to process microwave signals for passive remote sensing applications. Example applications include spectrometers, beam-forming arrays, correlation arrays, oscillators, noise sources, and other active or passive microwave instruments. Proposals should compare predicted performance and size, weight, and power (SWaP) to conventional radio frequency and digital processing methods. Proposers for specific Photonic Integrated Circuit (PIC) technology should instead see related STTR subtopic T8.02.

Expected TRL or TRL Range at completion of the Project: **3 to 5**

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- **Research**
- **Analysis**
- **Prototype**
- **Hardware**

Desired Deliverables Description:

Photonic systems to enable increased capability in passive microwave remote sensing instruments. This is a low-TRL emerging technology, so offerors are encouraged to identify and propose designs where photonic technology would be most beneficial.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:

The state of the art is currently the use of conventional microwave electronics for frequency conversion and filtering. Photonic systems for microwave remote sensing are an emerging technology not used in current NASA microwave missions, but they may enable significant increases in bandwidth or reduction in SWaP.

Relevance / Science Traceability:

Photonic systems may enable significantly increased bandwidth of Earth viewing, astrophysics, and planetary science missions. In particular, this may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

References:

- Chovan, Jozef; and Uherek, Frantisek: "Photonic Integrated Circuits for Communication Systems," *Radioengineering*, vol. 27, issue 2, pp. 357-363, June 2018.
- Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.

Scope Title:

Spectrometer Processing Technology for Microwave Radiometers

Scope Description:

Microwave spectrometry is used for characterizing radiances over absorption spectra and for mitigating radio-frequency interference (RFI). NASA requires technology for low-power, rad-tolerant broad-band microwave spectrometers. Possible Implementations could include:

- Digitizers starting at 20 Gsps, 20 GHz bandwidth, 4 or more bit. and simple interface to a field-programmable gate array (FPGA).

- Application-specific integrated circuit (ASIC) implementations of polyphase spectrometer digital signal processing with ~1 W/GHz; 10 GHz bandwidth polarimetric-spectrometer with 1,024 channels; Radiation-hardened and minimized power dissipation.
- Analog or photonic spectrum processors with size, weight, and power (SWaP) or performance advantages over digital technology.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

The desired deliverable of this Subtopic Scope is a low-power spectrometer for application-specific integrated circuit (ASIC) or other component that can be incorporated into multiple NASA radiometers.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:

Current FPGA-based spectrometers require ~10 W/GHz and are not flight qualifiable. High-speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10, but pose challenges in design and radiation tolerance. A low-power solution could be used in a wide range of NASA remote-sensing applications.

Relevance / Science Traceability:

Broadband spectrometers are required for Earth-observing, planetary, and astrophysics missions. Improved digital spectrometer capability is directly applicable to planetary science and enables radio-frequency interference (RFI) mitigation for Earth science.

References:

- Johnson, Joel T., et al.: "Real-Time Detection and Filtering of Radio Frequency Interference Onboard a Spaceborne Microwave Radiometer: The CubeRRT Mission," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13, pp. 1610-1624, 2020.
- Le Vine, David M.: "RFI and Remote Sensing of the Earth from Space," *Journal of Astronomical Instrumentation* 8.01 (2019), https://ntrs.nasa.gov/citations/20170003103

Scope Title:

Deployable Antenna Apertures at Frequencies up to Millimeter-Wave

Scope Description:

Deployable antenna apertures are required for a wide range of NASA passive remote-sensing applications from SmallSat platforms. Current deployable antenna technology is extremely limited above Ka-band. NASA requires low-loss deployable antenna apertures at frequencies up to 200 GHz. Deployed aperture diameters of 0.5 m or larger are desired, but proposers are invited to propose concepts for smaller apertures at higher frequencies.

NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves. Frequencies of interest start at 500 MHz. Loss should be as low as possible (less than 1%). The possibility of active thermal control is desired to improve system calibration stability.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables should consist of analysis and potential prototyping of key enabling technologies.

Phase II deliverables should include a deployable antenna prototype.

State of the Art and Critical Gaps:

Current low-loss deployable antennas are limited to Ka-band. Deployable apertures at higher frequencies are required for a wide range of applications, as aperture size is currently a instrument size, weight, and power (SWaP) driver for many applications up to 200 GHz.

Relevance / Science Traceability:

Antennas at these frequencies are used for a wide range of passive and active microwave remote sensing, including measurements of water vapor and temperature.

References:

- Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): https://gpm.nasa.gov/missions/GPM/GMI
- Chahat, N. et al.: "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review," *IEEE Antennas and Propagation Magazine*, vol. 61, no. 5, pp. 37-46, Oct. 2019, doi: 10.1109/MAP.2019.2932608.

S1.04 Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter (SBIR)

Lead Center: **JPL**

Participating Center(s): **ARC, GSFC, LaRC**

Scope Title:

Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter

Scope Description:

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys:

- Earth Science and Applications from Space: http://www.nap.edu/catalog/11820.html(link is external)
- New Frontiers in the Solar System: http://www.nap.edu/catalog/10432.html(link is external)
- Astronomy and Astrophysics in the New Millennium: http://www.nap.edu/books/0309070317/html/(link is external)

Please note:

1. Technologies for visible detectors are ***not*** *being solicited this year*.

2. *Proposers should direct proposals to S1.01 for technologies that don't address fundamental photodetection process improvements, (i.e., improvement in detection efficiency, excess noise, dark count rate, gain characteristics, afterpulsing, etc.), but instead focus on lidar-only solutions for detection and readout technologies not widely applicable to other fields. Please see the S1.01 scope for further clarification on what is being solicited.*

LOW-POWER AND LOW-COST READOUT INTEGRATED ELECTRONICS

- Photodiode Arrays: In-pixel Digital Readout Integrated Circuit (DROIC) for high-dynamic-range IR imaging and spectral imaging (10 to 60 Hz operation) focal plane arrays to circumvent the limitations in charge well capacity, by using in-pixel digital counters that can provide orders-of-magnitude larger effective well depth, thereby affording longer integration times.
- Microwave Kinetic Inductance Detector/Transition-Edge Sensor (MKID/TES) Detectors: A radiation-tolerant, digital readout system is needed for the readout of low-temperature detectors such as MKIDs or other detector types that use microwave-frequency-domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1,500 carrier tones in a bandwidth of at least 1 GHz with 14-bit precision and 1-kHz frequency placement resolution. The returning-frequency multiplexed signals from the detector array will be digitized with at least 12-bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1-GHz readout channel. That requirement would most likely indicate the use of a radio-frequency (RF) system on a chip (SoC) or application-specific integrated circuit (ASIC) with combined digitizer and channelizer functionality.
- Bolometric Arrays: Low-power, low-noise, cryogenic multiplexed readout for large format two-dimensional (2D) bolometer arrays with 1,000 or more pixels, operating at 65 to 350 mK. We require a superconducting readout capable of reading two TESs per pixel within a 1 mm^2 spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to 2D arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise \, and low detector noise-equivalent power degradation.
- Thermopile Detector Arrays: Mars Climate Sounder (MCS), the Diviner Lunar Radiometer Experiment (DLRE), and the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) are NASA space-borne radiometers that utilize custom thermopile detector arrays. Next-generation

radiometers will use larger format thermopile detector arrays, indium bump bonding to hybridize the detector arrays to the Readout Integrated Circuits (ROICs), low input-referred noise, and low power consumption. ROICs compatible with 128×64 element Bi-Sb-Te thermopile arrays with low 1/f noise, an operating temperature between 200 and 300 K, radiation hardness to 300 krad, and on-ROIC analog-to-digital converter (ADC) will be desirable.

LIDAR DETECTORS

- Enhanced photon detection efficiency (PDE), low excess noise, low dark noise, radiation-tolerant detectors for space-based 1.064-µm cloud profiling lidar applications. Detector should operate at a noncryogenic temperature. Solutions could include patterned/black silicon and III-V materials, but should optimize for signal-to-noise ratio in the ~3.7 fW to 190 nW optical power range (~2×10^4 to 1×10^{12} photons/sec) at 1.064 µm. Architectures might include massively parallel, fast-photon counting arrays of diodes operated in Geiger mode, or avalanche photodiodes (APDs) operated in linear mode with higher PDE than existing silicon APDs (PDE > 40%), but with a comparable or lower excess noise factor (ENF < 3). Improved absorption of 1.064 µm than bulk silicon is desired for better radiation tolerance and lower noise. A timing resolution of 67 ns (~10 m) is desired for atmospheric profiling, but resolutions of 1 ns (~15 cm) or better would make this detector more widely applicable to hard target ranging in areas such as planetary surface mapping, and vegetation/canopy lidar. Sensitivity of such a detector to the near-IR from 800 to 950 nm would also enable high-precision atmospheric profiling of key trace gases such as water vapor.

IR & Far-IR/SUBMILLIMETER-WAVE DETECTORS

- Novel Materials and Devices: New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH_4, N_2O) or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms. Of particular interest are new direct detector or heterodyne detector technologies made using high-temperature superconducting films (YBCO, MgB_2) or engineered semiconductor materials, especially 2D electron gas (2DEG) and quantum wells (QW).
- Array Receivers: Development of a robust wafer-level packaging/integration technology that will allow high-frequency-capable interconnects and allow two dissimilar substrates (i.e., silicon and GaAs) to be aligned and mechanically 'welded' together. Specially develop ball grid and/or through-silicon via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays. Compact and efficient systems for array receiver calibration and control are also needed.
- Receiver Components: Local oscillators capable of spectral coverage 2 to 5 THz; Output power up to >2 mW; frequency agility with >1 GHz near chosen THz frequency; Continuous phase-locking ability over the terahertz-tunable range with <100-kHz line width. Both solid-state (low-parasitic Schottky diodes) as well as quantum cascade lasers (for f > 2 THz) will be needed. Components and devices such as mixers, isolators, and orthomode transducers, working in the terahertz range, that enable future heterodyne array receivers are also desired. GaN-based power amplifiers at frequencies above 100 GHz and with power-added efficiency (PAE) > 25% are also needed. ASIC-based SoC solutions are needed for heterodyne receiver backends. ASICs capable of binning >6 GHz intermediate frequency bandwidth into 0.1- to 0.5-MHz channels with low power dissipation <0.5 W would be needed for array receivers.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

Desired Deliverables Description:

For Phase I activities the deliverables are nominally feasibility studies, detailed design, or determination of the trade space and detailed optimization of the design, as described in a final report. In some circumstances simple prototype models for the hardware can be demonstrated and tested.

For Phase II studies a working prototype that can be tested at one of the NASA centers is highly desirable.

State of the Art and Critical Gaps:

Efficient multipixel readout electronics are needed both for room-temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well infrared photodetectors, HgCdTe, and strained-layer superlattice would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future.

- Commercially available ROICs typically have well depths of less than 10 million electrons.
- 6- to 9-bit, ROACH-2 board solutions with 2,000 bands, <10 kHz bandwidth in each are state of the art (SOA).
- IR detector systems are needed for Earth imaging based on the recently released Earth Decadal Survey.
- Direct detectors with D ~ 10^9 cm-rtHz/W achieved in this range. Technologies with new materials that take advantage of cooling to the 30 to 100 K range are capable of D ~ 10^{12} cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5× to 10× the quantum limit in the submillimeter-wave range while operating at 30 to 77 K are an improvement in the state of the art due to higher operating temperature.
- Detector array detection efficiency <20% at 532 nm (including fill factor and probability of detection) for low after pulsing, low dead time designs is SOA.
- Far-IR bolometric heterodyne detectors are limited to 3-dB gain bandwidth of around 3 GHz. Novel superconducting material such a MgB_2 can provide significant enhancement of up to 9 GHz intermediate frequency (IF) bandwidth.
- Cryogenic Low Noise Amplifiers (LNAs) in the 4 to 8 GHz bandwidth with thermal stability are needed for focal plane arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSS), MKIDs, far-IR imager and polarimeters (FIPs), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few milliwatts.
- Another frequency range of interest for LNAs is 0.5 to 8.5 GHz. This is useful for HERO. Other NASA systems in the Space Geodesy Project (SGP) would be interested in bandwidths up to 2 to 14 GHz.
- 15 to 20 dB gain and <5 K noise over the 4 to 8 GHz bandwidth has been demonstrated.

- -Currently, all space-borne heterodyne receivers are single pixel. Novel architectures are needed for ~100 pixel arrays at 1.9 THz
- The current SOA readout circuit is capable of reading one TES per pixel in a 1-mm^2 area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce 2D circuits or to develop one capable of two TES-per-pixel readout. This work is extremely important to NASA's filled, kilopixel bolometer array program.
- 2D cryogenic readout circuits are analogous to semiconductor ROICs operating at much higher temperatures. We can produce millions-of-pixel detector arrays at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well infrared photodiode, HgCdTe, and strained-layer superlattice would not exist.
- For lidar detectors, extended-wavelength InGaAs detector/preamplifier packages operating at 2- to 2.1-µm wavelengths with high quantum efficiency (>90%) operating up to about 1 GHz bandwidth are available, as are packages operating up to about 10 GHz with lower quantum efficiency. Detectors that have >90% quantum efficiency over the full bandwidth from near DC to >5 GHz and capable of achieving near-shot-noise limited operation are not currently available.

Relevance / Science Traceability:

- Future short-, mid-, and long-wave IR Earth science and planetary science missions all require detectors that are sensitive and broadband with low power requirements.
- Future astrophysics instruments require cryogenic detectors that are supersensitive and broadband and provide imaging capability (multipixel).
- Aerosol spaceborne lidar as identified by 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace-gas lidar.
- Earth radiation budget measurement per 2007 decadal survey Clouds and Earth's Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as OST will need IR and far-IR detector and related technologies.
- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOReal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder, or other IR Earth-observing missions.
- Current science missions utilizing 2D, large-format cryogenic readout circuits:
  (1) HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy) future missions:
    - PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
    - PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission concept.
- Lidar detectors are needed for 3D wind measurements from space.

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S1.05 Detector Technologies for Ultraviolet (UV), X-Ray, Gamma-Ray Instruments (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC, MSFC**

Scope Title:

Detectors

Scope Description:

This subtopic covers detector requirements for a broad range of wavelengths from UV through to gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution. The proposed efforts must be directly linked to a requirement for a NASA mission. These include Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Earth Science Decadal Survey missions. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- Large-format, solid-state single-photon-counting radiation-tolerant detectors in charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) architecture—including 3D stacked architecture—for astrophysics, planetary, and UV heliophysics missions.
- Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications, for example, in spectropolarimetry as well as air quality and aerosol monitoring.
- UV detectors for O_3, NO_2, SO_2, H_2S, and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018).
- Significant improvement in wide-band-gap semiconductor materials (such as AlGaN, ZnMgO, and SiC), individual detectors, and detector arrays for astrophysics missions and planetary science composition measurements. For example, SiC avalanche photodiodes (APDs) must show:
  - Extreme-UV (EUV) photon counting, a linear mode gain $>10\times10^6$ at a breakdown reverse voltage between 80 and 100 V;
  - Detection capability of better than 6 photons/pixel/s down to 135 nm wavelength.
- Solar-blind (visible-blind) UV, far-UV (80 to 200 nm), and EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, and low voltage and power requirements—with or without photon counting.
- UV detectors suitable for upcoming ultra-high-energy cosmic ray (UHECR) mission concepts.
- Solar x-ray detectors with small independent pixels (10,000 count/s/pixel) over an energy range from <5 to 300 keV.
- Supporting technologies that would help enable the X-ray Surveyor mission that requires the development of x-ray microcalorimeter arrays with much larger field of view, ~10^5 to 10^6 pixels, of pitch ~25 to 100 µm, and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full-scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting. Improved long-wavelength blocking filters are needed for large-area, x-ray microcalorimeters.
- Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance electromagnetic interference (EMI) shielding (1 to 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with infrared transmissions less than 0.01% and ultraviolet transmission of less than 5% per filter. A means of producing filter diameters as large as 10 cm should be considered.
- Detectors with fast readout that can support high count rates and large incident flux from the EUV and x-rays for heliophysics applications, especially solar-flare measurements.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: results of tests and analysis of designs, as described in a final report.

Phase II deliverables: prototype hardware or hardware for further testing and evaluation is desired.

State of the Art and Critical Gaps:

This subtopic aims to develop and advance detector technologies focused on UV, x-ray, and gamma ray spectral ranges. The science needs in this range span a number of fields, focusing on astrophysics, planetary science, and UV heliophysics. A number of solid-state detector technologies promise to surpass the traditional image-tube-based detectors. Silicon-based detectors leverage enormous investments and promise high-performance detectors, while more complex material such as gallium nitride and silicon carbide offer intrinsic solar blind response. This subtopic supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

Relevance / Science Traceability:

Missions under study: Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, New Frontier-IO, Discovery-IVO

- LUVOIR- Large UV/Optical/IR Surveyor: https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
- NASA Astrophysics: https://science.nasa.gov/astrophysics/
- The Explorers Program: https://explorers.gsfc.nasa.gov/

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- Planetary Science Decadal Survey 2013-2022: "Vision and Voyages for Planetary Science in the Decade 2013-2022," http://solarsystem.nasa.gov/2013decadal/

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S1.06 Particles and Fields Sensors and Instrument Enabling Technologies (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL, MSFC**

Scope Title:

Particles and Fields Sensors and Instrument Enabling Technologies

Scope Description:

The 2013 National Research Council's "Solar and Space Physics: A Science for a Technological Society" motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced in-situ instrument technologies and components suitable for deployment on heliophysics missions. Advanced sensors for the detection of elementary particles (atoms, molecules, and their ions) and electric and magnetic fields in space along with associated instrument technologies are often critical for enabling transformational science from the study of the Sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the atmospheric composition of the planets and their moons. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technology developments that result in a reduction of mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited.

Improvements in particles and fields sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, Solar Terrestrial Probe (STP), Living With a Star (LWS), and planetary exploration missions. Specifically, this year the subtopic solicits instrument development that provides significant advances in the following areas:

- Faraday cup: 2-kHz alternating-current (AC) power supply with direct-current (DC) offset up to 40 kV and AC peak-to-peak at 10% of DC offset, operating temperature range -35 to +55 ºC, and radiation hardness >1 ~ 200 krad.
- Magnetically clean >2 m compact deployable booms for CubeSats.
- Innovative high-efficiency neutral particle ionizers based on thermionic, cold electron emission, or ultraviolet (UV) ionization.
- Direct neutral particle detectors to energies <1 eV.

Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: Concept study report, preliminary design, and test results.

Phase II deliverables: Detailed design, prototype test results, and a prototype deliverable with guidelines for in-house integration and test (I&T).

State of the Art and Critical Gaps:

High-Voltage Power Supplies DC and AC:

Low-energy particle instruments often require significant high-voltage DC power supplies up to 40 kV. Some applications such as Faraday cups require sine wave power supplies with a DC offset 0 to 40 kV and AC peak-to-peak at 10% of DC offset at oscillating frequency of 2 kHz, an operating temperature range from -35 to +55 °C, and radiation hardness >1 ~ 200 krad.

Importance: – Critical need for next-generation Faraday cups in order to extend the upper limit of solar wind speed measurement to >2,500 km/sec. Current Faraday cup high-voltage (HV) power supplies support maximum solar wind speeds of up to 1,500 km/sec. Very important for future space weather missions.

Existing direct neutral particle detectors are not capable of detecting, without ionization, neutral particles with energy <1 eV.

There is a need for nonthermionic ionizers to reduce power dissipation.

There is a need for magnetically clean, small booms for CubeSat magnetometers.

Relevance / Science Traceability:

Particles and fields instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in the National Research Council's, Solar and Space Physics: A Science for a Technological Society. In situ instruments and technologies play indispensable roles for NASA's LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particles and fields technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that Page 2 of 3 technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDES and H-FORT programs are in addition to Phase III opportunities. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamic Constellation.

References:

- For example missions, see: http://science.nasa.gov/missions (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument).

- For details of the specific requirements, see the National Research Council's Solar and Space Physics: A Science for a Technological Society, http://nap.edu/13060

S1.07 In Situ Instruments/Technologies for Lunar and Planetary Science (SBIR)

Lead Center: **JPL**

Participating Center(s): **ARC, GRC, GSFC, MSFC**

Scope Title:

In Situ Instruments/Technologies for Planetary Science

Scope Description:

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on in situ planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance—for both conventional missions as well as for small-satellite missions. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For examples of NASA science missions, see https://science.nasa.gov/missions-page. For details of the specific requirements see the National Research Council report "Vision and Voyages for Planetary Science in the Decade 2013-2022" (http://solarsystem.nasa.gov/2013decadal/), hereafter referred to as the Planetary Decadal Survey). Of particular interest are technologies to support future missions under the New Frontiers and Discovery programs.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- Mars:
    - Subsystems relevant to current in situ instrument needs (e.g., lasers and other light sources from UV to microwave, x-ray and ion sources, detectors, mixers, mass analyzers, and front-end ion/neutrals separation/transport technologies, etc.) or electronics technologies (e.g., field-programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high-voltage power supplies).
    - Technologies that support high-precision in situ measurements of the elemental, mineralogical, and organic composition of planetary materials.
    - Conceptually simple, low-risk technologies for in situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation.
    - Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (intensified charge-coupled devices (iCCDs), photomultiplier tube (PMT) arrays, etc.).
    - Instruments geared towards rock/sample interrogation prior to sample return. Sensors to measure dimensions of laser ablation pits in natural rock samples with unprepared rough

surfaces to support geochronology measurements on rock samples collected by a rover (spatial and depth resolution of 10 µm or better from a working distance of tens of centimeters desired to characterize ~1-mm-deep by ~0.5-mm-wide pits).

- Venus:
    - Sensors, mechanisms, and environmental chamber technologies for operation in Venus's high-temperature, high-pressure environment with its unique atmospheric composition.
    - Approaches that can enable precision measurements of surface mineralogy and elemental composition and precision measurements of trace species, noble gases, and isotopes in the atmosphere.
- Small bodies:
    - Technologies that can enable sampling from asteroids and from depth in a comet nucleus, improved in situ analysis of comets.
    - Imagers and spectrometers that provide high performance in low light environments.
    - Dust environment measurements and particle analysis, small body resource identification, and/or quantification of potential small-body resources (e.g., oxygen, water, and other volatiles; hydrated minerals; carbon compounds; fuels; metals; etc.).
    - Advancements geared towards instruments that enable elemental or mineralogy analysis (such as high-sensitivity x-ray and UV-fluorescence spectrometers, UV/fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and laser-induced breakdown spectroscopy (LIBS).
- Saturn, Uranus, and Neptune and their moons:
    - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low temperatures/high pressures of the atmospheric probes during entry. Note that in situ instruments and components focused on ocean worlds life detection are specifically solicited in S1.11 and are encouraged to be submitted to S1.11.
- The Moon:
    - This topic seeks advancement of concepts and components to develop a Lunar Geophysical Network as envisioned in the Planetary Decadal Survey. Understanding the distribution and origin of both shallow and deep moonquakes will provide insights into the current dynamics of the lunar interior and its interplay with external phenomena (e.g., tidal interactions with Earth). The network is envisioned to comprise multiple free-standing seismic stations that would operate over many years in even the most extreme lunar temperature environments.
    - Technologies to advance all aspects of the network including sensor emplacement, power, and communications in addition to seismic, heat flow, magnetic field and electromagnetic sounding sensors are desired.
    - This topic also seeks technologies for quantifying lunar water and measuring the D/H ratio in lunar water. Several evidences point to the presence of water ice at cold spots in the permanently shadowed regions at the lunar poles, with estimated abundance of ~5 to 10 wt%.

Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA mission.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

State of the Art and Critical Gaps:

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies (Mars, Venus, small bodies, Saturn, Uranus, Neptune, Moon, etc.).

There are currently various in situ instruments for diverse planetary bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars and plumes from planetary bodies, as well as a growing demand for in situ technologies amenable to small spacecraft.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities with lower mass, power, and volume.

Relevance / Science Traceability:

In situ instruments and technologies are essential bases to achieve SMD's planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies.

In addition to Phase III opportunities, SMD offers several instrument development programs as paths to further development and maturity. These include the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program, which invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology, as well as the Maturation of Instruments for Solar System Exploration (MatISSE) Program and the Development and Advancement of Lunar Instrumentation (DALI) Program, which invest in mid-TRL technologies and enable timely and efficient infusion of technology into planetary science missions.

References:

- Li et al.: "Direct evidence of surface exposed water ice in the lunar polar regions," *PNAS* 115 (2018), 8907-8912, https://www.pnas.org/content/pnas/115/36/8907.full.pdf
- Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., and Goldstein, D.: "Detection of water in the LCROSS ejecta plume," *Science*, 330 (2010), 463-468.
- Schultz, P. H., Hermalyn, B., Colaprete, A., Ennico, K., Shirley, M., and Marshall, W. S.: "The LCROSS cratering experiment," *Science*, 330 (2010), 468-472.
- Paige et al.: "Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region," *Science*, 330 (2010), 479-482.

S1.08 Suborbital Instruments and Sensor Systems for Earth Science Measurements (SBIR)

Lead Center: **LaRC**

Participating Center(s): **ARC, GSFC, JPL**

Scope Title:

Sensors and Sensor Systems Targeting Aerosols and Clouds

Scope Description:

Earth science measurements from space are considerably enhanced by observations from generally far less costly suborbital instruments and sensor systems. These instruments and sensors support NASA's Earth Science Division (ESD) science, calibration/validation, and environmental monitoring activities by providing ancillary data for satellite calibration and validation, algorithm development/refinement, and finer scale process studies. NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote-sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the Research Opportunities in Space and Earth Science (ROSES) solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth System. In situ sensor systems (airborne, land, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA's Airborne Science aircraft fleet or commercial providers, UAS, balloons, ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA's Earth science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition as well as minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the state.

Specific desired sensors or mated platform/sensors include:

- Combined aerosol absorption and scattering/extinction of atmospheric aerosols with calibrated accuracy and a particular emphasis on the ultraviolet (UV) or near-UV wavelengths.
- Spectrally resolved aerosol absorption, scattering, or extinction (UV to near-infrared (NIR) wavelengths).
- Aerosol scattering as a function of scattering angle (phase function or, preferably, phase matrix).
- Aerosol complex refractive index.
- Aerosols and cloud particle number and size distribution covering the diameter size range of 0.01 to 200 µm with 10% accuracy. Probes targeting cloud particles in the lower end of this size range (0.01 to 5 µm) are particularly encouraged.
- Cloud probes able to differentiate and quantify nonsphericity and phase of cloud particles.
- Liquid and ice water content in clouds with calibrated accuracy and precision.
- Liquid and ice water path in relevant tropical, midlatitude, and/or polar environments, including data inversion and analysis software.
- Spectrally resolved cloud extinction.
- Static air temperature measured from aircraft to better than 0.1 ºC accuracy.
- A well-calibrated airborne hyperspectral imager with spectral sensitivity in the UV to visible (VIS) (340 to 900 nm; preferably 320 to 1,080 nm) with spectral sampling of at least 2.5 nm, spectral resolution of at least 5 nm, and a wide dynamic range and sensitivity spanning from ocean radiances to cloud radiances for use in comparison to the PACE Ocean Color Instrument and other sensors.
- Portable hyperspectral UV-VIS-NIR (340 to 900 nm; preferably 320 to 1,100 nm) radiometric calibration system with a stabilized optical light source for verification of field radiometer stability by traceable National Institute of Standards and Technology (NIST) standards with variable flux levels.
  System must include thermal stabilization for the instrument to be independent of the ambient temperature for evaluation of radiometric stability as a function of time.
- Innovative, high-value sensors directly targeting a stated NASA need (including trace gases and ocean) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

The ideal Phase I proposal would demonstrate a clear idea of the problem to be solved, potential solutions to this problem, and an appreciation for potential risks or stumbling blocks that might jeopardize the success of the Phase I and II projects. The ideal Phase I effort would then address and hopefully overcome any major challenges to (1) demonstrate feasibility of the proposed solution and (2) clear the way for the Phase II effort. These accomplishments would be detailed in the Phase I final report and serve as the foundation for a Phase II proposal.

The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA including necessary hardware and operating software. The prototype would be fully functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps:

The S1.08 subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. Suborbital in situ and remote sensors sensors inform NASA ground, ship, and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, SGB, and A-CCP; see links in References). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns; e.g., ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ (see links in References).

Relevance / Science Traceability:

The S1.08 subtopic is and remains highly relevant to NASA SMD and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. In situ and ground-based sensors inform NASA ship and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, and A-CCP—see links in references). The solicited measurements will be highly relevant future NASA campaigns with objectives and observing strategies similar to past campaigns; e.g., NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ (see links in references). The need horizon of the subtopic sensors and sensors systems is BOTH near term (<5 yr) and midterm (5 to 10 yr).

Relevant Programs and Program Officers include:

- NASA ESD Ocean Biology and Biogeochemistry Program (Paula Bontempi and Laura Lorenzoni, HQ Program Managers)
- NASA ESD Tropospheric Composition Program (Barry Lefer, HQ Program Manager)
- NASA ESD Radiation Sciences Program (Hal Maring, HQ Program Manager)
- NASA ESD Airborne Science Program (Bruce Tagg, HQ Program Manager)

References:

Relevant current and past satellite missions and field campaigns include:

- Decadal Survey Recommended ACCP Mission focusing on aerosols, clouds, convection, and precipitation: https://science.nasa.gov/earth-science/decadal-surveys
- TEMPO Satellite Mission focusing on geostationary observations of air quality over North America: http://tempo.si.edu/overview.html
- CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science: https://espo.nasa.gov/camp2ex
- FIREX-AQ airborne and ground-based field campaign targeting wildfire and agricultural burning emissions in the United States: https://www.esrl.noaa.gov/csd/projects/firex-aq/

- KORUS-AQ airborne and ground-based field campaign focusing on pollution and air quality in the vicinity of the Korean Peninsula: https://espo.nasa.gov/korus-aq/content/KORUS-AQ
- DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States: https://discover-aq.larc.nasa.gov/
- NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: https://naames.larc.nasa.gov
- AToM airborne field campaign mapping the global distribution of aerosols and trace gases from pole-to-pole: https://espo.nasa.gov/atom/content/ATom
- PACE Satellite Mission, scheduled to launch in 2022, that focuses on observations of ocean biology, aerosols, and clouds: https://pace.gsfc.nasa.gov/
- EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: https://oceanexports.org
- OCO-2 Satellite Mission that targets spaceborne observations of carbon dioxide and the Earth's carbon cycle: https://www.nasa.gov/mission_pages/oco2/index.html

S1.09 Cryogenic Systems for Sensors and Detectors (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL**

Scope Title:

Low-Temperature/High-Efficiency Cryocoolers

Scope Description:

NASA seeks improvements to multistage low-temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available, and high efficiency. The desired cooling power is application specific, but an example is 0.2 W at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest. System- or component-level improvements that improve efficiency and reduce complexity and cost are desirable. In addition to the large coolers, there has recently been interest in small, low-power (~10-mW) 4 K coolers. For example, the Origins Space Telescope mission concept includes a cold telescope, requiring cooling to 4 K; and the Lynx X-ray Observatory mission concept requires a state-of-the-art cryogenic system to enable high-precision and high-resolution x-ray spectroscopy.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept demonstration.

Phase II: Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps:

Current spaceflight cryocoolers for this temperature range include linear piston-driven Stirling cycle or pulse tube cryocoolers with Joule-Thompson low-temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight point requirements, orders-of-magnitude improvement in the levels of exported vibration will be required. Some of these requirements are laid out in the "Advanced cryocoolers" Technology gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability:

Science traceability: Goal 1 and Objective 1.6 of NASA's Strategic Plan: Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars. Low-temperature cryocoolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report. Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey: Origins Space Telescope and Lynx microcalorimeter instrument.

References:

For more information on the Origins Space Telescope, see: https://asd.gsfc.nasa.gov/firs/

For more information on LYNX, see: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.html

Scope Title:

Actuators and Other Cryogenic Devices

Scope Description:

NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m. Devices that have reduced gravitational dependence and that can be made low profile, or integrated into structures such as radiators, are of particular interest.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype

- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept test on a breadboard-level device.

Phase II: Working prototypes ready for testing in the relevant environments.

State of the Art and Critical Gaps:

Motors and actuators: Instruments often have motors and actuators, typically for optical elements such as filter wheels and Fabry-Perot interferometers. Current cryogenic actuators are typically motors with resistive (copper) windings. While heat generation is naturally dependent on the application, an example of a recent case is a stepper motor used to scan a Fabry-Perot cavity; its total dissipation (resistive + hysteric) is ~0.5 W at 4 K. A flight instrument would need heat generation at least 20× smaller.

Cryogenic heat pipes: Heat transport in cryogenic instruments is typically handled with solid thermal straps, which do not scale well for larger heat loads. Currently available heat pipes are optimized for temperatures above ~ 20 K. They have limited capacity to operate against a gravitational potential.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, and Universe

Almost all instruments have motors and actuators for changing filters, adjusting focus, scanning, and other functions. On low-temperature instruments, for example on mid- to far-IR observatories, dissipation in actuators can be a significant design problem.

References:

For more information on earlier low-temperature heat pipes, see:

- Brennen, et al.: AIAA paper 93-2735, https://doi.org/10.2514/6.1993-2735 NTRS Document ID: 19930062491
- Prager, R.C.: AIAA paper 80-1484, https://doi.org/10.2514/6.1980-1484
- Alario, J. and Kosson, R.: AIAA paper 80-0212, https://doi.org/10.2514/6.1980-212

Scope Title:

Ultra-Lightweight Dewars

Scope Description:

NASA seeks extremely lightweight thermal isolation systems for scientific instruments. An important example is a large cylindrical, open-top dewar to enable large, cold balloon telescopes. In one scenario, such a dewar would be launched warm and so would not need to function at ambient pressure, but at altitude, under ~4 mbar external pressure, it would need to contain cold helium vapor. The ability to rapidly pump and hold a vacuum at altitude is necessary. An alternative concept is that the dewar would be launched at operating temperature, with some or all of the needed liquid helium. In both cases, heat flux through the walls should be less than 0.5 W/m^2, and the internal surfaces must be leak tight against superfluid helium. Initial demonstration units of greater than 1 m inner diameter and height are desired, but the technology must be scalable to an inner diameter of 3 to 4 m with a mass that is a small fraction of the net lift capability of a scientific balloon (~2,000 kg).

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Subscale prototypes that demonstrate critical properties of the concept, including scalability and leak-free containment of superfluid helium

Phase II: A working prototype of the scale described is desired.

State of the Art and Critical Gaps:

Currently available liquid helium dewars have heavy vacuum shells that allow them to be operated in ambient pressure. Such dewars have been used for balloon-based astronomy, as in the Absolute Radiometer for Cosmology, Astrophsyics, and Diffuse Emission (ARCADE) experiment. However, the current dewars are already near the limit of balloon lift capacity and cannot be scaled up to the required size for future astrophysics measurements.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

The potential for ground-based far-infrared astronomy is extremely limited. Even in airborne observatories, such as SOFIA, observations are limited by the brightness of the atmosphere and the warm telescope itself. However, high-altitude scientific balloons are above enough of the atmosphere that, with a telescope large enough and cold enough, background-limited observations are possible. The ARCADE project demonstrated that at high altitudes, it is possible to cool instruments in helium vapor. Development of ultra-lightweight dewars that could be scaled up to large size, yet still be liftable by a balloon would enable ground-breaking observational capability.

References:

For a description of a state-of-the art balloon cryostat, see:

- Singal, et al.: "The ARCADE 2 instrument," *The Astrophysical Journal*, 730:138 (12pp), 2011 April 1.

Scope Title:

Miniaturized/Efficient Cryocooler Systems

Scope Description:

NASA seeks miniature, highly efficient cryocoolers for instruments on Earth and planetary missions. A range of cooling capabilities is sought. Two examples include 0.2 W at 30 K with heat rejection at 300 K and 0.3 W at 35 K with heat rejection at 150 K. For both examples, an input power of ≤5 W and a total mass of ≤400 g is desired. The ability to fit within the volume and power limitations of a SmallSat platform would be highly advantageous. Cryocooler electronics are also sought in two general categories: (1) low-cost devices that are sufficiently radiation hard for lunar or planetary missions, and (2) very low cost devices for a relatively short term (~1 year) in low Earth orbit. The latter category could include controllers for very small coolers, such as tactical and rotary coolers.

For many infrared (IR) spectrometer instrument systems, the spectrometer can operate at a temperature more than 60 K higher than the focal plane array. A miniature two-stage cryocooler is ideal for this type of application to minimize the cooler input power. Therefore, NASA is seeking an innovative miniature two-stage cryocooler technology with low-exported vibrations. The lowest cooling temperature of interest for the lower stage is 80 K, and the maximum cooling power is about 1 W. The cooling temperature of the second stage should be 60 to 80 K higher than the lower stage, and the cooling power should be about 2 W. It is desirable that the cooler can efficiently operate over a wide heat sink temperature range, from -50 to 70 ºC.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Proof-of-concept demonstration.

Phase II: Desired deliverables include miniature coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps:

Present state-of-the-art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 g.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science—and some of its planetary—science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

References:

- An example of CubeSat mission using cryocoolers is given at: https://www.jpl.nasa.gov/cubesat/missions/ciras.php

Scope Title:

Sub-Kelvin Cooling Systems

Scope Description:

Future NASA missions will require requiring sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (>5 mW at 50 mK), low operating temperature (10 K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

1) Compact, lightweight, low-current superconducting magnets capable of producing a field of at least 4 tesla (T) while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:

- A high engineering current density (including insulation and coil packing density), preferably >300 A/mm^2.
- A field/current ratio of >0.33 T/A, and preferably >0.66 T/A.
- Low hysteresis heating.
- Bore size between 22 and 60 mm, depending on the application.

2) Lightweight active/passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current losses as well as low remanence. Also needed are lightweight, highly effective outer shields that reduce the field outside an entire multistage device to <5 µT. Outer shields must operate at 4 to 10 K and must have penetrations for low-temperature, noncontacting heat straps.

3) Heat switches with on/off conductance ratio >30,000 and actuation time of <10 s. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below 1 K; they must be impermeable to helium gas, have high strength, have stability against buckling, and have an inner diameter >20 mm.

4) High cooling power density magnetocaloric materials. Examples of desired materials include $GdLiF_4$, $Yb_3Ga_5O_{12}$, GdF_3, and Gd elpasolite. High-quality single crystals are preferred because of their high conductivity at low temperature, but high-density polycrystals are acceptable in some forms. Volume must be >40 cm^3.

5) 10 to 300 mK high-resolution thermometry.

6) Suspensions with the strength and stiffness, but lower thermal conductance from 4 to 0.050 K.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: For components, a subscale prototype that proves critical parameters. For systems, a proof-of-concept test.

Phase II: For components, functioning hardware that is directly usable in NASA systems. For systems, a prototype that demonstrates critical performance parameters.

State of the Art and Critical Gaps:

The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3-stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1-h periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, And Universe

Sub-Kelvin coolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report.

Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey:
• Origins Space Telescope (contact: michael.j.dipirro@nasa.gov)
• LYNX (microcalorimeter instrument) (contact: simon.r.bandler@nasa.gov)

Also: Probe of Inflation and Cosmic Origins, POC: Shaul Hanany, University of Minnesota

References:

For a description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission, see:

- Shirron, et al.: "Thermodynamic performance of the 3-stage ADR for the Astro-H Soft-X-ray Spectrometer instrument," Cryogenics 74 (2016) 24–30, and references therein.

For articles describing magnetic sub-Kelvin coolers and their components, see the July 2014 special issue of Cryogenics:

- Cryogenics 62 (2014) 129–220.

S1.10 Atomic Quantum Sensor and Clocks (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

Atomic Quantum Sensor and Clocks

Scope Description:

Space exploration relies on sensors for science measurements as well as spacecraft operation. As sensing precisions push their limits, quantum phenomena inevitably must be exploited. It is expected that sensors utilizing quantum properties will offer new and significantly improved capabilities. NASA is interested in advancing quantum sensing technologies and infusing them into space science missions. In particular, this call seeks the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties (e.g., optical atomic clocks, atom interferometers, Rydberg atom sensors, and artificial-atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.).

Recent developments of laser control and manipulation of atoms have led to new types of quantum sensors and clocks. Atomic particles, being intrinsically quantum mechanical, have demonstrated their unique advantages in metrology and sensing. Perhaps the most celebrated atomic metrology tool is the atomic clock. Atomic clocks in the optical frequency domain (i.e., optical primary frequency standards) have approached, and are expected to exceed, a frequency uncertainty beyond 1 part in 10^{18}. These optical clocks can be used, in turn, as precision sensors; for example, sensitivity to the fundamental physics constants have been explored for detection of dark matter and time variations in those fundamental constants. These approaches, when made Doppler sensitive, become exquisite inertial sensors, mostly in the form of atom interferometers. Because the center-of-mass motion is involved, atom interferometers use atomic particles as test masses and quantum matter-wave interferometry for motional measurements. Indeed, clocks and sensors are two sides of the same coin, sharing many common physical processes, technology approaches, and salient performance features. Therefore, this subtopic combines the two subject areas for leveraged and coordinated technology advancement.

The gaps to be filled and technologies to be matured include, but are not limited to, the following:

(1) Optical atomic clocks

- Subsystem and components for high-performance and high-accuracy optical clocks, mostly notably Sr and Yb lattice clocks as well as Sr+ and Yb+ singly trapped ion clocks. They comprise atomic physics packages, which are necessarily laser systems, and include clock lasers, optical frequency combs, as well as advanced electronics and controllers based on microprocessors or field-programmable gate arrays (FPGAs). They should have a path to a flight system.
- Space-qualifiable small-size low-power clock lasers at, or subsystems that can lead to, better than 3×10^{-15} Hz/$\sqrt{\tau}$ near 0.1 to 10 s (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- Technical approaches and methods for beyond state-of-the-art compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

(2) Atom interferometers

- Space-qualifiable high-flux ultra-cold atom sources, related components, and methods: e.g., $>1\times10^{6}$ total atoms near the point at <1 nK: Rb, K, Cs, Yb, and Sr.
- Ultra-high vacuum technologies and approaches for atom interferometer applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and are capable of maintaining $<1\times10^{-9}$ torr residual gas pressure. Consideration should be given to the inclusion of cold atom sources of interest, such as switchable and/or regulated atom vapor pressure or flux.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly visible and ultraviolet (UV):
    - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency.
    - Efficient electro-optic modulators: e.g., low bias drift, residual AM, and return loss; fiber-coupled preferred.
    - Miniature optical isolators: e.g., ~30 dB isolation or greater, ~ -2 dB loss or less.

- Robust high-speed high-extinction shutters: e.g., switching time <1 ms and extinction >60 dB are highly desired.

- Flight qualifiable: i.e., rugged and long-life lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest; Also, cooling and trapping lasers of 10 kHz linewidth and ~1 W or greater total optical power are generally needed, but offerors may define and justify their own performance specifications.
- Analysis and simulation tool of a cold atom system in trapped and freefall states relevant to atom interferometer and clock measurements in space.

(3) Other atomic and artificial atomic sensors

- Rydberg sensors or their subsystems/components for electric field or microwave measurements.
- Space qualifiable NV diamond or chip-scale atomic magnetometers.
- High-performance, miniaturized or chip-scale optical frequency combs.
- Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-quantifiable instrument.
- Because of the breath and diversity of the portfolio, performers are expected to be aware of specific gaps for specific application scenarios. All proposed system performances may be defined by offeror with clear justifications. Subsystem technology development proposals should clearly state the relevance to the anticipated system-level implementation and performance; define requirements, relevant atomic species, and working laser wavelengths; and indicate its path to a space-borne instrument. Finally, for proposals interested in quantum sensing methodologies for achieving the optimal collection of light for photon-starved astronomical observations, it is suggested to consider the STTR subtopic T8.06.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis
- Software

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report.

Phase II deliverables: prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps:

Many technology gaps exist in the development state of atomic sensors and clocks intended for NASA space applications. These gaps are mainly in the areas of reducing size, mass, and power, while increasing their performance and advancing them towards space qualification. These gaps may pertain to components, subsystems, instruments/devices, novel approaches and/or theoretical analysis tools. Most of the needed improvements are elements which are beyond current state-of-the art. These needed improvements include high-flux ultra-cold atom sources, atomic physics packages and atomic vacuum cell technology specific for clock and atom interferometer applications, miniature optical isolators, efficient modulators, active wave front and polarization devices, fast high-extension-ratio switches, efficient detectors, and novel frequency conversion methods/devices. Also needed are lasers and laser-optics system approaches with a high degree of integration and robustness, and suitable for atomic devices; small ultra-stabilized laser systems, and miniature self-referenced optical frequency combs. These are examples and not an exhaustive list.

Relevance / Science Traceability:

Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of atom optical-based gravity and time measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

- TX07.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
- TX08.1.2: Electronics (reliable control electronics for laser systems)
- TX08.1.3: Optical Components (reliable laser systems)
- TX08.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
- TX08.1.5: Lasers (reliable laser system w/ long lifetime)

References:

- 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
- 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE

S1.11 In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection (SBIR)

Lead Center: **JPL**

Participating Center(s): **ARC, GRC, GSFC**

Scope Title:

In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Scope Description:

This subtopic solicits development of in situ instrument technologies and components to advance the maturity of science instruments and plume sample collection systems focused on the detection of evidence of life, especially extant life, in the ocean worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). Technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are of particular interest. Technologies that allow collection during high-speed (>1 km/sec) passes through a plume are solicited as are technologies that can maximize total sample mass collected while passing through tenuous plumes. This fly-through sampling focus is distinct from S4.02, which solicits sample collection technologies from surface platforms.

These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.

Specifically, this subtopic solicits instrument technologies and components that provide significant advances in the following areas, broken out by planetary body:

- General to Europa, Enceladus, Titan, and other ocean worlds: Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, microelectromechanical systems (MEMS) chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, X-ray fluorescence, digital holographic microscope-fluorescence microscope, antibody microarray biosensor, nanocantilever biodetector, etc.). Technologies for high-radiation environments (e.g., radiation mitigation strategies, radiation-tolerant detectors, and readout electronic components), which enable orbiting instruments to be both radiation hard and undergo the planetary protection requirements of sterilization (or equivalent).
    - Collecting samples for a variety of science purposes is also sought. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Front-end system technologies include sample collection systems and subsystems capable of capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces.
    - Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids. Sample collection and sample capture for in situ imaging. Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses. Microfluidic sample collection systems that enable sample concentration and other manipulations. Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminates. These technologies would enable high-priority sampling and potential sample return from the plumes of Enceladus with a fly-by mission. This would be a substantial cost savings over a landed mission.
- Europa: Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (µg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and near-infrared (NIR) imaging spectrometers, thermal imagers, etc.), as well as instruments capable of improving our understanding of Europa's habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or

other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- Enceladus (including plume material and E-ring particles): Life detection approaches optimized for analyzing plume particles as well as for determining the chemical state of Enceladus icy surface materials (particularly near plume sites). Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts and/or minerals important to understand the present conditions of the Enceladus ocean are sought (such as high resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (µg to mg) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of monitoring the bulk chemical composition and physical characteristics of the plume (density, velocity, variation with time, etc.). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.
- Titan: Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for analyzing Titan's complex aerosols and surface materials. Mechanical and electrical components and subsystems that work in cryogenic (95 K) environments; sample extraction from liquid methane/ethane, sampling from organic "dunes" at 95 K, and robust sample preparation and handling mechanisms that feed into mass analyzers are sought. Balloon instruments, such as IR spectrometers; imagers; meteorological instruments; radar sounders; solid, liquid, and air sampling mechanisms for mass analyzers; and aerosol detectors are also solicited. Low-mass and low-power sensors, mechanisms and concepts for converting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc. to cryogenic environments (95 K). Other ocean worlds targets may include Ganymede, Callisto, Ceres, etc.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future ocean worlds exploration goals (see references).
- Existing flight instrument capability, to provide a comparison metric for assessing proposed improvements.

Proposed instrument architectures should be as simple, reliable, and low risk as possible while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired.

Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Analysis

- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

State of the Art and Critical Gaps:

In situ instruments and technologies are essential bases to achieve NASA's ocean worlds exploration goals. There are currently some in situ instruments for diverse ocean worlds bodies. However, there are ever increasing science and exploration requirements and challenges for diverse ocean worlds bodies. For example, there are urgent needs for the exploration of icy or liquid surface on Europa, Enceladus, Titan, Ganymede, Callisto, etc., and plumes from planetary bodies such as Enceladus.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower resource (mass, power, and volume) requirements.

Relevance / Science Traceability:

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) planetary science goals summarized in Decadal Study (National Research Council’s Vision and Voyages for Planetary Science in the Decade 2013-2022.) In situ instruments and technologies play indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies.

NASA SMD has two programs to bring this subtopic technologies to higher level: PICASSO and MatISSE. The Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology. The Maturation of Instruments for Solar System Exploration (MatISSE) Program invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions. The PICASSO and MatISSE are in addition to Phase III opportunities.

References:

- For the NASA Roadmap for Ocean World Exploration see: http://www.lpi.usra.edu/opag/ROW
- In situ instruments and technologies for NASA's ocean worlds exploration goals see: https://www.nasa.gov/specials/ocean-worlds/
- NASA technology solicitation, see ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call: https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECABCD2-A3783CB1AAC8}&path=init

- Instrument Concepts for Europa Exploration 2 (final text released May 17, 2018; PDF): https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=628697/solicitationId=%7B17B73E96-6B65-FE78-5B6384C804831035%7D/viewSolicitationDocument=1/C.23%20ICEE2%20Schulte%20POC.pdf

S1.12 Remote Sensing Instrument Technologies for Heliophysics (SBIR)

Lead Center: **GSFC**

Participating Center(s): **HQ**

Scope Title:

Remote-Sensing Instruments/Technologies for Heliophysics

Scope Description:

The 2013 National Research Council's, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060) motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced remote-sensing instrument technologies and components suitable for deployment on heliophysics missions. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For example missions, see https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All. For details of the specific requirements see the Heliophysics Decadal Survey. Technologies that support science aspects of missions in NASA's Living With a Star and Solar-Terrestrial Probe programs are of top priority, including long-term missions like Interstellar Probe mission (as called out in the Decadal Survey).

Remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities. Remote-sensing technologies amenable to CubeSats and SmallSats are also encouraged. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Light detection and ranging (LIDAR) systems for high-power, high-frequency geospace remote sensing, such as sodium and helium lasers.
- Technologies or components enabling auroral, airglow, geospace, and solar imaging at visible, far and extreme ultraviolet (FUV/EUV), and soft x-ray wavelengths (e.g., mirrors and gratings with high-reflectance coatings, multilayer coatings, narrowband filters, blazed gratings with high ruling densities, diffractive and metamaterial optics).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radio-frequencies from kHz to >10 MHz.
- Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).

- Technologies that enable the development of dedicated solar flare sensors with intrinsic ion suppression and sufficient angular resolution in the EUV to soft x-ray wavelength range such as fast cadence charge-coupled devices and complementary metal-oxide semiconductor devices.
- Technologies that enable x-ray detectors to observe bright solar flares in x-ray from 1 to hundreds of keV without saturation.
- Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1,000 across the energy range encompassing both low- and high-energy x-rays—preferably flight programmable.
- X-ray optics technologies to either reduce the size, complexity, or mass or to improve the point spread function of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range.
- Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals as set out in the Heliophysics Decadal Survey (2013-2022) and the NASA Heliophysics Roadmap (2014-2033). Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs, and present a feasible plan to fully develop a technology and infuse it into a NASA program. Detector technology proposals should be referred to the S116 subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables may include an analysis or test report, a prototype of an instrument subcomponent, or a full working instrument prototype.

Phase II deliverables must include a prototype or demonstration of a working instrument or subcomponent and may also include analysis or test reports.

State of the Art and Critical Gaps:

Remote-sensing instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) Heliophysics goals summarized in National Research Council’s, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA’s Living With a Star (LWS) and Solar Terrestrial Probe (STP) mission programs as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities—and at the same time with lower mass, power, and volume.

Relevance / Science Traceability:

Remote-sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA's LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to a higher level: Heliophysics Technology and Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (HFORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDeS would then be proposed to HFORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities.

References:

- For example missions, see: https://science.nasa.gov/missions
- For details of the specific requirements, see the National Research Council's, Solar and Space Physics: A Science for a Technological Society: http://nap.edu/13060
- For details of NASA's Heliophysics roadmap, see the NASA Heliophysics Roadmap: https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf

T8.06 Quantum Sensing and Measurement (STTR)

Lead Center: **GSFC**

Participating Center(s): **GRC, JPL, LaRC**

Scope Title:

Quantum Sensing and Measurement

Scope Description:

This Quantum Sensing and Measurement subtopic calls for proposals using quantum systems to achieve unprecedented measurement sensitivity and performance, including quantum-enhanced methodologies that outperform their classical counterparts. Shepherded by advancements in our ability to detect and manipulate single quantum objects, the so-called Second Quantum Revolution is upon us. The emerging quantum sensing technologies promise unrivaled sensitivities and are potentially game changing in precision measurement fields. Significant gains include technology important for a range of NASA missions such as efficient photon detection, optical clocks, gravitational wave sensing, ranging, and interferometry. Proposals focused on atomic quantum sensor and clocks and quantum communication should apply to those specific subtopics and are not covered in this Quantum Sensing and Measurement subtopic.

Specifically identified applications of interest include quantum sensing methodologies achieving the optimal collection light for photon-starved astronomical observations, quantum-enhanced ground penetrating radar, and quantum-enhanced telescope interferometry.

- Superconducting Quantum Interference Device (SQUID) systems for enhanced multiplexing factor reading out of arrays of cryogenic energy-resolving single-photon detectors, including the supporting resonator circuits, amplifiers, and room temperature readout electronics.
- Quantum light sources capable of efficiently and reliably producing prescribed quantum states including entangled photons, squeezed states, photon number states, and broadband correlated light pulses. Such entangled sources are sought for the visible infrared (vis-IR) and in the microwave entangled photons sources for quantum ranging and ground-penetrating radar.
- On-demand single-photon sources with narrow spectral linewidth are needed for system calibration of single-photon counting detectors and energy-resolving single-photon detector arrays in the midwave infrared (MIR), near infrared (NIR), and visible. Such sources are sought for operation at cryogenic temperatures for calibration on the ground and aboard space instruments.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

NASA is seeking innovative ideas and creative concepts for science sensor technologies using quantum sensing techniques. The proposals should include results from designs and models, proof-of-concept demonstrations, and prototypes showing the performance of the novel quantum sensor.

Phase I does not need to include a physical deliverable to the government but it is best if it includes a demonstration of feasibility through measurements. This can include extensive modeling, but a stronger proposal will have measured validation of models or designs that support the viability of the planned Phase II deliverable.

Phase II should include prototype delivery to the government. (It is understood that this is a research effort and the prototype is a best effort delivery where there is no penalty for missing performance goals.) The Phase II effort should be targeting a commercial product that could be sold to the government and/or industry.

State of the Art and Critical Gaps:

Quantum entangled photon sources.

Sources for generation of quantum photon number states. Such sources would utilize high detection efficiency photon energy-resolving single-photon detectors (where the energy resolution is used to detect the photon number) developed at NASA for detection. Sources that fall in the wavelength range from 20 µm to 200 nm are of high interest. Photon number state generation anywhere within this spectral range is also highly desired including emerging photon-number quantum state methods providing advantages over existing techniques. (Stobińska et al., Quantum interference enables constant-time quantum information processing. Sci. Adv. 5 (2019)).

Quantum dot source produced entangled photons with a fidelity of 0.90, a pair generation rate of 0.59, a pair extraction efficiency of 0.62, and a photon indistinguishability of 0.90, simultaneously. (881 nm light) at 10 MHz. (Wang Phys. Rev. Lett. 122, 113602 (2019)). Further advances are sought.

Spectral brightness of 0.41 MHz/mW/nm for multimode and 0.025 MHz/mW/nm for single-mode coupling. (Jabir: Scientific Reports volume 7, Article number: 12613 (2017)).

Higher brightness and multiple entanglement and heralded multiphoton entanglement and boson sampling sources. Sources that produce photon number states or Fock states are also sought for various applications including energy-resolving single-photon detector applications.

For energy-resolving single-photon detectors, current state-of-the-art multiplexing can achieve kilopixel detector arrays, which with advances in microwave SQUID mux can be increased to megapixel arrays. (Morgan Physics Today 71, 8, 28 (2018)).

Energy-resolving detectors achieving 99% detection efficiency have been demonstrated in the NIR. Even higher quantum efficiency absorber structures are sought (either over narrow bands or broadband) compatible with transition-edge sensor (TES) detectors. Such ultra-high- (near-unity-) efficiency absorbing structures are sought in the UV, vis-IR, NIR, mid-infrared, far-infrared, and microwave.

Absolute detection efficiency measurements (without reference to calibration standards) using quantum light sources have achieved detection efficiency relative uncertainties of 0.1% level. Further reduction in detection efficiency uncertainty is sought to characterize ultra-high-efficiency absorber structures. Combining calibration method with the ability to tune over a range of different wavelengths is sought to characterize cryogenic single-photon detector's energy resolution and detection efficiency across the detection band of interest. For such applications, the natural linewidth of the source lines must be much less than the detector resolution (for NIR and higher photon energies, resolving powers $R=E/\Delta E_{FWHM}=\lambda/\Delta\lambda_{FWHM} << 100$ are required). Quantum sources operating at cryogenic temperatures are most suitable for cryogenic detector characterization and photon number resolving detection for wavelengths of order 1.6 µm and longer.

For quantum sensing applications that would involve a squeezed light source on an aerospace platform, investigation of low SWaP (size, weight, and power) sources of squeezed light would be beneficial. From the literature, larger footprint sources of squeezed light have demonstrated 15 dB of squeezing [1]. For a source smaller in footprint, there has been a recent demonstration of parametric downconversion in an OPO (optical parametric oscillator) resulting in 9.3 dB of squeezing [2]. Further improvement of the state-of-the-art light squeezing capability (i.e., >10 dB), while maintaining low-SWaP parameters, is desired.

[1] . H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, “Detection of 15 dB Squeezed States of Light and their Application for the Absolute Calibration of Photoelectric Quantum Efficiency,” Phys. Rev. Lett., vol. 117, no. 11, p. 110801 (2016).

[2] J. Arnbak, C. S. Jacobsen, R. B. Andrade, X. Guo, J. S. Neergaard-Nielsen, U. L. Andersen, and T. Gehring, “Compact, Low-Threshold Squeezed Light Source,” Optics Express, vol. 27, issue 26, pp. 37877–37885 (2019).

Relevance / Science Traceability:

Quantum technologies enable a new generation in sensitivities and performance and include low baseline interferometry and ultraprecise sensors with applications ranging from natural resource exploration and biomedical diagnostic to navigation.

HEOMD—Astronaut health monitoring.

SMD—Earth, planetary, and astrophysics including imaging spectrometers on a chip across the electromagnetic spectrum from x ray through the infrared.

STMD—Game-changing technology for small spacecraft communication and navigation (optical communication, laser ranging, and gyroscopes).

STTR—Rapid increased interest.

Space Technology Roadmap 6.2.2, 13.1.3, 13.3.7, all sensors 6.4.1, 7.1.3, 10.4.1, 13.1.3, 13.4.3, and 14.3.3.

References:

- 2019 NASA Fundamental Physics and Quantum Technology Workshop. Washington DC (April 8-10, 2019).
- Quantum Communication, Sensing and Measurement in Space. Team Leads: Erkmen, Shapiro, and Schwab (2012):
  - http://kiss.caltech.edu/final_reports/Quantum_final_report.pdf(link is external)
- National Quantum Initiative Act:
  - https://www.congress.gov/congressional-report/115th-congress/house-report/950/1(link is external)
  - https://www.congress.gov/congressional-report/115th-congress/senate-report/389(link is external)
  - https://www.lightourfuture.org/getattachment/7ad9e04f-4d21-4d98-bd28-e1239977e262/NPI-Recommendations-to-HSC-for-National-Quantum-Initiative-062217.pdf(link is external)
- European Union Quantum Flagship Program: https://qt.eu(link is external).
- UK National Quantum Technologies Programme: http://uknqt.epsrc.ac.uk(link is external).
- DLR Institute of Quantum Technologies: https://www.dlr.de/qt/en/desktopdefault.aspx/tabid-13498/23503_read-54020/(link is external).
- Degen, C. L.; Reinhard, F.; and Cappellaro, P.: Quantum Sensing, Rev. Mod. Phys. **89**, 035002 (2017).
- Polyakov, Sergey V.: Single Photon Detector Calibration in Single-Photon Generation and Detection, Volume 45, 2013 Elsevier Inc. http://dx.doi.org/10.1016/B978-0-12-387695-9.00008-1.
- Stobińska, et al.: Quantum Interference Enables Constant-Time Quantum Information Processing. Sci. Adv. 5 (2019).

T8.07 Photonic Integrated Circuits (STTR)

Lead Center: **GSFC**

Participating Center(s): **GRC, LaRC**

Scope Title:

Photonic Integrated Circuits

Scope Description:

Photonic integrated circuits (PICs) generally integrate multiple lithographically defined photonic and electronic components and devices (e.g., lasers, detectors, waveguides/passive structures, modulators, electronic control, and optical interconnects) on a single platform with nanometer-scale feature sizes. PICs can enable size, weight, power, and cost reductions and improve the performance of science instruments, subsystems, and components. PIC technologies are particularly critical for enabling small spacecraft platforms. Proposals are sought to develop PIC technologies including the design and fabrication of PICs that use nanometer-scale structures and optical metamaterials. On-chip generation, manipulation, and detection of light in a single-material system may not be practical or offer the best performance, so hybrid packaging of different material systems are also of interest. This subtopic solicits methods, technology, and systems for development and incorporation of active and passive circuit elements for PICs for:

- PICs for in situ and remote sensors—NASA application examples include but are not limited to lab-on-a-chip systems for landers, 3D mapping lidar, front end and back end for remote-sensing instruments including trace gas lidars, optical spectrometers, gyroscopes, and magnetometers.
- PICs for analog radiofrequency (RF) applications—NASA applications require new methods to reduce the size, weight, and power of passive and active microwave signal processing. As an example, PICs having very low insertion loss (e.g., ~1 dB) and high spurious-free dynamic range for analog and RF signal processing and transmission that use monolithic high-Q waveguide micro-resonators or other filters with a few GHz RF passbands. These components should be suitable for designing chip-scale tunable optoelectronic RF oscillator and high-precision optical clock modules. Example applications include terahertz spectroscopy, microwave radiometry, and hyperspectral microwave sounding.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I does not need to include a physical deliverable to the government but it is best if it includes a demonstration of feasibility through measurements. This can include extensive modeling but a stronger proposal will have measured validation of models or designs.

Phase II should include prototype delivery to the government. (It is understood that this is a research effort and the prototype is a best effort delivery where there is no penalty for missing performance goals.) The phase II effort should be targeting a commercial product that could be sold to the government and/or industry.

State of the Art and Critical Gaps:

There is a critical gap between discrete and bulk photonic components and waveguide multifunction PICs. The development of PICs permits size, weight, power, and cost reductions for spacecraft microprocessors, communication buses, processor buses, advanced data processing, and integrated optic science instrument optical systems, subsystems, and components. This is particularly critical for small spacecraft platforms.

Relevance / Science Traceability:

HEOMD—Astronaut health monitoring.

SMD—Earth, planetary, and astrophysics compact science instrument (e.g., optical and terahertz spectrometers and magnetometers on a chip).

STMD—Game-changing technology for small spacecraft communication and navigation (optical communication, laser ranging, and gyroscopes).

STTR—Exponentially increasing interest and programs at universities and startups in integrated photonics.

Space Technology Roadmap 6.2.2, 13.1.3, 13.3.7, all sensors, 6.4.1, 7.1.3, 10.4.1, 13.1.3, 13.4.3, 14.3.3

References:

1. AIM integrated photonics: http://www.aimphotonics.com.
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4. Photonic Integrated Circuits for Communication Systems. By: Chovan, Jozef; Uherek, Frantisek: Radioengineering, vol. 27, issue 2, pp. 357-363, Published June 2018.
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6. Photonic Integrated Circuit Based on Hybrid III-V/Silicon Integration. By: de Valicourt, Guilhem; Chang, Chia-Ming; Eggleston, Michael S.; et al.: Journal of Lightwave Technology, vol. 36, issue 2, Special Issue, pp. 265-273, Published Jan. 15, 2018.
7. Silicon Nitride Photonic Integration Platforms for Visible, Near-Infrared and Mid-Infrared Applications. By: Munoz, Pascual; Mico, Gloria; Bru, Luis A.; et al.: Sensors, vol. 17, issue 9, Article Number 2088, Published Sept. 2017.

Focus Area 10 Advanced Telescope Technologies

Lead MD: **SMD**

Participating MD(s): **N/A**

The NASA Science Mission Directorate (SMD) seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture light-weight highly reflecting mirrors, deployable large structures and innovative metrology, control of unwanted radiation for high-contrast optics, precision formation flying for synthetic aperture telescopes, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold as 4 K. This topic will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from UV to millimeter waves, and also include gravity waves. The subtopics will consider all technologies associated with the collection and combination of observable signals. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, innovative structures, including nanotechnology, and wavefront sensing and control are needed to build telescopes for Earth science.

S2.01 Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

Control of scattered starlight with coronagraphs and starshades

Scope Description:

The goal of this subtopic is to address the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and near-infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concepts such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development and innovative instrument design, as well as in the fabrication of subsystem devices to include, but not limited to, the following areas:

Starlight Suppression Technologies:

- Hybrid metal/dielectric and polarization apodization masks for diffraction control of phase and amplitude for coronagraph-scaled starshade experiments.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of solar scatter in starshades.
- Low-reflectivity coatings for flexible starshade optical shields.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront Measurement and Control Technologies:

- Small-stroke, high-precision, deformable mirrors and associated driving electronics scalable to 10,000 or more actuators (both to further the state of the art towards flightlike hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state of the art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices.
- Multiplexers with ultralow power dissipation for electrical connection to deformable mirrors.
- Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and postprocessing of aberrations.
- Thermally and mechanically insensitive optical benches and systems.

Optical Coating and Measurement Technologies:

- Instruments capable of measuring polarization crosstalk and birefringence to parts per million.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.

In addition this subtopic solicits proposals to develop components that improve the footprint, robustness, power consumption, reliability, and wavefront quality of high-contrast, low-temporal bandwidth, adaptive optics systems. These include application-specific integrated circuit (ASIC) drivers that easily integrate with the deformable mirrors, improved connectivity technologies, as well as high-actuator-count deformable mirrors with high-quality, ultrastable wavefronts.

It also seeks coronagraph masks that can be tested in ground-based high-contrast testbeds in place at a number of institutions, as well as devices to measure the masks to inform optical models. The masks include transmissive scalar, polarization-dependent, and spatial apodizing masks, including those with extremely low reflectivity regions that allow them to be used in reflection.

The subtopic seeks samples of optical coatings that reduce polarization and can be applied to large optics as well as methods and instruments to characterize them over large optical surfaces.

Finally, for starshades, the subtopic seeks low-reflectivity and potentially diffraction-controlling edges that minimize scattered sunlight while also remaining robust to handling and cleaning. Low-reflectivity optical coatings that can be applied to the surfaces for the large (hundreds of square meters) optical shield are also desired.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Under this Subtopic a concept study provided as a final report in Phase I is acceptable and a prototype for Phase II is acceptable.

State of the Art and Critical Gaps:

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. Starshades will enable even deeper contrast over broader bands but to date have demonstrated deep contrast in narrow band light. The extent to which the telescope optics will limit coronagraph performance is a function of the quality of the optical coating and the ability to control polarization over the full wavefront. Neither of these technologies is well characterized at levels required for 10^{10} contrast. Wavefront control using deformable mirrors is critical. Controllability and stability to picometer levels is required. To date, deformable mirrors have been up to the task of providing contrast approaching 10^{10}, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

Relevance / Science Traceability:

These technologies are directly applicable to the Nancy Grace Roman Space Telescope (NGRST) coronagraph instrument (CGI), and the HabEx and LUVOIR concept studies.

References:

See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high-contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

Websites:

- Exoplanet Exploration - Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov
- Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/
- Goddard Space Flight Center: https://www.nasa.gov/goddard

S2.02 Precision Deployable Optical Structures and Metrology (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

Assembled Deployable Optical Metering Structures and Instruments

Scope Description:

Future space astronomy missions from ultraviolet to millimeter wavelengths will push the state of the art in current optomechanical technologies. Size, dimensional stability, temperature, risk, manufacturability, and cost are important factors, separately and in combination. The Large Ultraviolet Optical Infrared Surveyor (LUVOIR) calls for deployed apertures as large as 15 m in diameter; the Origins Space Telescope (OST), for operational temperatures as low as 4 K; and LUVOIR and the Habitable Exoplanet Observatory (HabEx), for exquisite optical quality. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and starshades for exoplanet imaging require deployment schemes to achieve 30- to 70-m-class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10- to 20-m-class, lightweight, ambient or cryogenic flight-qualified observatory systems and subsystems (telescopes, sunshields, starshades). Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems through validated models will be given preference. The target launch volume and expected disturbances, along with the estimate of system performance, should be included in the discussion. Novel metrology solutions to establish and maintain optical alignment will also be accepted.

Technologies including, but not limited to, the following areas are of particular interest:

Precision structures/materials:

- Low coefficient of thermal expansion/coefficient of moisture expansion (CTE/CME) materials/structures to enable highly dimensionally stable optics, optical benches, metering structures.
- Materials/structures to enable deep-cryogenic (down to 4 K) operation.
- Novel athermalization methods to join materials/structures with differing mechanical/thermal properties.
- Lightweight materials/structures to enable high-mass-efficiency structures.
- Precision joints/latches to enable submicron level repeatability.
- Mechanical connections providing microdynamic stability suitable for robotic assembly.

Deployable technologies:

- Precision deployable modules for assembly of optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures).
- Hybrid deployable/assembled architectures, packaging, and deployment designs for large sunshields and external occulters (20 to 50 m class).
- Packaging techniques to enable more efficient deployable structures.

Metrology:

- Techniques to verify dimensional stability requirements at subnanometer level precisions (10 to 100 pm).
- Techniques to monitor and maintain telescope optical alignment for on-ground and in-orbit operation.

A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5-m diameter for ground test characterization. Proposals should show an understanding of one or more relevant science needs, and present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

For Phase I, a successful deliverable would include a demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions on future designs.

For Phase II this should be demonstrated on units that can be scaled to future flight sizes.

State of the Art and Critical Gaps:

The James Webb Space Telescope, currently set to launch in 2021, represents the state of the art in large deployable telescopes. The Wide Field Infrared Survey Telescope’s (WFIRST) coronagraph instrument (CGI) will drive telescope/instrument stability requirements to new levels. The mission concepts in the upcoming Astro2020 decadal survey will push technological requirements even further in the areas of deployment, size, stability, lightweighting, and operational temperature. Each of these mission studies have identified technology gaps related to their respective mission requirements.

Relevance / Science Traceability:

These technologies are directly applicable to the WFIRST CGI and the HabEx, LUVOIR, and OST mission concepts.

References:

- Large UV/Optical/IR Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
- What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/
- NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope (SBIR)

Lead Center: **MSFC**

Participating Center(s): **GRC, GSFC, JPL, LaRC**

Scope Title:

Optical Components and Systems for Large Telescope Missions

Scope Description:

Accomplishing NASA's high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket, and balloon) requires low-cost, ultrastable, normal-incidence mirror systems with low mass-to-collecting area ratios. Here, a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture).

Current normal-incidence space mirrors cost \$4 million to \$6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5× to 50×, to between \$100K/m^2 and \$1M/m^2.

Specific metrics are defined for each wavelength application region:

1. Aperture diameter for all wavelengths, except far-infrared (IR):

- Monolithic: 1 to 8 m
- Segmented: 3 to 20 m

2. For ultraviolet (UV)/optical:

- Areal cost: <\$500K/m^2
- Wavefront figure: <5 nm rms (via passive design or active deformation control)
- Wavefront stability: <10 pm/10 min
- First mode frequency: 60 to 500 Hz
- Actuator resolution: <1 nm rms
- Optical pathlength stability: <1 pm/10,000 sec for precision metrology

- Areal density: <15 kg/m^2 (<35 kg/m^2 with backplane)
- Operating temperature range: 250 to 300 K

3. For far-IR:

- Aperture diameter: 1 to 4 m (monolithic) or 5 to 10 m (segmented)
- Telescope: diffraction-limited at <30 µm at operating temperature 4 K
- Cryodeformation: <100 nm rms
- Areal cost: <$500K/m^2
- Production rate: >2 m^2 per month
- Areal density: <15 kg/m^2 (<40 kg/m^2 with backplane)
- Thermal conductivity: at 4 K, >2 W/m·K
- Survivability at temperatures ranging from 315 to 4 K

4. For extreme ultraviolet (EUV):

- Surface slope: <0.1 µrad

Also needed is the ability to fully characterize surface errors and predict optical performance.

Proposals must show an understanding of one or more relevant science needs and present a feasible plan to develop the proposed technology for infusion into a NASA program: suborbital rocket or balloon; competed SMEX or MIDEX; or Decadal-class mission. Successful proposals will demonstrate an ability to manufacture, test, and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

Current normal incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5× to 50×, to between $100K/m^2 and $1M/m^2.

Relevance / Science Traceability:

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

References:

The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy.

- The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/pdf/interim_report.pdf.
- The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.
- The OST is a single-aperture telescope concept for the Far-Infrared Surveyor mission described in the NASA Astrophysics Roadmap, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades": https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf
- The OST mission is described on the website: https://origins.ipac.caltech.edu
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements description: https://asd.gsfc.nasa.gov/cosmology/spirit/
- LISA mission description: https://lisa.nasa.gov/

Scope Title:

Balloon Planetary Telescope

Scope Description:

Astronomy from a stratospheric balloon platform offers numerous advantages. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmosphere is below the balloon, and the attenuation due to the remaining atmosphere is small, especially in the near-ultraviolet (NUV) band and in the infrared (IR) bands near 2.7 and 4.25 µm. The lack of atmosphere nearly eliminates scintillation and allows the resolution potential of relatively large optics to be realized, and the small amount of atmosphere reduces scattered light and allows observations of brighter objects even during daylight hours.

Potential balloon science missions are either in the UV/optical (UVO) or in the infrared/far-infrared (IR/FIR).

- UVO science missions require a 1-m-class telescope diffraction limited at 500 nm or a primary mirror system that can maintain <10 nm rms surface figure error for elevation angles ranging from 0° to 60° over a temperature range of 220 to 280 K.
- IR science missions require 1.5-m-class telescopes diffraction limited at 5 µm.
- FIR missions require 2-m-class (or larger) telescopes diffraction limited at 50 µm.

In all cases, the telescopes need to achieve:

- Mass: <300 kg
- Shock: 10G without damage
- Elevation: 0° to 60°
- Temperature: 220 to 280 K

For packaging reasons, the primary mirror assembly must have a radius of curvature 3 m (nominal) and a mass <150 kg.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Phase I will produce a preliminary design and report including initial design requirements such as wavefront error budget, mass allocation budget, structural stiffness requirements, etc. as well as trade studies performed and and analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during Phase I, including trade studies and challenges to be addressed during Phase II with subsystem proof-of-concept demonstration hardware.
- If Phase II can only produce a subscale component, then it should also produce a detailed final design, including final requirements (wavefront error budget, mass allocation, etc.) and a performance assessment over the specified operating range.

State of the Art and Critical Gaps:

Current SOA (state-of-the-art) mirrors made from Zerodur(C) or ULE(C), for example, require lightweighting to meet balloon mass limitations and cannot meet diffraction limited performance over the wide temperature range due to the coefficient of thermal expansion limitations.

Relevance / Science Traceability:

“Vision and Voyages for Planetary Science in the Decade 2013-2022”

- Page 22, last paragraph of NASA Telescope Facilities within the Summary Section:
  Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground. Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA's Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science because typical planetary grants are too small to support these missions. A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program.
- Page 203, 5th paragraph of section titled Earth and Space-Based Telescopes:
  Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth's atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap.

Potential advocates include planetary scientists at Goddard Space Flight Center (GSFC), Johns Hopkins Applied Physics Laboratory (APL), and Southwest Research Institute, etc.

References:

- For additional discussion of the advantages of observations from stratosphere platforms, refer to: Dankanich et. al.: "Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report," available from: https://ntrs.nasa.gov/ (search for "NASA/TM-2016-218870").
- Additional information about scientific balloons can be found at: https://www.csbf.nasa.gov/docs.html

Scope Title:

Large Ultraviolet/Optical/near-IR (LUVOIR) Surveyor and Habitable Exoplanet (HabEx) Missions

Scope Description:

Potential ultraviolet/optical (UVO) missions require 4- to 16-m monolithic or segmented primary mirrors with <5 nm rms surface figures. Active or passive alignment and control is required to achieve system-level diffraction-limited performance at wavelengths less than 500 nm (<40-nm rms wavefront error, WFE). Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on the order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4-m and larger telescope. Potential enabling technologies include: active thermal control systems, ultrastable mirror support structures, athermal telescope structures, athermal mirror struts, ultrastable joints with low coefficient of thermal expansion (CTE) and high stability, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m^2 for a 5-m-fairing Evolved Expendable Launch Vehicle (EELV) versus 150 kg/m^2 for a 10-m-fairing Space Launch (SLS)). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-

m-class mirror (with 50 m^2 of collecting area) should have an areal cost of less than $2M/$m^2$. And, a 16-m-class mirror (with 200 m^2 of collecting area) should have an areal cost of less than $0.5M/$m^2$.

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test UVO quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have zero CTE at the desired scale.
- Mirror support structures, joints, and mechanisms that are ultrastable at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.
- Mechanisms and sensors to align segmented mirrors to <1 nm rms precisions.
- Thermal control (<1 mK) to reduce wavefront stability to <10 pm rms per 10 min.
- Dynamic isolation (>140 dB) to reduce wavefront stability to <10 pm rms per 10 min.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include, but are not limited to: ultra-uniform low-CTE glasses, silicon carbide, nanolaminates, or carbon-fiber-reinforced polymer. Potential solutions for mirror support structure material/architecture include, but are not limited to: additive manufacturing, nature-inspired architectures, nanoparticle composites, carbon fiber, graphite composite, ceramic or SiC materials, etc. Potential solutions for new fabrication processes include, but are not limited to: additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components. Potential solutions for achieving the 10-pm wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology; and passive and active thermal control.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

The precision fabrication of large mirrors is a daunting task. The fabrication process needs to be scaled from the state-of-the-art (SOA) Hubble mirror at 2.4 m both in precision and dimensions of the mirrors.

Relevance / Science Traceability:

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

References:

The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics, and solar system astronomy.

- The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/
- The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/

The OST is a single-aperture far-infrared telescope concept.

- The OST mission is described at: https://asd.gsfc.nasa.gov/firs/
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described at: https://asd.gsfc.nasa.gov/cosmology/spirit/

Scope Title:

Near-Infrared Lidar Beam Expander Telescope

Scope Description:

Potential airborne coherent lidar missions need compact 15-cm diameter 20× magnification beam expander telescopes. Potential space-based coherent lidar missions need at least 50-cm 65× magnification beam expander telescopes. Candidate coherent lidar systems (operating with a pulsed 2-µm laser) have a narrow, almost diffraction-limited field-of-view, close to 0.8 lambda/D half angle. Aberrations, especially spherical aberration, in the optical telescope can decrease the signal.

Additionally, the telescope beam expander should maintain the laser beam's circular polarization. The incumbent telescope technology is a Dall-Kirkham beam expander. Technology advance is needed to make the beam expander more compact with less mass while retaining optical performance, and to demonstrate the larger diameter. Additionally, technology for nonmoving scanning of the beam expander output is needed.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.15 m or a relevant subcomponent of a system. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range). Phase I and Phase II system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

The current state of the art (SOA) is a commercial off-the-shelf (COTS) beam expander with a 15-cm-diameter primary mirror, a heavy aluminum structure, an Invar rod providing thermally insensitive primary-to-secondary mirror separation, and a manually adjustable and lockable variable-focus setting by changing the mirror separation. Critical gaps include (1) a 50 -to 70-cm-diameter primary mirror beam expander that features near-diffraction-limited performance; low mass design; minimal aberrations with an emphasis on spherical; characterization of the polarization changes versus beam cross section, assuming input circular polarization; a lockable electronic focus adjustment; both built-in and removable fiducial aids for aligning the input laser beam to the optical axis; and a path to space qualification and (2) a 15-cm-diameter primary mirror beam expander with the same features for airborne coherent lidar systems.

Relevance / Science Traceability:

Science Mission Directorate (SMD) desires both an airborne coherent-detection wind-profiling lidar systems and space-based wind measurement. The space mission has been recommended to SMD by both the 2007 and 2017 Earth Science Decadal Surveys. SMD has incorporated the wind lidar mission in its planning and has named it "3-D Winds". SMD recently held the Earth Venture Suborbital competition for 5 years of airborne science campaigns. The existing coherent wind lidar at Langley, Doppler Aerosol Wind (DAWN), was included in three proposals that are under review. Furthermore, SMD is baselining DAWN for a second Convective Processes Experiment (CPEX-) type airborne science campaign and for providing calibration/validation assistance to the European Space Agency (ESA) Aeolus space mission. DAWN flies on the DC-8, and it is highly desired to fit DAWN on other NASA and National Oceanic and Atmospheric Administration (NOAA) aircraft. DAWN needs to lower its mass for several of the aircraft, and a low-mass telescope retaining the required performance is needed. Additionally, an electronic remote control of telescope focus is needed to adapt to aircraft cruise altitude and weather conditions during science flights.

References:

- NRC Decadal Surveys at: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm
- "Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area," https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/Weather_Focus_Area_Workshop_Report_2015_0.pdf
- A. K. DuVivier, J. J. Cassano, S. Greco and G. D. Emmitt: “A Case Study of Observed and Modeled Barrier Flow in the Denmark Strait in May 2015,” *Monthly Weather Review*, 145, 2385–2404 (2017), https://doi.org/10.1175/MWR-D-16-0386.1
    - See also supplemental material at: http://dx.doi.org/10.1175/MWR-D-16-0386.s1
- M. J. Kavaya, J. Y. Beyon, G. J. Koch, M. Petros, P. J. Petzar, U. N. Singh, B. C. Trieu, and J. Yu: “The Doppler Aerosol Wind Lidar (DAWN) Airborne, Wind-Profiling, Coherent-Detection Lidar System: Overview and Preliminary Flight Results,” *J. of Atmospheric and Oceanic Technology* 34 (4), 826-842 (2014), https://doi.org/10.1175/JTECH-D-12-00274.1
- Scott A. Braun, Ramesh Kakar, Edward Zipser, Gerald Heymsfield, Cerese Albers, Shannon Brown, Stephen L. Durden, Stephen Guimond, Jeffery Halverson, Andrew Heymsfield, Syed Ismail, Bjorn Lambrigtsen, Timothy Miller, Simone Tanelli, Janel Thomas, and Jon Zawislak: “NASA’s Genesis and Rapid Intensification Processes (GRIP) Field Experiment,” *Bull. Amer. Meteor. Soc. (BAMS)* 94(3), 345-363 (2013), https://doi.org/10.1175/BAMS-D-11-00232.1

Scope Title:

Fabrication, Test, and Control of Advanced Optical Systems

Scope Description:

Future ultraviolet (UV)/optical/near-infrared (NIR) telescopes require mirror systems that are very precise and ultrastable.

Regarding precision, this subtopic encourages proposals to develop technology that makes a significant advance in the ability to fabricate and test an optical system.

One area of current emphasis is the ability to nondestructively characterize coefficient of thermal expansion (CTE) homogeneity in 4-m-class Zerodur and 2-m-class ULE mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100×100. This characterization capability is needed to select mirror substrates before they undergo the expense of turning them into a lightweight space mirror.

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <10 pm rms over intervals of ~10 min during critical observations. The ~10-min time period of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront.

This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to 10s of minutes between wavefront control updates.

New methods may include: new techniques of using out-of-band light to improve sensing speed and spatial frequency content, new control laws incorporating feedback and feedforward for more optimal control, new algorithms for estimating absolute and relative wavefront changes, and the use of artificial guide stars for improved sensing signal-to-noise ratio and speed.

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low-power, high-reliability electronics are also needed.

Finally, metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are needed. High speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software

Desired Deliverables Description:

- An ideal Phase I deliverable would be a prototype demonstration of a fabrication, test or control technology leading to a successful Phase II delivery, or a reviewed preliminary design and manufacturing plan that demonstrates feasibility.
- While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

State of the Art and Critical Gaps:

Wavefront (WF) sensing using star images, including dispersed-fringe and phase-retrieval methods, is at TRL 6, qualified for space by the James Webb Space Telescope (JWST). WF sensing and control for coronagraphs, including electric field conjugation and low-order WF sensing (LOWFS), is at TRL4 and is being developed and demonstrated by Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI).

Laser-distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and on orbit by the LISA Pathfinder and Grace Follow-On mission. Application to telescope alignment metrology has been demonstrated on testbeds, to TRL4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

Edge sensors are in use on segmented ground telescopes but are not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space-qualified package.

Higher order WF sensing for coronagraphs using out-of-band light is beginning development, with data limited to computer simulations.

Relevance / Science Traceability:

These technologies are enabling for coronagraph-equipped space telescopes, segmented space telescopes, and others that utilize actively controlled optics. The Large UV/Optical/IR Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) mission concepts currently under study provide good examples.

References:

- The HabEx interim report is available at: https://www.jpl.nasa.gov/habex/
- The LUVOIR interim report is available at: https://asd.gsfc.nasa.gov/luvoir/reports/

Scope Title:

Optical Components and Systems for Potential Infrared/Far-Infrared Missions

Scope Description:

Far-infrared surveyor mission described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions":

In the context of subtopic S2.03, the challenge is to take advantage of relaxed tolerances stemming from a requirement for long-wavelength (30 µm) diffraction-limited performance in the fully integrated optical telescope assembly to minimize the total mission cost through innovative design and material choices and novel approaches to fabrication, integration, and performance verification.

A far-infrared surveyor is a cryogenic far-infrared (IR) mission, which could be either a large single-aperture telescope or an interferometer. There are many common and a few divergent optical system requirements between the two architectures.
Common requirements:

- Telescope operating temperature of ~4 K.
- Telescope diffraction-limited at 30 µm at the operating temperature.
- Mirror survivability at temperatures ranging from 315 to 4 K.
- Mirror substrate thermal conductivity at 4 K of >2 W/m·K.
- Zero or low CTE mismatch between mirror substrate and backplane.

Divergent requirements:

- Large single-aperture telescope:
    - Segmented primary mirror, circular. or hexagonal.
    - Primary mirror diameter 5 to 10 m.

  - Possible 3 degree-of-freedom (tip, tilt, and piston) control of mirror segments on orbit.
- Interferometer:
  - Monolithic primary mirrors.
  - Afocal, off-axis telescope design.
  - Primary mirror diameter 1 to 4 m.

Success metrics:

- Areal cost <$500K/m^2.
- Areal density <15 kg/m^2 (<40 kg/m^2 with backplane).
- Production rate >2 m^2 per month.
- Short time span for optical system integration and test.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a cryogenic optical system of at least 0.25 m and suitable for a far-infrared mission or a relevant subcomponent of a system. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m; a relevant subcomponent (with a TRL in the 4 to 5 range); or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

Current state of the art (SOA) is represented by the Herschel Space Observatory (3.5-m monolith; SiC) and James Webb Space Telescope (6.5-m segmented primary mirror; beryllium). Technologies are needed to advance the fabrication precision and the size of the mirrors, both monolithic and segmented, beyond the current SOA.

Relevance / Science Traceability:

The technology is relevant to the Far-Infrared Surveyor mission described in NASA's Astrophysics Roadmap and prioritized in NASA's Program Annual Technology Reports for Cosmic Origins and Physics of the Cosmos. A future NASA far-IR astrophysics mission will answer compelling questions, such as:

- How common are life-bearing planets?
- How do the conditions for habitability develop during the process of planet formation?
- How did the universe evolve in response to its changing ingredients (buildup of heavy elements and dust over time)?

To answer these questions, NASA will need telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity.

Novel approaches to fabrication and test developed for a far-IR astrophysics mission may be applicable to far-IR optical systems employed in other divisions of the NASA Science Mission Directorate (SMD), or to optical systems designed to operate at wavelengths shorter than the far-IR.

References:

- The Far-Infrared Surveyor is described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions," which can be downloaded from: https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure- Astrophysics_Roadmap_2013_0.pdf
- The Origins Space Telescope (OST) final report is at: https://asd.gsfc.nasa.gov/firs/
- Program Annual Technology Reports (PATR) can be downloaded from the NASA Physics of the Cosmos and Cosmic Origins (PCOS/COR) Technology Development website at: https://apd440.gsfc.nasa.gov/technology/

Scope Title:

Low-Cost Compact Reflective Telescope for CubeSAT Missions

Scope Description:

The need exists for a low-cost, compact (e.g., CubeSAT-class), scalable, diffraction-limited, athermalized, off-axis reflective telescopes. Typically, specialty optical aperture systems are designed and built as “one-offs,” which are inherently high in cost and often out of scope for smaller projects. A Phase I would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low-cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performances (STOP) analyses confirming diffraction limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

This Scope topic solicits solutions for two applications: near-infrared- and short-wave-infrared- (NIR/SWIR-) band communication and the Lightning Imaging Sensor.

NIR/SWIR optical-communication-support hardware should be assumed towards an integrated approach, including fiber optics, fast-steering mirrors, and applicable detectors.

The Lightning Imaging Sensor application requires a telescope that will fit inside a 6U or smaller CubeSAT with an 80° field-of-view, is diffraction limited at 500 nm (nominal), and has high spectral transmission at both 337 and 777 nm.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

- An ideal Phase I deliverable would be a prototype unobscured telescope with the required performance and size, or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system with the required performance for a CubeSAT mission. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

Currently, the state of the art for reflective optical system for communications applications are:

1. On-axis or axisymmetric designs are typically used for (space) optical communications and imaging, which inherently are problematic due to the central obscuration.
2. Off-axis designs provide superior optical performance due to the clear aperture, however, are rarely considered due to complex design, manufacturing, and metrology procedures needed.
3. Currently flying Lightning Imaging Sensor is a large refractive lens optimized for single-wavelength operation. A reflective system is required for dual-wavelength operation. Also, a compact design is required to fit inside a CubeSAT.

Relevance / Science Traceability:

Optical communications enable high-data-rate downlink of science data. The initial motivation for this scalable off-axis optical design approach is for bringing high-performance reflective optics within reach of laser communication projects with limited resources. However, this exact optical hardware is applicable for any diffraction-limited, athermalized, science imaging application. Any science mission could potentially be able to select from a “catalog” of optical aperture systems that would already have (flight) heritage and reduced risks.

References:

- An example of an on-axis design has been utilized in the Lunar Laser Communications Demonstration (LLCD): https://www.spiedigitallibrary.org/conference-proceedings- of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1
- An example of an off-axis design is being developed by the Jet Propulsion Laboratory (JPL) for Deep Space Optical Communications (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical- communications-DSOC-transceiver/10.1117/12.2256001.full
- Information about NASA's current (large-scale) Lightning Imaging Sensor can be found at: https://gpm.nasa.gov/missions/TRMM/satellite/LIS

S2.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL, MSFC**

Scope Title:

X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Scope Description:

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future x-ray observatory missions.

The Astrophysics Decadal specifically calls for optical coating technology investment for future ultraviolet (UV), optical, exoplanet, and infrared (IR) missions, and the Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines and improve space/solar-flux durability of extreme UV (EUV) optical coatings, as well as coating deposition to increase the maximum spatial resolution.

Future optical systems for NASA's low-cost missions, CubeSat, and other small-scale payloads, are moving away from traditional spherical optics to nonrotationally symmetric surfaces with anticipated benefits of free-form optics such as fast wide-field and distortion-free cameras.

This subtopic solicits proposals in the following three focus areas:

- X-ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology including carbon nanotubes (CNTs) for a wide range of wavelengths from x-ray to IR (x-ray, EUV, Lyman UV (LUV), vacuum UV (VUV), visible, and IR).
- Free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraphic instruments.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Typical deliverables based on sub-elements of this subtopic:

Phase I:

- X-ray optical mirror system: Analysis, reports, prototype.
- Coating: Analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: Analysis, design, software and hardware prototype of optical components.

Phase II:

- X-ray optical mirror system: Analysis and prototype.
- Coating: Analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: Analysis, design, software and hardware prototype of optical components

State of the Art and Critical Gaps:

This subtopic focuses on three areas of technology development:

- This work is a very costly and time consuming. Most of SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA straylight suppression is bulky and ineffective for wide-field of view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.
- Coating technology for wide range of wavelengths from x-ray to IR (x-ray, EUV, LUV, VUV, visible, and IR). The current x-ray coating is defined by NuSTAR. Current EV is defined by Heliophysics (80% reflectivity from 60 to 200 nm). Current UVOIR is defined by Hubble. MgFI2 over coated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 to 200 nm.
- Free-form optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability:

S2.04 supports variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of x-ray, coating technologies ranging from UV to IR, and free-form optics in preparation for Decadal missions such as HabEx, LUVOIR, and OST.

Optical components, systems, and stray light suppression for x-ray missions: The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Next Generation x-ray Optics, NGXO). The National Research Council (NRC) NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Free-form optics: NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to free-form optical surfaces because of changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small-size instruments is highly desirable, specifically if they could enable cost-effective manufacturing of these surfaces (CubeSat, SmallSat, NanoSat, various coronagraphic instruments).

Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)). Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); and Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:

The Habitable Exoplanet Observatory (HabEx) is a concept for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however, its main goal is, for the first time, to directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water, and be sensitive to gases in the atmosphere possibility indicative of biological activity, such as oxygen or ozone.

The study pages are available at:

- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- LUVOIR: https://asd.gsfc.nasa.gov/luvoir/
- Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
- The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multiwavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable—or even inhabited. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/
- The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study. NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an Origins Space Telescope mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a 3-order-of-magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new

spectroscopic capability. The community report is available at: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

Scope Title:

X-Ray Mirror Systems Technology

Scope Description:

NASA large x-ray observatory requires low-cost, ultrastable, lightweight mirrors with high-reflectance optical coatings and effective stray-light suppression. The current state of the art of mirror fabrication technology for x-ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arcsec angular resolutions and 1 to 5 m^2 collecting area are needed for this technology. Likewise, the stray-light suppression system is bulky and ineffective for wide-field-of-view telescopes.

In this area, we are looking to address the multiple technologies including: improvements to manufacturing (machining, rapid optical fabrication, slumping, or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable x-ray observatories while lowering the cost per square meter of collecting aperture and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies to bond mirrors that are made of silicon. The epoxies should absorb infrared (IR) radiation (with wavelengths between 1.5 and 6 µm that traverses silicon with little or no absorption) and therefore can be cured quickly with a beam of IR radiation. Currently, x-ray space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100K per square meter.

Additionally, proposals are solicited to develop new advanced-technology computer-numerical-control (CNC) machines to polish inside and/or outside surfaces of full-shell (between 100 and 1,000 mm in height, 100 to 2,800 mm in diameter, varying radial prescription along azimuth, and ~2 mm in thickness), grazing-incidence optics to x-ray quality surface tolerances (with surface figure error <1 arcsec half-power diameter (HPD), radial slope error <1 µrad, and out-of-round <2 µm). Current state-of-the-art technology in CNC polishing of full-shell, grazing-incidence optics yields 2.5 arcsec HPD on the outside of a mandrel used for replicating shells. Technology advances beyond current state of the art include application of CNC and deterministic polishing techniques that (1) allow for direct force closed-loop control, (2) reduce alignment precision requirements, and (3) optimize the machine for polishing cylindrical optics through simplifying the axis arrangement and the layout of the cavity of the CNC polishing machine.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

- Software

Desired Deliverables Description:

Typical deliverable based on sub-elements of this subtopic:
X-ray optical mirror system—Demonstration, analysis, reports, software, and hardware prototype:

- Phase I deliverables: Reports, analysis, demonstration, and prototype
- Phase II deliverables: Analysis, demonstration, and prototype

State of the Art and Critical Gaps:

X-ray optics manufacturing, metrology, coating, testing, and assembling complete mirror systems in addition to maturing the current technology. This work is very costly and time-consuming. Most of the SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA stray-light suppression is bulky and ineffective for wide-field of view telescopes. We seek a significant reduction in both expense and time. Reduce the areal cost of a telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.

The gaps to be covered in this track are:

- Lightweight, low-cost, ultrastable mirrors for large x-ray observatory.
- Stray-light suppression systems (baffles) for large advanced x-ray observatories.
- Ultrastable, inexpensive lightweight x-ray telescope using grazing-incidence optics for high-altitude balloon-borne and rocket-borne mission.

Relevance / Science Traceability:

The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Lynx and Advanced X-ray Imaging Satellite (AXIS)).

The National Research Council NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

References:

NASA High Energy Astrophysics (HEA) mission concepts including x-ray missions and studies are available at:

- https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

Scope Title:

Coating Technology for X-Ray-UV-OIR

Scope Description:

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are antireflective (AR) coating and high-reflective (HR) coating.

The current coating technology of optical components needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL 3 to 6.

To achieve these objectives requires sustained systematic investment.

The telescope optical coating needs to meet low-temperature operation requirement. It's desirable to achieve 35 K in future.

A number of future NASA missions require suppression of scattered light. For instance, the precision optical cube utilized in a beam-splitter application forms a knife-edge that is positioned within the optical system to split a single beam into two halves. The scattered light from the knife-edge could be suppressed by carbon nanotube (CNT) coating. Similarly, the scattered light for gravitational-wave application and lasercom system where the simultaneous transmit/receive operation is required, could be achieved by a highly absorbing coating such as CNT. Ideally, the application of CNT coating needs to:

- Achieve broadband (visible plus near infrared (IR)) reflectivity of 0.1% or less.
- Resist bleaching of significant albedo changes over a mission life of at least 10 years.
- Withstand launch conditions such as vibration, acoustics, etc.
- Tolerate both high continuous-wave (CW) and pulsed power and power densities without damage: ~10 W for CW and ~0.1 GW/cm^2 density, and 1-kW/nsec pulses.
- Adhere to the multilayer dielectric or protected metal coating, including ion beam sputtering (IBS) coating.

NASA's Laser Interferometer Space Antenna (LISA) mission on-axis design telescope operates both in transmission and reception simultaneously where the secondary mirror sends the transmitted beam directly back at the receiver. The apodized petal-shaped mask inherently suppress the diffraction once patterned at the center of the secondary mirror. The emerging cryogenic etching of black-silicon has demonstrated bidirectional reflectance distribution function (BRDF) ultralow specular reflectance of 1×10^{-7} in the range of 500 to 1,064 nm. The advancement of this technology is desired to obtain ultralow reflectivity.

- Improve the specular reflectance to 1×10^{-10} and hemispherical reflectance better than 0.1%.
- Improve the cryogenic etching process to provide a variation of the reflectance (apodization effect) by increasing or decreasing the height of the grass.
- Explore etching process and duration.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Coating—Analysis, reports, software, demonstration of the concept, and prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration and prototype.

State of the Art and Critical Gaps:

Coating Technology (for wide range of wavelengths from x-ray to IR: x-ray, extended UV (EUV), Lyman UV (LUV), vacuum UV (VUV), visible, and IR):

- The current x-ray coating is defined by Nuclear Spectroscopic Telescope Array (NuSTAR).
- Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
- Current UVOIR is defined by Hubble. MgFI2 overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm.

Metrics for X-Ray:

- Multilayer high-reflectance coatings for hard x-ray mirrors.
- Multilayer depth gradient coatings for 5 to 80 keV with high broadband reflectivity.
- Zero-net-stress coating of iridium or other high-reflectance elements on thin substrates (<0.5 mm).

Metrics for EUV:

- Reflectivity >90% from 6 to 90 nm onto a <2 m mirror substrate.

Metrics for Large UV/Optical/IR Surveyor (LUVOIR):

- Broadband reflectivity >70% from 90 to 120 nm (LUV) and >90% from 120 nm to 2.5 µm (VUV/visible/IR).
- Reflectivity non-uniformity <1% 90 nm to 2.5 µm.
- Induced polarization aberration <1% 400 nm to 2.5 µm spectral range from mirror coating applicable to a 1- to 8-m substrate.

Metrics for LISA:

- HR: Reflectivity >99% at 1,064+/-2 nm with very low scattered light and polarization-independent performance over apertures of ~0.5 m.
- AR: Reflectivity <0.005% at 1,064+/-2 nm.
    - Low-absorption, low-scatter, laser-line optical coatings at 1,064 nm.
    - High reflectivity, R > 0.9995.
    - Performance in a space environment without significant degradation over time, due for example to radiation exposure or outgassing.
    - High polarization purity, low optical birefringence over a range of incident angles from ~5° to ~20°.
    - Low coating noise (thermal, photothermal, etc.) for high-precision interferometric measurements.
    - Ability to endure applied temperature gradients (without destructive effects, such as delamination from the substrate).
    - Ability to clean and protect the coatings and optical surfaces during mission integration and testing. Cleaning should not degrade the coating performance.

Nonstationary Optical Coatings:

- Used in reflection and transmission that vary with location on the optical surface.

CNT Coatings:

- Broadband visible to NIR, total hemispherical reflectivity of 0.01% or less, adhere to the multilayer dielectric or protected metal coating.

Black-Silicon Cryogenic Etching (new):

- Broadband UV+visible+NIR+IR, reflectivity of 0.01% or less, adhere to the multilayer dielectric (silicon) or protected metal.

Software tools to simulate and assist the anisotropic etching by employing variety of modeling techniques such as rigorous coupled wave analysis (RCWA), method of moments (MOM), finite-difference time domain (FDTD), finite element method (FEM), transfer matrix method (TMM), and effective medium theory (ETM).

Relevance / Science Traceability:

- Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/optical and exoplanet missions.
- Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP), Ion-Neutral Coupling in the Atmosphere (INCA), Dynamic Geospace Coupling (DGC), Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS), Reconnection and Micro-scale (RAM), and Solar-C.
- LISA requires low-scatter HR coatings and low reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important.
- Nulling polarimetry/coronagraphy for exoplanets imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:

Laser Interferometer Space Antenna (LISA) is a space-based gravitational wave observatory building on the success of LISA Pathfinder and Laser Interferometer Gravitational-Wave Observatory (LIGO). Led by the European Space Agency (ESA), the new LISA mission (based on the 2017 L3 competition) is a collaboration between ESA and NASA.

- More information can be found at: https://lisa.nasa.gov

Scope Title:

Free-Form Optics

Scope Description:

Future NASA science missions demand wider fields of view in a smaller package. These missions could benefit greatly by free-form optics as they provide nonrotationally symmetric optics, which allow for better packaging while maintaining desired image quality. Currently, the design and fabrication of free-form surfaces is costly. Even though various techniques are being investigated to create complex optical surfaces, small-size missions highly desire efficient small packages with lower cost that increase the field of view and expand operational temperature range of un-obscured systems. In addition to the free-form fabrication, the metrology of free-form optical components is difficult and challenging because of the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope sensitive optical probe are highly desirable.

Specific metrics are:

- Design: Innovative design methods/tools for free-form systems, including applications to novel reflective optical designs with large fields of view (>30°) and fast F/#s (<2.0).
- Fabrication: 10-cm-diameter optical surfaces (mirrors) with free-form optical prescriptions >1 mm, spherical departure with surface figure error <10 nm rms, and roughness <5 Angstroms. 10-cm-diameter blazed optical reflective gratings on free-form surface shapes with >1 mm departure from a best-fit-sphere, and grating spacings from 1 to 100 µm. Larger mirrors are also desired for flagship missions for ultraviolet (UV) and coronagraphy applications, with 10-cm- to 1-m-diameter surfaces having figure error <5 nm rms and roughness <1 Angstroms rms.
- Metrology: Accurate metrology of "free-form" optical components with large spherical departures (>1 mm), independent of requiring prescription-specific null lenses or holograms.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Optical components—Demonstration, analysis, design, metrology, software, and hardware prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps:

Free-form optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field-of-view and fast F/#s is highly desirable.

Relevance / Science Traceability:

NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to freeform optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields-of-view and fast F/#s in small size instruments are highly desirable specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, and NanoSat). Additionally, design studies for large observatories such as Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor (LUVOIR, currently being proposed for the 2020

Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field-of-view afforded by free-form optics. Such programs will require advances in free-form metrology to be successful.

References:

A presentation on application of Freeform Optics at NASA is available at:

- Applications for Freeforms Optics at NASA, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf
- Alignment and Testing for a Freeform Telescope, https://ntrs.nasa.gov/citations/20180007557
- Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications, https://ntrs.nasa.gov/citations/20190025929

S2.05 Technology for the Precision Radial Velocity Measurement Technique (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

Components, Assemblies, and Subsystems for Extreme Precision Radial Velocity Measurements and Detection of Extrasolar Planets

Scope Description:

Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler modulated in time. This is the basis for the precision radial velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Because spectrographs have their own drifts, which must be separated from the periodic Doppler shift, a stable reference is always needed for calibration. Optical frequency combs (OFCs) and line-referenced etalons are capable of providing the spectral rulers needed for PRV detection of exoplanets. Although “stellar jitter” (a star’s photospheric velocity contribution to the RV signal) is unavoidable, the contribution to the error budget from Earth’s atmosphere would be eliminated in future space missions. Thus, there is a need to develop robust spectral references, especially at visible wavelengths to detect and characterize Earth-like planets in the habitable zone of their Sun-like host stars, with size, weight, and power (SWaP) suitable for space-qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to <~1 cm/s over multiple years of observations.

This subtopic solicits proposals to develop cost-effective component and subsystem technology for low-SWaP, long-lived, robust implementation of RV measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs.
- Spectrograph gratings.
- PRV spectrograph calibration sources.
- High efficiency photonic lanterns.

- Advanced optical fiber delivery systems and subsystems with high levels of image scrambling and modal noise reduction.
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:

- Phase I will emphasize research aspects for technical feasibility, infusion potential into ground or space operations, clear and achievable benefits (e.g., reduction in SWaP and/or cost, improved RV precision), and show a path towards a Phase II proposal. Phase I deliverables include feasibility and concept-of-operations of the research topic, simulations and measurements, validation of the proposed approach to develop a given product (TRL 3 to 4), and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development and delivery of prototype hardware/software is encouraged.
- Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software along with documentation of development, capabilities, and measurements (showing specific improvement metrics); and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

State of the Art and Critical Gaps:

High-resolving-power spectrographs (R ~ 150,000) with simultaneous UV, visible, and NIR coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints due to their large mass and limited optical flexibility. Integrated photonic spectrographs are wafer-thin devices that could reduce instrument volume by up to 3 orders of magnitude. Spectrometers that are fiber fed, with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

Traditional RV spectrographs would benefit from improvements in grating technology. Diffraction-limited PRV spectrographs require echelle gratings with low wavefront error and high efficiency, both of which are very challenging to achieve. Echelle spectrographs are designed to operate at high angle-of-incidence and very high diffraction order. Hence, the grating must have very accurate groove placement (for low wavefront error) and very flat groove facets (for high efficiency). For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve all aspects of the performance required for PRV instruments. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. As spectrograph stability imposes limits on how precisely RV can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only laser frequency combs (LFCs) and line-referenced Fabry-

Pérot etalons are capable of providing the broad spectral coverage and long-term stability needed for extreme PRV detection of exoplanets. Although both frequency combs and etalons can deliver high-precision spectrograph calibration, the former requires relatively complex hardware in the visible portion of the spectrum.

Commercial fiber laser astrocombs covering 450 to 1400 nm at 25 GHz line spacing and <3-dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects either do not use a LFC or include it only as a future upgrade. Alternatively, astrocombs produced by electro-optic modulation (EOM) of a laser source have been demonstrated in the NIR. EOM combs produce modes spaced at a radiofrequency (RF) modulation frequency, typically 10 to 30 GHz. Significantly, EOM combs avoid the line filtering step required by commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished by referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability. EOM combs must be spectrally broadened to provide the bandwidth necessary for PRV applications. This is accomplished through pulse amplification followed by injection into highly nonlinear fiber or nonlinear optical waveguides.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space-based PRV systems and motivates the development of a comb system that operates with less than 20 W of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption; ~10 to 30 GHz mode spacing; compact size; broad (octave spanning) spectral grasp across both the visible and NIR; low phase noise; stability traceable to the International System of Units definition of the second; and importantly, long life.

The intrinsic illumination stability of the spectrometer also sets a fundamental measurement floor. As the image of the star varies at the entrance to the spectrometer because of atmospheric effects and telescope guiding errors, so too does the recorded stellar spectrum, leading to a spurious RV offset. Current seeing-limited PRV instruments use multimode optical fibers, which provide some degree of azimuthal image scrambling, to efficiently deliver stellar light from the telescope focal plane to the spectrometer input. Novel-core-geometry fibers, in concert with dedicated optical double-scramblers, are often used to further homogenize and stabilize the telescope illumination pattern in both the image and pupil planes. However, these systems still demonstrate measurable sensitivity to incident illumination variations from the telescope and atmosphere. Furthermore, as spectral resolution requirements increase, the commensurate increase in instrument size becomes impractical. Thus, the community has turned to implementing image and pupil slicers to reformat the near or far fields of light entering the spectrometer by preferentially redistributing starlight exiting the fiber to maintain high spectral resolution, efficiency, and compact spectrometer size.

Relevance / Science Traceability:

The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report, which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra that the James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet’s surface gravity, which comes from its radius (from the transit data) and its mass (from PRV measurements or, in some cases, transit timing variations). Without knowledge of a planet's mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct-imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships, which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet's brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet's density, bulk composition, and surface gravity, which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamical (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth's atmosphere will limit precise radial velocity measurements to ~10 cm/s at wavelengths longer than ~700 nm and greater than 30 cm/s at wavelengths >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

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Focus Area 11 Spacecraft and Platform Subsystems

Lead MD: **SMD**

Participating MD(s): **STMD**

The Science Mission Directorate (SMD) will carry out the scientific exploration of our Earth, the planets, moons, comets, and asteroids of our solar system, and the universe beyond. SMD's future direction will be moving away from exploratory missions (orbiters and flybys) into more detailed/specific exploration missions that are at or near the surface (landers, rovers, and sample returns) or at more optimal observation points in space. These future destinations will require new vantage points or would need to integrate or distribute capabilities across multiple assets. Future destinations will also be more challenging to get to, have more extreme environmental conditions and challenges once the spacecraft gets there, and may be a challenge to get a spacecraft or data back from. A major objective of the NASA science spacecraft and platform subsystems development efforts are to enable science measurement capabilities using smaller and lower cost spacecraft to meet multiple mission requirements thus making the best use of our limited resources. To accomplish this objective, NASA is seeking innovations to significantly improve spacecraft and platform subsystem capabilities while reducing the mass and cost that would in turn enable increased scientific return for future NASA missions. A spacecraft bus is made up of many subsystems such as: propulsion; thermal control; power and power distribution; attitude control; telemetry command and control; transmitters/antenna; computers/on-board processing/software; and structural elements. High performance space computing technologies are also included in this focus area. Science platforms of interest could include unmanned aerial vehicles, sounding rockets, or balloons that carry scientific instruments/payloads, to planetary ascent vehicles or Earth return vehicles that bring samples back to Earth for analysis. This topic area addresses the future needs in many of these sub-system areas, as well as their application to specific spacecraft and platform needs. For planetary missions, planetary protection requirements vary by planetary destination, and additional backward contamination requirements apply to hardware with the potential to return to Earth (e.g., as part of a sample return mission). Technologies intended for use at/around Mars, Europa (Jupiter), and Enceladus (Saturn) must be developed so as to ensure compliance with relevant planetary protection requirements. Constraints could include surface cleaning with alcohol or water, and/or sterilization treatments such as dry heat (approved specification in NPR 8020.12; exposure of hours at 115° C or higher, non-functioning); penetrating radiation (requirements not yet established); or vapor-phase hydrogen peroxide (specification pending). The National Academies' Decadal Surveys for Astrophysics, Earth Science, Heliophysics, and Planetary Science discuss some of NASA's science mission and technology needs and are available at https://sites.nationalacademies.org/SSB/SSB_052297. In addition, the Heliophysics roadmap "The Solar and Space Physics of a New Era: Recommended Roadmap for Science and Technology 2009-2030" is available at http://hpde.gsfc.nasa.gov/2009_Roadmap.pdf.

S3.05 Terrestrial Balloons and Planetary Aerial Vehicles (SBIR)

Lead Center: **GSFC**

Participating Center(s): **AFRC, JPL**

Scope Title:

Planetary Aerial Vehicles for Venus

Scope Description:

NASA is interested in scientific exploration of Venus using aerial vehicles to perform in situ investigations of its atmosphere, surface, and interior structure. The 2019 Venus Exploration Analysis Group (VEXAG) Strategic Plan identified several key science objectives that are ideally suited to aerial platforms. The areas of scientific interest include:

Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging, and Geophysical Investigations.

Venus features a challenging atmospheric environment that significantly impacts the design and operation of aerial vehicles. NASA is currently developing concepts for controlled-variable-altitude balloons with payloads of up to 200 kg operating at an altitude range between 52 and 62 km over a latitude range of 0° to +/-60°. Proposals for the following Venus aerial vehicle components are encouraged: (1) Entry, deployment, inflation technologies for a Venus balloon, (2) Instrument sondes, and (3) Helium transfer pump.

1. The most critical phase of a Venus balloon mission is the transition from atmospheric entry to a free-flying configuration. Concepts for any or all of the critical phases of the transition are desired: deployment of the balloon from the atmospheric entry vehicle, inflation of the balloon, and separation of the balloon from the inflation system and parachute system.
2. Deployment of instrument sondes from the payload could enhance and lengthen the balloon mission operating lifetime by reducing payload mass as lift capability is lost over time. Sondes with a mass up to 5 or 10 kg should be capable of operating for several hours, carry a small science instrument payload, and be able to communicate with the primary balloon mission. The sondes envisioned for this solicitation are categorized into ascending and descending investigations. Ascending science investigations carry small science payloads up to 70 km altitude, and descending science investigations carry a small science payload down to near the surface (i.e., <10 km altitude). Proposals offering both heavier-than-air and lighter-than-air (relative to the Venus atmosphere) solutions are solicited. Furthermore, the sonde concepts may have powered propulsion or unpowered flight. Suggested vehicle types include, but are not limited to:
    - Solar-heated balloons that would operate on the sunlit side. This kind of sonde would be deployed from the payload gondola, auto-inflate in a free fall through the atmosphere, and attain float as the solar balloon heats from the Sun. This could possibly operate either above or below the primary balloon mission altitude range.
    - Probes deployed from the payload gondola that perform stabilized vertical descents, gliding descents, powered ascents, or a combination of both ascents and descents.
3. A controlled-variable-altitude balloon may use a pump to transfer helium from a zero-pressure balloon into a superpressure balloon. Pumping technologies capable of pumping helium with a pressure rise of 50 kPa at 100 liters per minute are desired. Multistage or parallel flow pump

solutions are acceptable for consideration. Light weight and high efficiency are important factors in the pump since it must fly with the balloon payload.

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Proposers should be familiar with the atmospheric pressure, temperature, solar, infrared (IR) heating, and corrosion aspects of the Venus atmosphere as described in this call. The atmospheric temperature ranges from -30°C at 62 km to 62°C at 52 km, the pressure ranges from about 18 kPa at 62 km to 80 kPa at 52 km (Venus International Reference Atmosphere, VIRA [see Kliore, 1985]), the solar flux can be as high as 2,300 W/m^2 at 62 km, and the IR heat flux coming up from the lower atmosphere can be as high as 830 W/m^2 at 52 km [Crisp, 1986]. The sulfuric acid *vapor* abundance is less than less than 1 ppmv at 52 km and above [Oschlisniok, 2012]. The sulfuric acid *liquid* aerosols have a concentration between 75% (pH -1.5) and 90% (pH -2.0) [Titov, 2018]. Although the cloud droplets are highly acidic, they are very small, typically in the range of 1 to 10 µm in diameter, and fairly diffuse, with cloud droplet abundance only on the order of 100 droplets/cm^3 for the 1-µm-sized particles; and on the order of 10 droplets/cm^3 for the larger (r > 3µm) particles. The maximum observed aqueous H_2SO_4 content in the balloon operating environment is on the order of only 30 mg/m^3 [Knollenberg, 1980]. Additional information on the Venus atmospheric environment can be found in the References section.

Expected TRL or TRL Range at completion of the Project: 2 to 3

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. Phase II deliverable should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps:

Terrestrial-based aerial vehicles, including lighter-than-air and heavier-than-air vehicles, are mature technologies and continue advancing in capability, reliability, and autonomy. However, these need adaptation for operation in the Venus environment.
Several gaps exist in aerial vehicle technology for Venus atmospheric flight:

1. There is a strong need for aerial deployment systems for balloons and their payloads since most balloons are launched from the ground and from the upper atmosphere. Methods for deployment may leverage techniques for Mars entry vehicle systems that deploy from an aeroshell and eventually separate from a parachute. However, a balloon inflation inserted into the middle of this sequence is a complicating element and preventing damage to the balloon is paramount.
2. Small instrument sondes or vehicles for expanding the exploration range and mission duration have not been sufficiently developed for a Venus mission to be included as part of future mission

proposals. Novel vehicles for conducting science that can be deployed from the balloon payload could play an important role in meeting these objectives. The guidance, stabilization, and control of sondes has been identified as a need for collecting images of the surface during a deep atmospheric descent.

3. Altitude variation of a balloon requires changing the density of the lifting gas. There are no commercially available pumps in the market today that have the pressure rise and flow rate capabilities needed for a Venus balloon. Most pumps or compressors are not built to be lightweight, which is of critical importance on a balloon mission.

Relevance / Science Traceability:

Relevance: The Mars Helicopter, Ingenuity, and the Titan Dragonfly mission show there is significant interest in planetary aerial vehicles for science investigations. It is in NASA's interest through the SBIR program to continue fostering innovative ideas to extend our exploration capabilities by developing technologies for Venus aerial mission concepts.

JPL's Solar System Mission Formulation Office and the NASA Science Mission Directorate's Planetary Science Division advocate Venus aerial vehicle platform development. NASA recently completed the Venus Flagship Mission concept study, which included a balloon system for the Planetary Decadal Survey [Gilmore, 2020].

Science Traceability: The 2019 VEXAG Venus Strategic Plan identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include: Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging and Geophysical Investigations. The variable-altitude aerial vehicle platform is ideal for investigating these science goals and objectives. Building the variable-altitude balloon requires the development of several key components as identified in this call.

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- Titov, D., Ignatiev, N. I., K. McGouldrick, Wilquet, V., and Wilson, C. F. (2018): “Venus III: Clouds and hazes of Venus,” *Space Sci. Rev.* 214, 126.
- The VEXAG Strategic Plan 2019 is found at: https://www.lpi.usra.edu/vexag/reports/Combined_VEXAG_Strategic_Documents_Current.pdf
- The Venus Atmospheric Properties are available in Kliore, A. J., Moroz, V. I., Keating G. M., Eds. (1985): “The Venus International Reference Atmosphere,” *Adv. Space Res.*, Vol. 5, No. 11, pp 8+305, ISBN 0-08-034631-6.

Scope Title:

Improved Downlink Satellite Communications for Balloons

Scope Description:

Improved downlink bit rates and innovative solutions using satellite relay communications from balloon payloads are needed. Long-duration balloon flights currently utilize satellite communications systems to relay science and operations data from the balloon to ground-based control centers. The current maximum downlink bit rate is 150 kbps, operating continuously during the balloon flight. Future requirements are for bit rates of 1 Mbps or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high-bit-rate systems are needed. Tracking and Data Relay Satellite System (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18 dBi gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I: Desired deliverables include: (1) results of analysis or simulation or (2) test results of actual prototype hardware and/or software.

Phase II: Deliverables could include a prototype that could be test flown on a balloon mission.

State of the Art and Critical Gaps:

Current commercially available satellite relays systems that could be used for balloon flight are either too costly or do not provide the needed downlink data rates. Tracking and Data Relay Satellite System (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18-dBi-gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

Relevance / Science Traceability:

Science Mission Directorate (SMD) - NASA HQ (Astrophysics Division) enables multiple Research Opportunities in Space and Earth Science (ROSES) opportunities, Small Explorer (SMEX) Announcement of Opportunity (AO) (Astrophysics), Astrophysics Mission of Opportunity, and Hands-On Project Experience (HOPE) (annually).

Improvements to satellite communications for research balloons would enable greater and better data collection, possibly extended flight duration, and other such potential benefits.

References:

- NASA's SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: https://sites.wff.nasa.gov/code820/

- GUSTO (Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory) mission is a planned high-altitude balloon mission that will carry an infrared telescope to measure emissions from the interstellar medium. The mission is being developed by NASA's Explorers Program - GUSTO, University of Arizona (Prof. Chris Walker).
- Scientific balloon information: https://sites.wff.nasa.gov/code820/technology_capabilities.html
- 2020 NASA Technology Taxonomy: https://www.nasa.gov/offices/oct/taxonomy/index.html

Scope Title:

Steerable Recovery/Parachute System

Scope Description:

NASA is looking for an innovative way to reduce the termination dispersions from a few miles to within 1/2 to 1/4 mile of the predicted termination point by the use of a steerable parachute recovery system (SPRS). The SPRS will need to be able to maneuver around infrastructure (e.g., oil wells, power lines, wind mills), protected areas (e.g., national parks, special habitats), natural resources (e.g., rivers, mountains, lakes), and other areas of interest (e.g., farm land). The SPRS will need to be provide real-time maneuverability for a science gondola from a remote operations control room using the communications and telemetry systems provided by the Columbia Scientific Balloon Facility (CSBF). The system should be lightweight, no more than 75 lb including power.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.X Other Guidance, Navigation, and Control

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

The deliverables for Phase I include a trade study of the potential systems, a simulation of how each system should work, and a report on the recommendation of one to two systems to be further developed in Phase II. It is anticipated that these products are achievable given the SBIR time and funding constraints.

The deliverables for Phase II includes an engineering development unit and testing with a report of the results.

State of the Art and Critical Gaps:

A scientific balloon floats at an average altitude of 110,000 ft or more and carries science payloads up to 8,000 lb. At the end of a scientific balloon mission, the science payload on the gondola (from this point on "science gondola") is separated from the balloon and falls to Earth on a parachute following the wind currents at the time of release and lands on cardboard crush pads. In most cases this allows recovery of the science gondola, though the payload and gondola may be in areas that are hard to reach using conventional recovery trucks. However, there are rare cases where the science gondola falls either in water or in areas that require special equipment or are difficult for recovery (e.g., inaccessible area).
Currently, trajectory predictions for termination are within a few miles and are dependent on models, map

overlays (showing restricted air space, national/state parks), and observations from a plane on areas along the trajectory to determine the best area to terminate the balloon and bring the science gondola safely to the ground. Some items that are considered during the termination discussions are science mission minimums, trajectory predications (e.g., national or state parks, lakes, mountains, rivers, infrastructure, crop lands), weather conditions, and risk to the public. Current state of the art does not include steerable systems in balloon parachutes. Success in this endeavor will entail primarily steerability, but this also results frequently in a safety analysis, which will allow more "green lights" for launch than would otherwise be the case.

Relevance / Science Traceability:

This subtopic will be relevant to any mission directorate, commercial entity, or other government agency that drops payloads from an altitude, including the Balloon Program. Other potentially interested projects include NASA sounding rockets, UAV, and aircraft programs.

References:

https://patents.google.com/patent/EP1463663A4/en

https://www.airforce-technology.com/features/featurejpads-circumventing-gps-for-next-gen-precision-airdrops-4872436/

Scope Title:

Relative Wind Speed Sensor for Scientific Balloons

Scope Description:

A trajectory control system (TCS) for high-altitude scientific ballooning has been a long-term goal of NASA's Balloon Program Office (BPO). One milestone in the critical path of TCS development is the ability to measure the speed of the winds seen by the gondola during a balloon mission. In addition, NASA has identified wind-speed measurements from a balloon explorer under the TX10.1.2 of the 2020 NASA Technology Taxonomy (see References below). Currently, the BPO has no method of measuring relative winds (wind speed relative to the gondola) in situ above ~15 km in altitude for terrestrial applications. Although several methods of wind speed measurement exist for a variety of applications, there is effort required to port those technologies for the conventional balloon float environment. The goal of this technology development is to develop a sensor to meet the following specifications:

1. Measure relative wind in three axes (u, v, and w).
2. Operate at 4.4 mbar (~36.5 km altitude) or lower pressure.
3. Operate in air temperature from -70 to +65 °C.
4. Accuracy of 10 cm/s or better.
5. Resolution of 5 cm/s or better.
6. Sample rate of 1 Hz or faster.
7. Power consumption of 30 W or less at steady state.
8. Mass of 20 kg or less.
9. Withstand shocks of 10g or greater.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I: Deliver a conceptual design package for a prototype unit that meets the design goals and accuracy.

Phase II: Deliver a prototype and an accompanying acceptance package that describes the prototype unit in detail and provides experimental validation of the unit having met the design goals and accuracy as well as all accompanying software/firmware required for operation of the sensor.

State of the Art and Critical Gaps:

Wind speed measurements at balloon float altitudes have several benefits: First, a relative wind sensor will enable the TCS development by providing a means to measure the speed imparted to the balloon by a future TCS concept. Second, science gondolas with fine pointing requirements must point against the relative wind. Currently, a data set of example relative wind does not exist, which requires science groups to design robust control systems for their telescopes or instruments. Third, relative wind is responsible for any convective cooling seen on large structures, such as baffles on telescopes, which is currently poorly understood. In general, relative wind speed measurements will aide in prolonging flights (both with a TCS and by refining flight prediction capabilities) and enable more informed design of gondola structures and heating systems.

Commercially available wind speed sensors (anemometers) have been shown to not be capable of accurately measuring the wind speed above ~15 km in altitude. In addition, this technology (if realized) would enable the development of a trajectory control system for balloon missions, which is critical for achieving the goal of 100-day missions at 36 km in the Southern Hemisphere.

Relevance / Science Traceability:

A relative wind sensor for balloon missions would benefit the Science Mission Directorate (SMD)/Astrophysics mission by furthering the state of the art in sensor technology. In addition, the development of a relative wind sensor is a key milestone in the path towards a trajectory control system for high-altitude balloons. Specifically, NASA's Super Pressure Balloon (SPB) would benefit from trajectory control while pursuing 100-day flights in the Southern Hemisphere.

References:

Scientific balloon information: https://sites.wff.nasa.gov/code820/technology_capabilities.html

2020 NASA Technology Taxonomy: https://www.nasa.gov/offices/oct/taxonomy/index.html

S3.08 Command, Data Handling, and Electronics (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL, LaRC, MSFC**

Scope Title:

Command, Data Handling, and Electronics

Scope Description:

NASA's space-based observatories, flyby spacecraft, orbiters, landers, and robotic and sample-return missions require robust command and control capabilities. Advances in technologies relevant to command and data handling and instrument electronics are sought to support NASA's goals and several missions and projects under development.
The 2021 subtopic goals are to develop platforms for the implementation of miniaturized highly integrated avionics and instrument electronics that:

- Are consistent with the performance requirements for NASA missions.
- Minimize required mass/volume/power as well as development cost/schedule resources.
- Can operate reliably in the expected thermal and radiation environments.

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. Note that environmental requirements vary significantly from mission to mission. For example, some low-Earth-orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), whereas planetary missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this subtopic include:

- Radiation-hardened mixed-signal structured application-specific integrated circuit (ASIC) platforms to enable miniaturized and low-power science sensor readout and control, with sufficient capability to implement 12-bit digital-to-analog converters (DACs) monotonic and 12- to 16-bit digital-to-analog converters (ADCs) (<100 kHz 16-bit and 1 to 2 MHz 12-bit) and also charge-sensitive amplifiers for solid-state detectors and readout integrated circuit (ROIC) for silicon photomultipliers.
- Radiation-hardened ASIC devices to enable direct capture of analog waveforms.
- Multiple-output point-of-load power regulator: This module, preferably implemented utilizing one or more controller ASICs, will source a minimum of three settable output voltages when provided with an input voltage between +5 and +12 V. Output voltages shall be independently settable to any voltage between 3.3 and 0.9 V with efficiency of at least 95%. Regulation, noise filtering, and other operational specifications should be commensurate with industry standards for space-based systems. Output current in the 10 A range to handle field-programmable gate array (FPGA) core requirements. The module should provide standard spacecraft power supply features, including overvoltage protection, fault tolerance, load monitoring, sequencing, synchronization, and soft start and should allow control and status monitoring by a remote power system controller. Using fewer external components is also highly desirable. There is also interest in a capability to provide data over power line communication to the converter for control and monitoring functions. The offeror should determine radiation-tolerance levels achievable utilizing commercially available processes and indicate, in the proposal, the radiation-tolerance goals.
- High-density high-reliability interconnections: A high-reliability connector or interconnect mechanism that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible is desired. The connector wiring and cabling in addition to the connector shape and size should be considered in providing a complete system that further reduces the size and weight of the harnessing. The design should handle everything from carrying power to high-speed (10+ Gbps) impedance-controlled connections. The design should be scalable in different sizes to accommodate fewer connections

and save board space. Low insertion force is desirable. Right angle and stacking design options should be considered.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Desired Phase I deliverables include designs, simulations, and analyses to demonstrate viability of proposed components.

Desired Phase II deliverables:

- For mixed-signal structured ASIC platforms—include a prototype mixed-signal ASIC implemented with a proof-of-concept end-user design. The proof-of-concept design should demonstrate the stated performance capabilities of the ASIC.
- For the direct analog waveform capture ASIC—should include a prototype ASIC device implemented on a test board and demonstration of the wave form capture capabilities of the device.
- For the multiple output point of load switcher—a prototype multi-output point of load regulator. The regulator should be integrated onto a test board and be performance tested under varying resistive, capacitive, and transient load conditions.
- For the high density high-reliability interconnect—prototypes of the connection system (different size, orientations, wiring, etc.). The connector should be integrated onto a test board where its performance (speed, cross talk, etc.) can be verified.

State of the Art and Critical Gaps:

There is a need for a broader range of mixed-signal structured ASIC architectures. This includes the need for viable options for mixed ASICs with high-resolution, low-noise analog elements, especially 12-bit DACs and 12- to 16-bit ADCs. The current selection of mixed-signal structured ASICs is limited to 10-bit designs, which do not provide the accuracy or resolution to perform the science required of many of the instruments currently being flown. Mixed-signal structured ASICs can integrate many functions and therefore can save considerable size, weight, and power over discrete solutions—significantly benefiting NASA missions. The lack of parts with high-precision analog is greatly limiting their current application.
There are multiple output point-of-load converters available from commercial companies. The existing commercial parts require many external components, eliminating their space savings. Commercial parts are not built on radiation-tolerant processes.
Current connectors and interconnect harnessing are too large, especially for small satellites and CubeSats. As the size of the printed circuit boards has shrunk, the percent of board space being used by the input/output (I/O) connectors has become unacceptable. The connectors are taking away from circuitry and sensors that could be providing additional functionality and science products. High-density commercial connectors tend to be lacking in their general ruggedness, outgassing, and ability to prevent intermittent connections in high-vibration environments like orbital launches.

Relevance / Science Traceability:

Mixed-signal structured ASIC architectures are relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions to harsh radiation environments. For all missions, the higher accuracy would provide better science or allow additional science through the higher density integration.
Multi-output point-of-load converters and high-density high-reliability interconnects are relevant to miniaturizing electronics. Miniaturized flight electronics allows one to fit more functionality into less volume, allowing smaller spacecraft to perform science that was previously done by larger satellites. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions.

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

- NASA Technical Reports Server: https://ntrs.nasa.gov/
- NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/
- NASA/GSFC Radiation Effects and Analysis Home Page: https://radhome.gsfc.nasa.gov/top.htm

S4.03 Spacecraft Technology for Sample Return Missions (SBIR)

Lead Center: **JPL**

Participating Center(s): **GRC, GSFC**

Scope Title:

Critical Technologies for Sample-Return Missions

Scope Description:

This Subtopic focuses on robotic sample-return (SR) missions that require landing on large bodies (e.g., Luna, Mars Sample Return (MSR)), as opposed to particulate-class SR missions (e.g., Genesis, Hayabusa) or touch-and-go (TAG) missions to relatively small asteroids or comets (e.g., OSIRIS-Rex, Hayabusa2). The mission destinations envisioned are dwarf planets (e.g., Vesta, Ceres) and planet or planet moons (e.g., Phobos, Europa). These are the most challenging missions in NASA's portfolio but also the most scientifically promising, given the vast array of instruments available on Earth to study the retrieved samples. The challenges associated with these SR missions may be grouped into four categories: (1) Mass-efficient spacecraft architectures (e.g., efficient propulsion or materials that significantly reduce the mass of the launch payload required), (2) Sample handling (e.g., subsurface acquisition mechanisms), (3) Sample integrity (e.g., surviving reentry), and (4) Planetary protection/contamination control (PP/CC) (e.g., preventing leakage into the orbital sample (OS) canister). This Subtopic seeks potential solutions to areas (1), (3), and (4), considering it best that technologies associated with (2), sample handling, be directed to Subtopic S4.02. The intent is to have this Subtopic S4.03 manage only those technologies in areas (1), (3), and (4) that are specifically related to SR missions; technology solutions related to other classes of missions should instead be directed to Subtopics S4.04 (Extreme Environments) and S4.05 (Contamination Control and Planetary Protection).

The heightened need for mass-efficient solutions in these SR missions stems from their extreme payload mass “gear ratio.” For example, the entire MSR campaign will require three heavy launch vehicle launches with rough spacecraft mass of 5,000 kg each in order to bring back multiple samples with an estimated total mass of 0.5 kg. Clearly, any mass savings in the ascent vehicle’s gross liftoff mass (GLOM) or in the lander mass, for example, would yield many times more savings in the launch payload mass, enhancing the feasibility of these missions.

Once acquired, samples must be structurally and thermally preserved through safe landing and transport to Johnson Space Center (JSC) for analyses. Sample integrity technology solutions that address the long, high-radiation return trip, as well as the dynamic and high-temperature environment of reentry, are sought. Potential solutions include near isotropic and crushable high-strength energy-absorbent materials that can withstand the ballistic impact landing. Materials that offer thermal isolation in addition to energy absorption are highly desirable given the reentry environment. In the case of cryogenically preserved samples, the technical challenge includes development of thermal control systems to ensure volatiles are conserved.

Finally, acquired samples must be chemically and biologically preserved in their original condition. Examples of PP/CC technology solutions sought include:

- Materials selection: selection of metallic materials (non-organic) for the interior of the OS capsule as well as materials that allow preferable surface treatments and bake-out sterilization approaches.
- Surface science topics: Adsorber coatings/materials for contaminant adsorption (getter-type materials, such as aluminum oxide, porous polymer resin) and/or low-surface-energy materials to minimize contaminant deposition.
- Characterization of contamination sources on lander, rover, capsule, ascent vehicle, and orbiter, for design of adequate mitigation measures.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

A Phase I deliverable would be a final report that describes the requisite research and detailed design accomplished under the project.

A Phase II deliverable would be successful demonstration of an appropriate-TRL performance test, such as at representative scale and environment, along with all the supporting analyses, design, and hardware specifications.

State of the Art and Critical Gaps:

The kind of SR missions targeted in this solicitation are those that require landing on an extraterrestrial body. This most challenging kind of SR mission has only been successfully done in the Soviet Luna program that returned 326 g of Moon samples in three missions—out of eleven attempts—in the early 1970s. Hayabusa2 and OSIRIS-Rex are TAG SR missions that are expected to return samples in December 2020 from asteroid Ryugu and in September 2023 from asteroid Bennu, respectively. The first segment of NASA's MSR mission is the sample collection rover Perseverance, launch of which took place in July 2020. The MSR sample retrieval segment (lander, fetch rover, Mars Ascent Vehicle) is scheduled to begin Phase A development in October 2020 for a 2026 launch. The third MSR segment will be ESA's Earth return vehicle (ERV).

The content and breath of this Solicitation is informed by lessons learned in MSR over the Pre-Phase A years. Future SR missions are in need of technology improvements in each of the critical areas targeted: mass efficiency, sample acquisition, sample integrity, and planetary protection.

This solicitation seeks proposals that have the potential to increase the Technology Readiness Level from 3 or 4 to 6 within 5 years, and within the cost constraints of the Phases I, II, and III of this SBIR Program. Such progress would allow full flight qualification of the resulting hardware within 5 to 10 years.

Relevance / Science Traceability:

Medium- and large-class SR missions address fundamental science questions such as whether there is evidence of ancient life or prebiotic chemistry in the sampled body. Table S.1 of *Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011)* correlates ten "Priority Questions" drawn from three Crosscutting Science Themes, with "Missions in the Recommended Plan that Address Them". SR missions are shown to address eight out of the ten questions and cover every crosscutting theme, including Building New Worlds, Planetary Habitats, and Workings of Solar Systems.

References:

Vision and Voyages for Planetary Science in the Decade 2013-2022, http://nap.edu/13117

Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review (2018), http://nap.edu/25186

Mars Sample Return (MSR), https://www.jpl.nasa.gov/missions/mars-sample-return-msr/

Comet Nucleus Sample Return (CNSR), https://ntrs.nasa.gov/search.jsp?R=20180002990

S4.04 Extreme Environments Technology (SBIR)

Lead Center: **JPL**

Participating Center(s): **GRC, GSFC, LaRC**

Scope Title:

Extreme Environments Technology

Scope Description:

This subtopic addresses NASA's need to develop technologies for producing space systems that can operate without environmental protection housing in the extreme environments of NASA missions. Key performance parameters of interest are survivability and operation under the following conditions:

1. Very low temperature environments (e.g., temperatures at the surface of Titan and of other Ocean Worlds as low as -180 °C; and in permanently shadowed craters on the Moon).
2. Combination of low-temperature and radiation environments (e.g., surface conditions at Europa of -180 °C with very high radiation).
3. Very high temperature, high pressure, and chemically corrosive environments (e.g., Venus surface conditions, having very high pressure and temperature of 486 °C).

NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets through the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures and high pressures is also required for deep atmospheric probes to the giant planets. Proposals are sought for technologies that are suitable for remote-sensing applications at cryogenic temperatures and in situ atmospheric and surface explorations in the high-temperature, high-pressure environment at the Venusian surface (485 °C, 93 atm) or in low-temperature environments such as those of Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets, and other small bodies.

Also, Europa-Jupiter missions may have a mission life of 10 years, and the radiation environment is estimated at 2.9 Mrad total ionizing dose (TID) behind 0.1-in-thick aluminum. Proposals are sought for technologies that enable NASA's long-duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low outgassing characteristics are highly desirable. Special interest lies in development of the following technologies that are suitable for the environments discussed above:

- Wide-temperature-range precision mechanisms: for example, beam-steering, scanner, linear, and tilting multi-axis mechanisms.
- Radiation-tolerant/radiation-hardened low-power, low-noise, mixed-signal mechanism control electronics for precision actuators and sensors.
- Wide-temperature-range feedback sensors with sub-arcsecond/nanometer precision.
- Long-life, long-stroke, low-power, and high-torque force actuators with sub-arc-second/nanometer precision.
- Long-life bearings/tribological surfaces/lubricants.
- High-temperature analog and digital electronics, electronic components, and in-circuit energy storage (capacitors, inductors, etc.) elements.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant/radiation-hardened radio-frequency (RF) electronics.
- Radiation-tolerant/radiation-hardened low-power/ultra-low-power, wide-operating-temperature, low-noise mixed-signal electronics for space-borne systems such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened wide-operating-temperature power electronics.
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness, and materials used in advanced electronics assembly).

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

Provide research and analysis for Phase I as a final report.

Deliverables for Phase II include proof-of-concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

State of the Art and Critical Gaps:

Future NASA missions to high-priority targets in our solar system will require systems that have to operate at extreme environmental conditions. NASA missions to the surfaces of Europa and other Ocean Worlds bodies will be exposed to temperatures as low as -180 °C and radiation levels that are at megarad levels. Operation in permanently shadowed craters on the Moon is also a region of particular interest. In addition, NASA missions to the Venus surface and deep atmospheric probes to Jupiter or Saturn will be exposed to high temperatures, high pressures, and chemically corrosive environments.

Current state-of-practice for development of space systems for the above missions is to place hardware developed with conventional technologies into bulky and power-inefficient environmentally protected housings. The use of environmental protection housing will severely increase the mass of the space system and limit the life of the mission and the corresponding science return. This solicitation seeks to change the state of the practice by support technologies that will enable development of lightweight, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

Relevance / Science Traceability:

Relevance to SMD (Science Mission Directorate) is high.

Low-temperature survivability is required for surface missions to Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), small bodies, and comets. Mars diurnal temperatures range from -120 °C to +20 °C. For the Europa Clipper baseline concept with a mission life of 10 years, the radiation environment is estimated at 2.9 Mrad TID behind 0.1-in-thick aluminum. Lunar equatorial region temperatures swing from -180 °C to +130 °C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 °C.

Advanced technologies for high-temperature systems (electronics, electromechanical, and mechanical) and pressure vessels are needed to ensure NASA can meet its long-duration (days instead of hours) life target for its science missions that operate in high-temperature and high-pressure environments.

References:

Proceedings of the Extreme Environment Sessions of the IEEE Aerospace Conference, https://www.aeroconf.org/ or via IEEE *Xplore* Digital Library.

Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG), https://www.lpi.usra.edu/vexag/

Proceedings of the meetings of the Outer Planet Assessment Group (OPAG), https://www.lpi.usra.edu/opag/

S4.05 Contamination Control and Planetary Protection (SBIR)

Lead Center: **JPL**

Participating Center(s):

Scope Title:

CC and PP Implementation and Verification

Scope Description:

The planetary protection (PP) and contamination control (CC) subtopic focuses on mission-enabling and capability-driven technologies to improve NASA's ability to prevent forward and backward contamination. Forward contamination is the transfer of viable organisms from Earth to another body. Backward contamination is the transfer of material posing a biological threat back to Earth's biosphere. NASA is seeking innovative technologies or applications of technologies to facilitate meeting portions of forward and backward contamination requirements to include:

- Improvements to spacecraft cleaning and sterilization that remain compatible with spacecraft materials and assemblies.
- Prevention of recontamination and cross contamination throughout the spacecraft lifecycle.
- improvements to detection and verification of organic compounds and biologicals on spacecraft, to include microbial detection and assessments for viable organism and deoxyribonucleic-acid- (DNA-) based verification technologies to encompass sampling devices, sample processing, and sample analysis pipelines.
- Active in situ recontamination/decontamination approaches (e.g., in situ heating of sample containers to drive off volatiles prior to sample collection) and in situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.
- Enabling end-to-end sample return functions to assure containment and pristine preservation of materials gathered on NASA missions.

For CC efforts, understanding contaminants and preventing contamination supports the preservation of sample science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination, low-energy surface material coatings to prevent contamination, and modeling and analysis of particles to ensure hardware and instrumentation meet organic contamination requirements.

Examples of outcomes:

- End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems.
- Microbial reduction/sterilization technology for spacecraft components.
- Ground-based biological contamination/recontamination mitigation system that can withstand spacecraft assembly and testing operations.
- In-flight spacecraft component-to-component cross-contamination mitigation system.
- Viable organism and/or DNA sample collection devices, sample processing (e.g., low biomass extraction), and sample analysis (e.g., bioinformatic pipelines for low biomass).
- Real-time, rapid device for detection and monitoring of viable organism contamination on low-biomass surfaces or in cleanroom air.
- Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions.
- DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces.
- An applied molecular identification technology to tag/label biological contamination on outbound spacecraft.
- Low surface area energy coatings.

- Molecular adsorbers ("getters").
- Experimental technologies for measurement of outgassing rates lower than $1.0{\times}10^{-15}$ $g/cm^2/s$ with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Physics-based technologies for particulate transport modeling and analysis for continuum, rarefied, and molecular flow environments, with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
- Modeling and analysis technologies for view-factor computation technologies for complex geometries with articulation (e.g., rotating solar arrays, articulating robotic arms).

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.3 Mission Operations and Safety

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverable: proof-of-concept study for the approach to include data validation and modeling.

Phase II: detailed analysis and prototype for testing.

Areas to consider for deliverables are, technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

State of the Art and Critical Gaps:

PP state of the art leverages the technologies resulting from the 1960s to 1970s Viking spacecraft assembly and test era. The predominant means to control biological contamination on spacecraft surfaces is using some combination of heat microbial reduction processing and solvent cleaning (e.g., isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA-approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tends to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction, the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. Biological cleanliness is then verified through the NASA standard assay, which is a culture-based method. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Terminal sterilization has been conducted with recontamination prevention for in-flight biobarriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware developed approaches for compliance, environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air.

Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, while metagenomic approaches are currently undergoing development. Thus, the critical PP gaps include the assessment of DNA from low-biomass surfaces (<0.1 ng/µL DNA, using current technologies, from 1 to 5 m^2 of surface), sampling devices that are suitable for low biomass and compounds (e.g., viable organisms, DNA) but also compliant with cleanroom and electrostatic discharge limits, quantification of the widest spectrum of viable organisms, enhanced microbial reduction/sterilization modalities that are compatible with flight materials, and a ground- and flight-based recontamination systems.

CC requirements and practices are also evolving rapidly as mission science objectives targeting detection of organics and life are driving stricter requirements and improved characterization of flight-system- and science-instrument-induced contamination. State-of-the-art CC includes:

- Testing and measurement of outgassing rates down to 3.0×10^{15} g/cm^2/s with massspectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Particulate transport modeling and analysis for continuum, rarefied, and molecular flow environments with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
- Modeling and analysis of molecular return flux using direct simulation Monte Carlo (DSMC) and the Bhatnagar–Gross–Krook (BGK) formulations.

Relevance / Science Traceability:

Protection requirements has emerged in recent years with increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. The development of such technologies would enable missions to be able to be responsive to PP requirements as they would be able to assess viable organisms and establish microbial reduction technologies to achieve acceptable microbial bioburden levels for sensitive life detection instruments to prevent inadvertent "false positives," to ensure compliance sample return planetary protection and science requirements, and to provide a means to comply with probabilistic-based planetary protection requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

Planetary Protection, https://planetaryprotection.nasa.gov/

Handbook for the Microbial Examination of Space Hardware, https://explorers.larc.nasa.gov/2019APSMEX/SMEX/pdf_files/NASA-HDBK-6022b.pdf

Z2.02 High-Performance Space Computing Technology (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

High-Performance Space Computing Technology

Scope Description:

Most current NASA missions utilize 20-year-old space computing technology that is inadequate for future missions. Newer processors with improved performance are becoming available from industry but still lack the performance, power efficiency, and flexibility needed by the most demanding mission applications. The NASA High-Performance Spaceflight Computing (HPSC) project is addressing these needs. This subtopic solicits technologies that can enable future high-performance, multicore processors, along with the supporting technologies needed to fully implement avionics systems based on these processors.

- Runtime system software security: Software support to enable secure boot, signed applications, and runtime system monitoring is needed to ensure the integrity of onboard, real-time computing systems.
- Compilers that support software-implemented fault tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for multicore processors are desired.
- Technologies are needed to enable radiation-tolerant and fault-tolerant onboard networks with >10 Gbps bandwidth per lane, including intellectual property (IP) cores for endpoints and switches, software stack, and verification and test tools.
- A fault-tolerant RISC-V processor IP core is needed that is augmented to provide data parallelism, which is needed to accelerate image processing and science data processing.
- Solid-state data recorders are needed that are suitable for operation in the space environment, support the space extensions to Serial Rapid IO, and have redundant interfaces.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.X Other Flight Computing and Avionics

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables:

For software and hardware elements, a solid conceptual design, plan for full-scale prototyping, and simulations and testing results to justify prototyping approach. Detailed specifications for intended Phase II deliverables.

Phase II Deliverables:

For software and hardware elements, a prototype that demonstrates sufficient performance and capability and is ready for future development and commercialization.

State of the Art and Critical Gaps:

Most NASA missions utilize processors with in-space qualifiable high-performance computing that has high power dissipation (approximately 18 W), and the current state of practice in Technology Readiness Level 9 (TRL-9) space computing solutions have relatively low performance (between 2 and 200 DMIPS (Dhrystone million instructions per second) at 100 MHz). A recently developed radiation-hardened processor provides 5.6 GOPS (giga operations per second) performance with a power dissipation of 17 W. Neither of these systems provide the performance, the power-to-performance ratio, or the flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements.

Onboard network standards exist that can provide >10 Gbps bandwidth, but not everything is available to fully implement them.

Relevance / Science Traceability:

The HPSC ecosystem is enhancing to most major programs in the Human Exploration and Operations Mission Directorate (HEOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by HEOMD, including the Safe and Precise Landing - Integrated Capabilities Evolution (SPLICE) project. Within the Science Mission Directorate (SMD), strong mission pull exists to enable onboard autonomy across Earth science, astrophysics, heliophysics, and planetary science missions. There is also relevance to other high-bandwidth processing applications within SMD, including adaptive optics for astrophysics missions and science data reduction for hyperspectral Earth science missions.

References:

RISC-V: https://riscv.org/news/2019/09/risc-v-gains-momentum-as-industry-demands-custom-processors-for-new-innovative-workloads/

Next Generation Space Interconnect Standard: http://www.rapidio.org/wp-content/uploads/2014/10/RapidIO-NGSIS-Seminar-July-23-2014.pdf

He, J. et al. Provably Correct Systems. Formal Techniques in Real-Time and Fault-Tolerant Systems. pp 288-335. ProCoS. 1994.

Reis, G.A. SWIFT: software implemented fault tolerance. International Symposium on Code Generation and Optimization. IEEE. 2004.

Focus Area 12 Entry, Descent, and Landing Systems

Lead MD: **STMD**

Participating MD(s): **HEOMD, STTR**

The SBIR focus area of Entry, Descent and Landing (EDL) includes the suite of technologies for atmospheric entry as well as descent and landing on both atmospheric and non-atmospheric bodies. EDL mission segments are used in both robotic planetary science missions and human exploration missions beyond Low Earth Orbit, and many technologies have application to emerging commercial space capabilities such as lunar landing, low-cost space access, small spacecraft, and asset return.

Robust, efficient, and predictable EDL systems fulfill the critical function of delivering payloads to lunar and planetary surfaces through challenging environments, within mass and cost constraints. Future NASA Artemis and planetary science missions will require new technologies to break through historical constraints on delivered mass, enable sustained human presence, or to go to entirely new planets and moons. Even where heritage systems exist, no two planetary missions are exactly “build-to-print,” leading to frequent challenges from environmental uncertainty, risk posture, and resource constraints that can be dramatically improved with investments in EDL technologies. EDL relies on validated models, ground tests, and sensor technologies for system development and certification. Both new capabilities and improved assessment and prediction of state-of-the-art systems are important facets of this focus area.

The subtopics in this Focus Area have been renamed, this year, with the intent of more comprehensive coverage of the Entry, Descent, and Landing flight regimes, as well as ground and flight test and instrumentation areas. In future solicitations, the intent is to maintain these four subtopic titles, and to rotate the content within the subtopics as Agency needs and priorities change and as technologies are matured.

The renamed subtopics and their overarching content descriptions are:

Z7.01 Entry, Descent and Landing Flight Sensors and Instrumentation: Seeks sensors and components for precision landing and hazard detection, as well as heatshield instrumentation and other EDL flight systems diagnostics and electronics

Z7.03 Entry and Descent Systems Technologies: Contains hypersonic materials, aeroshell systems, and modeling advances, including deployable aeroshells for EDL and asset return and recovery. Includes smaller-scale systems appropriate for small spacecraft applications.

Z7.04 Landing Systems Technologies: Covers landing engines, plume-surface interaction modeling, testing, and instrumentation, and landing attenuation systems

Z7.06 EDL Terrestrial Testing Technologies: Solicits for new diagnostic, characterization, and uncertainty quantification capabilities related to EDL-specific ground test facilities, including arcjets, wind tunnels, shock tubes, and ballistic ranges

Please refer to the subtopic write-ups for the specific content and scope solicited this year.

H5.02 Hot Structure Technology for Aerospace Vehicles (SBIR)

Lead Center: **MSFC**

Participating Center(s): **AFRC, JSC, LaRC**

Scope Title:

Hot Structures Technology for Aerospace Vehicles

Scope Description:

This subtopic deals with the development of reusable nonmetallic hot structure technology for structural components exposed to extreme heating environments on aerospace vehicles. Desired hot structure systems encompass multifunctional structures that can reduce or eliminate the need for active cooling or separate thermal protection system (TPS) materials. The potential advantages of using hot structure systems in place of actively cooled structures or a TPS with underlying cool structure include reduced mass, increased mission performance (such as reusability), improved aerodynamics for aeroshell components, improved structural efficiency, and increased ability for nondestructive inspections. Hot structure is an enabling technology for reusability between missions or mission phases, such as advanced propulsion systems requiring multiple engine firings and vehicles requiring aerocapture/aerobraking followed by entry, descent, and landing. The development of hot structure technology for (a) combustion-device liquid rocket engine propulsion systems and (b) aerodynamic structures for aeroshells, control surfaces, wing leading edges, and heatshields is of great interest. Examples of prior flight-proven hot structures include: (a) the nozzle extension for the Centaur RL10B-2 upper-stage rocket engine, and (b) wing leading edges and control surfaces for the Space Shuttle Orbiter, Hyper-X (X-43A), and/or X-37B.

This subtopic seeks to develop innovative, low-cost, damage-tolerant, reusable, and lightweight fiber-reinforced hot structure technology applicable to aerospace vehicles and components exposed to extreme temperatures. At a minimum, materials developed under this subtopic should be capable of operating at a temperature of at least 1,371 °C (2,500 °F)—higher temperatures are of even greater interest, such as up to 2,204+ °C (4,000+ °F). These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during liquid rocket engine firings and/or atmospheric entry. The material systems of interest for use in developing hot structure technology include advanced carbon-carbon (C-C) and ceramic matrix composite (CMC) materials. Potential applications of interest for hot structure technology include: (a) propulsion system components (hot-gas valves, combustion chambers, and nozzle extensions), and (b) primary load-carrying aeroshell structures, control surfaces, leading edges, and heatshields.

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability, and material system properties, as well as the need to reduce cost and manufacturing time requirements. Focus areas should address one or more of the following:

- Improvements in manufacturing processes and/or material designs to achieve repeatable uniform material properties, while minimizing data scatter, that are representative of actual vehicle components: specifically, material property data obtained from flat-panel test coupons should correlate directly to the properties of prototype and flight test articles.
- Material/structural architectures and multifunctional systems providing significant toughness and/or durability improvements over typical 2D interlaminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include incorporating through-the-thickness stitching, braiding, or 3D woven preforms. Advancements in oxidation protection that enhance durability are also of interest: matrix inhibition, oxidation resistant matrices, exterior environmental coatings, etc.
- Manufacturing process methods that enable a significant reduction in the cost and time required to fabricate materials and components. There is a great need to reduce cost and processing time for hot structure materials and components – current state-of-the-art materials are typically expensive and have fabrication times often in the range of 6 to 12 months, which can limit or exclude the use of such materials. Approaches enabling reduced costs and manufacturing times should not lead, however, to significant reductions in material properties. Advanced manufacturing methods may include but are not limited to the following: (a) rapid densification cycles, (b) high char-yield resins, (c) additive manufacturing (AM), and (d) automated weaving, braiding, layup, etc.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

Research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstrations. Phase I feasibility studies should also address cost and the risks associated with the hot structures technology.

In addition to the final report, delivery of a representative sample(s) of the material and/or technology addressed by the Phase I project should be provided at the conclusion of the Phase I contract—for example: (a) coupons appropriate for thermal and/or mechanical material property tests, or (b) arc-jet test specimens. Plans for potential Phase II contracts should include the delivery of manufacturing demonstration units to NASA or a Commercial Space industry partner during Phase II. Testing of such test articles should be a part of the anticipated Phase II effort. Depending upon the emphasis of the Phase II work, such test articles may include subscale nozzle-extension test articles or arc-jet test specimens/hot structure components.

State of the Art and Critical Gaps:

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1,093 to 1,593 °C (2,000 to 2,900 °F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before reuse. Critical gaps or technology needs include:(a) increasing operating temperatures to 1,649 to 2,204+ °C (3,000 to 4,000+ °F); (b) increasing resistance to environmental attack (primarily oxidation); (c) increasing manufacturing technology capabilities to improve reliability, repeatability, and quality control; (d) increasing durability/toughness and interlaminar mechanical properties (or introducing 3D architectures); (e) decreasing cost, and (f) decreasing overall manufacturing time required.

Relevance / Science Traceability:

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance, and the durability to withstand long-duration space exploration missions. The ability to allow for delivery and/or return of larger payloads to various space destinations, such as the lunar South Pole, is also of great interest.
The Advanced Exploration Systems (AES) Program would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial Space programs, such as Commercial Orbital Transportation Services (COTS), Commercial Lunar Payload Services (CLPS), and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology include the Space Launch System (SLS) and the Human Landing System (HLS) for propulsion applications.
Potential NASA users of this technology exist for a variety of propulsion systems, including the following:

- Upper-stage engine systems, such as those for the Artemis SLS.
- In-space propulsion systems, including nuclear thermal propulsion systems.
- Lunar/Mars lander descent/ascent propulsion systems.
- Propulsion systems for the Commercial Space industry, which is partnering with and supporting NASA efforts.

Finally, the U.S. Air Force is interested in such technology for its National Security Space Launch (NSSL), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA) and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composites technology.

References:

Liquid Rocket Propulsion Systems:

- “Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper-Stage Liquid Rocket Engines;” Paul R. Gradl and Peter G. Valentine; 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA; AIAA-2017-5064; July 2017; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170008949.pdf
- “Extreme-Temperature Carbon- and Ceramic-Matrix Composite Nozzle Extensions for Liquid Rocket Engines;” Peter G. Valentine and Paul R. Gradl; 70th International Astronautical Congress (IAC), Washington DC; IAC-19-C2.4.9; October 2019;

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190033315.pdf

Hypersonic Hot Structures:

- "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles;" David E. Glass; 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, OH; AIAA-2008-2682; April-May 2008; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017096.pdf
- "A Multifunctional Hot Structure Heatshield Concept for Planetary Entry;" Sandra P. Walker, Kamran Daryabeigi, Jamshid A. Samareh, Robert Wagner, and Allen Waters; 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Glasgow, Scotland; AIAA 2015-3530; July 2015; https://arc.aiaa.org/doi/pdf/10.2514/6.2015-3530

Note: The above references are open literature references. Other references exist regarding this technology, but they are International Traffic in Arms Regulations (ITAR) restricted. Numerous online references exist for the subject technology and projects/applications noted, both foreign and domestic.

T9.02 Rapid Development of Advanced High-Speed Aerosciences Simulation Capability (STTR)

Lead Center: **ARC**

Participating Center(s): **JSC, LaRC**

Scope Title:

Aerothermal Simulation on Advanced Computer Architectures

Scope Description:

Aerothermodynamic simulations of planetary entry vehicles such as Orion and Dragonfly are complex and time consuming. These simulations, which solve the multispecies, multitemperature Navier-Stokes equations, require detailed models of the chemical and thermal nonequilibrium processes that take place in high-temperature shock layers. Numerical solution of these models results in a large system of highly nonlinear equations that are exceptionally stiff and difficult to solve efficiently. As a result, aerothermal simulations routinely consume 20 to 50 times the compute resources required by more conventional supersonic computational fluid dynamics (CFD) analysis, limiting the number of simulations delivered in a typical engineering design cycle to only a few dozen. Moreover, entry system designs are rapidly increasing in complexity, and unsteady flow phenomena such as supersonic retropropulsion are becoming critical considerations in their design. This increases the compute resources required for aerothermal simulation by an additional one to two orders of magnitude, which precludes the delivery of such simulations in engineering-relevant timescales.

In order to deliver the aerothermal simulations required for NASA's next generation of entry systems, access to greatly expanded compute resources is required. However, scaling up conventional central processing unit (CPU-) based supercomputers is problematic due to cost and power constraints. Many-core accelerators, such as Nvidia's general-purpose graphical processing units (GPGPUs), offer increased compute capability with reduced cost and power requirements and are seeing rapid adoption in top-end supercomputers. As of June 2020, 144 of the top 500 fastest supercomputers leveraged accelerators or co-processors, including 6 of the top 10 [1]. All three of the U.S. Department of Energy's upcoming exascale supercomputers will be accelerated using GPGPUs [2]. NASA has deployed Nvidia v100 GPGPUs to the Pleiades supercomputer [3]. Critically, NASA's aerothermal simulation tools are fundamentally unable to run on many-core accelerators, and must be reengineered from the ground up to efficiently exploit such devices.

This scope seeks to revolutionize NASA's aerothermal analysis capability by developing novel simulation tools capable of efficiently targeting the advanced computational accelerators that are rapidly becoming standard in the world's fastest supercomputers. A successful solution within this scope would demonstrate efficient simulation of a large-scale aerothermal problem of relevance on an advanced many-core architecture, for example, the Nvidia Volta GPGPU, using a prototype software package.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

The desired deliverable at the conclusion of Phase I is a prototype software package capable of solving the multispecies, multitemperature, reacting Euler equations on an advanced many-core accelerator such as an Nvidia v100 GPGPU. Parallelization across multiple accelerators and across nodes is not required. The solver shall demonstrate offloading of all primary compute kernels to the accelerator, but may do so in a nonoptimal fashion, for example, using managed memory, serializing communication and computation, etc. Some noncritical kernels such as boundary condition evaluation may still be performed on a CPU. The solver shall demonstrate kernel speedups (excluding memory transfer time) when comparing a single accelerator to a modern CPU-based, dual-socket compute node. However, overall application speedup is not expected at this stage. The solver shall be demonstrated for a relevant planetary entry vehicle such as FIRE-II, Apollo, Orion, or the Mars Science Laboratory.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for mission use and commercialization. Kernels for evaluating viscous fluxes shall be added, enabling computation of laminar convective heat transfer to the vehicle. Parallelization across multiple accelerators and multiple compute nodes shall be added. Good weak scaling shall be demonstrated for large 3D simulations (>10M grid cells). The implementation shall be sufficiently optimized to achieve an ~5x reduction in time-to-solution compared to NASA's Data-Parallel Line Relaxation (DPLR) aerothermal simulation code, assuming each dual-socket compute node is replaced by a single accelerator (i.e., delivered software running on eight GPGPUs shall be 5 times faster than DPLR running on eight modern, dual-socket compute nodes). Finally, the accuracy of the delivered software shall be verified by comparing to the DPLR and/or LAURA codes. The verification study shall consider flight conditions from at least two of the following planetary destinations: Earth, Mars, Titan, Venus, and Uranus/Neptune.

State of the Art and Critical Gaps:

NASA's existing aerothermal analysis codes (LAURA, DPLR, US3D, etc.) all utilize domain-decomposition strategies to implement coarse-grained, distributed-memory parallelization across hundreds or thousands of conventional CPU cores. These codes are fundamentally unable to efficiently exploit many-core accelerators, which require the use of fine-grained, shared-memory parallelism over hundreds of thousands of compute elements. Addressing this gap requires reengineering our tools from the ground up and developing new algorithms that expose more parallelism and scale well to small grain sizes.

Many-core accelerated CFD solvers exist in academia, industry, and government. Notable examples are PyFR from Imperial College London [4], the Ansys Fluent commercial solver [5], and NASA Langley's FUN3D code, which recently demonstrated a 30x improvement in node-level performance using Nvidia v100 GPUs [6].

However, nearly all previous work has focused on perfect gas flow models, which have different algorithmic and resource requirements compared to real gas models. The Sandia Parallel Aerodynamics and Reentry Code (SPARC) solver is the only project of note to have demonstrated efficient real-gas capability at scale using many-core accelerators [7].

Relevance / Science Traceability:

This scope is directly relevant to NASA space missions in both HEOMD and SMD with an entry, descent, and landing (EDL) segment. These missions depend on aerothermal CFD to define critical flight environments and would derive large, recurring benefits from a more responsive and scalable simulation capability. This scope also has potential cross-cutting benefits for tools used by ARMD to simulate airbreathing hypersonic vehicles. Furthermore, this scope directly supports NASA's CFD Vision 2030 Study, which calls for sustained investment to ensure that NASA's computational aeroscience capabilities can effectively utilize the massively parallel, heterogeneous (i.e., GPU-accelerated) supercomputers expected to be the norm in 2030.

References:

1. "Japan Captures TOP500 Crown with Arm-Powered Supercomputer," June 22, 2020.
2. R. Smith: "El Capitan Supercomputer Detailed: AMD CPUs & GPUs To Drive 2 Exaflops of Compute," March 4, 2020.
3. NASA HECC Knowledge Base: "New NVIDIA V100 Nodes Available," 21 June, 2019.
4. F. Witherden, et al.: "PyFR: An Open Source Framework for Solving Advection–Diffusion Type Problems on Streaming Architectures Using the Flux Reconstruction Approach," Computer Physics Comm., vol. 185, no. 11, pp. 3028-3040, 2014.
5. V. Sellappan and B. Desam: "Accelerating ANSYS Fluent Simulations with NVIDIA GPUs," 2015.
6. E. Neilsen, et al.: "Unstructured Grid CFD Algorithms for NVIDIA GPUs," March 2019.
7. M. Howard, et al.: "Employing Multiple Levels of Parallelism for CFD at Large Scales on Next Generation High-Performance Computing Platforms," ICCFD10, Barcelona, Spain, 2018.
8. J. Slotnick, et al.: "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR–2014-218178, March 2014.

Scope Title:

Robust Aerothermal Simulation of Complex Geometries

Scope Description:

NASA's production aerothermodynamic flow solvers all share a common characteristic: they utilize second-order accurate finite volume schemes to spatially discretize the governing flow equations. Schemes of this type are ubiquitous in modern compressible CFD solvers. They are simple to implement, perform well on current computer architectures, and provide reasonable accuracy for a wide range of problems. Unfortunately, one area where these schemes struggle to deliver high accuracy is at hypersonic speeds when a strong shock wave forms ahead of the vehicle. In such cases, the computed surface heat flux exhibits extreme sensitivity to the design of the computational grid near the shock [1], which must be constructed from cell faces that are either parallel or perpendicular to the shock to minimize error.

This stringent requirement for shock-aligned grids precludes the use of fully unstructured tetrahedral meshes in aerothermal simulation. While this restriction is manageable for simple or idealized entry systems [2], unstructured grids have significant accuracy and efficiency benefits for complex vehicle geometries, for example, ADEPT, and flow fields, for example, Mars 2020 reaction control system (RCS) firings, where large disparities in length scales must be resolved accurately. Moreover, unstructured grids can be developed much more rapidly and with a much higher degree of automation than traditional structured grid topologies [3]. As such, they are widely used in most other CFD subdisciplines.

Fortunately, recent research has demonstrated that high-order, finite-element schemes such as the Discontinuous Galerkin (DG) method can achieve high-quality solutions for shock-dominated flows on unstructured grids when appropriate stabilization mechanisms are employed [4][5]. This research also suggests high-order methods are largely insensitive to the choice of the upwind flux function, potentially resolving a long-standing deficiency of second-order finite volume schemes at high speeds. However, while DG methods are robust and commonly applied in subsonic regimes, their continued development for aerothermal applications is hampered by ad hoc implementations in research-level codes.

This scope seeks to revolutionize NASA’s aerothermal analysis capability by enabling rapid, robust, and highly automated analysis of complex entry systems using fully unstructured tetrahedral grids. A successful solution within this scope would demonstrate accurate simulation of a 3D capsule geometry at conditions relevant to planetary entry using DG or an equivalent numerical scheme in a prototype software package.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype

Desired Deliverables Description:

The desired deliverable at the conclusion of Phase I is a prototype software package capable of solving the two-dimensional, multispecies, multitemperature, reacting Euler equations on unstructured triangular grids at planetary entry velocities (>7 km/s). The software shall demonstrate robust capturing of the bow shock ahead of a simple cylinder at a variety of flight conditions without requiring adjustment of algorithm parameters, for example, artificial viscosity scale factors. The postshock flow field shall be free of the numerical noise in the entropy field, which is typical of conventional second-order finite volume schemes on triangular grids. Convergence to machine precision shall be demonstrated for all calculations.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for use on mission-relevant engineering problems. Extension to the laminar, multispecies, multitemperature Navier-Stokes equations shall be implemented. Extension to three spatial dimensions using unstructured tetrahedral grids shall be implemented, with efficient multinode parallelization targeting modern high-performance computing (HPC) platforms such as the NASA Pleiades supercomputer. The software shall be demonstrated on a range of planetary entry problems that include at least two of the following destinations: Earth, Mars, Titan, Venus, and Uranus/Neptune. Surface heat flux predictions shall be verified by comparison with NASA's DPLR and/or LAURA simulation codes, and must be free of numerical noise typically observed when using second-order finite volume codes on unstructured tetrahedral grids. Computational performance, as measured by total time-to-solution for a given heat flux accuracy, shall be characterized and compared to DPLR/LAURA, but no specific performance targets are required.

State of the Art and Critical Gaps:

Multiple academic [4][5][6][7] and NASA [8] groups have demonstrated promising results when using high-order DG/finite element methods (FEMs) to perform steady-state aerothermodynamic analysis at conditions relevant to planetary entry. The bulk of these studies were conducted using structured grids with some degree of shock alignment (though not sufficient alignment to support a second-order finite volume scheme). However, [4] and [5] demonstrate equally accurate results on fully unstructured grids, suggesting that their technologies are capable of meeting the objectives of this scope. An additional shortcoming of current research is that all efforts examine the same 5 km/s flight condition (relatively slow for planetary entry) with simplistic, nonionized flow models. An infusion of resources is needed to mature these promising algorithms into scalable, production-ready software that can be tested across a full entry trajectory with best-practice thermochemical models.

Relevance / Science Traceability:

This scope is directly relevant to NASA space missions in both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) with an EDL segment. These missions depend on aerothermal CFD to define critical flight environments and would see significant, sustained reductions in cost and time-to-first-solution if an effective unstructured simulation capability is deployed. This scope also has strong crosscutting benefits for tools used by ARMD to simulate airbreathing hypersonic vehicles, which have stringent accuracy requirements similar to those in aerothermodynamics. Finally, this scope aligns with NASA's CFD Vision 2030 Study, which calls for a "much higher degree of automation in all steps of the analysis process" with the ultimate goal of making "mesh generation and adaptation less burdensome and, ultimately, invisible to the CFD process." In order for the aerothermal community to realize these goals, we must eliminate our dependence on manually designed, carefully tailored, block structured grids. This scope is an enabling technology for that transition.

References:

1. Candler, et al.: "Unstructured Grid Approaches for Accurate Aeroheating Simulations." AIAA-2007-3959, 2007.
2. Saunders, et al.: "An Approach to Shock Envelope Grid Tailoring and Its Effect on Reentry Vehicle Solutions." AIAA 2007-0207, 2007.
3. Kleb, et al.: "Sketch-to-Solution: A Case Study in RCS Aerodynamic Interaction." AIAA-2020-067, 2020.
4. Ching, et al.: "Shock Capturing for Discontinuous Galerkin Methods With Application to Predicting Heat Transfer in Hypersonic Flows." Journal of Computational Physics, Issue 376, pp. 54-75, 2019.
5. Gao, et al.: "A Finite Element Solver for Hypersonic Flows in Thermochemical Non-equilibrium, Part II." International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 30 No. 2, pp. 575-606, 2020.

Scope Title:

Efficient Grid Adaption for Unsteady, Multiscale Problems

Scope Description:

The current state of the art for production CFD simulation in EDL is the solution of steady-state problems on fixed computational grids. However, most of the current challenge problems in the discipline are unsteady. Examples include supersonic retropropulsion, where engine plumes exhibit unsteady behavior across a wide range of timescales [1]; capsule dynamic stability, where the vehicle pitch motion is amplified by the unsteady wake dynamics [2]; and single-event drag modulation, where a high-drag decelerator is separated from the main vehicle at hypersonic speeds [3]. Successful analysis of these phenomena require simulating many seconds of physical time while simultaneously resolving all features of the flow field with high accuracy. Since critical features, for example, shocks, shear layers, etc., will evolve and move through the computational domain over time, current practice requires large, globally refined grids and stringent limitations on simulation time step. This makes these problems computationally infeasible without dedicated access to leadership-class supercomputers.

One promising method to reduce the cost of these simulations is to employ feature-based grid adaption such that the computational grid is only refined in the vicinity of critical flow features. Adaptive techniques, particularly metric-aligned anisotropic adaption [4], have been shown to dramatically reduce computational cost for a wide range of steady-state flow problems, often by as much as an order of magnitude. These techniques have been successfully used to solve large-scale, EDL-relevant problems with high Reynolds number boundary layers by incorporating prismatic near-wall layers [5]. Application of efficient adaptive techniques to unsteady problems is less established, but recent advancements have demonstrated a nearly 100x reduction in compute time required to achieve an equivalent level of space-time accuracy relative to globally refined grids [6].

This scope seeks to accelerate the infusion of cutting-edge algorithms for unsteady grid adaption that promise to radically reduce the time required to simulate unsteady fluid phenomena. A successful solution within this scope would demonstrate an order of magnitude reduction in computational cost without compromising solution accuracy for an unsteady supersonic or hypersonic flow problem relevant to EDL.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.4 Vehicle Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

The desired deliverable at the conclusion of Phase I is a prototype software package employing adaptive grid refinement algorithms for the simulation of unsteady, shocked flows in at least two spatial dimensions. An inviscid, perfect gas model is acceptable for Phase I efforts. The prototype software shall be demonstrated on a suitable challenge problem. Suggested challenge problems are prescribed motion of a cylinder relative to the computation domain subject to Mach 6+ supersonic flow or 2D axisymmetric simulation of a shock tube with an initial pressure ratio >50. Other challenge problems of similar complexity are acceptable. The prototype software is not expected to be scalable or performant at this stage.

A successful Phase II deliverable will mature the Phase I prototype into a product ready for use on mission-relevant engineering problems. The code shall be extended to solve the unsteady laminar Navier-Stokes equations in three spatial dimensions with appropriate controls to manage adaption in the boundary layer and the far field, if needed. Extension to reacting, multitemperature gas physics is desired, but not required. The software shall be parallelized to enable simulation of large-scale problems using modern HPC platforms such as the NASA Pleiades supercomputer. The software shall be demonstrated on a 3D challenge problem such as a single jet supersonic retropropulsion configuration at zero angle of attack; free-to-pitch simulation of the Orion entry capsule at supersonic free-stream conditions; or aerodynamic interaction and separation of multiple spheres in a supersonic free stream. The software shall demonstrate a 10x speedup relative to a nonadaptive, time-marched calculation without significantly degrading simulation accuracy as measured by an appropriate solution metric (average reflectance measurement system (RMS) pressure fluctuation, final capsule pitch angle, etc.).

State of the Art and Critical Gaps:

Multiple academic, government, and commercial software packages exist that implement some form of solution-adaptive mesh refinement. NASA's LAURA and DPLR codes offer simplistic clustering algorithms for structured grids that solve the limited problem of resolving strong bow shocks [7][8]. NASA's FUN3D code implements an advanced metric-based, anisotropic refinement capability that has been demonstrated on large-scale aerospace calculations [7]. However, unsteady solution-adaptive algorithms have yet to be demonstrated for EDL-relevant problems outside of academic research codes. Significant investment is required to implement these algorithms into a production-quality flow solver with the performance and scaling characteristics required to address NASA's requirements for unsteady flow simulation.

Relevance / Science Traceability:

This scope has extremely broad applicability across multiple NASA mission directorates. In particular, ARMD, HEOMD, SMD, and STMD each contend with complex, unsteady flow phenomena that could be more readily analyzed with the aid of the proposed technology: flutter analysis, parachute inflation, fluid slosh, and atmospheric modeling are just a few examples. In EDL specifically, a robust time-space adaption capability would enable simulation of supersonic retropropulsion at Mars using NASA's existing supercomputing assets. Capsule stability could be analyzed in the preliminary design phase, allowing mission designers to utilize low-heritage capsule shapes without adding significant cost or risk to the project. Drag skirt separation could be modeled in detail to reduce risk prior to a technology demonstration mission. The potential benefits of this technology are widespread, making this a critical investment area for the Agency.

References:

1. Korzun, et al.: "Effects of Spatial Resolution on Retropropulsion Aerodynamics in an Atmospheric Environment." AIAA-2020-1749, 2020.
2. Hergert, et al.: "Free Flight Trajectory Simulation of the ADEPT Sounding Rocket Test Using US3D." AIAA-2017-446, 2017.
3. Rollock, et al.: "Analysis of Hypersonic Dynamics During Discrete-Event Drag Modulation for Venus Aerocapture." AIAA-2020-1739.
4. Alauzet, et al.: "A decade of progress on anisotropic mesh adaptation for computational fluid dynamics." Computer Aided Design, Issue 72, pp. 13-39, 2016.
5. Sahni, et al.: "Parallel Anisotropic Mesh Adaptation with Boundary Layers for Automated Viscous Flow Simulations." Engineering With Computers, Issue 33, pp. 767–795, 2016.
6. Alauzet, et al.: "Time-accurate multi-scale anisotropic mesh adaptation for unsteady flows in CFD." J. of Computational Physics, Issue 373, pp. 28-63, 2018.
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8. Gnoffo: "A finite-volume, adaptive grid algorithm applied to planetary entry flowfields." AIAA Journal, Volume 21, No. 9, 1983.
9. Bartels, et al.: "FUN3D Grid Refinement and Adaptation Studies for the Ares Launch Vehicle." AIAA-2010-4372, 2010.

Z7.01 Entry, Descent, and Landing Flight Sensors and Instrumentation (SBIR)

Lead Center: **JSC**

Participating Center(s): **ARC, GSFC, JPL, LaRC**

Scope Title:

High-Accuracy, Lightweight, Low-Power Fiber-Optic or Recession Sensing System for Thermal Protection Systems and Low-Cost Data Acquisition System

Scope Description:

Current NASA state-of-the-art entry, descent, and landing (EDL) instrumentation and associated data acquisition are very expensive to design and incorporate on planetary missions because they must meet functional and performance requirements during and after exposure to loads and environments associated with spaceflight and atmospheric entry.

Commercial fiber-optic systems offer an alternative to traditional sensors that could result in a lower overall cost and weight reduction while actually increasing the number of measurements. Fiber-optic systems are also immune to electromagnetic interference (EMI), which reduces design and qualification efforts. This would be highly beneficial to future planetary missions requiring thermal protection systems (TPSs). In addition, as NASA looks to the future of science missions to the outer planets, extreme entry environments will require the new, 3D-woven Heatshield for Extreme Entry Environment Technology (HEEET) TPS recently matured within the Agency. Gathering flight performance data on this new material will be key—particularly the measurement of recession, which was so very important on the Galileo probe mission to Jupiter. Minimizing the sensor intrusion of the outer mold line is critical in this case because the extreme environment dictates that the TPS be as aerothermally monolithic as possible. In applications to planetary entry vehicles greater than about 1 m in diameter, however, the HEEET TPS is expected to contain seams that might be used for accommodating instrumentation.

Recession measurements in carbon fiber/phenolic TPSs such as Phenolic Impregnated Carbon Ablator (PICA) and AVCOAT are also of interest. When ablation is not severe and/or rapid, accurate measurements have proven difficult with the historic Galileo-type sensor, which was based on the differential resistance resulting from sensor materials that have charred.

To be considered against NASA state-of-the-art TPS sensing systems for future flight missions, fiber-optic systems must be competitive in sensing capability (measurement type, accuracy, and quantity) and associated data acquisition system mass, size, power, and cost. Therefore, NASA is looking for a fiber-optic system that can meet the following requirements:

- TPS Temperature
    - Measurement Range: -200 to 1,250 ºC (up to 2,000 ºC is preferred).
    - Accuracy: +/-5 ºC desired.
- Surface Pressure
    - Measurement Range: 0 to 15 psi.
    - Accuracy: < +/-0.5%.

Destinations such as Mars, Venus, and Titan pose many challenges for EDL data acquisition systems, including radiation, g-loading, and volume constraints. Recent notable examples of such systems are the Mars Entry, Descent, and Landing Instrument (MEDLI) sensor suite, which successfully acquired EDL data in 2012, and the upcoming MEDLI2 system, which will gather data during EDL at Mars in February of 2021. The NASA MEDLI and MEDLI2 data systems are very well designed and robust to the extreme environments of space transit and EDL, but this comes at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limiting the EDL science that can be conducted by NASA. In an effort to bring EDL instrumentation to all missions, NASA is seeking a low-cost, robust, high-accuracy data acquisition system that can meet the following requirements:

- Performs instrument signal conditioning and analog-to-digital conversion, and includes a spacecraft bus serial interface.
- Weight: 5 kg or less.
- Size: Modularity encouraged; maximum module size 10 cm^3; 4 modules maximum.
- Power: 16 W or less.
- Measurement Resolution: 12-bit or higher.
- Accuracy: +/-0.5% of full-scale output.
- Acquisition Rate per Measurement: 8 Hz or higher.
- Radiation Tolerant by Design: Minimum of 10 kRad (30 kRad or better desired).
- Axial Loading Capability: Minimum 15g (Venus missions could require 100g to 400g).
- Operating Temperature Capability: -40 °C to 85 °C.
- Cost: Fully qualified target of ~$1M (recurring).
- Sensor Compatibility.
    - Minimum 15 thermocouples with at least 2 Type R and 8 Type K.
    - Minimum 8 pressure transducers (120 or 350 ohm bridge).

For recession measurements acquired in extreme entry environments requiring 3D woven TPSs, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above and meet the following requirements:

- Up to 5,000 W/cm^2 total heat flux (convective plus radiative).
- Up to 5 atmospheres of pressure on the vehicle surface.
- Minimum recession measurement accuracy within +/-1 mm.

For recession measurements in moderate entry environments requiring carbon fiber/phenolic TPSs, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

- 150 to 2,000 W/cm^2 total heat flux (convective plus radiative).
- Up to 1 atmosphere of pressure on the vehicle surface.
- Minimum recession measurement accuracy within +/-1 mm.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

- Hardware
- Software

Desired Deliverables Description:

Phase I Goals: Design and proof of concept, including the production approach to achieve the cost goals.

Phase II Goals: Prototype/breadboard validation in laboratory environment.

State of the Art and Critical Gaps:

NASA now requires instrumentation on all EDL missions, including competed science missions, and these cost- and mass-constrained missions cannot use the state-of-the-art instrumentation.

Relevance / Science Traceability:

EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation, and in-flight performance of planetary entry systems. Improved understanding of entry environments and TPS performance could lead to reduced design margins, enabling a greater payload mass-fraction and smaller landing ellipses. Improved real-time measurement knowledge during entry could also minimize the landing dispersions for placing advanced payloads onto the surface of atmospheric and airless bodies.

NASA science missions are frequently proposed that include high-speed Earth return (New Frontiers, Discovery, and Mars Sample Return) and Venus and Mars entry. Capsules used for these missions must withstand both convective and radiative aeroheating, and NASA now requires EDL instrumentation for these missions. Current radiative measurement techniques (radiometers) provide only an integrated heating over a limited wavelength range; past interpretation of such flight data [Ref. 3, 4] shows the need for spectrally resolved measurements from spectrometers. For Earth and Venus, the radiative component may be the dominant source of heating, and emission comes from the vacuum ultraviolet (VUV), which NASA currently has no capability to measure. For Mars and Venus, the aftbody radiation is dominated by midwave infrared (MWIR). Again, NASA does not have a method to measure MWIR radiation in flight; the current radiometers integrate across several band systems. Miniaturized spectrometers that can measure in VUV and MWIR would have immediate application to Science Mission Directorate (SMD) planetary missions. Such spectrometers may also inform what ablation species are emitted from the heat shield and backshell during entry.

References:

1. M. Munk, A. Little, C. Kuhl, D. Bose, and J. Santos, "The Mars Science Laboratory (MSL) Entry, Descent and Landing Instrumentation (MEDLI) Hardware," Proc. AAS/AIAA Space Flight Mechanics Conference, AAS 13-310, Kauai, HI, 2013.
2. F. Milos, "Galileo Probe Heat Shield Ablation Experiment," Journal of Spacecraft and Rockets, Vol. 34, No. 6, Nov-Dec 1997.
3. B. A. Cruden and C. O. Johnston, "Characterization of EFT-1 Radiative Heating and Radiometer Data," 46th AIAA Thermophysics Conference, Washington, D.C., June 2016.
4. A. Brandis, C. O. Johnston, B. A. Cruden, D. Prabhu, and D. Bose, "Uncertainty Analysis and Validation of Radiation Measurements for Earth Reentry," Journal of Thermophysics and Heat Transfer, Vol. 29, No. 2, 2015, pp. 209-221.

Scope Title:

Novel Lidar Component Technologies Applicable to Guidance, Navigation, and Control (GN&C) for Precise Safe Landing

Scope Description:

NASA is seeking the development of component technologies for advanced lidar sensors that will be utilized within Entry, Descent, and Landing (EDL) and Deorbit, Descent, and Landing (DDL) Guidance, Navigation, and Control (GN&C) systems for precise safe landing on solid solar system bodies, including planets, moons, and small celestial bodies (e.g., asteroids and comets). The EDL phase applies to landings on bodies with atmospheres, whereas DDL applies to landings on airless bodies. For many of these missions, EDL/DDL represents one of the riskiest flight phases. NASA has been developing technologies for precision landing and hazard avoidance (PL&HA) to minimize the risk of the EDL/DDL phase of a mission and to increase the accessibility of surface science targets through precise and safe landing capabilities. One flight instrumentation focus of PL&HA technology has been in the development of lidar technologies that either provide terrain mapping (range point cloud) capability or direct velocity measurement. The continued maturation of these technologies is targeting (1) further size, mass, and power reductions of components; (2) multicomponent integration; and (3) multimodal operation (i.e., combing mapping and velocimetry functions).

This solicitation is requesting specific lidar system components and not complete lidar solutions. To be considered, all component technologies proposed must show a development path to operation within the applicable EDL/DDL spaceflight environment (radiation, thermal, vacuum, vibration, etc.). The specific lidar component technologies desired include the following:

- Dense focal plane arrays for simultaneous ranging and Doppler velocimetry, plus associated signal processing approaches including photonic integrated circuits (PICs), with the following characteristics:
    - Simultaneous measurements from each pixel or from subsets of pixels.
    - Functionality (when integrated into a lidar system) that would operate up to 8 km range.
    - Functionality (when integrated into a lidar system) for measuring velocity from 0 m/sec along the line of sight (LOS) up to 200 m/sec or greater.
    - PICs approaches that integrate multiple components into a single device or provide a single component in a miniaturized robust package (e.g., master laser, modulator, and detectors).
    - Ability to reject false locks on dust plumes due to exhaust.
    - Implementation for low power, mass, and size.
    - Optical losses comparable with fiber-optic or bulk optical components.
- High-speed (5 MHz) wavelength tuning laser modules with low power driving electronics, which have random wavelength access or predefined wavelength-lookup-table tuning, and meet the following requirements:
    - Semiconductor laser module.
    - Tuning range: 1550 nm with tuning range of C-band.
    - Tuning speed: 5 MHz, and less than 100 ns settling time.
    - Wavelength grid: 10,000 evenly distributed over the whole tuning range.
    - Tuning fashion: Random wavelength grid access, or sequential predefined wavelength lookup table tuning.
    - High wavelength and power repeatability.

- Low temperature or environmental dependency.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The following deliverables are desired for Phase I: (1) Hardware demonstrations of sensor components and applicable support hardware and/or (2) Analysis and software simulations of component proofs of concept within simulated environments. Responses must show a path for the proposed capabilities to be compatible with the environmental conditions of spaceflight.

The following deliverables are desired for Phase II: (1) Hardware demonstrations of sensor components and applicable support hardware and (2) Analysis of components in laboratory or relevant environment (depending on TRL). Phase II products will need to demonstrate a path for the capabilities to be compatible with the environmental conditions of spaceflight.

State of the Art and Critical Gaps:

The EDL GN&C and sensors community has been developing for more than a decade the technologies to enable precise safe landing. Infusion of these capabilities into spaceflight missions and spinoff into the commercial sector remains the critical gap. Bridging this gap requires additional component technology advancements for specific lidar sensors that enhance operational performance, increase dynamic envelope, reduce size/mass/power/cost, and enable spaceflight qualification.

Relevance / Science Traceability:

GN&C/PL&HA technologies for precise safe landing are critical for future robotic science and human exploration missions to locations with hazardous terrain and/or pre-positioned surface assets (e.g., cached samples or cargo) that pose significant risks to successful spacecraft touchdown and mission surface operations. The PL&HA technologies enable spacecraft to land with minimum position error from targeted surface locations, and they implement hazard-avoidance diverts to land at locations safe from lander-sized or larger terrain hazards (e.g., craters, rocks, boulders, sharp slopes, etc.). PL&HA has maintained consistent prioritization within the NASA and National Research Council (NRC) space technology roadmaps for more than a decade, and multiple near-term science missions, such as Mars 2020, are starting to infuse some of the PL&HA capabilities.

References:

1. *A. Martin et al., "Photonic integrated circuit-based FMCW coherent LiDAR," in Journal of Lightwave Technology, vol. 36, no. 19, 4640-4645, Oct.1, 2018, doi: 10.1109/JLT.2018.2840223.*
2. *C.V. Poulton, A. Yaacobi, D.B. Cole, M.J. Byrd, M. Raval, D. Vermeulen, and M.R. Watts, "Coherent solid-state LIDAR with silicon photonic optical phased arrays," Opt. Lett. 42, 4091-4094 (2017).*

3. *F. Amzajerdian, G.D. Hines, D.F. Pierrottet, B.W. Barnes, L.B. Petway, and J.M. Carson, "Demonstration of coherent Doppler lidar for navigation in GPS-denied environments," Proc. SPIE 10191, Laser Radar Technology and Applications XXII, 1019102 (2017).*

Z7.03 Entry and Descent System Technologies (SBIR)

Lead Center: **LaRC**

Participating Center(s): **ARC**

Scope Title:

Entry and Descent System Technologies

Scope Description:

Background: NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan, as well as payload return to Earth from low Earth orbit. The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system are not constrained by the launch vehicle shroud. They have the flexibility to more efficiently use the available shroud volume and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology also enables delivery of very large (20 metric tons or more) usable payload, which will likely be needed to support human exploration. The technology also allows for reduced cost access to space by enabling the recovery of launch vehicle assets. This subtopic area solicits innovative technology solutions applicable to deployable entry concepts. Specific technology development areas include:

1. Advancements in textile manufacturing technologies that can be used to simplify production, reduce the mass, or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their flexible thermal protection system. Thermal protection concepts can also lead to improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1,200 °C). Concepts can be either passive or active dissipation approaches. For smaller scale inflatable systems for small-spacecraft/satellite applications, less than 5 m in diameter, thin-ply or thin-film manufacturing approaches that can be used to reduce the minimum design gauge are of particular interest for inflatable structures.
2. High-temperature-capable structural elements to support mechanically deployable decelerators that surpass the performance capability of metallic ribs, joints, and struts. Anticipated systems would include composite elements or hybrid approaches that combine metallic structures with high-temperature-capable interface materials to improve thermal performance. Minimum-mass approaches that address volumetric/packing efficiencies at small-scale (approx. 1 to 2 m) implementations are of interest for small-satellite applications.
3. Development of gas-generator technologies used as inflation systems that result in improved mass efficiency and system complexity over both current pressurized cold gas systems and present state-of-the-art gas generators for inflatable structures. Inflation gas technologies can include warm or hot gas generators, sublimating powder systems, or hybrid systems; however, the final delivery gas temperature must not exceed 200 °C. Lightweight, high-efficiency gas inflation technologies capable of delivering gas at 250 to 10,000 standard liters per minute (SLPM) are sought. This range spans a number of potential applications. Thus, a given response need not address the entire range. Additionally, the final delivery gas and its byproducts must not harm

aeroshell materials, such as the fluoropolymer liner of the inflatable structure. Minimal solid particulate is acceptable as a final byproduct. Water vapor as a final byproduct is also acceptable for lower flow (250 to 4,000 SLPM) and shorter duration missions, but it is undesirable for higher flow (8,000 to 10,000 SLPM) and longer duration missions. Chillers and/or filters can be included in a proposed solution, but they will be included in assessing the overall system mass versus amount of gas generated.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Reports documenting analysis and development results, including description of any hardware or prototypes developed. Focus for Phase I development should be material coupon up to subscale manufacturing demonstration articles that demonstrate proof of concept, and lead to Phase II manufacturing scaleup and testing in relevant environments for applications related to Mars entry, Earth return, launch asset recovery, or the emergent small-scale satellite community.

State of the Art and Critical Gaps:

The current state of the art for deployable aerodynamic decelerators is limited due to the novelty of this technology. Developing more efficient, lighter, and thinner flexible thermal protection system component materials with higher temperature capability could potentially enable more efficient designs and extend the maximum range of use of the concepts. Novel and innovative high-temperature structural concepts are needed for the mechanically deployed decelerator. Development of gas generator technologies that improve mass efficiency over current pressurized cold gas systems for inflatable structures is needed.

Relevance / Science Traceability:

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan, as well as payload return to Earth from low Earth orbit. The Human Exploration and Operations Mission Directorate (HEOMD), Space Technology Mission Directorate (STMD), and Science Mission Directorate (SMD) can benefit from this technology for various exploration missions.

References:

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- Bose, D. M, et al., “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389.
- Olds, A. D., et al., “IRVE-3 Post-Flight Reconstruction,” AIAA Paper 2013-1390.
- Cassell, A., et al., “ADEPT, A Mechanically Deployable Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions,” SSC18-XII-08, 32nd Annual AIAA/USU Conference on Small Satellites.
- Cassell, A., et al., "ADEPT Sounding Rocket One Flight Test Overview," AIAA Paper 2019-2896.

Z7.04 Landing Systems Technologies (SBIR)

Lead Center: **MSFC**

Participating Center(s): **GRC, LaRC**

Scope Title:

Landing Systems Technologies

Scope Description:

Plume-Surface Interaction (PSI) Instrumentation, Ground Testing, and Analysis

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in close proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission needs to consider include landers with single and multiple engines, both pulsed and throttled systems, landed mass from 400 to 40,000 kg, and both lunar and Mars destinations.

NASA is seeking support in the following areas:

1. Ground test data, test techniques, and diagnostics across physical scales and environments, with particular emphasis on nonintrusive approaches and methodologies.
2. PSI-specific flight instrumentation, with particular emphasis on in situ measurements of particle size and particle velocity during the landing phase.
3. Solutions to alleviate or mitigate the PSI environments experienced by propulsive landers.
4. Validated computational fluid dynamics (CFD) models and tools for predicting PSI physics for plumes in low-pressure and rarefied environments, time-evolving cratering and surface erosion, and near-field and far-field ejecta transport.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020, and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.3 Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Deliverables of all types can be infused into the prospect missions due to early design maturity.

For PSI ground test data, flight instrumentation, diagnostics, and mitigation approaches, Phase I deliverables should include detailed test plans, with prototype and/or component demonstrations as appropriate. Phase II deliverables should include complete data products, fully functional hardware, and validated performance in relevant environments.

For PSI modeling and simulation, Phase I deliverables should demonstrate proof of concept and a minimum of component-level verification, with detailed documentation on future data needs to complete validation of the integrated model and uncertainty quantification methodology. Phase II deliverables must demonstrate verification and validation beyond the component level, with validation demonstrated through comparisons with relevant data and documented uncertainty quantification.

State of the Art and Critical Gaps:

The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model PSIs on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools for validation purposes. The validation dataset, as well as the expertise, grows as a result of each mission and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability in order to provide data for tool validation.

The current post-landing analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically-validated tools, because there has been no dedicated fundamental research investment in this area. Flight test data does not exist in the environments of interest.

Relevance / Science Traceability:

Current and future lander architectures will depend on knowledge of PSI, such as:

- Artemis Human Lander System (HLS)
- Commercial robotic lunar landers (CLPS or other)
- Planetary mission landers (Mars Sample Retrieval Lander and others)
- Human Mars landers

References:

Lander Technologies: https://www.nasa.gov/content/lander-technologies

Metzger, Philip, et al. ISRU implications for lunar and martian plume effects. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. 2009.

Plemmons, D. H., et al. (2008). Effects of the Phoenix Lander descent thruster plume on the Martian surface. Journal of Geophysical Research: Planets, 113(E3).

Mehta, M., et al. (2013). Thruster plume surface interactions: Applications for spacecraft landings on planetary bodies. AIAA Journal, 51(12), 2800-2818.

Vangen, Scott, et al. International Space Exploration Coordination Group Assessment of Technology Gaps for Dust Mitigation for the Global Exploration Roadmap. AIAA SPACE 2016. 2016. 5423.

Z7.06 Entry, Descent, and Landing (EDL) Terrestrial Testing Technologies (SBIR)

Lead Center: **ARC**

Participating Center(s): **LaRC**

Scope Title:

Optical and Laser-Spectroscopic Imaging Techniques for High-Enthalpy Arc-Heated Test Facilities

Scope Description:

Arc-heated high-enthalpy test facilities at NASA's Ames and Langley Research Centers are used for evaluation and certification of high-temperature materials and structures of an entry vehicle's thermal protection system (TPS). Future exploration missions will utilize new ablative TPS materials that release decomposition products into the gas stream ahead of the vehicle, influencing flow-field behavior. Data and observations from materials testing programs using NASA's arc jet facilities are critical for validation of high-fidelity modeling and simulation tools used to design and margin TPS specifications for entry vehicles. However, the complex multiphysics processes that manifest as entry aeroheating of ablative TPSs present formidable challenges for model validation. The available diagnostic techniques for arc jet testing provide little direct evidence of the subject aerothermal and thermophysical processes.

NASA is seeking advanced and new optical and laser-spectroscopic techniques applied to arc jet testing programs. Experimental methods for arc jet facility characterization strive to quantify thermodynamic and gas dynamic properties of the arc jet stream and serve multiple purposes, such as verification of test conditions (facility operations), validation of arc heater and flow-field simulations, and measurement of incident/boundary conditions for material response simulations. Of equal importance are methods that can detect and identify pyrolysis gases and particles injected into the shocked gas region ahead of TPS material test articles, providing needed insight to the complex interactions of the flow field with material response. Experimental methods that measure recession, temperature, and optical properties of the TPS surface enable characterization of surface thermal response phenomenology.

The off-body gas phase diagnostics are to detect and quantify:

- Major species in the arc jet stream (N, O, N_2, NO for air; CO and CO_2 for facilities capable of operating with CO_2 mixtures).
- Ablation species and recombination products in the shock layer (C, CN, CH, H, Ca).
- Spalled particles from test articles penetrating the shock layer.

Also of importance are measurements of velocity and free stream and shock layer temperatures, including vibrational temperature. Planar or line imaging techniques are desired to characterize spatial distributions with 1-mm or smaller resolution at kHz data rates. Burst mode (>100 kHz) imaging approaches that enable correlation of temporal-spatial intermittencies are of particular interest.

The requested surface imaging diagnostics are to measure test-article temperature and spectral emissivity, topology, and recession rate. Hyperspectral techniques are preferred if they enable characterization of multiple surface properties simultaneously while discriminating from shock layer radiation. Spatial resolutions and acquisition rates of <1 mm and >30 Hz, respectively, are desired. Adaptation of standoff surface spectroscopy techniques may hold promise for time-resolved species detection and identification.

Spallation characterization requires measurements of ejected particle size distributions, 2D and 3D trajectories, and velocity distributions. Techniques for both stagnation and shear testing configurations are desired. Imaging spatial resolution and field of view needs to account for particle trajectories that travel upstream and penetrate shock waves. Methods that provide insight to the chemical composition of spalled particles would be particularly valuable. Anticipated particle size and speeds are 1 to 100 µm and 1 to 200 m/s, respectively.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Assessment study of potential diagnostic techniques.
Phase II: Prototype instrument demonstration in relevant environment with hardware delivery to NASA.

State of the Art and Critical Gaps:

The requirements for spatially resolved, species-specific measurements of high-temperature-reacting gas properties necessitate the use of optical-spectroscopic methods. The state of the art at NASA's arc-heated facilities are techniques based on nanosecond-pulsed laser-induced fluorescence (ns-LIF). Pointwise flow property measurement requires approximately 60 to 90 sec per acquisition to recover properties calibrated to engineering units (velocity, temperature, species densities) at one location. The low sensitivity and long standoff distances in arc-heated facilities preclude line or planar imaging. The long acquisition times result in a poor use of expensive testing resources. The ns-LIF approach is not suitable for post-shock and near-surface regions, as the moderate pressures, high temperatures, and strong gas and surface luminosity confound signal interpretation, effectively prohibiting quantitative ablation species detection. Emission spectroscopy techniques for free-stream and shock-layer measurements have been used with success for many years, but these are limited to observation of excited-state populations along integrated lines of sight. Tunable laser absorption spectroscopy can target ground-state or excited-state populations of certain species of interest; however, the low-density/high-temperature test conditions and the short path lengths yield absorbances too low for detection with demonstrated laser absorption techniques.

Recent advances in tunable amplified sources pumped by kHz and burst-mode femtosecond-pulse lasers has enabled the development of several nonlinear laser spectroscopy techniques. These new techniques have capabilities that directly address the sensitivity, temporal, and spatial resolution shortcomings identified above.

For spallation diagnostics, both active interrogation/response and passive imaging techniques have potential for characterizing size distributions, trajectories, and velocity distributions. NASA's current capability for observing and quantifying spallation is the use of high-speed gated video, which is limited to situations where particle luminosity can be distinguished from background sources.

Relevance / Science Traceability:

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars Sample Return, high-speed crewed return, high-mass Mars landers, Venus, and gas/ice giant probes. With few exceptions, entry vehicle TPS for these missions will be composed of materials currently under development and without certification heritage in multiple gases. Arc jet testing at conditions relevant for certification will invariably be required for each of these proposed missions. Ground testing at more extreme environments for future missions will challenge existing capabilities. There is a compelling need now to bring research-level diagnostic technologies forward to ensure that facility operations can confidently demonstrate required performance to TPS technology projects.

Conventional instrumentation will continue to be the primary source of facility characterization data. The purposes of the advanced techniques are to provide validating evidence for the conventional instrumentation, reveal error and bias in interpretation of heat flux measurements, and ultimately reduce uncertainty in facility performance data provided to test programs.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. The first-line project is the Space Technology Mission Directorate's Entry Systems Modeling Project.

References:

1. Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/
2. O. Chazot, "Experimental Studies on Hypersonic Stagnation Point Chemical Environment," RTO-EN-AVT-142, Experiment, Modeling and Simulation of Gas-Surface Interactions for Reactive Flows in Hypersonic Flights, pp. 13-1 to 13-32.
3. A. Gülhan, "Heat Flux Measurements in High Enthalpy Flows," RTO EN-8, Measurement Techniques for High Enthalpy and Plasma Flows, April 2000.
4. J. Grinstead, et al., "Consolidated laser-induced fluorescence diagnostic systems for the NASA Ames arc jet facilities," AIAA 2016-4159.
5. S. Bailey, et al., "Experimental analysis of spallation particle trajectories in an arc-jet environment," Experimental Thermal and Fluid Science v. 93, pp. 319-325 (2018).

6. D.A. Codron, “Emission Spectroscopy Characterization of Thermal Protection System Materials in Arc-Heated Flows,” AIAA 2014-2112.
7. J.A. Inman, et al., “Nitric Oxide PLIF Measurements in the Hypersonic Materials Environmental Test System (HYMETS),” AIAA Journal Vol. 51, No. 10, pp. 2365-2379, October 2013.
8. D.J. Bamford, et al., “Characterization of the H1 Arc Heater Facility by Laser-Induced Fluorescence,” AIAA 2013-0035.
9. P. Danehy, et al., “Quantitative Spectral Radiance Measurements in the HYMETS Arc Jet,” AIAA 2012-0856.
10. M. Winter, et al., “Non-Equilibrium Analysis of Emission Spectroscopy Data Taken in the Freestream of the NASA IHF Arc Jet Facility,” AIAA 2015-2963.

Scope Title:

Advanced Instrumentation for NASA's Shock Tube and Ballistic Range Facilities

Scope Description:

NASA Ames Research Center operates two specialized-use impulse test facilities for aerodynamic and aerothermodynamic research investigations that support atmospheric entry systems modeling and validation. The Electric Arc Shock Tube (EAST) facility replicates shocked gas environments encountered by entry vehicles transiting planetary atmospheres at hypersonic velocities. EAST creates these environments through calibrated gas mixtures of target atmospheres (Earth, Venus, Mars, Titan, gas giants, etc.) and prescribed preshock pressures and shock speeds. Radiative heating of both fore- and after-body surfaces of an entry vehicle can influence, and in some cases dominate, the design requirements for thermal protection systems. Spectroscopic instrumentation is used to characterize the absolute radiance and gas kinetics behind a traveling shock wave. The Hypervelocity Free Flight Aerodynamic Facility (HFFAF), an enclosed aeroballistic range, is used for the study of dynamically similar supersonic and hypersonic aerodynamics, transition to turbulence, and laminar and turbulent convective heat transfer. Optical imaging instrumentation is used to characterize aerodynamic forces and moments of scaled models launched through the range. Thermographic and spectral imaging instrumentation is used to characterize spatially resolved heating rates to scaled models.

NASA is seeking innovative imaging and spectroscopic measurement techniques for these two facilities. New electro-optic products and methods will enable measurement of quantities unattainable with current capabilities as well as improve current practices.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: Assessment study of potential diagnostic techniques or technology upgrades.
Phase II: Prototype instrument demonstration in relevant environment (preferably with hardware delivery to NASA).

State of the Art and Critical Gaps:

The EAST facility's instrumentation acquires data for shocked gas phenomenology and facility performance characterization. Measurements of radiance, absorbance, electron density, and temperature are used for validation of comprehensive radiation transport simulations of planetary atmospheres. Those measurements are primarily acquired using calibrated optical-spectroscopic instruments with sufficient temporal and/or spatial resolution to correlate observed magnitudes with localized, spectrally resolved absolute radiant fluxes or columnar property densities (including electron densities). Ancillary instrumentation is used to measure shock arrival times and transient pressures at the tube wall to establish shock speeds adjacent to the science instruments.

Measurement techniques that correlate observables to atomic and molecular state populations and radiance magnitudes enable validation of radiance models. Emission spectroscopy techniques, which capture the transient characteristics of excited atomic and molecular state populations, have reached a high degree of maturity and performance.

However, post-shock electron and ground-state or other dark-state population dynamics also influence shock radiance. Measurement of these states rely on more complicated absorption, induced fluorescence, or scattering (spontaneous and coherent) techniques. The lack of light sources and/or detectors with suitable spectral and temporal characteristics, or the challenges of implementation in impulse facilities, have limited the opportunities for such measurements. Techniques that enable measurement of these states would greatly expand opportunities for radiation transport model validation, particularly for conditions in which self-absorption would influence emission spectroscopy measurements. Specific quantities of interest are rotational/translation and vibrational temperatures, electron temperatures, and ground-state population densities of N_2, N_2+, N, O, CO, CN, H_2, H.

Spatiotemporal resolution is necessary to discern nonequilibrium relaxation processes behind a traveling shock wave and is the key requirement for EAST diagnostics. Field imaging at a single instant in time, or time-resolved imaging of a single point in space, must have resolutions equivalent to >1 mm and >1 µs to capture these relaxation processes.

For the HFFAF, shadowgraph and schlieren photography are used to provide time-resolved imagery for aerodynamic force and moment analyses of scaled flight vehicles in free flight. A high-speed shutter (40-ns duration) and a spark-gap light source enable images to be captured without motion blur or image fogging from shocked gas radiance enveloping a test model. The shuttering system relies on Kerr cells filled with benzonitrile and a 35 kV pulse-shaping and switching network. Advances are sought for the eventual replacement of the 32 heritage light source/shutter systems with components that offer equal or greater performance as well as improved safety and reliability.

Relevance / Science Traceability:

Several potential future missions outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses have ED/EDL (entry and descent or entry, descent, and landing) architectures: Mars sample return, high-speed crewed return, high-mass Mars landers, and Venus and gas/ice giant probes. Entry vehicles to these destinations will encounter radiative heating to varying degrees. Radiative heating of a vehicle's backshell has been recognized as a significant concern, so ensuring a full range of diagnostic techniques for expanding flows has become a high priority for the EDL community.

Characterizing the aerodynamic stability of emerging deployable drag devices for entry vehicles is also of high importance for future high-mass lander missions. The HFFAF will be a key ground-test facility for acquiring crucial free-flight aerodynamic data for study and simulation validation.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. Technology development projects supporting these programs are potential beneficiaries of new instrumentation for the EAST and HFFAF.

References:

1. Entry Systems Modeling Project: https://gameon.nasa.gov/projects/entry-systems-modeling-esm/
2. ADEPT (Adaptable Deployable Entry and Placement Technology) Project: https://gcd.larc.nasa.gov/projects-2/deployable-aeroshell-concepts-and-flexible-tps/
3. Many journal papers, conference proceedings, and technical reports describing the NASA Ames EAST and HFFAF test facilities and research are available in the open literature.

Focus Area 13 Information Technologies for Science Data

Lead MD: **SMD**

Participating MD(s): **N/A**

NASA Missions and Programs create a wealth of science data and information that are essential to understanding our earth, our solar system, and the universe. Advancements in information technology will allow many people within and beyond the Agency to more effectively analyze and apply these data and information to create knowledge. For example, modeling and simulation are being used more pervasively throughout NASA, for both engineering and science pursuits, than ever before. These tools allow high fidelity simulations of systems in environments that are difficult or impossible to create on Earth, allow removal of humans from experiments in dangerous situations, provide visualizations of datasets that are extremely large and complicated, and aid in the design of systems and missions. In many of these situations, assimilation of real data into a highly sophisticated physics model is needed. Information technology is also being used to allow better access to science data, more effective and robust tools for analyzing and manipulating data, and better methods for collaboration between scientists or other interested parties. The desired end result is to see that NASA data and science information are used to generate the maximum possible impact to the nation: to advance scientific knowledge and technological capabilities, to inspire and motivate the nation's students and teachers, and to engage and educate the public.

S5.01 Technologies for Large-Scale Numerical Simulation (SBIR)

Lead Center: **ARC**

Participating Center(s): **GSFC**

Scope Title:

Exascale Computing

Scope Description:

NASA scientists and engineers are increasingly turning to large-scale numerical simulation on supercomputers to advance understanding of complex Earth and astrophysical systems and to conduct high-fidelity aerospace engineering analyses. The goal of this subtopic is to increase the mission impact of NASA's investments in supercomputing systems and associated operations and services. Specific objectives are to:

- Decrease the barriers to entry for prospective supercomputing users.

- Minimize the supercomputer user's total time-to-solution (e.g., time to discover, understand, predict, or design).
- Increase the achievable scale and complexity of computational analysis, data ingest, and data communications.
- Reduce the cost of providing a given level of supercomputing performance for NASA applications.
- Enhance the efficiency and effectiveness of NASA's supercomputing operations and services.

Expected outcomes are to improve the productivity of NASA's supercomputing users, broaden NASA's supercomputing user base, accelerate advancement of NASA science and engineering, and benefit the supercomputing community through dissemination of operational best practices. The approach of this subtopic is to seek novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's high-end computing (HEC) projects: the High End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic are engaged to interact with one or both HEC projects and with key HEC users where appropriate. During the project the lead PI is encouraged to interact with the technical monitor on NASA HEC needs. Projects that require access to NASA HEC resources must provide adequate justification, and proposers should realize that it takes significant amount of time to gain access to on-site resources due to security requirements, which could jeopardize Phase I deliverable timelines. In addition, these resources are heavily used and would be limited for use for SBIR projects.

The technology areas of this subtopic are aligned with two objectives of the NSCI, the National Strategic Computing Initiative, announced by the White House in July 2015. These technologies that are amenable to quick, small efforts for advancement: (1) Technologies to accelerate delivery of a capable exascale computing system delivering approximately 100× the performance of current systems across a range of applications (NSCI Objective 1) and (2) Technologies to increase coherence between the technology base used for modeling and simulation and that used for data analytic computing (NSCI Objective 2).

Expected TRL or TRL Range at completion of the Project: 5 to 7

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.6 Ground Computing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

Novel software and hardware technologies that provide notable benefits to NASA's supercomputing users and facilities, and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's HEC projects: the High End Computing Capability project at Ames and the Scientific Computing project at Goddard.

The expected deliverable for Phase I is research that demonstrates technical feasibility as described in a final report, and the deliverable for Phase II is a prototype demonstration.

Offerors should demonstrate awareness of the state of the art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate. Open-source software and open standards are strongly preferred. Note that the NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict information technology (IT) security requirements.
- Communication-intensive applications.
- Massive computations requiring high concurrency.
- Complex computational workflows and immense datasets.
- The need to support hundreds of complex application codes—many of which are frequently updated by the user/developer.

State of the Art and Critical Gaps:

The state of the art and the critical gaps of the main technologies areas are:

1. NASA science requires at least 100× more powerful supercomputers and 1000× higher application parallelism in 10 years, at the same power.
2. Current technologies for high-fidelity computational simulations and data analytics are distinct, and interfacing them is inefficient.

Relevance / Science Traceability:

Virtually all high-end computing systems and applications can benefit from the deliverables of this subtopic. As the demand for high-end computing continue to grow, there is an increasing need for the solicited technologies in both the government and industry.

References:

NASA High-End Computing Capability Project: https://www.nas.nasa.gov/hecc/about/hecc_project.htm

The National Strategic Computing Initiative: https://www.nitrd.gov/nsci/index.aspx

S5.03 Accelerating NASA Science and Engineering through the Application of Artificial Intelligence (SBIR)

Lead Center: **GSFC**

Participating Center(s): **ARC, JPL, LaRC**

Scope Title:

Accelerating NASA Science and Engineering Through the Application of Artificial Intelligence

Scope Description:

NASA researchers are increasingly using artificial intelligence (AI) and machine learning (ML) technologies across science and engineering to address questions that previously could not be studied, in order to open up new insights. From both the Government and commercial sectors the volume and variety of datasets is increasing at an exponential rate, making it more of a challenge to NASA science and engineering. This subtopic is looking for innovative proposals using AI/ML to address the following unique problems across

NASA. Proposals MUST specify and be in alignment with existing and/or future NASA programs to address or extend a specific need.

This subtopic has the following three critical areas: (1) AI/ML at the Extreme Edge, (2) Rapid Detection of Land Coverage Change, and (3) Rapid Identification of Events in High-Resolution Earth System Model Data. This goal is accomplished by more completely specifying smaller, better defined areas that rest squarely within Focus Area 13 (Information Technologies for Science Data). Proposals for fault management should be addressed in S5.05 Fault Management Technologies (Focus Area 3 Autonomous Systems for Space Exploration). Further, proposals for small spacecraft trajectory control should be addressed in Z3.02 Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control (Focus Area 11 Spacecraft and Platform Subsystems), and proposals for autonomous systems should be addressed in the STTR Topic T4 Autonomous Systems for Space Exploration (subtopic - Integrated Data Uncertainty Management & Representation for Trusted Autonomy in Space).

Proposals should address one of the following focus areas:

- AI/ML at the Extreme Edge
    - With the increase in data rates for instruments, there is an increasing need to compute at the edge, often in constrained computing environments.
    - NASA is interested in the application of AI/ML on spacecraft, rovers, within a constellation of SmallSats, or other remote sensing platforms where the latency and bandwidth between the remote platform and the ground station are not sufficient to adequately download all data. An example of this is the Magnetospheric Multiscale (MMS) mission where a fraction (approximately 2%) of the data taken will be transferred back to Earth.
    - How can training of models be done efficiently at the edge to detect anomalies, perform classifications, segmentation, or run other types of AI/ML models?
- Rapid Detection of Land Cover Change
    - Remote-sensing data of the Earth (both from NASA and commercial sources) is also continuing to increase at dramatic rates, and NASA is interested in using AI/ML to enable the rapid detection of changes in the land use and anomalies across multiple data sets.
    - This will require the potential fusion of multiple satellite datasets, intersensor calibration, geolocation, and more.
- Rapid Identification of Events in High-Resolution Earth System Model Data
    - The Global Modeling and Assimilation Office (GMAO) uses a general circulation model (GCM) called the Goddard Earth Observing System (GEOS) high-performance application to produce model output for instrument design. These nature runs are free-running atmospheric models that are driven by sea surface temperatures with resulting datasets being very large (on the order of petabytes).
    - Instrument teams then use the GEOS output to study the potential impact of additional observations on specific weather phenomena such as hurricanes, weather fronts, mesoscale convective cells, and more.
    - NASA is interested in models that can be trained to rapidly identify these various weather phenomena in the GEOS nature run data. This will be used to create a searchable catalogue of these events for use in observing system simulation experiments (OSSEs).

Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists and/or engineers, show a path toward a Phase II prototype demonstration, with significant communication with missions and programs to later plan a potential Phase III infusion. It is highly desirable that the proposed projects lead to solutions that will be infused into NASA programs and projects.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing
Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Research

Desired Deliverables Description:

Data products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. It is expected that the training sets, models, and resulting data products will be publicly accessible.

In general, the desired outcomes for this subtopic include: (1) new or accelerated science and engineering products, (2) training data sets and trained models specifically for a given problem but that can also be used as a basis for furthering other science and engineering research and development, and (3) resulting data products that can be used and infused in NASA science projects and potentially used to develop new missions.

More specifically,

- Phase I should be used to establish a proof of concept with deliverables including a final report, any software developed, training sets, etc.
- Phase II will expand on this proof of concept to a full prototype with a very similar set of deliverables, including a final report, software, training sets, etc.

State of the Art and Critical Gaps:

NASA science and engineering is making large strides in the use of AI technologies (which includes both machine learning and deep learning). However, the datasets and requirements are growing so rapidly that additional support is needed to fill in gaps. In addition, emerging computational platforms now provide significant improvements in computing capabilities to enable AI to be applied to a wide variety of applications in science and engineering. These emerging computational capabilities have the potential to dramatically speed up AI calculations, and these systems are even being used as the reference architecture for exascale high-performance computing systems.

Relevance / Science Traceability:

Broad applicability across throughout the decadal surveys and satellite development requirements. Specific missions include the Europa Lander, Mars 2020, and more:

- Spacecraft, rovers, constellation of SmallSats, or other remote sensing platforms.
- Global Modeling and Assimilation Office (GMAO) assimilation: Augment Earth system modeling or data assimilation.
- Carbon Cycle Ecosystems Office (CCOE): Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements.
- Earth Observing System Data and Information System (EOSDIS)/Distributed Active Archive Centers (DAACs): Harnessing the potential for new discoveries across the wide array of observation data.

- Earth Science Technology Office (ESTO/AIST): New technology and services to exploit NASA and non-NASA data.
- Computational and Information Sciences and Technology Office (CISTO - Code 606): Technologies used for new data science.
- NASA Center for Climate Simulation (NCCS - Code 606.2): Building applications toward exascale computing.

References:

- Most Recent Decadal Surveys: https://science.nasa.gov/about-us/science-strategy/decadal-surveys
- Mission to Europa—Europa Lander: https://www.jpl.nasa.gov/missions/europa-lander/
- Mars 2020 Mission: https://mars.nasa.gov/mars2020/
- Global Modeling and Assimilation Office: https://gmao.gsfc.nasa.gov/
- NASA Goddard Institute for Space Studies: https://www.giss.nasa.gov/
- NASA Earth Science Data: https://earthdata.nasa.gov/
- NASA Center for Climate Simulation: https://www.nccs.nasa.gov/
- NASA High-End Computing (HEC) Program: https://www.hec.nasa.gov/

In addition, proposers are encourage to search the NASA Technical Report Server (NTRS) for additional information to help guide potential solutions:

- https://ntrs.nasa.gov/

S5.04 Integrated Science Mission Modeling (SBIR)

Lead Center: **JPL**

Participating Center(s): **GSFC**

Scope Title:

Innovative System Modeling Methods and Tools

Scope Description:

NASA seeks innovative systems modeling methods and tools addressing the following needs:

- Define, design, develop, and execute future science missions by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem modeling while enabling these models to be developed earlier in the lifecycle. Ideally, the proposed solutions should leverage MBSE (Model-Based Systems Engineering)/SysML (System Markup Language) approaches being piloted across NASA, allow for easier integration of disparate model types, and be compatible with current agile design processes.
- Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.

- Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.
- Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:
    - Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; methods for characterizing and selecting optimum candidates from those trade spaces, particularly at the architectural level. There is specific interest in models and tools that facilitate comprehensive comparison of architectural variants of systems.
    - Capabilities for rapid-generation models of function or behavior of complex systems at either the system or the subsystem level. Such models should be capable of eliciting robust estimates of system performance given appropriate environments and activity timelines, and should be tailored:
        - To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of autocoding.
        - To operate within highly distributed, collaborative design environments, where models and/or infrastructure that support/encourage designers are geographically separated (including Open Innovation environments). This includes considerations associated with near-real-time (concurrent) collaboration processes and associated model integration and configuration management practices.
    - To be capable of execution at variable levels of fidelity/uncertainty. Ideally, models should have the ability to quickly adjust fidelity to match the requirements of the simulation (e.g., from broad-and-shallow to in-depth and back again).Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc., and associated tools and methods that allow for integration into system design/process models for simulation of instrument responses. These models may be algorithmic or numeric, but should be useful to designers wishing to optimize remote sensing systems for those planets

Note that this topic area addresses a broad potential range of science mission-oriented modeling tools and methods. This includes the integration of these tools into broader model-based engineering frameworks, and also includes proposals with MBSE/SysML as the primary focus.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Research

Desired Deliverables Description:

Phase I should provide a final report that describes the methodology and proof of concept of adaptability of the model for NASA use.

At the completion of Phase II, NASA desires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model—including any and all work performed to verify and validate it—should be documented.

State of the Art and Critical Gaps:

There currently are a variety of models, methods, and tools in use across the Agency and with our industry partners. These are often custom, phase-dependent, and poorly interfaced to other tools. The disparity between the creativity in the early phases and the detail-oriented focus in later phases has created phase transition boundaries, where missions not only change teams but tools and methods as well. We aim to improve this.

As NASA continues its move into greater use of models for formulation and development of NASA projects and programs, there are recurring challenges to address. This subtopic focuses on encouraging solutions to these cross-cutting modeling challenges.

These cross-cutting challenges include: greater modeling breadth (e.g., cost/schedule), depth (scalability), variable fidelity (precision/accuracy vs. computation time), trade space exploration (how to evaluate large numbers of options), and processes that link them together. The focus is not on specific tools, but demonstrations of capability and methodologies for achieving the above.

The explosion of MBX (model-based everything) has led to a proliferation of models, modeling processes, and the integration/aggregation thereof. The model results are often combined with no clear understanding of the fidelity/credibility. While some NASA personnel are looking for greater accuracy and "single source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing the cross-cutting challenges cited above.

Relevance / Science Traceability:

Several concept/feasibility studies for potential large (flagship) Astrophysics missions are in progress: Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), and Lynx. Following the 2020 Astrophysics decadal rankings, one of these will likely proceed to early Phase A, where the infusion of new and advanced systems modeling tools and methods would be a potential game-changer in terms of rapidly navigating architecture trades, requirements development and flow-down, and design optimization.
A variety of planetary missions requires significant modeling and simulation across a variety of possible trade spaces. The portions of this topic area focused on breadth and variable fidelity will support them.

References:

- Large Ultraviolet Optical Infrared Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
- Origins Space Telescope (OST): https://asd.gsfc.nasa.gov/firs/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- Lynx: https://wwwastro.msfc.nasa.gov/lynx/
- Laser Interferometer Space Antenna (LISA): https://lisa.gsfc.nasa.gov/
- Wide Field Infrared Survey Telescope (WFIRST): https://www.nasa.gov/content/goddard/wfirst-wide-field-infrared-survey- telescope
- Mars Exploration/Program & Missions: https://mars.nasa.gov/programmissions/
- JPL Missions: https://www.jpl.nasa.gov/missions/

S5.06 Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development (SBIR)

Lead Center: **GSFC**

Participating Center(s): **ARC, JPL, JSC, LaRC, MSFC**

Scope Title:

Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development

Scope Description:

Space weather has the potential to disrupt telecommunications; aircraft and satellite systems; electric power subsystems; and position, navigation, and timing services. Given the importance of these systems to our national well-being, NASA's Heliophysics Division invests in activities to improve the understanding of these phenomena and to enable new monitoring, prediction, and mitigation strategies.

The national direction for this work is organized by the Space Weather Operations, Research, and Mitigation (SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

NASA's role under the National Space Weather Strategy and Action Plan is to provide increased understanding of the fundamental physics of the Sun-Earth system through space-based observations and modeling, the development of new space-based space weather technologies and missions, and monitoring of space weather for NASA's space missions. This includes research that advances operational space weather needs.

This subtopic solicits new, enabling space weather technologies as part of NASA's response to these national objectives. While this subtopic will consider all concepts demonstrably related to NASA's R2O/O2R responsibilities outlined in the Strategy and Action Plan, four areas have been identified for priority development:

1. Space Weather Forecasting Technologies and Techniques: Innovative technologies and techniques are solicited that explore and enable the transition of tools, models, data, and knowledge from research to operational environments. This includes the preparation and validation of existing science models that may be suitable for transition to operational use. Consultation with existing NASA capabilities that prepare space weather forecasting products for later use—such as the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC), and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC)—may be appropriate. Areas of special interest include, but are not limited to:
    - Lunar space environment characterization tools that can be employed by NASA to enhance protection of crewed and uncrewed missions to cis-lunar and lunar surface missions.
    - Specifications and/or forecasts of the energetic particle and plasma conditions encountered by spacecraft within Earth's magnetosphere, as well as products that directly aid in spacecraft anomaly resolution; and end-users such as spacecraft operators.

- Approaches that potentially lead to a 2- to 3-day forecasting of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in low-Earth-orbit (LEO) altitude ranges (up to ~2000 km).
- Techniques that enable the characterization and prediction of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems.
- Longer range (2 to 3 days) forecasting of SPEs (solar particle events) and an improved all-clear SPE-forecasting capability.

2. Space Weather Advanced Data-Driven Discovery Techniques: A particular challenge is to combine the sparse, vastly distributed data sources available with realistic models of the near-Earth space environment. Data assimilation and other cutting-edge data- driven discovery innovations are solicited that enable tools and protocols for the operational space weather community. Priority will be given to proposals that:
    - Develop data assimilation space weather applications or technologies desired by established space weather operational organizations.
    - Integrate data from assets that typically do not share similar time series, utilize different measurement techniques (e.g., imaging vs. in situ particles and fields), or are distributed throughout the heliosphere.
    - Provide new data-driven operational forecasting tools that can be straightforwardly validated by the CCMC or another equally robust validation methodology.
    - Integrate underutilized resources (e.g., space-based radio occultation for ionospheric specification or U.S. Geological Survey (USGS) ground conductivity measurements related to geomagnetically induced currents).

3. Space Weather Mitigation Technologies: The 2019 National Space Weather Strategy and Action Plan specifically calls out the need to test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or radiation events on satellites. Additionally, it identifies a need for robust situational awareness capabilities, driven by improved understanding and characterization of the effects space weather phenomena have on Earth and in the space environment, to inform decision making and enable the execution of missions susceptible to disruptions from space weather. It also includes the development of processes to improve the transition of research approaches to operations.
4. Space Weather Instrumentation: Heliophysics science relies on a wide variety of instrumentation for its research and often makes its data available in near real time for space weather forecasting purposes. Concepts are solicited for instrumentation concepts, flight architectures, and reporting systems that enable enhanced, more informative, robust, and effective measurements for space weather monitoring and forecasting systems. Opportunities for improving measurements include increased spatial and temporal resolution, fidelity, promptness, and measurement system reliability. This includes the miniaturization of existing systems and/or technologies deployable as an array of CubeSats, as a hosted payload on satellite or other platform, or as a small complete mission making use of a rideshare opportunity. In order to be considered for investment, SBIR technologies should demonstrate comparable, or better, precision and accuracy when compared to the current state of the art. Further, SBIR instrument designs should avoid duplicating current NASA research spacecraft arrays or detector systems, including those currently in formulation or

development (e.g., Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Medici, Explorer concepts, etc.).

Proposals must demonstrate an understanding of the current state of the art, describe how the proposed innovation is superior, and provide a feasible plan to develop the technology and infuse it into a specific activity listed within the National Space Weather Strategy and Action Plan.

Expected TRL or TRL Range at completion of the Project: 3 to 8

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Space weather is a broad umbrella encompassing science, engineering, applications, and operations. The ultimate goal of this SBIR subtopic is to generate products or services ("deliverables") that enable end-user action. The deliverables can be applied, for example, to space weather hazard assessments, to real-time situational awareness, or to plan protective mitigation actions. Deliverables can be in the form of new data, new techniques, new instrumentation, and/or predictive models that are prepared/validated for transition into operations.

- Phase I deliverables are proof-of-concept data and/or detailed technique, instrument, or model development plans with sufficient fidelity to assess technical, management, cost, and schedule risk. Phase I deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily requires further development after Phase II.
- Phase II deliverables are functioning prototype versions of the proposed technologies that have been tested in a realistic environment or within a standard space weather community development and validation framework. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

We do not yet know how to predict what needs to be predicted, we do not yet know how quantitatively good/bad our operational capabilities are (metrics), mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models, and
the research environment advances understanding rather than the improvement of operational products.

Space weather poses a constant threat to the Nation's critical infrastructure, our satellites in orbit, and our crewed and uncrewed space activities. Extreme space weather events can cause substantial harm to our Nation's security and economic vitality.

Preparing for space weather events is an important aspect of American resilience that bolsters national and homeland security and facilitates continued U.S. leadership in space. A robust space weather program and its associated forecasting capabilities are essential for NASA's future exploration success.

Relevance / Science Traceability:

This SBIR subtopic enables NASA to demonstrate progress against NASA Goal 1.4: Understand the Sun and its interactions with Earth and the solar system, including space weather.

These applied research projects directly address NASA's role within the SWORM Working Group, which is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

The Heliophysics Space Weather Science and Applications (SWxSA) Program establishes an expanded role for NASA in space weather science under a single element. It is consistent with the recommendation of the National Research Council (NRC) Decadal Survey and the OSTP/SWORM 2019 National Space Weather Strategy and Action Plan. It competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. The SWxSA program is distinguishable from other heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather and then apply this progress to enable more accurate characterization and predictions with longer lead time. The Heliophysics Living with a Star (LWS) Program has established a path forward to meet NASA’s obligations to the research relevant to space weather and is a significant source of input to SWxSA.

Further involvement by the emerging Heliophysics space weather commercial community has the potential to significantly advance the space weather application obligations portion of the mandate.

Astronauts are not protected by the Earth's atmosphere and are exposed to space radiation such as galactic cosmic rays and solar energetic particles. A robust space weather program and associated forecasting capabilities is essential for NASA's future exploration success.

References:

- Executive Order 13744—Coordinating Efforts to Prepare the Nation for Space Weather Events: https://www.federalregister.gov/documents/2016/10/18/2016-25290/coordinating-efforts-to-prepare-the-nation-for-space- weather-events
- The SWORM Working Group is a Federal interagency coordinating body organized under the SWSH Subcommittee. THE SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019. See: https://www.sworm.gov/
- The White House Executive Office of Science and Technology Policy released the National Space Weather Strategy and Action Plan on March 26th, 2019, during the National Space Council meeting in Huntsville, Alabama. The announcement was made by the Office of Science and Technology Policy Director, Kelvin K. Droegemeier. This strategy and action plan is an update to the original National Space Weather National Space Weather Strategy and Space Weather Action Plan, released in October 2015. See: https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf
- Space Weather Phase 1 Benchmarks: https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf
- An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMP) was released by the White House on March 26, 2019. The EO identifies the disruptive impacts an EMP has on technology and critical infrastructure systems, whether the EMP is human made or naturally occurring. The EO outlines how the Federal Government will prepare for and mitigate the

effects of EMPs by an efficient and cost-effective approach. See: https://www.whitehouse.gov/presidential-actions/executive-order-coordinating-national-resilience-electromagnetic-pulses/

Focus Area 14 On-orbit Servicing, Assembly, and Manufacturing (OSAM)

Lead MD: **STMD**

Participating MD(s): **STTR**

NASA is seeking technological innovations that will accelerate development and adoption of advanced serving, assembly and manufacturing technologies supporting a wide range of NASA Missions. In the area of on-orbit servicing, NASA is seeking technology developments related to end of robot arm force-torque sensors. Force torque sensors for robots are a major limiting factor in robot system designs on all of NASA's current robotic manipulator-based systems (including OSAM-1 and Mars Sample Return.) In the area of on-orbit assembly, NASA is seeking technology developments for trusted and certified-safe autonomous systems with machine intelligence and robotic capabilities of responding to both nominal and unexpected situations. In the area of on-orbit manufacturing, NASA is seeking technology developments centered around material joining technologies, large-scale additive manufacturing process developments and technologies focused on the ability to recycle and reuse metallic materials. Cutting-edge servicing, assembly and manufacturing technologies offer the ability to dramatically increase performance and reduce the cost of NASA's programs. The ability to improve cost, launch mass, system resiliency and extended life time by advancing technologies to enable large structures that can be deployed, assembled/constructed, reconfigured and serviced in-space or on planetary surfaces is also imperative to NASA's Missions. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit for NASA testing at the completion of the Phase II that could be turned into a proof-of-concept system for flight demonstration. To understand the full technology needs and requests see the detailed topic and subtopic descriptions.

T12.06 Extensible Modeling of Additive Manufacturing Processes (STTR)

Lead Center: **JPL**

Participating Center(s):

Scope Title:

Process Modeling of Additive Manufacturing

Scope Description:

The subtopic of modeling of additive processes is highly relevant to NASA as the Agency is currently on a path to implement additive processes in spaceflight systems with little or no ability to model the process and thereby predict the results. In order to reliably use this process with a variety of materials for spaceflight applications, NASA has to have a much deeper understanding of the process. NASA is currently considering these processes for the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC), ion engines, and other spacecraft structural and multifunctional applications. Additive manufacturing of development and flight hardware with metallic alloys is being developed by NASA and its various partners for a variety of spacecraft applications. These components are expected to see extreme environments coupled with a need for high-reliability (e.g., manned spaceflight), which requires a deeper understanding of the manufacturing processes. Modeling of the additive processes to provide accurate dimensional designs, preferred microstructures that are defect free is a significant challenge that would dramatically benefit from a joint academic-industry approach. The objective would be to create process models that are compatible with current alloys systems and additive manufacturing equipment, which will provide accurate prediction of outcomes from a variety of additive manufacturing process parameters and materials combinations. The primary alloys of interest to NASA at this time include: Inconel 625 and 718, stainless steels, such as 304 and 316, Al10SiMg, Ti-6Al-4V, and copper alloys (GrCop-84). It is desired that the modeling approach address a focused material system, but be readily adaptable to eventually accommodate all of these materials. Therefore, the model should incorporate modest parameter changes coupled with being easily extensible for future alloys of interest to NASA. NASA is interested in modeling of the Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Laser Engineered Net Shaping (LENS) processes.

Expected TRL or TRL Range at completion of the Project: 1 to 2

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

- A functional process model covering the specific area by the proposer, using open source or code shared with the Agency. The deliverables can be either stand-alone software or modules for existing, commercially available software.
- The Phase I deliverable should be preliminary modeling results, an accurate description of the software with revision tracking, and an architecture plan demonstrating the output data (if stand-alone software) or modularity (if the software connects to commercially existing products).
- The Phase II deliverable should be a copy of the software, along with modeling results, as well as a final report stating relevant data, such as boundary conditions, assumptions, process simplifications used for quicker computing, etc. The output data should be in a clearly defined format with a clear description and discussion of how it can be imported into other modeling tools used for additive manufacturing, to create a truly extensible framework. If the product is a module for existing software, then the final report should demonstrate functionality with that software (including computing elements required, version of the software, etc.) and that the results can feed into other aspects of the commercially available software.

State of the Art and Critical Gaps:

Additive manufacturing will be used for spaceflight applications. NASA and its suppliers currently have very little knowledge of what is happening with these processes. Modeling of these additive processes is essential for NASA to be able to use these processes reliably. NASA is currently working on a specification for these processes and modeling would help that effort as well.

Relevance / Science Traceability:

Process modeling of additive manufacturing is relevant to Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD), all of which have extant efforts in additive manufacturing. HEOMD is focusing heavily on the use of additive manufacturing for propulsion systems (e.g., RS-25 and RL10) for SLS, SMD is using additive manufacturing on the Planetary Instrument for X-ray Lithochemistry (PIXL) on the Mars 2020 mission, the Psyche Mission, as well as various ESI initiatives through STMD.

References:

Stranza, M. et al., Materials Letters, accepted (https://doi.org/10.1016/j.matlet.2018.07.141)

Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems, NASA/CR—2018-219771

Keller, T., et al., Acta Materiala (https://doi.org/10.1016/j.actamat.2017.05.003)

Z3.03 Development of Advanced Joining Technologies, Large-Scale Additive Manufacturing Processes, and Metal Recycling Technologies for On-Orbit Manufacturing (SBIR)

Lead Center: **MSFC**

Participating Center(s): **GSFC, LaRC**

Scope Title:

Development of Advanced Joining Technologies for On-Orbit Manufacturing

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material welding capability is an important supporting technology for the long-duration, long-endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically, structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space welding capability will greatly reduce constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures. Welding is an essential complementary capability to large-scale additive manufacturing technologies being developed by NASA and commercial partners. Welding is also a critical capability for repair scenarios (e.g., repair of damage to a structure from micrometeorite impacts).

This subtopic seeks innovative engineering solutions to robotically weld materials, both fully autonomous and semiautonomous, for manufacturing in the unpressurized space environment. Current state-of-the-art (SOA) terrestrial welding methods such as laser beam, electron beam, and friction stir should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for on-orbit manufacturing applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a damaged structure or build new structures may require the need to not only weld material but to cut and remove material. A process that can weld material is the priority, but a robust process with cutting and removal capabilities adds value. The Phase I effort should provide a laboratory demonstration of the welding process and its applicability to aerospace-grade metallic materials and/or thermoplastics, focusing on joint configurations that represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios—for example, repair of a metal panel following micrometeorite damage, longitudinal welding of two metal curved panels, and welding of a truss to an adjacent truss. The Phase I effort should also provide an assessment of the proposed process operational capabilities (e.g., classes of materials that can be welded with the process, joint configurations that can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be welded may also be included in the Phase I effort.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I requires laboratory demonstration/proof of concept that (a) the system enables high-value applications of repair and assembly and (b) the system shows potential for being operated remotely with very little intervention/setup. A preliminary design and concept of operations are also deliverables under Phase I.

Phase II includes finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Exploration Crew Module (ECM), Gateway, OSAM-1, OSAM-2, lunar lander payload, or as a free-flyer.

State of the Art and Critical Gaps:

Unpressurized environment in-space manufacturing has primarily focused on fabrication of structures in the space environment. Welding is an essential supporting technology to these capabilities. Research on welding tapered off to some extent following the cancellation of the In-Space Welding Experiment (ISWE) for the space shuttle. With the emergence of the OSAM initiative, a renewed interest and focus on manufacturing structures in the space environment as an enhancing capability for long-duration missions, and as a way to remove design constraints imposed by payload fairings and launch loads, additional work on development of an in-space welding capability should be a priority. In-space welding represents an essential complementary technology to in-space fabrication techniques.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module (ECM), Gateway, Lunar Base Camp, OSAM-1 and OSAM-2, in-Space Assembled Telescope (iSAT) and SmallSat.

References:

G. L. Workman and W. F. Kaukler, “Laser Welding in Space,” 1989.

D. Tamir et al., "In-Space Welding: Visions and Realities," 1993.

B. E. Paton and V. F. Lapchinskiĭ, "Welding in Space and Related Technologies," Cambridge International Science Publishing, 1997.

I. D. Boyd, R. S. Buenconsejo, D. Piskorz, B. Lal, K. W. Crane, and E. De La Rosa Blanco, "On-Orbit Manufacturing and Assembly of Spacecraft: Opportunities and Challenges," 2017.

S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft," 2018.

Scope Title:

Development of Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

The ability to additively manufacture large-scale structures in-space is an enabling capability needed to fully realize the game-changing impacts of OSAM. Current state-of-the-art (SOA) on-orbit manufacturing systems are constrained to a build volume similar to terrestrial additive manufacturing processes, and others are focused on linear beam and truss designs. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. Large-scale, free-form additive manufacturing capabilities can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures.

This subtopic seeks innovative engineering solutions to fabricate and/or repair large structures, using fully autonomous or semi-autonomous systems, in the unpressurized space environment. Current SOA terrestrial large-scale additive manufacturing processes such as wire-fed directed energy deposition, pellet-fed extruder systems, and additive friction stir deposition should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic large-scale additive manufacturing process and system for unpressurized in-space manufacturing applications. Targeted applications for this technology include fabrication of truss structures, build-up of structural material for retrofitting spent tanks to habitat modules, and/or solar array back planes. Additional targeted applications include the repair of structures such as spacecrafts and/or payloads damaged during the ascent stage, habitat modules with micrometeoroid impact, and out-of-service components due to unforeseen circumstances and/or scheduled repairs. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. Work under Phase I will inform preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase I requires a demonstration/proof of concept that (a) the system enables high-value applications of in-space fabrication of large-scale structures and (b) the system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:

Phase I requires a demonstration/proof of concept that (a) the system enables high-value applications of in-space fabrication of large-scale structures and (b) the system shows potential for being operated remotely with very little intervention/setup. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase II includes finalization of the design and demonstration of a ground-based prototype system including autonomous capability.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

State of the Art and Critical Gaps:

Unpressurized structure in-space manufacturing has primarily focused on fabrication of 3D-printed truss structures and beams. The OSAM-1 and OSAM-2, funded by the STMD (Space Technology Mission Directorate) Technology Demonstration Mission Program, are planning the demonstration of 3D-printed truss structures and beams. The technology advancement to multiple degrees of freedom, large-scale fabrication of structures is a priority for on-orbit manufacturing.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and in-Space Assembled Telescope (iSAT).

References:

R. G. Clinton, Jr., "NASA's In Space Manufacturing Initiatives: Conquering the Challenges of In-Space Manufacturing," 2017. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011108.pdf [Accessed: 10-Oct-2019].

I. D. Boyd, R. S. Buenconsejo, D. Piskorz, B. Lal, K. W. Crane, and E. De La Rosa Blanco, "On-Orbit Manufacturing and Assembly of Spacecraft: Opportunities and Challenges," 2017.

S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft," 2018.

Scope Title:

Development of Metal Recycling Processes for On-Orbit Manufacturing

Scope Description:

Deep space missions will require a shift in the logistics paradigm to enable reuse and recycling of materials. Recycling is a significantly enhancing capability for space missions and would enable what would otherwise be nuisance material (spent components, waste items) to be utilized as feedstock for further manufacturing. This subtopic seeks innovative engineering solutions to facilitate recycling of metals commonly used in space systems in either an intravehicular (IVA) or extravehicular (EVA) environment. In an IVA use scenario, technologies might be used inside a habitat to process spent components by breaking down the structure, generating chips, and consolidating the chips into feedstock that can be used to generate new components through various in-space manufacturing processes. In an EVA use scenario, recycling technologies might be used to take metal material scavenged from large structures (such as space habitats, satellites, and spent upper stages) and reprocess it into material feedstock for on-orbit servicing, assembly, manufacturing, and repair applications. High-value materials for metal recycling include those commonly used in large-scale space structures and components of space systems: aluminum alloys, stainless steel, and titanium.

Current state of the art (SOA) includes metal recycling technologies commonly applied in industry (e.g., shredding, melting, solidification), but these must be modified to fit the physical footprint, power, and mass requirements for on-orbit applications. For an IVA environment, the system for initial demonstration would be constrained to an EXPRESS* rack, occupying some portion of its 0.45-m^3 volume. An EXPRESS rack is designed to support up to eight individual payloads, each occupying one EXPRESS locker (each locker has an internal volume of approximately 0.057 m^3, with the total rack of eight lockers providing in excess of 0.45 m^3 of payload volume). The width of a single locker is 0.44 m, the height is 0.25 m, and the depth is 0.52 m. The full rack can accommodate approximately 260 kg. In an EVA environment, the metal recycling capability would likely operate as a free-flyer platform.

*EXPRESS is an acronym for "EXpedite the PRocessing of Experiments to the Space Station."

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Analysis

- Prototype
- Hardware

Desired Deliverables Description:

Phase I is a feasibility study and proof of concept of a system for in-space recycling of one or more metal materials. Targeted applications for the technology include processing of spent components into feedstock for in-space manufacturing and/or processing of large-scale structures (such as spent upper stages) into material forms for further use. While the focus should be on material processing (which may include shredding, melting, solidifying, and other processes necessary to obtain a final feedstock form), other ancillary techniques such as sorting, purification, and material delivery/transport may also be considered as part of an overall concept of operations. How the system will be deployed and operated in either an IVA or EVA environment should also be considered. The Phase I effort should also include a laboratory demonstration of the core recycling technique with an aerospace-grade metallic material and some characterization of properties post-recycling. Relevant metrics such as power consumption, system footprint, and mass of system should also be reported, with an emphasis on scalability and adaptation to the relevant space environment. This work will collectively inform preliminary design of a metal recycling capability for in-space use. An additional constraint is that the system must be operated remotely with very little intervention/setup. Even in an IVA environment with crew, the availability of crew time to tend or service a recycling system will be very limited. An EVA environment would require fully remote operation.

Phase II would include finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology to a flight demonstration for ISS (internal or external payload) or as a free-flyer.

State of the Art and Critical Gaps:

The current SOA is terrestrial systems for metal recycling, but these processes must be adapted to operate in the relevant space environment and comply with the system constraints of their intended use (for example, in an IVA environment as a payload). The capability to break down spent components and larger structures and repurpose them into a useful product is needed on long-duration space missions where logistics are constrained. Recycling of polymer materials on the International Space Station (ISS) into manufacturing feedstock (for 3D printing) has been previously demonstrated, but there are no current recycling capabilities for metals on the ISS. For external applications of metal recycling, NASA has funded some Next Space Technologies for Exploration Partnerships (NextSTEP) work previously on repurposing of spent rocket stages left in-orbit. Recycling, reuse, and repurposing of metals is seen as a critical gap for on-orbit servicing, assembly, and manufacturing (OSAM) and shifting the logistics paradigm from pre-positioning of spare parts to point-of-use manufacturing.

Relevance / Science Traceability:

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and in-Space Assembled Telescope (iSAT).

References:

T. Prater et al., "In-Space Manufacturing at NASA Marshall Space Flight Center: A Portfolio of Fabrication and Recycling Technology Development for the International Space Station," 2018.

Z3.04 Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) (SBIR)

Lead Center: **LaRC**

Participating Center(s): **MSFC**

Scope Title:

Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly, and Manufacturing (OSAM)

Scope Description:

As NASA seeks to extend its presence into deep space, ground-based human intelligence applied to supervision, control, and intervention of operations will no longer be viable due to system and mission complexity and communication delays. Therefore, trusted and certified-safe autonomous systems with machine intelligence and robotic capabilities of responding to both nominal and unexpected situations will be needed. These systems should be capable of:

- Sensing and perception.
- Acquiring measurements on-orbit or on planetary surfaces.
- Achieving situational awareness.
- Making decisions.
- Taking action.
- Teaming with humans and other machine agents.
- Using experiential data to update capabilities.
- Verifying autonomy algorithms and behavior.
- Validating as-assembled structure shape and interface integrity.

As such, autonomy, system modularity, metrology, and modeling and simulation are four critical aspects required to enable OSAM. The hardware and software components of an in-space assembled structure must be modular to facilitate servicing, component replacement, and reconfiguration of the spacecraft. Assembly by autonomous robots can reduce the workload of astronauts and ground crew and can mitigate inefficiencies due to communication delays associated with teleoperation. The OSAM paradigm requires multiple autonomous agents to collaborate in a complex, dynamic environment. These agents will need to accurately perceive both their environment (the worksite) and each other in order to efficiently allocate tasks, plan trajectories, and respond to disturbances—all in the presence of uncertainties such as unknown payload characteristics and unmodeled effects.

Modular structures will increase ease of access to space. Modular platforms could host flight hardware and share power, data, GN&C (guidance, navigation, and control), and thermal regulation capabilities. Under this paradigm, technology demonstrations could be performed without the need to design and operate an entire spacecraft. Modules could simply occupy space on an already existing platform. This constitutes a plug-and-play architecture that will require a common interface between modules such that required structural loads can be supported as well as power, data, and other services.

Modeling and simulation of structures and assembly agents is necessary for verifying autonomous agent algorithms and behavior used for structures that cannot be assembled on the ground. Accurate sensing of complex and uncertain environments is necessary to provide autonomous agents with situational awareness to accomplish assembly tasks. Validation of the autonomous system behavior and in-space assembled structure accuracy in situ will require in-space metrology capabilities.

The scope of this subtopic includes modular hardware and software systems:

- Element 1: Algorithms and software for sensing, planning, and control of both autonomous robots and mission/task management agents.
- Element 2: Novel hardware designs (modular robots and structures).
- Element 3: Hardware and software for global (worksite-scale) metrology systems for accurately sensing agent and structure pose within an on-orbit or lunar assembly worksite.
- Element 4: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections and independent verification and validation for dynamics-based rigid multi-body mathematical models.

A solution for autonomous modular technologies for OSAM will be built on the following foundational areas:

- Heterogeneous multi-agent planning and control: Algorithms for collaboration on shared tasks for assembly of large modular space structures; task allocation among multiple agents; trajectory planning through the worksite and real-time updating of tasks and trajectories to respond to unplanned scenarios; robust and adaptive control for guaranteed performance or graceful degradation of performance for robotic manipulators and/or novel assembly agents; and teaming of humans and machines for planning, validation, and post-assembly analysis.
- Strategies and solutions for error detection and correction during the assembly process: Perception systems and/or classification algorithms independent from the assembly agent for verifying assembly steps and characterizing assembly errors. Fault/anomaly detection, diagnosis, and response to restore nominal operations or derive an acceptable alternative goal.
- Metrology systems: Global metrology systems or sensing tools that can map a worksite to facilitate agent and structure assembly path-planning for real-time task management and situational awareness and facilitate verification and validation of assembly tasks. A scalable system that can accurately measure structures at an in-space (orbital or surface) worksite with a focus on minimal supporting infrastructure is desired. Concepts with potential for integration and repurposing after construction are favored.
- Modular structures, systems, and tools: Deployables that are rigidizable by an accompanying in situ system (i.e., trusses or functional modules), can be serviced (due to modularity), are capable of moving along truss structures of variable geometries, and/or can interface with agents or be stored/stowed at a worksite where the agent mostly acts as a driver for a mobility system. Of particular interest are approaches to efficiently connect truss modules together—hardware concepts that support the interconnection of modules in the 100- to 5,000-kg range using some form of space robotics. The objective is to minimize the parasitic mass of the completed spacecraft from the modularity features that are required for intermodule assembly. Features can be added and removed to reduce this parasitic mass. Proposals are preferred that include features to connect both electrical (power and data) and structural features, noting that the connections can occur sequentially. Joining strategies that support fluid connections are of interest but are not necessary to be responsive to this subtopic area. The structural connection should occur at a minimum of three discrete locations, fixing the rigid-body motion of the two modules in all six degrees of freedom while isolating (minimizing) forces resulting from thermal-induced strain between the modules consistent with a low Earth orbit (LEO) orbit. The three (or more) connections do not have to occur simultaneously.
- Modeling and simulation: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections with nonlinear effects (for example, slider, ball, or slot connections) and independent verification and validation for dynamics-based rigid multibody

mathematical models. Of particular interest are accurate dynamics-based models for joining of modules on-orbit or in planetary environments.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:

Phases I and II should both result in the following deliverables:

- Software implementations of designed algorithms.
- Documentation verifying the efficacy of the designed algorithms.
- Physical prototypes of designed hardware.
- Design documentation for any designed hardware.

Level of detail in the documentation should be commensurate with project phase.

State of the Art and Critical Gaps:

As humans venture into deeper space, communication latency will increase to the point that autonomous operations are crucial. Current technologies for autonomous robots are low Technology Readiness Level (TRL), application specific, and fragile with respect to environmental uncertainties. To enable OSAM, these technologies must be made more resilient. Many interesting ideas exist in academia but have yet to be made into a viable product.

Existing interfaces for modular trusses are purely structural. A critical gap is the development of interfaces that can exchange power, data, and other services over the interface.

Relevance / Science Traceability:

Achieving a robust and resilient autonomous solution for OSAM requires the intersection of many disciplines, including mechanical and electrical systems, robotics, dynamics modeling, control theory, and computer science. NASA goals that would directly benefit from this work are future lunar exploration missions, including sustained human presence on the Moon and persistent space platforms.

References:

NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

NASA Raven:
https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=1734

NASA Robotic Refueling Mission (RRM3): https://sspd.gsfc.nasa.gov/RRM3.html

NASA Restore-L: https://sspd.gsfc.nasa.gov/restore-L.html

NASA Dragonfly: https://www.nasa.gov/mission_pages/tdm/irma/nasas-dragonfly-project-demonstrates-robotic- satellite-assembly-critical-to-future-space.html

Autonomous Systems NASA Capability Overview:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180007804.pdf

Z3.05 Satellite Servicing Technologies (SBIR)

Lead Center: **GSFC**

Participating Center(s): **LaRC, MSFC**

Scope Title:

Adjustable End-of-Robot-Arm Force-Torque Sensor Technique

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets. An end-of-arm force-torque sensing technique that is adjustable is needed to enable a variety of OSAM mission-specific tasks to be performed. A ground-based demonstration of the technique is of interest.

Current state of the art in end-of-arm force-torque sensors is that they are not placed close enough to the sensing point to minimize the load distal of the sensor, do not work in both unrestricted 1g and 0g environments, and cannot simultaneously handle large (6× to 10×) full-range overload for launch loads while providing absolute accuracy stability for at least 30 min before zeroing. A sensing technique is needed that can provide the following:

- Range of 0 to 200-500 N, resolution of 2 N, and absolute accuracy of ±5 N for surface contact measurements.
- Range of ±120 N, resolution of 0.1 N to 0.2 N, and absolute accuracy of ±2 N for servicing tasks.
- Range of 0 to 20 N, resolution of 0.02 N, and absolute accuracy of ±0.1 N for payload determination measurements.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.

- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard force-torque sensor.

Phase II deliverables include:

- Demonstration using the brassboard force-torque sensor.
- Environmental testing of key components.

State of the Art and Critical Gaps:

Current state of the art in end-of-arm force-torque sensors is that they are not placed close enough to the sensing point to minimize the load distal of the sensor, do not work in both unrestricted 1g and 0g environments, and cannot simultaneously handle large (6× to 10×) full-range overload for launch loads while providing absolute accuracy stability for at least 30 min before zeroing.

Relevance / Science Traceability:

An adjustable force-torque sensor is relevant to dexterous robotic missions such as OSAM-1, OSAM-2, International Space Station (ISS) robotics, robotic sample return missions, Gateway, and in-Space Assembled Telescope.

References:

On-Orbit Satellite Servicing Study Project Report, October 2010,
https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf

Scope Title:

Centralized Robot Actuator Servo Controller Board for MUSTANG (Modular Unified Space Technology Avionics for Next Generation) Form Factor

Scope Description:

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets. A robot actuator servo control electronic board that fits in the Modular Unified Space Technology Avionics for Next Generation (MUSTANG) form factor is needed to enable a variety of OSAM and robotic sample return missions. A ground-based demonstration of the control electronics is of interest.

Current state of the art for robot actuator servo control electronic boards is that they do not read all of the sensors necessary for closed-loop control, are too big (>30 by 30 cm), and weigh too much (>2 kg). An actuator servo control electronic board is needed that fits the MUSTANG form factor, reads all of the necessary sensors (Hall effect sensor, resolver), and weighs less than 2 kg.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Deliverables include a ground-based demonstration of a robot actuator servo control electronic board in the MUSTANG form factor commanding a robot actuator.

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard robot actuator servo control electronic board.

Phase II deliverables include:

- Demonstration using the brassboard robot actuator servo control electronic board.
- Environmental testing of key components.

State of the Art and Critical Gaps:

Existing centralized robot actuator servo control electronics do not fit the MUSTANG form factor or require additional resources other than those provided by the rest of the MUSTANG avionics platform.

Relevance / Science Traceability:

Robot actuator servo control electronics are relevant to dexterous robotic missions such as OSAM-1, OSAM-2, International Space Station (ISS) robotics, robotic sample return missions, Gateway, and in-Space Assembled Telescope.

References:

On-Orbit Satellite Servicing Study Project Report, October 2010, https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf

MUSTANG (Modular Unified Space Technology Avionics for Next Generation): https://ntrs.nasa.gov/citations/20190028692

Focus Area 15 Materials, Materials Research, Structures, and Assembly

Lead MD: **STMD**

Participating MD(s): **HEOMD, STTR**

As NASA embarks on its mission for human exploration of the Moon as a step towards the human mission to Mars, taking full advantage of the potential offered by new and existing technologies will be critical to enable sustainable Lunar and Mars presence. The Advanced Manufacturing, Materials Research, Structures and NDE focus area seeks to address challenges such as lowering the cost of exploration, changing structural design paradigms to take advantage of advanced materials, enabling efficient, reliable operations on-surface and capitalizing on capabilities provided by sensor integration.

Improvement in all of these areas is critical to future missions. Since this focus area covers a broad area of interests, specific topics and subtopics are chosen to enhance and or fill gaps in the space and exploration technology development programs, as well as to complement other mission directorate manufacturing, structures, materials and NDE needs.

H5.01 Lunar Surface Solar Array Structures (SBIR)

Lead Center: **LaRC**

Participating Center(s): **GRC**

Scope Title:

Lunar Surface Solar Array Structures

Scope Description:

NASA intends to land near the lunar South Pole (between 85 and 90 S latitude) by 2024 in Phase I of the Artemis Program and then establish a sustainable long-term presence by 2028 in Phase II. At exactly the lunar South Pole (90 S), the Sun elevation angle varies between -1.5º and 1.5º during the year. At 85 S latitude, the elevation angle variation increases to between -6.5º and 6.5º. These persistently shallow Sun grazing angles result in the interior of many polar craters never receiving sunlight (and accumulating volatiles including water ice) while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the excessively cold 354-hr nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

This subtopic seeks structural and mechanical innovations for 10 kW relocatable solar arrays near the South Pole for powering in situ resource utilization (ISRU) equipment, lunar bases, dedicated power landers and rovers, and that can deploy and retract at least 5 times. Retraction will allow valuable solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m above the surface to reduce shadowing from local terrain are required [Ref. 3]. The ability to be relocated is assumed to be through use of a separate surface-mobility system (i.e., not part of the solar array system), but design of array structures and mechanisms should accommodate loads likely to be encountered during transport along the lunar surface. Suitable variations of existing array concepts [e.g., Ref. 4-5] are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 35 m^2 (10 kW at beginning of life) per unit.
- Single-axis sun tracking about the vertical axis.
- Up to 10-m height extension boom to reduce shadowing from local terrain.

- Deployable, stable base for supporting tall vertical array on unprepared lunar surface.
- Base must accommodate a local 15º terrain slope.
- Adjustable leveling to within 1º of vertical.
- Retractable for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Lunar dust, radiation, and temperature resistant components.
- Specific mass: >75 W/kg including all mechanical and electrical components.
- Specific packing volume: >20 kW/m^3 including all mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Lifetime: 10 years.

Suggested areas of innovation include:

- Novel array and support base packaging, deployment, retraction, and modularity concepts.
- Lightweight, compact components including booms, trusses, ribs, substrates, and mechanisms.
- Novel actuators for telescoping solar arrays such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Optimized use of advanced lightweight materials (but not materials development).
- Integration of existing structural health monitoring technologies.
- Validated modeling, analysis, and simulation techniques.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts; e.g., thinned rigid panel or 3D-printed solar arrays, nonrotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays. Solar array concepts should be compatible with state-of-the-art solar cell technologies with documented environmental degradation properties. Design, build, and test of scaled flight hardware or functioning lab models to validate proposed innovations is of high interest.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests.

In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their Technology Readiness Level (TRL). TRLs at the end of Phase II of 4 or higher are desired.

State of the Art and Critical Gaps:

Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for lunar surface power. Furthermore, there is usually no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 10-kW solar array for surface electrical power near the lunar South Pole for diverse needs including ISRU, lunar bases, dedicated power landers, and rovers.

Relevance / Science Traceability:

Robust, lightweight, redeployable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the Moon. New this year, the subtopic extends the focus area from landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10 to 40 kW of power. The 10-kW-class solar array structures are also applicable for Science Mission Directorate (SMD) ConOps (concept of operations) on the Moon to recharge batteries on a Mars Science Laboratory- (MSL-) class rover.

References:

1. Burke, J., “Merits of a Lunar Pole Base Location,” in Lunar Bases and Space Activities of the 21st Century, Mendell, W. (editor), 1985, https://www.lpi.usra.edu/publications/books/lunar_bases/
2. Fincannon, J., “Characterization of Lunar Polar Illumination From a Power System Perspective,” NASA TM-2008-215186, May 2008, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080045536.pdf.
3. Mazarico, E. et al., “Illumination Conditions of the Lunar Polar Regions Using LOLA Topography,” Icarus, February 2011, https://doi.org/10.1016/j.icarus.2010.10.030.
4. McEachen, M. et al., “Compact Telescoping Array: Advancement from Concept to Reality,” AIAA Paper 2018-1945, January 2018, https://doi.org/10.2514/6.2018-1945.

T12.05 Use of Additive Manufacturing for Thermal Protection Systems (STTR)

Lead Center: **JSC**

Participating Center(s): **ARC, GSFC, LaRC**

Scope Title:

Use of Additive Manufacturing for Thermal Protection Systems

Scope Description:

Background

NASA has a need to significantly improve the manufacturing processes of Thermal Protection Systems (TPS) used on human-rated spacecraft and robotic missions with the intention of reducing cost and improving quality and system performance. The fabrication and installation of current TPS are labor intensive, cost prohibitive, and result in many seams between the segments. Future human missions to Mars will require the landing of large-mass payloads on the surface, and these large entry vehicles will require large areas of TPS to protect the structure. A sustained lunar presence will require the development of lunar-return vehicles, which will also need TPS. In order to reduce the cost and complexity of these vehicles, new TPS materials and compatible additive manufacturing (AM) techniques are needed such that both spacecraft TPS and structures can be manufactured with automated systems. Furthermore, a future capability to use AM to fabricate and repair TPS in space will be needed. Basic requirements and goals for the development of this technology are provided in this solicitation.

Objectives

The overall objective is to develop the materials and compatible AM technologies to automate the fabrication of an integrated spacecraft structure and TPS. There are two approaches to designing the spacecraft aeroshell: (1) parasitic TPS: design and fabricate the flight structure and apply the thermal protection to the structure surface and (2) integrated aeroshell: design and fabricate a high-temperature flight structure that forms the outer mold line and apply insulative thermal protection to the inner surfaces of the structure. Both of these approaches are of interest to NASA and have applications to future NASA missions.

For the first approach, the objective for this solicitation is to develop the materials and processes to deposit and adhere the thermal protection to an existing structure. It can be assumed that the structure has already been designed and fabricated. For the second approach, the objective is to develop the materials and processes to fabricate both the high-temperature structure and the integrated, internal insulation. The proposer should select one of the design approaches to address.

The intent of this solicitation is to develop the materials and technologies for automating the fabrication and integration of a thermal protection onto a spacecraft. Therefore, NASA is not interested in materials and methods to fabricate a better block of material that would need to be manually bonded onto a structure with gaps between the blocks.

Material Characteristics

AM has the potential to provide capabilities to design a material to achieve the desired properties and to vary the material constituents during the fabrication process. Fibers can be added and aligned to obtain desired mechanical and thermal properties. Additives can be used to reduce density and modify other key properties and to aid the fabrication process. Although it is not a requirement for this solicitation, material systems that have a potential future development path for reusability are desirable.

The desired material properties depend on the spacecraft flight regime and the aeroshell design approach. For the purpose of this solicitation, three TPS options have been defined and the approximate desired material properties provided.

Low-Density, Low Heat Flux (<60 W/cm^2) Parasitic TPS:

- Density ~0.3 g/cc (or lower)
- CTE <5×10^{-6} 1/°F
- Through-the-thickness thermal conductivity <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >1.3 MPa

High Heat Flux (100 to 600 W/cm^2) Parasitic TPS:

- Density ~0.6 g/cc (or lower)
- CTE <5×10^{-6} 1/°F
- Through-the-thickness thermal conductivity <0.2 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >3 MPa
- Char yield >50%

Moderate Heat Flux (>200 W/cm^2) Integrated Aeroshell:

- Density: Structure ~1.5 g/cc; Insulation 0.3 to 0.5 g/cc
- CTE <5×10^{-6} 1/°F
- Through-the-thickness thermal conductivity: Structure ~5 W/m/K; Insulation: <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength: Structure >120 MPa; Insulation: >1.3 MPa
- Char yield >50%

Since additive manufacturing techniques provide the capability to vary the material during fabrication, combinations of the materials in a single system is of interest. For example, a system may consist of an outer layer of High Heat Flux Parasitic TPS and then transition to a low-density, low heat flux material closer to the structure. The proposer can select one or a combination of the material categories to address in their proposal.

In order to achieve the desired properties and inhibit material failure in high aerodynamic shear environments, strategies that print a honeycomb or iso-grid reinforcement with filled cells may also be considered.

Printing and Curing Approach

The selected printing approach must be capable of fabricating the TPS using the selected materials and with limited manual intervention. The system must be scalable to fabricate TPS for flat and curved surfaces for vehicles several meters in diameter. A significant concern for all of the printed and cured materials is large porosity and voids. The proposer should describe controls to minimize these defects. Defects can be controlled by material and cure process selection and/or by print techniques. Print technique controls could include rollers/deflectors to consolidate the material and/or sensors and feedback loops during printing.

Material curing, depending on the resin system, is often achieved by a thermal cycle in an oven. For this solicitation, oven cures are acceptable as long as the thermal cycle does not exceed 180 °C for the parasitic TPS. This constraint is driven by temperature limits on the flight structure. If curing is needed, it is highly desirable to cure the material in situ using the material chemistry, local heating, laser sintering, or ultraviolet/radiofrequency energy.

The high-level goals for a scaled-up TPS additive manufacturing system are provided below.

1. System should include all of the elements for the entire workflow from material formulation to fabrication and final finishing and print quality controls.
2. System functions should be automated with minimal manual processes such that it can be operated by fewer than three technicians.
3. Post-print processing should be minimized.
4. For parasitic TPS, a 5-m-diameter dome should be completely fabricated within 1 month; 3 months for an integrated aeroshell of this size.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

During Phase I, the proposer should:

1. Develop the conceptual design of the entire manufacturing process tailored to the appropriate feed-stock proposed.
2. Demonstrate the capability to fabricate using AM the candidate materials.
3. Conduct material property tests and compare to goals.
4. Conduct aerothermal tests of the printed material.
5. Deliver to NASA small test articles for testing.

During Phase II, the proposer should:

1. Design and assemble a prototype automated system to fabricate the TPS.
2. Demonstrate the capability to fabricate the TPS for nonplanar surfaces.
3. Conduct material property tests for larger range of conditions.
4. Conduct integrated TPS/structure tests such as flexure tests.
5. Conduct aerothermal tests of the printed material.

State of the Art and Critical Gaps:

Current state of the art (SOA) for manufacturing and installing thermal protection on NASA space vehicles is too labor intensive and costly. Furthermore, the heat shield designs are constrained by manufacturing processes that result in segmented blocks with gap fillers that create flight performance issues. To develop an automated additive manufacturing process for spacecraft heat shields that are monolithic, the development of the materials and technologies to deposit and cure the materials on the flight structures are needed.

Relevance / Science Traceability:

Both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) would benefit from this technology. All missions that include a spacecraft that enters a planetary atmosphere require TPS to protect the structure from the high heating associated with hypersonic flight. Improved performance and lower cost heat shields benefit the development and operation of these spacecraft. Human missions to the Moon and Mars would benefit from this technology. Commercial Space programs would also benefit from TPS materials and manufacturing processes developed by NASA.

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T12.07 Design Tools for Advanced Tailorable Composites (STTR)

Lead Center: **LaRC**

Participating Center(s): **MSFC**

Scope Title:

Design Tools for Advanced Tailorable Composites

Scope Description:

Affordable space exploration beyond the lower Earth orbit will require innovative lightweight structural concepts. Use of composite material systems is one of the means of lightweighting exploration vehicles, space habitats, and other space hardware. Lightweighting potential stemming from application of composite materials oftentimes fails to fully exploit the potential for reducing mass due to the lack of design tools tailored to yield designs with optimal load paths. Consequently, highly tailorable material systems are commonly used to produce quasi-isotropic ("black aluminum") or otherwise off-optimal designs.

This solicitation seeks to advance the design capabilities for layered pre-impregnated composite materials reinforced with either continuous or short fibers and with a wide variety of ply thicknesses, from ultrathin (with the fiber areal weight in single digits when expressed in grams per square meter (gsm)), to standard (approx. in the 145- to 190-gsm range). A design tool development and its demonstration to a relevant structure is sought. The design tool shall be developed leveraging the broadly adopted and accessible engineering codes including but not limited to MSC.Patran/Nastran, Abaqus, Hypersizer, Hyperworks, LSOPT, etc. Development in a form of "wrapper" or "plug-in" codes is strongly preferred over redeveloping functionalities that readily exist and can be incorporated within the design tool. Intuitive user-friendly code interfaces for the design definition set up are also highly desirable.

Demonstration problems of interest include fiber-steered or otherwise highly tailored structural designs representative of cryogenic tanks, pressurized habitats, and other primary space structure components, including dry and unpressurized, such as lander truss cages or landing gears. Advantages of a new highly tailored composite design shall be demonstrated by its weight-saving potential over a legacy/conventional design while observing typical manufacturability constraints (determined, e.g., based on a literature survey). Other aspects, such as improved damage tolerance, extended service time, reusability, lower cost, or multifunctionality are also considered significant. Demonstration of improved performance of a highly tailored design relative to a conventional composite design (e.g., black aluminum approach) satisfies the requirements of this solicitation. However, comparisons to the metallic designs are also of interest as they ultimately can demonstrate the design goodness progression in the three-element series involving metallic, conventional composite, and highly tailored composite designs. Examples of relevant applications include but are not limited to current vehicle architectures being constrained for the return to the Moon missions are to fit within a 15-ft-diameter shroud, thus tank and habitat maximum dimensions are likely on the order of this 15-ft-diameter constraint. For tanks, nominal operating pressures in the range of 40 to 65 psi are considered common. The internal pressures for habitats can be guided by the International Space Station's internal pressure of 14.7 psi.

While a global-local analysis might be beneficial and warranted in the overall design process, demonstration problems can include smaller structural components, such as hardpoint attachment brackets, fittings, clevises, etc. Ability of the proposed design approach and related code to tailor not only general sections/acreages but also highly discontinuous sections of primary structures, such as hatches, windows, or hardpoint attachments present within the thin-wall overall architecture are highly sought features of the proposed design tool.

Expected TRL or TRL Range at completion of the Project: 5 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Analysis
- Software
- Research

Desired Deliverables Description:

Phase I of the award shall deliver a proposed implementation of the design tool with a functioning code, however, its capabilities can be truncated relative to the overall proposed development. The truncated code shall include enough capabilities to be able to produce a simplified demonstration case that would also constitute a part of the Phase I deliverable.

The Phase II deliverable shall include a releasable version of the design tool with the complete proposed functionality and a refined demonstration study case. For both Phase I and II developments, an open code architecture is of value such that the end users can gain insight into the implementation and possibly alter or add functionalities. From a practical standpoint, use of Python in conjunction with Abaqus implementation or PCL in conjunction with MSC.Patran/Nastran implementation might be considered examples of "open architectures." Use of an existing design optimization tool, for example, LSOPT, is also allowed and encouraged.

State of the Art and Critical Gaps:

Present composite designs are typically limited to straight fiber arrangements and lamination stacking sequences resulting in quasi-isotropic material properties. No commercially available design tools exist to produce advanced highly tailorable designs with optimized load paths.

Relevance / Science Traceability:

Examples of potential uses include: Space Technology Mission Directorate, Artemis/HLS programs, developers of air-launched systems (e.g., Generation Orbit Launch Services; Aeronautics Research Mission Directorate) next-generation airframe technology beyond "tube and wing" configurations (e.g., hybrid/blended wing body).

References:

- Guimaraes, T., Castro, S., Cesnik, C., Rade, D., Supersonic Flutter and Buckling Optimization of Tow-Steered Composite Plates, AIAA Journal, Vol. 57(1), 2019.
- Singh, K., Kapania, R. K., Optimal Design of Tow-Steered Composite Laminates with Curvilinear Stiffeners, AIAA-2018-2243, AIAA SciTech Forum, Kissimmee, FL, 2018.
- Antunes, N., Dardis, J., Grandine, T., Farmer, B., Hahn, G., Design Optimization of Short Fiber Composite Parts, AIAA-2020-0163, AIAA SciTech Forum, Orlando, FL, 2020.

Z4.04 Real-Time Defect Detection, Identification, and Correction in Wire-Feed and Fused-Filament Additive Manufacturing (SBIR)

Lead Center: **LaRC**

Participating Center(s): **MSFC**

Scope Title:

Real-Time Defect Detection, Identification, and Correction in Wire-Feed and Fused-Filament Additive Manufacturing

Scope Description:

Additive manufacturing (AM) (also referred to here as 3D printing) offers the ability to build lightweight components that are optimally suited for use in aerospace applications. AM can also support sustainable exploration of the surfaces of the Moon and Mars by enabling needed components to be fabricated onsite. Significant strides have been made in the development of AM, with 3D-printed components now being part of active aircraft and spacecraft. While the use of AM has enabled nontraditional designs and decreased part counts, full inspection of each component is typically required postbuild to determine fitness for the final application. Complex geometries, rough as-built surface finishes, and porosity can hinder inspection. If 100% inspection is not possible, proof test logic or some other method of proving fitness for use must be applied. Defects that occur can force a complete reprint. The ultimate promise of AM is to enable on-demand production of customized unique components. For utility in space applications, printed parts have to be fully functional, with zero to minimal postprocessing. Ideally, parts need to be built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service. To enable the full realization of the potential of 3D printing, a capability for closed-loop control of the process that integrates in situ monitoring, real-time defect detection and identification, and print parameter modification is required.

Wire-feed or extrusion-type AM, with its relative simplicity, wide range of feedstocks, and build volume flexibility, is a popular 3D-printing technique that is well suited to space applications. Fused filament fabrication (FFF) of thermoplastics and electron beam free-form fabrication (EBF3) of metals are useful examples of wire-feed processes to illustrate the limitations placed on AM by presently available design and process control tools. After designing an object using 3D modeling software, the geometry is passed to a slicing and tool path planning code, which generates the list of instructions needed by the printing hardware. Once received by the printer, no further modifications or corrections can be made, and the process continues to completion.

Proposals are invited to advance the manufacturing technology by incorporating an in situ defect detection and correction capability into wire-feed processing of metallic parts and FFF or related extrusion processing of thermoplastic, thermoset, or composite components.

In Phase I, contractors should prove the feasibility of integrating sensor feedback with appropriate software tools and computation resources to be able to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects to the part performance and the correction of those defects. Solutions sought include software that can be integrated into the 3D-printing workflow, hardware requirements to run that software for real-time data processing, and sensors capable of operating in the build environment to provide data, also in real time. The proposed approach should be demonstrable at least on the coupon scale for shapes such as circles or boxes.

The proposed solution must include all of the following: (1) defect sensing and detection, (2) assessment of the impact of the defect on part performance, and (3) corrective actions other than scrapping of the build. Proposals that do not clearly include these three elements will be considered out of scope.

Phase II should demonstrate the feasibility of Phase I concepts to arrive at closed-loop solutions to build parts in which information on the processing generated from gathering and analyzing sensor data is used for the prediction of part performance, unique to each individual part, as it is being built. Incorporation of defect correction during fabrication, rather than requiring a print to be scrapped and restarted, should be demonstrated on sample parts.

Expected TRL or TRL Range at completion of the Project: 2 to 3

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Phase I: Concept studies documenting the feasibility of incorporating sensor data feedback and appropriate software tools and computation resources to be used to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects on the performance of the parts and the correction of those defects.

The proposed solution must include all of the following: (1) defect sensing and detection, (2) assessment of the impact of the defect on part performance, and (3) corrective actions other than scrapping of the build. Proposals that do not clearly include these three elements will be considered out of scope.

Phase II: Scale demonstration of a printer with closed-loop control that incorporates defect detection, identification, and correction during fabrication. The complexity of defects that are detected and corrected, as well as the size of the parts, should demonstrate the challenges that would come up in full-scale use of the control processes. Printed part sizes should be at least 10 cm per side for cubes, with detectable defects down to the mm scale or smaller. The defects should have a demonstrable effect on the part performance, such as a decrease in mechanical properties, that is then corrected for by the process.

State of the Art and Critical Gaps:

AM is seeing rapidly expanding applications in many areas, including in aerospace. Despite this growth in AM, filling its full potential has always been limited by quality-control issues and certification of the manufactured parts, as each component that is built is unique. Some work has begun to add defect detection and correction to powder-based manufacturing processes, such as direct metal laser sintering (DMLS) and wire-feed AM.

There has, however, not been the requisite advance in ensuring that defect detection and identification is coupled with the real-time correction of those defects and ensuring final performance of the manufactured part in a particular application.

Gap: Real-time defect detection, identification, and correction in AM processes that would ensure the performance of the as-printed parts without relying on postproduction inspection processes, with parts built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service, has not been demonstrated.

Relevance / Science Traceability:

This topic fits under STMD (Space Technology Mission Directorate). It supports Advanced Manufacturing of Lightweight Structures. Enhancing quality control in AM opens up its use in many industrial applications as well as its use by NASA. In particular, in-space use of AM in future Gateway, lunar, and Mars exploration missions will require that parts that are produced are ready for use as-produced, because there will be limitations in availability of material for reprinting as well as limitations on crew time and equipment for postprinting inspection.

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2. https://newatlas.com/superdraco-test/32292/ [New Atlas: “SpaceX completes qualification test of 3D-printed SuperDraco thruster”] (last visited on 09/28/2020)
3. https://3dprintingindustry.com/news/rocket-lab-celebrates-100th-3d-print-of-its-rutherford-engine-158380/ [3D Print Industry: "Rocket Lab Celebrates 100th Rutherford Engine Build"] (last visited on 09/28/2020)
4. https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf[MSFC Technical Standard EM20: "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals," MSFC-STD-3716] (last visited on 09/28/2020)
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7. https://www.engineering.com/AdvancedManufacturing/ArticleID/19416/The-Importance-of-Closed-Loop-Control-in- Directed-Energy-Deposition-Additive-Manufacturing.aspx[Isaac Maw engineering.com: “The Importance of Closed-Loop Control in Directed Energy Deposition Additive Manufacturing”] (last visited on 09/28/2020)
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Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis (SBIR)

Lead Center: **LaRC**

Participating Center(s): **ARC, GSFC**

Scope Title:

Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis

Scope Description:

NASA's NDE SBIR subtopic will address a wide variety of NDE disciplines. These disciplines include but are not limited to structural health monitoring (SHM), novel NDE sensor development, and NDE modeling and analysis. All three of these disciplines can be used on aerospace structures and materials systems, including but not limited to Inconel, titanium, aluminum, carbon fiber, Avcoat, ATB-8, Phenolic Impregnated Carbon Ablator (PICA), and thermal blanket structures. Sensor systems, SHM, and modeling can target any set of these materials in common aerospace configurations, such as micrometeoroid and orbital debris (MMOD) shielding, truss structures, and stiffened structures. In addition, NDE can target material and material systems in a wrought state in process, and NDE techniques that could be used to inspect additively manufactured components post production would be favored. Current NDE computational tools do not have sufficient resolution to provide representation on the order of finite-element models (FEMs) allowing for a digital twin. Depending on the size of the critical flaw in the material system/structure, this resolution can range from 500 nm to 100 cm realistically. As NDE tool resolution grows, larger volumes of data are created, and thus new computational tools are required. At the same time, low-cost emerging computational hardware, such as graphics processing units (GPUs), is enabling the growing use of advanced physics-based models for improved NDE inspection and for advanced data analysis methods such as machine learning. In addition, as NASA strives to go deeper and longer, new tools need to be developed in order to support long-duration spaceflight.

NDE Sensors and Data Analysis

Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.

Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multiwall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) radiators, or aerospace structural components.

Additionally, techniques for quantitative data analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material foreign object debris (FOD) and/or defects and evaluation of bondline and in-depth integrity for lightweight rigid and/or flexible ablative materials. Typical internal void volume detection requirements for ablative materials are on the order of less than 6 mm, and bondline defect detection requirements are less than 25 mm.

Additive manufacturing is rapidly becoming a manufacturing method targeting fracture-critical components; as such, NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and its effect on diffracting energy sources. Development of NDE techniques, sensors, and methods addressing these issues would be highly desired, but techniques addressing weld inspection will also be considered. Most of the aerospace components will be metallic in nature, and critical flaws are on the range of 1 mm or smaller and can be volumetric or fracturelike in nature.

Structural Health Monitoring (SHM)

Future manned space missions will require spacecraft and launch vehicles that are capable of monitoring the structural health of the vehicle and diagnosing and reporting any degradation in vehicle capability. This subtopic seeks new and innovative technologies in SHM and integrated vehicle health management (IVHM) systems and analysis tools.

Techniques sought include modular/low mass-volume systems; low-power, low-maintenance systems; and systems that reduce or eliminate wiring, as well as standalone smart-sensor systems that provide processed data as close to the sensor as practical and systems that are flexible in their applicability. Examples of possible systems include surface-acoustic-wave- (SAW-) based sensors, passive wireless sensor tags, flexible sensors for highly curved surfaces, and direct-write film sensors. Damage detection modes include leak detection, ammonia detection, micrometeoroid impact, and others. Reduction in the complexity of standard wires and connectors and enabling sensing functions in locations not normally accessible with previous technologies is also desirable. Proposed techniques should be capable of long-term service with little or no intervention. Sensor systems should be capable of identifying material state awareness and distinguishing aging-related phenomena and damage-related conditions. It is considered advantageous that these systems perform characterization of age-related degradation in complex composite and metallic materials. Measurement techniques and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc., in complex composite material systems and in adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Some consideration will be given to the IVHM/SHM ability to survive in on-orbit and deep space conditions, allow for additions or changes in instrumentation late in the design/development process, and enable relocation or upgrade on orbit. The system should allow NASA to gain insight into performance and safety of NASA vehicles as well as commercial launchers, vehicles, and payloads supporting NASA missions.

Inclusion of a plan for detailed technical operation and deployment is highly favored.

NDE Modeling

Technologies sought under this SBIR include near real-time realistic NDE and SHM simulations and automated data reduction/analysis methods for large datasets. Simulation techniques will seek to expand NASA's use of physics-based models to predict inspection coverage for complex aerospace components and structures and to utilize inverse methods for improved defect characterization. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space-flight structures and components, and may involve methods such as machine learning and domain transformation. NASA's interest area is lightweight structural materials for spaceflight, such as composites and thin metals. Future purposes will include application to long-duration space vehicles as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction (i.e., NDE) simulations for high-strength lightweight material systems and include energy interaction with realistic damage in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals, but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, laser, microwave, terahertz, infrared, x-ray, x-ray computed tomography, fiber optic, backscatter x-ray, and eddy current. It is assumed that any data analysis methods will be focused on NDE techniques with high-resolution, high-volume data. Modeling efforts should be physics-based, and it is desired that they can account for material aging characteristics and induced damage, such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, and fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. It is advantageous to use coprocessor/accelerator-based hardware (e.g., field-programmable gate arrays (FPGAs) and GPUs) for simulation and data reduction. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables: For proposals focusing on NDE sensors: Lab prototype and feasibility study or software package, including applicable data or observation of a measurable phenomenon on which the prototype will be built. For proposals focusing on NDE modeling: Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (Technology Readiness Level (TRL) 2 to 4). Inclusion of a proposed approach to develop a given methodology to a TRL of 2 to 4. All Phase I proposals will include minimum of short description for Phase II prototype/software. It will be highly favorable to include a description of how the Phase II prototype or methodology will be applied to structures.

Phase II Deliverables: Working prototype or software of proposed product, along with full report of development, validation, and test results. Prototype or software of proposed product should be of TRL 5 to 6. Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

State of the Art and Critical Gaps:

NDE tools for flight still do not have sufficient resolution to provide representation on the order of finite-element models (FEMs) allowing for a digital twin. Also, as NDE tools grow and sensors get faster, larger volumes of data are created and thus new computational tools are required. At the same time, low-cost emerging computational hardware, such as GPUs, is enabling the growing use of advanced physics-based models for improved NDE inspection and for advanced data analysis methods such as machine learning. Development of new techniques are enabling Orion to meet its 100% inspected mission directive. In addition, as NASA strives to go deeper and longer, new tools need to be developed in order to support long-duration spaceflight.

Relevance / Science Traceability:

Several missions could benefit from technology developed in the area of NDE. Currently, NASA is returning to manned spaceflight. The Artemis program's Orion spacecraft and Space Launch System have had inspection difficulties, and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently, Orion is using several techniques and prototypes that have been produced under the NDE

SBIR topic. The Space Launch System is NASA's next heavy-lift system, capable of sending hundreds of metric tons into orbit. Inspection of the various systems is ongoing and will continue to have challenges, such as verification of the friction stir weld on the fuel tanks. As NASA continues to push into deeper space, smart structures that are instrumented with SHM systems can provide real-time mission-critical information on the status of the structure.

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Z4.06 Manufacturability Assessment as a Design Constraint for Advanced Tailorable Composites (SBIR)

Lead Center: **LaRC**

Participating Center(s): **MSFC**

Scope Title:

Manufacturability Assessment as a Design Constraint for Advanced Tailorable Composites

Scope Description:

While use of composite material systems in space vehicle structures is increasing, their broader implementation is still facing multiple challenges. One of these challenges, especially relevant in the context of advanced tailorable composites, is a manufacturability assessment that could be leveraged as a design constraint early in the development. Absence of a reliable and comprehensive manufacturability assessment often restricts exploitation of the full potential of the composite material system and promotes conservative fabrication approaches that can negate potential mass benefits of composites. Suboptimal designs such as quasi-isotropic lamination stacking sequence treat the material as “black aluminum,” failing to permit tailored load paths possible with composites. Consequently, a material system that can enable large reductions in system mass ends up being used in the design process in a way that results in structural components that are much heavier than necessary.

This solicitation seeks to advance the analytical predictive manufacturability assessment capabilities for layered composites. Such an assessment is required as a constraint in the structural design and optimization process. Layered pre-impregnated composite materials reinforced with either continuous or short fibers, and with a broad spectrum of ply thicknesses, are in the scope of this solicitation. For the continuous-fiber composites, the typical fiber areal weights range from approximately 30 grams per square meter (gsm) to just under 200 gsm. For short-fiber applications, the ultrathin plies in the single-digit gsm range are also of interest. Since a broad variety of composite material systems is within the scope of this solicitation, the scope of related manufacturability constraints can be tailored to the proposed material system. Consequently, the examples of manufacturability considerations provided in this solicitation are not all-inclusive, and parameters not listed below can be offered up for investigation when a compelling rationale is presented. The list of potential implementations of advanced tailorable composites is also provided to aid in the determination of manufacturing constraints of primary importance. The overarching approach should be based on recognizing that the more aggressive the tailoring of a composite material system, the greater the risk of developing defects in the manufacturing process. While avoiding any defects can be one countermeasure, quantifying the effects of defects can provide additional insights. Specifically, if the effect of defect can be quantified and it can be demonstrated that the benefits gained from the associated design tailoring can overcome the adverse effect of a small defect, then a rationale for the more aggressive tailoring can be justified. Examples of defects include, but are not limited to, tow gaps, overlaps, foldovers, or poor compaction/separation from the underlying plies. In cases where a placement imperfection can be subjected to restorative actions, analysis of how successful such actions can be is also of value.

The manufacturability assessment shall be based on analytical tools validated with experimentation/actual manufacturability trials. Examples of the performance-based manufacturing constraints for the continuous-fiber composites include, but are not limited to, determination of the minimum allowable steering radius, relative proximity of ply terminations such that no significant adverse interaction occurs, and minimizing thermal warping in the cure process when nonsymmetric lamination stacking sequence is present. For example, one of the important examples of the manufacturability assessment for short-fiber composites is determination of an initial preform thickness distribution that would produce a desired thickness distribution after forming that involves preform expansion and/or turning or steering (i.e., forming similar to deep-stamping or closed-cross-section forming with a clamshell tool and an expandable bladder). Similarly, estimation of the short-fiber orientation distortions in the forming process and predictive countermeasures to this behavior are also sought.

Subscale manufacturing demonstrations representative of the challenges that can be encountered in the full-scale applications are sought as the manufacturability predictive analysis validation cases. The full-scale structures of interest that can be scaled down for the manufacturing demonstrations include cryogenic tanks, crew modules, pressurized habitats, and other dry and unpressurized primary structural components or portions of thereof. Discrete features such as hatches, access and windows cutouts, and hard point attachments can be considered as manufacturability challenges to be encountered in the full-scale applications in addition to the general acreage considerations. Furthermore, manufacturability assessment for short-fiber composites is expanded to allow smaller size demonstrations, for example, those representative of hard point attachment brackets, hinges, clevises, etc.

Expected TRL or TRL Range at completion of the Project: 5 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

In Phase I, a comprehensive identification of manufacturability constraints shall be conducted for a selected material system and application. Analytical and experimental results shall be obtained for at least one selected aspect of the manufacturability assessment.

In Phase II, the analytical tool capabilities and related manufacturability trials shall be expanded to a more comprehensive and exhaustive list of manufacturability constraints identified in Phase I. A manufacturing demonstration article and the computational tool available for release shall be delivered at the conclusion of Phase II.

State of the Art and Critical Gaps:

Present composite designs are typically limited to straight fiber arrangements and lamination stacking sequences resulting in quasi-isotropic material properties. Apart from the lack of structural design and optimization tools, highly tailored fabrication of composites presents manufacturing challenges and is prone to introducing manufacturing defects. Manufacturability assessment is often performed via the trial-and-error approach, which is costly, time consuming, and very limited in scope. A validated computational manufacturability assessment tool would enable more rapid and comprehensive manufacturability assessment that can inform the design effort in its early stages.

Relevance / Science Traceability:

- Space Technology Mission Directorate (STMD), Artemis/HLS (human landing systems) programs, developers of air-launched systems, e.g., Generation Orbit Launch Services.

- Aeronautics Research Mission Directorate (ARMD), next-generation airframe technology beyond "tube and wing" configurations, e.g., hybrid/blended wing body.
- Developers of the in situ nondestructive evaluation inspection capabilities within both space and aeronautics programs.

References:

1. Brooks, T. R., Martins, J. R., On Manufacturing Constraints for Tow-Steered Composite Design Optimization, Composite Structures, Vol. 204, pp. 548-559, November 2018.
2. Grenoble, R. Nguyen, T., McKenney, M., Przekop, A., Juarez, P., Gregory, E., Jegley, D., Oremont, L., Fabrication of a Composite Tow-Steered Structure for Air-Launch Vehicle Applications, AIAA-2018-1376, AIAA SciTech Forum, Kissimmee, FL, 2018.
3. Wu, K., Tatting, B., Smith, B., et al., Design and Manufacturing of Tow-Steered Composite Shells Using Fiber Placement, AIAA-2009-2700, Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA, 2009.
4. Antunes, N., Dardis, J., Grandine, T., Farmer, B., Hahn, G., Design Optimization of Short Fiber Composite Parts, AIAA-2020-0163, AIAA SciTech Forum, Orlando, FL, 2020.

Focus Area 16 Ground & Launch Processing

Lead MD: **HEOMD**

Participating MD(s): **STTR**

Ground processing technology development prepares the agency to test, process and launch the next generation of rockets and spacecraft in support of NASA's exploration objectives by developing the necessary ground systems, infrastructure and operational approaches for terrestrial and off-planet surface systems.

This topic seeks innovative concepts and solutions for both addressing long-term ground processing and test complex operational challenges and driving down the cost of government and commercial access to space. Technology infusion and optimization of existing and future operational programs, while concurrently maintaining continued operations, are paramount for cost effectiveness, safety assurance, and supportability.

A key aspect of NASA's approach to long term sustainability and affordability is to make test, processing and launch infrastructure available to commercial and other government entities, thereby distributing the fixed cost burden among multiple users and reducing the cost of access to space for the United States.

Unlike previous work focusing on a single kind of launch vehicle such as the Saturn V rocket or the Space Shuttle, NASA is preparing common infrastructure to support several different kinds of spacecraft and rockets that are in development. Products and systems devised at a NASA center could be used at other launch sites on earth and eventually on other planets or moons.

Specific emphasis to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations includes development of ground test and launch environment technology components, system level ground test systems for advanced propulsion, autonomous control technologies for fault detection, isolation, and recovery, including autonomous propellant management, and advanced instrumentation technologies including Intelligent wireless sensor systems.

H10.01 Advanced Propulsion Systems Ground Test Technology (SBIR)

Lead Center: **SSC**

Participating Center(s): **KSC**

Scope Title:

Advanced Propulsion Test Technology Development

Scope Description:

Rocket propulsion development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and nonchemical propulsion, boost stage, in-space propulsion, and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test systems that enhance chemical and advanced propulsion technology development and certification. The goal is to advance propulsion ground test technologies to enhance environment simulation; minimize test program time, cost, and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, technology needs include stable combustion of oxygen and hydrogen in a low-pressure duct, developing robust materials, and advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Design of technology/techniques for oxygen injection into a duct that assures stable combustion with hot (>1,700 R) hydrogen at low pressure (<25 psia), having an oxidizer to fuel mixture ratio of 9 for an oxygen flow rate of approximately 2.7 lbm/sec. This technology solution must be extensible to a system having an oxygen flow rate of approximately 270 lbm/sec.
- Devices for measurement of pressure, temperature, strain, and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultrahigh pressure (>8,000 psi), high flow rate (>100 lbm/sec), and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiently in high-vibroacoustic environments.
- Advanced materials to resist high-temperature (<4,400 °F), hydrogen embrittlement, and harsh environments.
- Tools using computational methods to accurately model and predict system performance, that integrate simple interfaces with detailed design and/or analysis software, are required. Stennis Space Center (SSC) is interested in improving capabilities and methods to accurately predict and model the transient fluid structure interaction between cryogenic fluids and immersed components to predict the dynamic loads and frequency response of facilities.

- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; and fluid-structure interactions in internal flows.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.1 Infrastructure Optimization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I as a final report and show a path toward Phase II hardware/software demonstration, with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps:

This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies, and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids; reduce logistics costs; reduce times required for ground processing and launch; reduce mission risk; and reduce hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DOD), and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next-generation testing requires the ability to produce very high temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

Relevance / Science Traceability:

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at SSC, and other propulsion system development centers.

References:

https://www.nasa.gov/centers/stennis/home/index.html

https://technology.ssc.nasa.gov/

H10.02 Autonomous Operations Technologies for Ground and Launch Systems (SBIR)

Lead Center: **KSC**

Participating Center(s): **ARC, LaRC, SSC**

Scope Title:

Autonomous Operations Technologies for Ground and Launch Systems

Scope Description:

For the scope of this solicitation, ground systems are considered to be the planetary or lunar surface-based infrastructure and processes used to assemble, validate, support, and maintain launch vehicles and payloads (including nonspacecraft payloads) in preparation for flight. Launch systems are considered to be the planetary or lunar surface-based infrastructure and processes used to transition launch vehicles to flight operation.

Autonomous operations technologies (AOT) are required to manage ground and launch systems activities where human intervention/interaction/presence needs to be minimized or eliminated, such as in hazardous locations/operations and in support of remote operations. AOT are required to reduce operations and maintenance (O&M) costs of flight system and payload processing operations on the ground, and to increase ground systems availability to support mission operations. AOT will also be required for extended surface O&M on the Moon and Mars.

AOT performs functions such as system and component fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision making and control; and intelligent components and devices.

AOT will be integrated into activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will enable surface O&M, which requires a high degree of autonomy and reliability for unattended operations during extended periods of time. AOT will complement in situ resource utilization (ISRU) operations by supporting ISRU ground systems infrastructure with O&M autonomy. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants used in launch vehicles and maneuvering systems. APM includes preplanned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting, and system reconfiguration.

AOT solutions may enable the autonomous command, monitoring, and control of entire integrated systems, such as a propellant loading system and all other associated support systems involved in the loading process. AOT will also support tasks such as systems setup, testing and checkout, troubleshooting, maintenance, upgrades, and repair. These additional tasks drive the need for autonomous element-to-element interface connection and separation, multi-element inspection, and recovery of high-value cryogenic propellants and gases to avoid system losses.

AOT software may include prerequisite control logic (PCL) and reactive control logic (RCL), and may utilize machine learning or other forms of artificial intelligence to manage nominal system behavior and adapt to off-nominal conditions.

In addition to propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high-pressure gases for purging, pressurization, or conditioning. Propellant management systems may also include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and observe vehicle states during propellant management operations.

Specifically, this subtopic seeks the following:

- Development of technologies for automated/autonomous propellant (including cryogenic propellants) management and the servicing of commodities for launch vehicles and payloads.
- Development of high-fidelity physics-based cryogenic-thermal models and ground process simulations capable of real-time and faster than real-time performance.
    - Development of automated/autonomous algorithms for ground systems applications.
    - Machine learning environments (simulation and learning agent) for ground systems processes and applications.
    - Development of high-fidelity models and simulations for complex payload system processing, servicing, maintenance, etc.
    - Development of test and evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models, and simulations.
- Development of technologies for ground systems Health Determination and Fault Management.
    - Prediction, prognosis, and anomaly detection algorithms and applications.
    - Detection, isolation, and recovery of system and component faults and degradation.
    - Development of T&E, and V&V methods for Health Determination and Fault Management algorithms and applications.
- Development of technologies for automated/autonomous planning and scheduling (P&S).
    - Automated/autonomous assets management tools and applications.
    - Scheduling and prioritization algorithms and applications.
    - Human-machine information interactions and intent inferencing.
- Development of technologies for automated/autonomous inspection, maintenance, and repair (IM&R).
    - Use of robotic caretakers for IM&R needs.
    - Self-diagnosis in systems and components to inform condition-based maintenance.
    - Software to aid robotic agents or systems to learn IM&R functionality.
- Development of technologies for enhanced logistics and reliability.

    - Optimization and/or reduction of logistics needs (design for maintainability, commonality, and reusability).
    - Commonality of maintenance equipment, tools, and consumables.
    - Automated/autonomous asset management.
    - Automated/autonomous personnel location and condition determination.
    - Intelligent devices (sensors, actuators, and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.).
- Standardization of architectures and interfaces for ground and launch systems.
- Standardization of ground systems design (design for maintainability, commonality, and reusability).

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I, show a path toward Phase II demonstration and deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).

Expected TRL or TRL Range at completion of the Project: 5 to 8

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables: Research, identify, and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms to enable autonomy of ground systems. Demonstrate technical feasibility and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. It should identify improvements over the current state of the art and the feasibility of the approach in a multicustomer environment. Bench or lab-level demonstrations are desirable. Deliverables shall include a report documenting findings.

Phase II deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions using analog ground systems hardware and processes. Deliverables shall include a report detailing performance testing results, a plan for maturing and applying the technology to mission-worthy systems, and other relevant documentation. Delivery of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps:

There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1. High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9).
2. Simulation component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9).
3. Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9).
4. Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9).
5. Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9).

Relevance / Science Traceability:

In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration and Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation, and maintenance of ground systems and systems on the surfaces of other planets and moons. The directive from the President to accelerate the timeline for landing astronauts on the Moon, with the goal of a sustainable lunar presence after 2028, has made these technologies even more relevant to mission success. These technology development areas are identified in the 2020 NASA Technology Taxonomy, published by the Office of the Chief Technologist, under TX04 - Robotic Systems, TX10 - Autonomous Systems, and TX13 - Ground, Test, and Surface Systems.

This subtopic also produces technologies useful to the Space Technology Mission Directorate (STMD).

References:

NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html)

NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/offices/oct/home/sstip.html)

T13.01 Intelligent Sensor Systems (STTR)

Lead Center: **SSC**

Participating Center(s):

Scope Title:

Advanced Instrumentation for Rocket Propulsion Testing

Scope Description:

Rocket propulsion system development is enabled by rigorous ground testing to mitigate the propulsion system risks inherent in spaceflight. Test articles and facilities are highly instrumented to enable a comprehensive analysis of propulsion system performance. Advanced instrumentation has the potential for substantial reduction in time and cost of propulsion systems development, with substantially reduced operational costs and evolutionary improvements in ground, launch, and flight system operational robustness.

Advanced instrumentation would provide a wireless, highly flexible instrumentation solution capable of measurement of heat flux, temperature, pressure, strain, and/or near-field acoustics. Temperature and pressure measurements must be acquired from within the facility mechanical systems or the rocket engine itself. These advanced instruments should function as a modular node in a sensor network, capable of performing some processing, gathering sensory information, and communicating with other connected nodes in the network. The collected sensor network must be capable of integration with data from conventional data acquisition systems adhering to strict calibration and timing standards to support static propulsion system testing standards. Synchronization with Inter-Range Instrumentation Group—Time Code Format B (IRIG-B) and National Institute of Standards and Technology (NIST) traceability is critical to propulsion test data analysis.

Rocket propulsion test facilities also provide excellent testbeds for testing and using the innovative technologies for possible application beyond the static propulsion testing environment. These sensors would be capable of addressing multiple mission requirements for remote monitoring such as vehicle health monitoring in flight systems, autonomous vehicle operation, or instrumenting inaccessible measurement locations, all while eliminating cabling and auxiliary power. It is envisioned these advanced instrumentation would support sensing and control applications beyond those of propulsion testing. For example, inclusion of expert system or artificial intelligence technologies might provide great benefits for autonomous operations, health monitoring, or self-maintaining systems.

This subtopic seeks to develop advanced wireless instrumentation capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network. Sensor systems should have the ability to provide the following functionality:

- Acquisition and conversion to engineering units for quantifying heat flux, temperature, pressure, strain, and/or near-field acoustics such that it contributes to rocket engine system performance analysis within established standards for error and uncertainty.
- Capable of in-place calibrations with NIST traceability.
- Collected data must be time-stamped to facilitate analysis with other collected datasets.
- Transfer data in real time to other systems for monitoring and analysis.
- Interface to flight-qualified sensor systems, which could be used for multivehicle use.
- Determine the quality of the measurement and instrument state of health.
- Self-contained to collect information and relay measurements through various means by a sensor-web approach to provide a self-healing, autoconfiguring method of collecting data from multiple sensors, and relaying for integration with other acquired datasets.
- Function reliably in extreme environments, including rapidly changing ranges of environmental conditions, such as those experienced in space. These ranges may be from extremely cold temperatures, such as cryogenic temperatures, to extremely high temperatures, such as those experienced near a rocket engine plume.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.1 Infrastructure Optimization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

For all above technologies, research should be conducted to demonstrate technical feasibility with a final report at Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps:

Highly modular, remote sensors are of interest to many NASA tests and missions. Real-time data from sensor networks reduces risk and provides data for future design improvements. Wireless sensors offer a highly flexible solution for scientists and engineers to collect data remotely. They can be used for thermal, structural, and acoustic measurement of systems and subsystems and also provide emergency system halt instructions in the case of leaks, fire, or structural failure. Other examples of potential NASA applications include (1) measuring temperature, strain, voltage, and current from power storage and generation systems, (2) measuring pressure, strain, and temperature in pumps and pressure vessels, and (3) measuring strain in test structures and ground support equipment and vehicles, including high-risk deployables.

There are many other applications that would benefit from increased real-time sensing in remote hard-to-test locations. For example, sensor networks on a vehicle body can give measurement of temperature, pressure, strain, and acoustics. This data is used in real time to determine safety margins and test anomalies. The data is also used post-test to correlate analytical models and optimize vehicle and test design. Because these sensors are small and low mass, they can be used for ground test and for flight. Sensor module miniaturization will further reduce size, mass, and cost.

No existing wireless sensor network option meets NASA’s current needs for flexibility, size, mass, and resilience to extreme environments.

Relevance / Science Traceability:

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate. It supports all test programs at Stennis Space Center (SSC) and other propulsion system development centers, and potential advocates are the Rocket Propulsion Test (RPT) Program Office and all rocket propulsion test programs at SSC.

References:

1. Fernando Figueroa, Randy Holland, David Coote, "NASA Stennis Space Center integrated system health management test bed and development capabilities," Proc. SPIE 6222, Sensors for Propulsion Measurement Applications, 62220K (10 May 2006)
2. J. Schmalzel; F. Figueroa; J. Morris; S. Mandayam; R. Polikar, "An architecture for intelligent systems based on smart sensors," IEEE Transactions on Instrumentation and Measurement (Volume: 54, Issue: 4, Aug. 2005)
3. S. Rahman, R. Gilbrech, R. Lightfoot, M. Dawson, "Overview of Rocket Propulsion Testing at NASA Stennis Space Center," NASA Technical Report SE-1999-11-00024-SSC
4. David J. Coote, Kevin P. Power, Harold P. Gerrish, Glen Doughty, "Review of Nuclear Thermal Propulsion Ground Test Options," 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum (AIAA 2015-3773)
5. H. Ryan, W. Solano, R. Holland, W. Saint Cyr, S. Rahman, "A future vision of data acquisition: distributed sensing, processing, and health monitoring," IMTC 2001. Proceedings of the 18th IEEE Instrumentation and Measurement Technology Conference. Rediscovering Measurement in the Age of Informatics (Cat. No.01CH 37188)
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7. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040053475.pdf

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9. https://www.nasa.gov/centers/wstf/pdf/397001main_Prop_test_data_acq_cntl_sys_DACS_doc.pdf

Focus Area 17 Thermal Management Systems

Lead MD: **STMD**

Participating MD(s): **SMD**

From the smallest satellite to the most complicated human rated spacecraft, thermal is seen as an enabling function to a vehicle. Temperatures must be maintained within design limits, whether those be cryogenic systems for science instruments, or comfortable shirt sleeve operations temperatures for crew missions. As missions evolve and waste energy rejection becomes more of a demand, NASA seeks components for both active and passive thermal systems. Such components complete the thermal cycle which includes waste energy acquisition, transport, rejection/storage, and insulation. The intended goal for any advanced thermal development is to enable new mission concepts while maintaining minimal impact to thermal system mass, volume, and power to maintain a spacecraft at specific temperature limits.

S3.06 Thermal Control Systems (SBIR)

Lead Center: **GSFC**

Participating Center(s): **JPL, JSC, LaRC, MSFC**

Scope Title:

Coatings for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments

Scope Description:

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Radiator surface coatings with desired emissivity and absorptivity provides a passive means for instrument temperature control. The utilization of variable emittance devices further enables active control of the instrument temperature when the heat output from the instrument or the thermal environment of the radiator changes. With NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean and sanitary is needed. New coating formulations utilizing durable, anticontamination and self-cleaning properties that will disallow the accumulation of dust, dirt, and foreign materials are highly desirable. These coatings can have low absorptance and high infrared (IR) emittance properties or be transparent for use on existing thermal coating systems. The goal of this technology is to preserve optimal long-term performance of spacecraft and habitation components and systems. Furthermore, coatings that can survive and operate in extreme environments (cryogenic or high temperature) are desirable.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.3 Thermal Protection Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis

- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables

- Successfully develop the formulations of the coating that leads to the desired dust mitigation.
- Deliverable of coupon.
- Samples of the hardware for further testing at NASA facilities.
- Final report.

Phase II Deliverables

- Results of performance characterization tests.
- Results of stability test of the coating formulations and its mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Deliverable of test coupon
- Final report.

State of the Art and Critical Gaps:

There are limited options for durable, stable thermal control coatings that are dust shedding in charging environments. Current state-of-the-art, sprayable radiation-stable coatings are able to coat complex, irregular surfaces, but they are porous and will become imbedded with dust and particulates. Other surface films tend to be less optically stable and may charge in the plasma environment, thereby attracting lunar regolith to their surfaces. Mirrors have the limitations of requiring flat surfaces and are not conformal in nature. Currently, no single thermal control surface appears to provide stability, durability, and meet optical property requirements for sustained durations in space and lunar environments.

Relevance / Science Traceability:

Many Science Mission Directorate (SMD) missions will greatly benefit from this dust mitigation thermal coating technology: any lunar-relating project and projects involved with robotic science rovers and landers.

References:

- The following website provides links to some references for dust mitigation coatings such as lotus thermal coatings: https://ntrs.nasa.gov/search.jsp?R=20150020486
- The following website provides links to some references for extreme environment coatings: https://vfm.jpl.nasa.gov/files/EE-Report_FINAL.pdf
- References in Subtopic Z13.01, Active and Passive Dust Mitigation Surfaces.

Scope Title:

Heat Pumps for High-Temperature Sink Environments

Scope Description:

Operations in extreme environments where the environment sink temperature exceeds spacecraft hardware limits will require active cooling if long-duration survivability is expected. Robotic science rovers operating on the Lunar surface over diurnal cycles face extreme temperature environments. Landers with clear views of the sky can often achieve sufficient heat rejection with a zenith or, if sufficiently far from the equator, an anti-Sun-facing radiator. However, science rovers must accommodate random orientations with respect to the surface and Sun. Terrain features can then result in hot environment sink temperatures beyond operating limits, even with shielded and articulated radiator assemblies. Lunar dust degradation on radiator thermo-optical properties can also significantly affect effective sink temperatures. During the Lunar night, heat rejection paths must be turned off to preclude excessive battery mass or properly routed to reclaim nuclear-based waste heat.

Science needs may drive rovers to extreme terrains where steady heat rejection is not otherwise possible. The paradigm of swarms or multiple smaller rovers enabled by commercial lander opportunities will need to leverage standard rover bus designs to permit flexibility. A heat pump provides the common extensibility for thermal control over the lunar diurnal. Active cooling systems or heat pumps are commonly used on spacecraft. Devices used include mechanical cryocoolers and thermoelectric coolers. For higher loads, vapor compression systems have been flown and, more recently, reverse turbo-Brayton-cycle coolers are being developed under NASA's Game Changing program for high load, high-temperature-lift cryocoolers. However, technology gaps exist for midrange heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 to 100 W.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Conceptual design.
- Physics-based analysis or model.
- Proof-of-concept hardware (Phase I).
- Proof-of-concept hardware tested against simulated loads in proposed environments (Phase II).
- Final report.

State of the Art and Critical Gaps:

Specifically, heat pump systems are needed for the following:

- Temperature lift from a cold side at <50 °C to an environmental sink temperature as high as 75 °C (temperature lift of 50 °C or heat rejection rate of 230 W/m^2), with a system coefficient of performance >2.5.
- System should be tolerant of being powered down during the lunar night and restarted during the day reliably over multiple diurnals.
- Exported vibrations, if any, should be minimal for compatibility with science instruments.

Novel heat pump systems are desired. Enabling improvements over state-of-the-art systems are also welcome.

Relevance / Science Traceability:

NASA's lunar initiative and Planetary Science Division form the primary customer base for this technology. Missions that directly address the National Research Council Planetary Science Decadal Survey may be users of this technology.

References:

- Apollo Lunar Roving Vehicle Documentation: https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html
- Apollo Experience Report - Thermal Design of Apollo Lunar Surface Experiments Package: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf
- Thermal Considerations for Designing the Next Lunar Lander: https://aip.scitation.org/doi/10.1063/1.2437438

Scope Title:

Advanced Manufacturing of Loop Heat Pipe Evaporator

Scope Description:

A loop heat pipe (LHP) is a very versatile heat transport device that has been used on many spacecraft. At the heart of the LHP is the evaporator and reservoir assembly. During the manufacturing, tedious processes are required to machine the porous primary wick and insert it into the evaporator, and both ends of the wick need to be sealed for liquid and vapor separation. One commonly used method for vapor seal is to use a bimetallic knife-edge joint, which is more prone to failure over long-term exposure to thermal cycles and shock and vibration. These tedious manufacturing processes add to the cost of the traditional LHP. A new manufacturing technique that will allow the primary wick to be welded directly to the reservoir without the use of a knife-edge seal is needed in order to reduce the cost and enhance the reliability.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly.
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup optimized to operate in simulated realistic environments with appropriate cycling (Phase II).
- Final report.

State of the Art and Critical Gaps:

The LHP evaporator contains a porous wick, which provides the capillary pumping capability to sustain the fluid flow in the loop. The smaller the pore size of the wick, the higher its capillary pumping capability. However, a smaller pore size results in a higher flow resistance that must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 µm and porosity around 0.4 to 0.6. In order to replace the traditional porous wick, the new wick produced by the advanced manufacturing technology must have comparable pore size and porosity. The smallest pore size currently produced by direct metal laser sintering is on the order of 10 µm.

Relevance / Science Traceability:

Traditional LHPs are used on many NASA missions including ICESat (Ice, Cloud, and Land Elevation Satellite), ICESat-2, Swift, Aura, Geostationary Operational Environmental Satellite (GOES), Geostationary Operational Environmental Satellite-R Series (GOES-R), and Surface Water and Ocean Topography (SWOT). Similar future SMD (Science Mission Directorate) missions, especially those using small satellites, can greatly benefit from this technology.

References:

Richard, Bradley, et al.: "Loop Heat Pipe Wick Fabrication via Additive Manufacturing," *NASA Thermal & Fluid Analysis Workshop*, August 21-25, 2017, Marshall Space Flight Center, Huntsville, AL.

Scope Title:

Approaches and Techniques for Lunar Surface Payload Survival

Scope Description:

The lunar environment poses significant challenges to small, low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately one Earth month. During that time, surface temperatures on the lunar surface can reach 400 K at local solar noon or drop to below 100 K during the lunar night—and even colder in permanently shadowed regions. These hot and cold conditions can last several Earth days, because of the slow rotation of the Moon, or permanently in shadowed craters. Lunar dust deposited on heat-rejection surfaces and coatings will increase the heat absorbed from the Sun, thus reducing the effectiveness of radiators for heat rejection. The lunar gravity, which is 1/6th of the Earth's, will limit the ability of typical low-power heat transport devices, but the gravity field may provide advantages that could be utilized. Higher heat dissipation capacity should be addressed in Z2.01.
This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Example technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerant, zero- or low-power nonconsumable/regenerative heat generation sources, high-thermal-capacitance thermal storage, advanced insulation, and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired. Technologies should show substantial increase over the state of the art. Technology proposals should address power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, temperature drops through the system, heat storage/release amount, sensitivity to lunar topography and orientation, etc.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis

- Prototype
- Hardware

Desired Deliverables Description:

Thermal management approaches, techniques, and hardware components to enable the accommodation of temperature extremes encountered in the lunar environment. Concept model deliverable for Phase I and prototype demonstration in relevant environment in Phase II.

State of the Art and Critical Gaps:

Missions like Surveyor and Lunokhod hibernated during the night or reduced operational power near noon, in attempts to survive single or multiple lunar cycles. ALSEPs (Apollo Lunar Surface Experiments Packages) were deployed on several Apollo missions and had select experiments that operated for many lunar cycles. However, both Lunokhod and ALSEP benefited from radioisotope heat and power sources, which are either too expensive or not likely to be available for near-term future lunar science experiments. In fact, most modern lunar surface mission planning is based on solar power and batteries and typically avoids the challenges associated with surviving the full lunar cycle or shadowed regions.

While interest in lunar science and the development of abilities to deliver payloads to the lunar surface are resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

Relevance / Science Traceability:

Science Mission Directorate (SMD) lunar surface science investigations will employ small, low-power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020, and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References:

- NASA Prepares for Performing New Science on the Moon: https://www.jpl.nasa.gov/news/news.php?release=2007-068
- The Surveyor Program: https://history.nasa.gov/TM-3487/ch2-1.htm
- The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/(link is external)
- Missions - Lunokhod 01: https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/
- Missions - Lunokhod 02: https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/

Z2.01 Spacecraft Thermal Management (SBIR)

Lead Center: **JSC**

Participating Center(s): **GRC, GSFC, JPL, MSFC**

Scope Title:

Spacecraft Thermal Management

Scope Description:

NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

- Novel three-way valves that can operate to either mix or split single-phase fluid flow passively.
- Lunar lander/surface asset thermal technologies.
- Embedded cooling of power electronics.
- Concepts for closed-loop extravehicular activity (EVA) thermal systems.

These areas are considered of equal priority, and no award preference is expected for one area over another.

Passive Three-Way Valves

NASA seeks novel three-way valves that can operate as either a mixing valve (two liquid input ports and one liquid output port) or splitting valve (one liquid input port and two liquid output ports) that can be used to passively control loop temperatures by the degree fraction of radiator bypass. Such miniature passive thermal control valves could find use in a number of single-phase mechanically pumped fluid thermal control systems. Proposed technologies must address the following design goals:

- Design shall autonomously operate without power.
- <0.1% flow rate through the shutoff port, with a goal of having a provision for no leakage/adjustable leakage through the use of a pre-installed orifice.
- Control range of 5 to 10 ^{o}C, with pre-adjustable setpoint control.
- Operational temperature limits -55 to 90 ^{o}C, nonoperational limits of -55 to 125 ^{o}C.
- Designs shall be compatible with FC-72 working fluid as well as with those used on the International Space Station (ISS) thermal control loops (water and ammonia). Retrofit of soft goods is acceptable.
- Mass desired <250 g (maximum mass 500 g).
- Unit volume <50 cm^3 (maximum 100 cm^3).
- Leak rate 1×10^{-6} scc/s gHe at 200 psia.
- Minimum 4,000 full actuation cycles, desired 17,500 cycles.
- Rad hard to 300 krad.
- 200 psia maximum expected operating pressure, 200 psia proof pressure, 800 psia burst pressure.

- Pressure drop <1.5 psi at 1.5 L/min of FC-72 working fluid.

Lunar Surface Thermal Technology Development

NASA is seeking focused efforts to develop large human-class lunar lander technologies. Technologies should address a gap associated to long-duration habitation on the lunar surface, where temperatures range from -193 °C or lower in shadow regions (including night) to 120° C at the equatorial subsolar point. System technologies should be orientation insensitive; for example, lander side-mounted radiators must provide their function regardless of lunar surface temperature condition. Technologies are needed that allow a single vehicle design to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. Adding heaters can lead to increased vehicle mass due to additional power generation and storage requirements and are not considered a novel architecture approach. Proposed radiator technologies should also address micrometeoroid and orbital debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include the deposition of dust on radiators leading to degraded optical properties, contamination-insensitive evaporators/sublimators to enable long mission life, and self-healing coolant tubes for MMOD-impact resilience. Technologies should be suitable for use in medium-sized landers that operate near 1-kW average heat dissipation capacity.

Alternatively, technologies that utilize the conditions provided by the lunar environment to provide a critical function may also be considered; for example, air-water separator technologies that leverage the gravity field of the lunar surface, or concepts that explore the viability of utilizing the lunar surface regolith to provide long-duration thermal control function. As appropriate, such systems should also address functional capability in the microgravity environment that will be experienced prior to lunar surface operations.

Proposed technologies should also be extensible to human-class landers that will have variable heat loads and average loads between 2 and 6 kW. All technologies should support a minimum flight duration of 5 years and be compatible with the encountered aerospace environment.

This subtopic is different from S3.06 subtopic, which is focused on thermal control technologies for payloads and smaller robotic landers. Technologies directly applicable to that scale vehicle should consider reviewing the S3.06 Thermal Control Systems subtopic.

Embedded Cooling of Power Electronics

To optimize the performance of state-of-the-art power and propulsion systems, it is often advantageous to directly embed thermal control mechanisms within the packaged hardware. The key advantages are to enable a lower temperature drop between the heat source and heat rejection to allow for higher rejection temperatures, to remove heat from concentrated areas (avoid localized hot spots), and to provide more uniform temperatures within the electronics package. Applications for such technologies range from very high power nuclear electric propulsion (NEP) systems, to compact laser diodes, to embedded cooling of rotating equipment. Here we specifically desire concepts that have the potential to efficiently manage high-performance power electronics in common compact packages.

At the device level, applications such as low-inductance GaN packages rely on low thermal impedance heat-sinking strategies which also facilitate mechanical compliance and often electrical isolation. Current state-of-the-art thermal gap fillers have functional thermal impedances of 1.5 to 11 K/W for 12-mm^2 GaN devices with thermal transfer of 200 to 400 mW/mm^2 [Ref. 6]. Solutions that improve these thermal impedances values by >50% are sought.

At the system level, NASA has interest in the cooling of standard 3U boards to assist in the Advanced Modular Power Systems (AMPS) program. This program calls for semiconductor to circuit board power transfer of >200 mW/mm^2, circuit board to backplane interface >5mW/mm^2, and backplane interface through wedgelock rail >15 mW/mm^2 with minimum thermal impedance [Ref. 7].

Example solutions include but are not limited to single-phase liquid jet cooling, heat pipes, and evaporation techniques. Any proposed solution should consider the material compatibility with the heat source and heat delivery to the vehicle's primary active thermal control system as well as any adverse effects on the cooled electronics. Here, solutions may consider integration with either a traditional single-phase (liquid) vehicle active thermal loop or a two-phase (liquid-vapor) mechanically pumped active thermal loop. Power requirements to operate active systems must be addressed with the goal to minimize power. The transient performance of the proposed mechanism should be considered within the scope of the award in order to identify any key limitations of the design.

Closed-Loop EVA Thermal Technologies

EVA thermal control has traditionally relied on the dissipation of water to space. The current suit relies on a water sublimator, whereas the next-generation exploration spacesuit will include a water evaporator. In either case, water is consumed at an average rate of ~1 lb/hr over the course of the spacewalk. Here, NASA seeks novel closed-loop EVA thermal control technologies that have general potential for integration into future iterations of spacesuit design.

Concepts should address the following key performance parameters, at a minimum:

- Nominal average heat rejection >350 W.
- Accommodate peak heat rejection of at least 700 W for 15 min, with little or no consumable loss.
- Support EVA duration of at least 4 hr, stretch goal of 8 hr.
- Demonstrate viability of integration with the liquid cooling garment operating at a minimum continuous temperature between 8 and 10 oC.
- Time to regenerate/recharge the system <12 hr.
- Any regeneration/recharge impacts to the spacecraft should be addressed within the scope of the award (vehicle mass, power, volume impact assessment).
- Mechanism power <20 W including any controller electronics.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology. Any delivered math models should include supporting data that validates the assumptions used within the model.

State of the Art and Critical Gaps:

These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft. Additionally, the exploration of embedded thermal control technologies may have a direct impact on the AMPS program in the near term and provide valuable insight into techniques for other embedded cooling applications. These improvements may come through either novel hardware solutions or modernization of software tools used to assess human vehicle interactions. The current state of the art in thermal control results in vehicle power and mass impact of greater than 25% to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent control (both actively and passively) within the thermal control system becomes more apparent. Science payloads will continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be readily provided by traditional thermal control methods due to vehicle-level impacts of overall performance, mass/volume, and power.

Relevance / Science Traceability:

- Advanced Modular Power System
- Europa Clipper/Lander
- Lunar Lander
- Long-duration habitats (Moon, Mars, etc.)
- EVA

References:

1. Kandilian, R., Bhandari, P., & Mastropietro, A. J. (2018). Thermal and Flow Analysis of Europa Clipper Thermal Control Valves. NASA Thermal and Fluids Analysis Workshop. TFAWS18-AT-14.
2. Hartenstine, J., Walker, K., and Anderson W. (2012). Passive Control of a Loop Heat Pipe with Thermal Control Valve for Lunar Lander Application. AIAA 2012-354
3. Stephan, R. (2011). Overview of the Altair Lunar Lander Thermal Control System Design and the Impacts of Global Access. AIAA 2011-5001.
4. Ewert, M.K. (1993). Investigation of Lunar Base Thermal Control System Options. SAE Transactions. J. of Aerospace. 102(1). 829-840.
5. Nyberg, K. L., Diller, K. R., & Wissler, E. H. (2001). Model of human/liquid cooling garment interaction for space suit automatic thermal control. Journal of biomechanical engineering. 123(1). 114-120.
6. Pallo, N., et al., (2018). Modular heat sink for chip-scale GaN transistors in multilevel converters. 2018 IEEE Applied Power Electronics Conference and Exposition (APEC). San Antonio, TX. 2798-2805. doi: 10.1109/APEC.2018.8341414.
7. Colozza, A. J., &Gardener, B. G. (2019, May 1). Advanced Modular Power System Electronics Enclosure Thermal Testing. NASA Glenn Research Center. Cleveland, OH. NASA/TM-2019-220011.
8. Izenson, M., Phillips, S., Chepko, A., Quinn, G., Steele, J., & Bue, G. (2016, July). Design of a Lithium Chloride Absorber Radiator for Flight Testing on an Extravehicular Mobility Unit. 46th International Conference on Environmental Systems.
9. Bue, G., Makinen, J., Vogel, M., Tsioulos, G., Honas, M., Dillon, P., & Porwitz, D. (2011, July). Hollow Fiber Flight Prototype Spacesuit Water Membrane Evaporator Design and Testing. 41st International Conference on Environmental Systems.

Focus Area 18 Air Vehicle Technology

Lead MD: **ARMD**

Participating MD(s): **STTR**

This focus area includes tools and technologies that contribute to both the Advanced Air Vehicles Program (AAVP) and the Transformative Aeronautics Concepts Program (TACP) encompassing technologies in all six Strategic Thrusts within the NASA Aeronautics Mission Directorate (ARMD). AAVP studies, evaluates, and develops technologies and capabilities for new aircraft systems, and also explores far-future concepts that hold promise for revolutionary air-travel improvements. Innovative AAVP design concepts for advanced vehicles integrate technologies focus on fuel burn, noise, emissions, and intrinsic safety. The goal: to enable new aircraft to fly safer, faster, cleaner, quieter, and use fuel far more efficiently. Partnering with industry, academia, and other government agencies, AAVP pursues mutually beneficial collaborations to leverage opportunities for effective technology transition. TACP encourages revolutionary concepts, creates the environment for researchers to experiment with new ideas, performs ground and small-scale flight tests, and drives rapid turnover into potential future concepts to enable aviation transformation. Research is organized to aggressively engage both the traditional aeronautics community and non-traditional partners. Although TACP focuses on sharply focused studies, the program provides flexibility for innovators to assess new-technology feasibility and provide the knowledge base for radical aeronautics advances in noise reduction technology.

A1.01 Aerodynamic and Structural Efficiency - Integration of Flight Control with Aircraft Multidisciplinary Design Optimization (SBIR)

Lead Center: **ARC**

Participating Center(s): **AFRC, LaRC**

Scope Title:

Integration of Flight Control with Aircraft Multidisciplinary Design Optimization

Scope Description:

Successful design tools for advanced aircraft concepts typically require close interaction among the various design disciplines involved: aerodynamics, structures, propulsion, flight control, etc. This is particularly true for advanced modern transports such as the Boeing 787 and nontraditional aircraft concepts currently being studied at NASA, such as the Transonic Truss-Braced Wing or the blended wing body, where the level of coupling across the various disciplines can be very complex. It has been shown that substantial benefits could be realized by including many of these disciplines within a single multidisciplinary design optimization (MDO) process, rather than optimizing each discipline in isolation. Furthermore, nontraditional flight control design philosophies are becoming increasingly more common as the aircraft industry is responding to the new urban air mobility (UAM) market. The NASA X-57, for example, could employ many modes of flight control distributed throughout the aircraft enabled by distributed electric propulsion. Thus, integration of flight control into an aircraft MDO process can produce more advanced aircraft design capabilities through improved and integrated methods and tools.

This subtopic seeks proposals that develop new methods and tools that enable the inclusion of flight control in an aircraft MDO process. The proposed control approach should directly contribute to aircraft overall design objectives, such as fuel burn, aircraft takeoff gross weight, or other aircraft performance metrics. The resulting tightly coupled MDO environment should be capable of handling the interactions among relevant disciplines, such as structures, aerodynamics, flight control (including the control effector design parameters and actuator weight/power), and propulsion. Design variables may include structural details (e.g., skin thickness, structural layout, and materials), aerodynamic details (planform shape, jig twist, and airfoil shape distributions), control law details (type, objective function, and control gains), control effector and sensor design parameters (size, layout, locations, and quantity), propulsion design parameters (thrust distribution, integrated allocation, and scheduling), etc. The control law may be parameterized in such a way that the resulting parameters are suitable to a numerical optimizer. Control design tools may utilize advanced distributed sensors such as fiber optic shape sensors or surface pressure sensors to achieve improved aircraft design objectives.

Appropriate design constraints should be imposed within the integrated MDO tool to ensure proper aerodynamic limits, such as stall and buffet; structural limits, such as maneuver and gust load response and flutter margins; as well as control-centric constraints, such as stability margins, control actuator power and authority, position and rate limits, and sensor and actuator requirements that dictate controllability and observability.

Applications of these integrated MDO approaches could be implemented for realistic and relevant aircraft configurations to demonstrate the impact of the proposed methods. Performance gains should be actively derived from the system response to a control policy such as cruise-drag optimization, gust load alleviation, flutter suppression, flight-propulsion control, and multiobjective flight control. To integrate flight control into an MDO environment with a large number of design variables and constraints, new tools that would enable increased computational efficiency, such as adjoint-based optimization, are of interest using appropriate-fidelity aircraft models capable of capturing nonlinear aerodynamics. The proposed tools could be stand-alone or added capabilities to available open-sourced NASA MDO environments.

This subtopic does not seek proposals that propose vehicle conceptual design and analysis studies or control methods that have no clear transition paths to commercial applications.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.6 Vehicle Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Software
- Prototype
- Hardware

Desired Deliverables Description:

For Phase I, the deliverables include flight control integrated MDO methods and tools.

For Phase II, the deliverables include more mature and validated flight control integrated MDO methods and tools which are to be integrated with open-sourced NASA MDO environments.

State of the Art and Critical Gaps:

Increasingly, more advanced aircraft concepts utilize innovative flight control design philosophies, such as the modern Boeing 787 with trailing edge variable camber, and Airbus A350 with adaptive drooped hinge flaps, as well as a wide variety of UAM aircraft design concepts with distributed electric propulsion. The current state of the art in research does not usually consider integration of flight control systems into an aircraft MDO process. Some low-level research effort of addressing flight control integration in an MDO process exists within the Aeronautics Research Mission Directorate (ARMD) Advanced Air Transport Technology (AATT) Project, but the effort does not consider a wide range of integration of flight control systems including actuators, sensors, and flight control laws. This critical research gap area could be filled by this subtopic.

Relevance / Science Traceability:

Under the NASA Advanced Air Vehicle Program (AAVP), the AATT Project is conducting research in distributed electric propulsion and adaptive wing technologies. Both of these research elements could benefit from this subtopic. Also, under the NASA AAVP, the Revolutionary Vertical Lift Technologies (RVLT) Project is conducting research in the area of UAM aircraft using distributed electric propulsion for electrical vertical takeoff and landing (eVTOL). This subtopic could complement the research conducted under the RVLT Project.

References:

NASA Aeronautics Research Mission Directorate (ARMD), https://www.nasa.gov/aeroresearch

Advanced Air Vehicles Program (AAVP), https://www.nasa.gov/aeroresearch/programs/aavp

Advanced Air Transport Technology (AATT) project, https://www.nasa.gov/aeroresearch/programs/aavp/aatt

Revolutionary Vertical Lift Technology (RVLT) project, https://www.nasa.gov/aeroresearch/programs/aavp/rvlt

A1.02 Quiet Performance - Airframe Noise Reduction (SBIR)

Lead Center: **LaRC**

Participating Center(s): **GRC**

Scope Title:

Airframe Noise Reduction

Scope Description:

Innovative methods and technologies are necessary for the design and development of efficient and environmentally acceptable aircraft. In particular, the impact of aircraft noise on communities around airports is the predominant limiting factor on the growth of the nation's air transportation system. Reductions in aircraft noise could lead to wider community acceptance, lower airline operating costs where noise quotas or fees are employed, and increased potential for air traffic growth on a global scale. In support of the Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP), improvements in noise prediction and noise control are needed for subsonic, transonic, and supersonic vehicles targeted. Solutions are sought that target airframe noise sources and the noise sources due to the aerodynamic and acoustic interaction of the airframe and engines. Innovations in the following specific areas are solicited:

- Prediction and/or mitigation of aerodynamic noise sources including those from the airframe, propulsion-airframe interactions, or aeroacoustic integration effects associated with high-aspect ratio truss-braced vehicles.

- Concepts for active and passive control of broadband aeroacoustic noise sources for conventional, truss-braced, and other advanced aircraft configurations. Technologies of interest include adaptive flow control and noise control enabled by advanced aircraft configurations, including integrated airframe-propulsion control methodologies.
- Innovative design approaches or technologies, including acoustic liner or porous surface concepts, to reduce airframe noise sources and/or propulsion/airframe aeroacoustic interactions. However, engine nacelle liner applications are specifically excluded.
- System-level noise prediction methodologies for operational aspects (as opposed to certification conditions) of high-aspect ratio, truss-braced subsonic transports, or technology variants thereof.
- Fundamental and applied computational fluid dynamics techniques for aeroacoustic analysis which can be adapted for design purposes.
- Prediction and/or mitigation of aerodynamic noise sources including those from the airframe and those that arise from significant interactions between airframe and high-bypass ratio and/or small-core propulsion systems.
- Prediction of sound propagation from the aircraft through a complex atmosphere to the ground. This should include interactions between noise sources and the airframe and its flow field.
- Innovative source identification techniques for airframe (e.g., landing gear and high-lift systems) noise sources, including turbulence details related to flow-induced noise typical of separated flow regions, vortices, shear layers, etc.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Concepts, technologies, and tools that enable rapid assessment of the noise impact of novel engine/airframe configurations, mitigate component noise issues associated with novel aircraft configurations, and/or aid in the development and optimization of noise control approaches for component noise sources that enable new aircraft configurations such as truss-braced wing and small-core turbofan engines.

Phase I deliverables can include laboratory demonstrations that establish proof of concept of noise reduction technologies, or applications of novel computational tools with limited scope that demonstrate the potential for success on problems of greater scope.

Phase II deliverables can include system or subsystem demonstrations concurrent with the establishment of a realistic path to concept production, or incorporation of novel computational tools into existing modeling toolchains with validation cases to document capabilities.

State of the Art and Critical Gaps:

State-of-the-art technologies for noise reduction on conventional transport aircraft are generally passive and do not incorporate advanced material systems or adaptive mechanisms that can modify their performance based on the noise state of the vehicle. Advanced material systems for airframe noise control are still in their infancy, especially in the context of certifiability and robustness. Novel material systems that could be applied to component noise sources on the aircraft are needed, such as shape memory alloy actuators, or active or adaptive systems. In addition, future aircraft designs, such as high-aspect ratio, truss-braced configurations, are envisioned that either leverage noise benefits of complex geometrical configurations or introduce noise challenges with engine/airframe integration. Efficient computational tools that enable rapid-turn evaluations of multiple configurations at the design stage are lacking. Numerical methods to study complex engine/airframe configurations are complex and difficult to leverage at the aircraft design stage where configuration details are not specified. Improvements to numerical methods and models for studying the noise aspects of advanced airframe configurations, including engine integration, would ease consideration of acoustics in the design, rather than leaving acoustics to the late design stage where noise control solutions are costly and less effective. Improved tools would also enable more rapid evaluation and development of novel noise control approaches that may be needed for these novel aircraft configurations.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from noise reduction technologies that could reduce the aircraft noise footprint at landing and takeoff. Configurations with novel engine placement, such as above the fuselage, can reduce the noise footprint, but technologies are needed to efficiently model the performance and noise impacts of these novel engine installations. In addition, novel configurations and technologies such as truss-braced wing and small-core turbofan engines will introduce new noise challenges that must be addressed to enable their successful deployment.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance the ability to consider acoustics earlier in the aircraft design process. The TTT project would also benefit from the development and demonstration of simple material systems, such as advanced liner concepts with reduced drag or adaptive material and/or structures that reduce noise, as these component technologies could have application in numerous vehicle classes in the AAVP portfolio, including subsonic and supersonic transports as well as vertical lift vehicles.

References:

AAVP - Advanced Air Transport Technology (AATT) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/aatt

AAVP - Commercial Supersonic Technology (CST) Project:
https://www.nasa.gov/aeroresearch/programs/aavp/cst

TACP - Transformational Tools and Technologies (TTT) Project:
https://www.nasa.gov/aeroresearch/programs/tacp/ttt

A1.03 Propulsion Efficiency - Propulsion Materials and Structures (SBIR)

Lead Center: **GRC**

Participating Center(s):

Scope Title:

Advanced Materials and Structures Technologies Enabling New Highly Efficient Propulsion Systems for Subsonic Transport Vehicles

Scope Description:

Materials and structures research and development (R&D) contributes to NASA's ability to achieve its long-term aeronautics goals, including the development of advanced propulsion systems. Proposals are sought for advanced materials and structures technologies that will be enabling for new propulsion systems for subsonic transport vehicles with high levels of thermal, transmission, and propulsive efficiency. Integrated computational and experimental approaches are needed that can reduce the time necessary for development, testing, and validation of new materials systems and components.
Advanced high-pressure-ratio compact gas turbine engines will include components of sufficiently compact size that new approaches to processing and advanced manufacturing will be needed. Temperature capability, thermomechanical performance, environmental durability, reliability, and cost-effectiveness are important considerations.

The increased use of various types of modeling to improve R&D effectiveness and enable more rapid and revolutionary materials design has been identified as critical. NASA recently sponsored a study to define a potential 25-year goal for integrated, multiscale modeling of materials and systems to accelerate the pace and reduce the expense of innovation in future aeronautical systems. Through a series of surveys, workshops, and validation exercises, this study identified critical cultural changes and gaps facing the multiscale modeling community. The results of this study were published in a NASA report, "Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems" [Ref. 1]. Some of the critical gaps identified in this report are: (1) under-development of physics-based models that link length and time scales, (2) inability to conduct real-time characterization at appropriate length and time scales, (3) lack of optimization methods that bridge scales, (4) lack of models that compute input sensitivities and propagate uncertainties, and (5) lack of verification and validation methods and data.

Proposals emphasizing modeling can address topics which shall address gaps in that 2040 vision. The range of topics could include data management, data analytics, machine learning, linkage and integration across spatiotemporal scales, and characterization of materials over their lifecycle. Proposals may address any material class associated with aeronautics propulsion for subsonic transport vehicles, multiscale modeling and measurements, multiscale optimization methods, and verification and validation of models and methods. However, approaches should rely on iterative, predictive methods that integrate experiments and simulations to describe the behavior and response of materials at various length and time scales.

Technology areas of interest this year include:

- Computational materials and multiscale modeling tools, including methods to predict properties, and/or durability of propulsion materials based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional, and adaptive materials.
- Robust and efficient methods/tools to design and model advanced propulsion system materials and structures at all scale levels, including approaches that are adaptable for a multiscale framework.
- Multiscale design tools that integrate novel materials, mechanism design, and structural subcomponent design into system level designs.
- Advancing technology for ceramic matrix composites (CMCs) and their environmental barrier coatings (EBCs) for gas turbine engine components operating at 1,482 °C (2,700 °F) or higher. Focus areas include increased thermomechanical durability, increased resistance to environmental interactions, cost-effectiveness of processing and manufacturing, and improved approaches to

component fabrication and integration. Computational tools and integrated experimental/computational methods are sought, including models/tools to predict degradation and failure mechanisms.

- Additive manufacturing and other advanced processing/manufacturing approaches for structural components or materials to enable improved engine efficiency through decreasing weight and/or improving component design, properties, and performance.
- In support of future aircraft with hybrid electric or all electric propulsion systems, advanced cross-cutting materials technologies are needed. For example: (1) soft magnetic material with high magnetic saturation and/or lower losses for 100 to 300 kHz operation, (2) hard magnetic materials with an energy product greater than neodymium iron boron, (3) conductors for power cables with a specific resistivity less than copper or aluminum, and (4) novel materials systems and structures to enable functionality, such as power harvesting, thermal management, self-sensing, and actuation.
- Design and development of unique materials such as shape memory alloys and high entropy alloys for subsonic transport vehicle propulsion system structures and components.
- Propulsion aeromechanics, damping devices, and analysis and mistuning analysis for turbomachinery rotating blades.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

NASA's intent is to select proposals that have the potential to move a critical technology beyond Phase II SBIR funding and transition it to Phase III, where NASA's aeronautics programs, another Government agency, or a commercial entity in the aeronautics sector can fund further maturation as-needed, leading to actual usage in an enhanced propulsion system.

The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA needs. Phase I should demonstrate advancement of a specific technology, supported by analytical and experimental studies that are documented in a final report. Phase IIs could yield: (1) models supported with experimental data, (2) software related to a model that was developed, (3) a material system or subcomponent that has been demonstrated to have better properties/performance (ability to operate at a higher temperature, carry more current, etc.), and (4) modeling tools for incorporation in software, etc. that can be infused into a NASA project or lead to commercialization of the technology.

Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology.

State of the Art and Critical Gaps:

This subtopic would support R&D on advanced materials and structures technologies that will be enabling for new propulsion systems for subsonic transport vehicles with high levels of thermal, transmission, and propulsive efficiency. The needs are specified in the scope description. One of the major NASA Glenn Research Center core competencies is Materials and Structures for Extreme Environments. This subtopic supports that type of research—enabling materials and structures research that allows more efficient propulsion systems.

In general, integrated computational and experimental approaches are needed that can reduce the time necessary for development, testing, and validation of new materials systems and components. The increased use of various types of modeling to improve R&D effectiveness and enable more rapid and revolutionary materials design has been identified as critical. NASA recently conducted a study that identified critical cultural changes and gaps facing the multiscale modeling community.

For future aircraft with hybrid electric or all electric propulsion systems, advanced materials technology is needed for power components including electric machines and power cables.

Advanced high-pressure-ratio compact gas turbine engines will include components of sufficiently compact size that new approaches to processing and advanced manufacturing will be needed. Improvements in temperature capability, thermomechanical performance, environmental durability, reliability, and cost-effectiveness are important considerations.

Relevance / Science Traceability:

Aeronautics Research Mission Directorate (ARMD) projects that would/could support each of the specified areas of interest are listed below, along with advocates for the technologies. The technologies would lead to improved propulsion efficiencies (subsonic transport vehicles).

- Computational materials and multiscale modeling tools, including methods to predict properties, and/or durability of propulsion materials based upon chemistry and processing for conventional as well as functionally graded, nanostructured, multifunctional, and adaptive materials. TTT (Transformational Tools and Technology) Project.
- Robust and efficient methods/tools to design and model advanced propulsion system materials and structures at all scale levels, including approaches that are adaptable for a multiscale framework. TTT Project.
- Multiscale design tools that integrate novel materials, mechanism design, and structural subcomponent design into system level designs. TTT Project.
- Advancing technology for CMCs and their EBCs for gas turbine engine components operating at 1,482 °C (2,700 °F) or higher. TTT and AATT (Advanced Air Transport Technology) Projects.
- Additive manufacturing and other advanced processing/manufacturing approaches for structural components or materials to enable improved engine efficiency through decreasing weight and/or improving component design, properties, and performance. TTT Project.
- Soft magnetic material with high magnetic saturation and/or lower losses for 100 to 300 kHz operation, hard magnetic materials with an energy product greater than neodymium iron boron, conductors with a specific resistivity less than copper or aluminum, and cable insulation materials with increased dielectric breakdown strength, and significantly higher thermal conductivity (≥1 W/m·K) and resistance to ageing effects such as corona, ozone, humidity, and dust operating at greater than 3 kV. TTT, AATT, CAS (Convergent Aeronautics Solutions) Projects/HGEP (Hybrid Gas-Electric Propulsion) subproject.

- Novel materials systems and structures to enable functionality, such as power harvesting, thermal management, self-sensing, and actuation. Approaches may include use of nanotechnology and novel processing to tailor and control properties such as thermal conductivity, electrical conductivity, thermoelectric response, microstructure and porosity, and shape-memory behavior. TTT Project.
- Design and development of unique materials such as shape-memory alloys and high-entropy alloys for aeronautics structures and components. TTT and CAS Projects.
- Propulsion aeromechanics, damping devices, and analysis and mistuning analysis for turbomachinery rotating blades. TTT Project/AATT - UPAI (Unconventional Propulsion Airframe Integration)

References:

1. Vision 2040: A Roadmap for Integrated, Multiscale Modeling and Simulation of Materials and Systems, NASA/CR-2018-219771, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180002010.pdf

HGEP:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170004515.pdf

Hybrid Electric Propulsion:
https://www1.grc.nasa.gov/aeronautics/hep/
https://www.grc.nasa.gov/www/cdtb/aboutus/workshop2016/HybridElectricPropulsionReportOut-LCCPCDRoadmapWorkshop.pdf

TTT:
https://www.nasa.gov/aeroresearch/programs/tacp/ttt/description
https://www.nasa.gov/aeroresearch/programs/tacp/ttt

CAS:
https://www.nasa.gov/aeroresearch/programs/tacp/cas
https://nari.arc.nasa.gov/
https://www.nasa.gov/aeroresearch/programs/tacp
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006909.pdf

A1.04 Electrified Aircraft Propulsion (SBIR)

Lead Center: **GRC**

Participating Center(s): **AFRC, LaRC**

Scope Title:

Electrified Aircraft Propulsion

Scope Description:

Proposals are sought for the development of energy storage, propulsion airframe integration, power distribution, thermal, tools/modeling approaches, electric machines, and electrical power conversion that will be required for aircraft that use turboelectric, hybrid electric, or all-electric power generation as part of the propulsion system. Turboelectric, hybrid electric, and all-electric power generation, as well as distributed propulsive power, have been identified as candidate transformative aircraft configurations with reduced fuel consumption/energy use and emissions. However, components and management methods for power generation, distribution, and conversion are not currently available in the high power ranges with the necessary efficiency, power density, electrical stability, and safety required for thin haul/short haul or transport-class aircraft. Novel developments are sought in:

- Energy storage systems with specific energy >400 Whr/kg at the system level under continuous 2C rate discharge conditions, with cycle life >10,000 cycles. Materials or strategies to promote rapid charging are desirable. This subtopic seeks energy solutions in the Technology Readiness Level (TRL) 3 to 5 range, appropriate for near-term applications.
- Lightweight electrical insulation materials/composites for high-altitude, high-voltage power transmission with dielectric breakdown strength (V/m) of the insulation minimally 2.5× that of the operating electric field stress at the conductor surface (operating voltages expected to be 1 to 20 kV), high resistivity at high temperature (>10^6 up to 10^{20} Ω•cm), low dielectic dissipation factor (tan δ), insulation Class C with operating temperature performance ≥240 to 400 ˚C, moisture resistant, good mechanical properties (low creep under high-voltage stresses) and with thermal conductivity ≥1 up to 10 W/m•K.
- Innovative tools for the design and analysis of airframe-integrated, high-performance distributed electric propulsion (DEP) inlet/fan systems and the resulting effect on: (1) distortion and swirl at the aerodynamic interface plane (AIP), (2) fan efficiency, stability, and structural robustness, and (3) operation of adjacent flow paths for DEP inlet/fan concepts and/or boundary layer ingestion (BLI) aircraft.
- Additive manufacturing processes and advanced materials for future generation MW-class electric motor designs and windings, which provide lower costs, compact designs (>25% volume reduction), lighter weight (>30% reduction), advanced cooling/improved thermal conductivity, multimaterials and/or greatly improved material or component properties that significantly contribute toward improved electric machine performance. Maintaining electrical insulating and lifetime properties over repetitive thermal cycling, along with being resistant to corona effects, is of interest.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Deliverables vary considerably within the topic, but ideally proposals would identify a technology pull area (with a market size estimate), how the proposed idea addresses the needs of the technology pull area and then deliver a combination of analysis and prototypes that substantiate the idea's merit.

For Phase I, it is desirable that the proposed innovation clearly demonstrates that it is commercially feasible and addresses NASA's needs.

Deliverables for a Phase II should be focused on the maturation, development, and demonstration of the proposed technical innovation.

State of the Art and Critical Gaps:

The critical technical need is for lightweight, high-efficiency power distribution systems and energy storage that have flight-critical reliability. Typically, the weight needs to be reduced by a factor of 2 to 3 and efficiency needs to be improved. Higher efficiency reduces losses and makes thermal management more achievable in an aircraft. Another need for medium to large aircraft is the ability to operate at voltages above 600 V. This capability results in reduced weight, however, is called out specifically because it impacts all of the power system components.

Technologies that address these gaps enable Electrified Aircraft Propulsion (EAP) which enables new aircraft configurations and capabilities for the point-to-point on-demand mobility market and a new type of innovation for transport aircraft to reduce fuel consumption and emissions.

Relevance / Science Traceability:

EAP is an area of strong and growing interest in Aeronautics Research Mission Directorate (ARMD). There are emerging vehicle level efforts in Urban On-Demand Mobility, the X-57 electric airplane being built to demonstrate EAP advances applicable to thin and short haul aircraft markets and an ongoing technology development subproject to enable EAP for single aisle aircraft. Additionally, NASA is starting the new Electrified Powertrain Flight Demo (EPFD) project to enable a MW-class aircraft.

Key outcomes NASA intends to achieve in this area are:

- Outcome for 2015-2025: markets will begin to open for electrified small aircraft.
- Outcome for 2025-2035: certified small-aircraft fleets enabled by electrified aircraft propulsion will provide new mobility options. The decade may also see initial application of electrified aircraft propulsion on large aircraft.
- Outcome for >2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems that will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Project
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project
- TACP/Transformational Tools and Technologies (TTT) Project

References:

EAP is called out as a key part of Thrust 3 in the ARMD strategic plan:
https://www.nasa.gov/aeroresearch/strategy

Overview of NASA's EAP Research for Large Subsonic Aircraft:
https://ntrs.nasa.gov/search.jsp?R=20170006235

NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html

A1.05 Computational Tools and Methods (SBIR)

Lead Center: **LaRC**

Participating Center(s): **ARC, GRC**

Scope Title:

Computational Tools and Methods

Scope Description:

Computational fluid dynamics (CFD) plays an important role in the design and development of a vast array of aerospace vehicles, from commercial transports to space systems. With the ever-increasing computational power, usage of higher fidelity, fast CFD tools and processes will significantly improve the aerodynamic performance of airframe and propulsion systems, as well as greatly reduce nonrecurring costs associated with ground-based and flight testing. Historically, the growth of CFD accuracy has allowed NASA and other organizations, including commercial companies, to reduce wind tunnel and single-engine component tests. Going forward, increased CFD fidelity for complete vehicle or engine configurations holds the promise of significantly reducing development costs, by enabling certification by analysis. Confidence in fast, accurate CFD and multidisciplinary analysis tools allow engineers to reach out of their existing design space and accelerate technology maturation schedules. Uncertainty quantification is a key technology in enhancing confidence in the prediction capability of the computational tools. NASA’s CFD Vision 2030 Study (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf) highlighted the many shortcomings in the existing computational technologies used for conducting high-fidelity simulations, including multidisciplinary analysis and optimization, and made specific recommendations for investments necessary to overcome these challenges.

High-quality mesh generation was recognized by the Vision Study as a bottleneck in the CFD workflow as it impacts both the solution accuracy and the time to solution. Therefore, improved mesh technology is a continued need for high-fidelity simulations and proposals are solicited in two focused areas related to the overall grid generation theme. First, adaptive mesh capabilities have been very successful in unstructured and Cartesian grid paradigms, but application to structured overset grids have been limited to mesh refinement based on solution gradients which leads to too many grid points for full-scale three-dimensional configurations. Mesh redistribution algorithms use a fixed number of grid points, and locally refine (and coarsen) the mesh to equally distribute the error. This allows the "best" solution for a fixed computation cost with respect to the defined error metric. Adaptive mesh redistribution algorithms are needed for structured overlapping grids that are robust in that given a valid structured overlapping grid system with no negative volumes, no orphan points, and a valid error-metric field, the redistributed mesh must also have no negative volumes and no orphans. The error metrics need to be based on solution and geometric gradients, solution Hessian, and adjoint-based error measures for achieving accurate lift and drag, pressure signatures, resolved turbulent kinetic energy, etc. These error-metric fields should be able to be read in and/or computed internally from an existing CFD solution. The error metric should be relevant to the CFD analysis being performed and the redistributed mesh should minimize the error with respect to the chosen metric. Finally, the cost of the redistribution algorithm (excluding the computation of the error-metric field in the case of an adjoint-based error metric) should only be a small percentage of the cost of a steady-state Reynolds-averaged Navier-Stokes (RANS) CFD solve on the structured overlapping grid being analyzed, less than 10%. Many private companies utilize NASA-structured overset grid tools such as Chimera Grid Tools and OVERFLOW, and several mesh generation software companies continue to develop and enhance their own structured grid generation capabilities. The addition of a solution- (or adjoint-) based adaptive mesh redistribution software package will have a large impact on reducing the generation of accurate overset grids, database generation, reduce uncertainty in computed solutions, and provide quantitative measures of solution error. This will impact the quality of CFD analysis being performed and lead to better products by industry.

The second focused grid-related area for which proposals are being solicited is automated and scalable mesh generation for wall-modeled large eddy simulations (WMLES). Unstructured approaches can be used to discretize highly complex flow configurations but, in addition to automation, there is a need to generate the mesh robustly and efficiently regardless of geometric complexity. The mesh quality aspect is especially critical for scale resolving simulations where numerical methods benefit significantly from element regularity and alignment. The goal of the solicited work is to encourage development of such mesh generation software that can be interfaced and integrated with NASA CFD solvers. The requirements for the solicited mesh software include: (1) it should be able to efficiently handle arbitrarily complex geometries; (2) the software should be message passing interface (MPI) parallel, scalable to billion+ cell meshes as are typical for NASA applications; (3) the mesh generation process needs to take a water-tight bounding volume definition as input, where the surface of the bounding volume can be marked with prescribed mesh resolution(s), in addition to any user prescribed volume refinement metrics (such as adjoint-based error metrics, prescribed volumes, etc.). Such mesh technology has the potential to drastically improve turn-around time for scale resolving simulations for complex configurations and enabling wider use of high-fidelity CFD analysis for challenging turbulent flow problems. This research effort is expected to enable NASA solvers to interface with the resulting tool. The meshing tool should be designed to perform well on the emerging high-performance computing hardware. An additional area of research may include adaptive mesh refinement while a WMLES is progressing.

Another focused area of research and development within this subtopic is the prediction of aeroelastic effects with uncertainty quantification. Application of computational aeroelastic simulations involving complex flow fields (e.g., flow separation) toward practical engineering applications is hindered by many factors beyond the large computational cost. The large volume of output data must be postprocessed nondeterministically, and new data-based methods are required to adequately understand the output, and further draw connections between the flow and events/mechanisms of interest, such as aeroelastic flutter. These methods may include machine learning, nonlinear transforms, classical parameters indicative of flutter onset (e.g., aerodynamic center location and generalized aerodynamic forces), higher-order statistical characterizations, etc. In addition to statistical flow outputs, the inputs to the flow simulations are often uncertain as well; methods are then required to propagate these uncertainties through the flow simulation in a cost-effective manner, and properly accommodate the uncertainties in the data-driven postprocessing methods. A possible and desired outcome is a toolbox of nonintrusive software that wraps around aeroelastic CFD simulations. Included in the envisioned work and products are uncertainty quantification- (UQ-) based postprocessing tools that would serve to guide an analysis team to characterize flutter onset (among other aeroelastic phenomena) in a nondeterministic manner. Phase I demonstrations of the UQ methodologies and tools on a single NASA-FUN3D flutter problem are desired. Phase II efforts would require more complete development of an automated and user-friendly toolbox. The awardees could then wrap the developed UQ tools around other CFD/aeroelastic solvers for commercialization.

In summary, proposals are being solicited in the above three focused areas under this subtopic. Successful awardees in all three research areas should note that it is NASA's intention to use developed software tools with NASA's CFD solvers. Therefore, fully functional application programming interfaces (APIs) will be required as deliverables.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Research
- Analysis

Desired Deliverables Description:

For focused area 1, the suggested research and development (including deliverable) during Phase I and II include:

Phase I:

- Single-zone demonstrations using airfoil geometry for O-grid or C-grid topologies with precomputed error-metric scalar/vector fields.
- Structured multiblock (without overset) grid for wing geometry.
- Structured overset grids for the wing geometry.
- Demonstrate capability of grid redistribution with up to 200 million grid cells within 20 minutes of wall-clock time.
- Provide an executable or an API for independent assessment by NASA teams.

Phase II:

- Collaborate with NASA team to develop API for coupled RANS-based grid adaptation.
- Assessment on four open-source complex structured grids: (1) Drag Prediction Workshop 6 (Wing-body-nacelle-pylon), (2) nozzle with baseline ramp (5th AIAA Propulsion Aerodynamics Workshop), (3) Sonic-Boom Prediction Workshop (C608 geometry), and (4) High Lift Prediction Workshop (HLPW-4).
- Demonstrate distributed memory strong scalability on grid sizes up to 1 billion with granularity at 500,000 points per core in under 5 minutes of wall-clock time.

For focused area 2, the suggested research and development during Phase I and II include:

Phase I:

- Given a bounding surface mesh (tri/quad/poly), demonstrate fully automated body-fitted polyhedral volume mesh generation for canonical geometries as proof of concept.
- Ability to export grid in CFD General Notation System (CGNS) (version greater than 4.1) file format.
- Demonstrate required cell quality metrics:
    - For each face, vector connecting the left and right cell centroids are aligned with face normal.

    - For each face, face centroid is half-way between left and right cell centroids.
- User defined refinement criteria should allow for:
    - Spatially varying wall-distance specified on the surface.
    - Minimum cell-centroid to face-centroid distance criteria specified by the user.
- Provide executable to NASA teams for preliminary testing.

Phase II:

- Demonstrations on three complex topologies: (1) HLPW-4, (2) Benchmark for Airframe Noise Computations (BANC-4) landing gear (PDCC-NLG), and (3) Multistream Chevron nozzle (TMP17) satisfying the requirements established in Phase I.
- Performance assessment on a HLPW-4 geometry:
    - Demonstrate distributed memory weak scaling up to 10 billion cells at better than 10 million cells per core hour.
    - Demonstrate strong scaling on 10 billion cells mesh up to a granularity of 100,000 cells per core.
- Demonstrate the ability to conform to a user specified set of cell centroids.
- Develop API in collaboration with NASA CFD code developers.
- Demonstrate ability to regrid based on modified refinement criteria accessible through the API.

For focused area 3, demonstrations of the UQ methodologies and tools on a single NASA-FUN3D flutter problem are desired during Phase I. Phase II efforts would require more complete development of an automated and user-friendly toolbox.

State of the Art and Critical Gaps:

NASA's CFD Vision 2030 Study identified several impediments in computational technologies and this solicitation addresses one of those related to application of scale resolving simulations needed for expanding the scope of application of CFD across the aircraft flight envelope, particularly in the prediction of maximum lift.

Relevance / Science Traceability:

Various programs and projects of NASA missions use CFD for advanced aircraft concepts, launch vehicle design, and planetary entry vehicles. The developed technology will enable design decisions by Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD).

References:

https://www.nasa.gov/aeroresearch/programs/aavp

https://www.nasa.gov/aeroresearch/programs/tacp

NASA’s CFD Vision 2030 Study: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf

A1.06 Vertical Lift Technology and Urban Air Mobility (SBIR)

Lead Center: **GRC**

Participating Center(s): **AFRC, ARC, LaRC**

Scope Title:

Electric Vertical Takeoff and Landing (eVTOL) Electric Propulsion Safety and Reliability

Scope Description:

The expanding Urban Air Mobility (UAM) vehicle industry has generated a significant level of enthusiasm among aviation designers and manufacturers, resulting in numerous vehicle configurations. The majority of the prototype UAM vehicles have more than 4 rotors or propellers, have electric propulsion, carry 2 to 6 passengers, fly more like a helicopter (vertical takeoff and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many technical challenges facing industry's development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. One of those challenges is the subject of this SBIR subtopic, namely, safety and reliability of the electric power system and electric powertrain for these UAM /eVTOL vehicles.
This solicitation is seeking advancements in technologies that will improve the safety and reliability of the electrical power system/powertrain of UAM vehicles. There are three areas of main interest for this solicitation focused on the safety and reliability of the electrical power/powertrain system: (1) prognostic and diagnostic technologies for electric motors, (2) fault protection of high-voltage power system, and (3) advancements in thermal management technologies for electric motor systems. Based on industrial motor research and field data, use of continuous monitoring of conditions, such as temperature and vibration, can reduce the failure rate of motors by about two-thirds [Ref. 1]. This conclusion is based on data from large motors, but the physics of aviation motor degradation may be similar and future service experience may produce a similar overall trend. Due to the power levels envisioned for UAM vehicles, most will require high voltage ($\geq$540 V) operation, with the corresponding high-voltage direct current (DC) protection devices to ensure safe systems [Ref. 2]. Advancements in thermal management technologies, noted below, are also of interest given that temperature influences the overall safety and reliability of the power/powertrain system.
The application of the requested technologies should be relevant to the NASA Revolutionary Vertical Lift Technology (RVLT) project's reference concept vehicles [Refs. 3-4], which embody the key vehicle characteristics of the UAM vehicle configurations being designed throughout industry. Technologies proposed for this solicitation should be relevant to 100 kW class motor-rotor powertrain elements with scalability in the 20 to 500 kW class.

Through this solicitation, NASA is seeking advanced technologies supporting UAM electric/hybrid-electric propulsion in the areas of:

- Prognostic/diagnostic technologies: Operational performance diagnostics and prognostics technologies for electric motors and motor controllers to improve life and reliability of the system and reduce unscheduled maintenance for improved affordability. Technologies of interest related to motors/motor controllers include novel sensor and/or sensing technologies, data analysis algorithms, and methods to classify, fuse, or otherwise combine multiple sources of information for diagnostics, prognostics, and remaining useful life assessments. Proposers should consider the anticipated vehicle usage that will require differing motor power requirements for different phases of likely UAM flight profiles and maneuvers (power transients). The proposers should quantify any additional mass and/or power required (for example, mass of any additional sensors and associated cabling). Solutions that add minimal or no extra mass are of higher value and interest. The topic scope for the operational performance diagnostics and prognostics technologies is limited to the powertrain, motor controllers, and associated supporting systems for lubrication and cooling. The scope does not include batteries, fuel cells, fuel burning engines, avionics, communications equipment, or airframe structures.

- High-voltage protection devices: The high voltages expected in these systems will require properly rated protection devices. These do not currently exist for aeronautics-rated applications. While DC and alternating current (AC) architectures are both under consideration by designers, the focus here is on DC systems as these are the first being investigated by NASA. For this call, advanced technology high-voltage protection devices proposed should be applicable for systems with these characteristics: Voltage of 540 to 1,000 V, 100 to 200 A continuous operation with <5 msec clearing time. Other aspects of interest are current-limiting capability, high efficiency, and high reliability.
- Thermal management technologies: Lightweight, durable, and efficient thermal management solutions for 100 kW continuous-class electric motors are sought. Preferable are solution technologies that could be scaled and applied to aviation motors in a continuous power range of 20 to 500 kW. The most prevalent motor topology proposed and studied for this application are the permanent magnet motor family. Both passive and active approaches for thermal management may be applicable. Examples of technologies sought include integrated channels in rotor components, integrated heat pipes, and solutions enabled by additive manufacturing. Intended outcomes are effective and invasive solutions for motor rotors and windings with minimal mass and efficiency penalty. Solutions that demonstrate an improvement in reliability of the cooling system will be given extra consideration. Proposals should address the continuous motor specific power enabled by the innovations and the associated mass and efficiency penalties.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Research
- Prototype

Desired Deliverables Description:

Phase I of the SBIR should develop design concepts for specific technology advancements that address safety and reliability supported by analytical studies including modeling and simulation. Phase I effort should establish Phase II goals and should quantify projections of improvements to safety, reliability, and unscheduled maintenance assuming success of Phase II goals.

Phase II of the SBIR should further develop the designs and validate achievement of goals through additional analysis, modeling, and simulation and through system/component functionality experiments. Phase II incorporates experiments with aircraft relevant hardware available commercially or through partnership with an aircraft component supplier and modified with innovative technology from this SBIR effort.

State of the Art and Critical Gaps:

There are over 200 UAM vehicle concepts in varying stages of development. The immediate focus of the vehicle developers is overcoming obstacles on the path to certification. The public has experience flying in large transport aircraft and regional fixed-wing aircraft and are calibrated to associated safety levels for commercial air transportation. Detailed certification requirements for UAM vehicles are still under development by the relevant certifying authorities. For UAM aircraft, research is needed that addresses safety and reliability expectations of the traveling public and certifying authorities.

Relevance / Science Traceability:

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) Revolutionary Vertical Lift Technology (RVLT) Project under the Advanced Air Vehicle Program. The goal of the RVLT Project is to develop and validate tools, technologies, and concepts to overcome key barriers for vertical lift vehicles. The project scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment, and safety for both conventional and nonconventional vertical lift configurations. This subtopic directly aligns with the mission goals and scope in addressing safety and reliability of nonconventional vertical lift configurations.

References:

1. Penrose, H., “Large Electric Motor Reliability: What Did The Studies Really Say?”, 2012. (https://www.efficientplantmag.com/2012/03/large-electric-motor-reliability-what-did-the-studies-really-say/ ; accessed July 21, 2020).
2. Terorde, M., Grumm, F., Schulz, D., Wattar, H., and Lemke, J., “Implementation of a Solid-State Power Controller for High-Voltage DC Grids on Aircraft”, 2015.
3. Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” 2018 Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, 2018. [AIAA 2018-3847].
4. Johnson, W., Silva, C., and Solis, E., “Concept Vehicles for VTOL Air Taxi Operations,” AHS Specialists’ Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, 2018.
5. Darmstadt, P. R., Catanese, R., Beiderman, A., Dones, F., Chen, E., Mistry, M. P., Babie, B., Beckman, M., and Preator, R., "Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems," NASA/CR-2019-220217, NASA/CR-2019-220217, The Boeing Company, Philladelphia, PA.

A1.07 Electric Power Generation Via Thermionic Conversion for Hypersonic Applications (SBIR)

Lead Center: **LaRC**

Participating Center(s): **GRC**

Scope Title:

Thermionic Energy Harvetsing

Scope Description:

When employing a nonrotating propulsive device (engine), conventional generators for electrical power are not generally a viable design option; therefore, an alternative option is to utilize direct thermal-to-electric power conversion methods. One such technique is thermionic energy extraction applied to the primary flow path. Thermionic devices have been shown to be efficient in exploiting extreme temperature differentials, like those that typically characterize hypersonic flight environments, and also have a higher/larger energy density than that of standard batteries. The applications of thermionic devices in hypersonic vehicles are numerous, and broaden the design space, since 10 to 100 kW/m^2 of electrical power are compatible with realistic hardware implementation strategies. Significant, prior efforts in the 1960s, by both the U.S. and Soviet Union, were explored for space applications, but hypersonic atmospheric applications have not been extensively investigated.

For hypersonic atmospheric applications, the operational environments, relevant to the thermionic conversion process, are characterized by free-stream flight trajectories having dynamic pressures bounded by 750 to 3,500 (lbf/ft)/ft, and internal-flow path, peak static temperatures associated with adiabatic-flame temperatures (of a combusting hydrocarbon/air stoichiometric mixture). Additionally, volumetric and weight constraints of a novel thermionic device need to be competitive, and/or exceed, existing state-of-the-art battery technology in order to create viable design alternatives for system-design exploration. Although U.S. governmental restrictions typically apply to hypersonic-flight systems, this is not deemed to be a limiting factor in this Phase I activity, due to the low TRL; however, this issue will need to be further addressed during a Phase II award cycle, via coordination with appropriate U.S. governmental and industrial entities.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.X Other Aerospace Power and Energy Storage

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I - Design of a testable prototype, capable of generating a few W/cm^2.

Phase II - Generation of experimental data in a relevant test environment with a thermionic device to quantify basic performance parameters and initiate scaling study.

State of the Art and Critical Gaps:

The specifics of designing a device with acceptable work functions for both emitter and collector surfaces is a significant technical issue. Additionally, manufacturing a volumetrically efficient device is not codified.

Relevance / Science Traceability:

The applications of power generator in harsh environments is relevant to atmospheric flight and numerous other commercial applications associated with energy conversion needs.

References:

(1) Herring, C. and Nichols, M. H., "Thermionic Emission," Reviews of Modern Physics, Vol. 21, No. 2, 1949.

(2) Rasor, N.S., "Thermionic Energy Converter," Fundamentals Handbook of Electrical and Computer Engineering," pg. 668 ISBN-0471-86213-4 (1983).

(3) Mahefkey, T., "Thermionics Quo Vadis?", National Academy Press (2001).

(4) SECOND INTERNATIONAL CONFERENCE ON THERMIONIC ELECTRICAL POWER GENERATION, Stresa, Italy - May 27-31, 1968.

A1.08 Aeronautics Ground Test and Measurement Technologies (SBIR)

Lead Center: **LaRC**

Participating Center(s): **ARC, GRC**

Scope Title:

Boundary Layer Velocity Profile Measurement On Models in Wind Tunnels

Scope Description:

NASA's aeroscience ground test facilities include wind tunnels, air-breathing engine test facilities, and simulation and loads laboratories. They play an integral role in the design, development, evaluation, and analysis of advanced aerospace technologies and vehicles. These facilities provide critical data and fundamental insight required to understand complex phenomena and support the advancement of computational tools for modeling and simulation. The primary objective of the Aeronautics Ground Test and Measurements Technologies subtopic is to develop innovative tools and technologies that can be applied in NASA’s aeroscience ground test facilities to revolutionize testing and measurement capabilities and improve utilization and efficiency. Of primary interest are technologies which can be applied to NASA’s portfolio of large-scale ground test facilities.

Spatially and temporally resolved velocity measurements are sought to study boundary layers on test articles in NASA’s large-scale ground test facilities. Proposed measurement capabilities could be used to measure boundary layer thickness, velocity profiles, and transition from laminar to turbulent flow, as well as detecting flow separation that could potentially be used for flow control. Measurement systems should be reliable and robust enough to be implemented in various wind tunnel facilities such as the National Transonic Facility, the 11-Foot Transonic Unitary Plan Facility, the Transonic Dynamics Tunnel, and 8- by 6-Foot Supersonic Wind Tunnel. These facilities operate using a variety of media, including air, nitrogen, and other gases such as R134a.

Technology for measuring boundary layers on models in cryogenic wind tunnels is relatively undeveloped so innovative techniques which can operate at cryogenic conditions are especially of interest. In one potential application in a transonic cryogenic wind tunnel, the boundary layer thickness can be as small as 0.1 mm (e.g., on a wing) but could be as large as 10 mm (e.g., on a fuselage). In this same application, the flow velocity could range from -50 to 200 m/sec. While light projection and remote detection capabilities will be considered, fiber optic light delivery could be advantageous, particularly if the fiber optic transmission could utilize an existing pressure tap (or multiple taps) in the wind tunnel model. Scattering from light transmitted by a fiber optic embedded in the model could be detected by a remote, high magnification detection system or locally on the model (though that would result in additional cost to modify the wind tunnel model, which is less attractive).

Discrete sensor systems could be proposed that both transmit and collect light from a single location. Considerations for selection include the following: the ability to measure at multiple spatial locations, with higher spatial resolution, with higher temporal resolution, over a wider range of conditions, with higher accuracy and higher precision, and probes with potential for measuring multiple parameters (multiple velocity components or temperature, density, or other). Molecular- and particle-based approaches will also be considered. Such a sensor may have medical or industrial applications. Plans for device calibration and risk mitigation should be provided. Expected accuracy, precision, and spatial and temporal resolution should be estimated.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.X Other Ground, Test, and Surface Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Phase I: The desired deliverable would be a detailed system design for measuring thin boundary layers on model surfaces in both air and cryogenic conditions. This concept or system design should preferably be verified by simulation or testing and capable of being developed into a prototype system as part of a Phase II effort.

Phase II: Desired deliverables include a prototype system to measure boundary layers on a representative aerodynamic surface at room and cryogenic temperatures, a robust process for calibrating the system, and well-documented results from functional/operation tests including quantified uncertainty. It is anticipated that the technology would be demonstrated in a NASA ground-based test facility as part of the Phase II effort or shortly thereafter under Phase III funding.

State of the Art and Critical Gaps:

As NASA continues in the quest to advance computational methods and predictive tools as part of CFD 2030, one of the nemeses to significant advancement and validation is the lack of velocity information in the boundary layer. At both low and high speeds, making this measurement requires probe-based systems to be positioned close to the surface or optical-based systems to be focused near the surface. This is quite challenging due to (1) the thickness of the boundary layer, which can be as small as 0.1 mm, (2) conditions on the surface of the test article, (3) vibration of the test article, and (4) drastic temperature changes in the wind tunnel, which can range from room temperature to as low as -200 °C at cryogenic temperatures. There is currently no measurement system available to measure thin boundary layers, especially at cryogenic conditions, and NASA's inability to obtain this critical data in ground-based facilities at near-flight Reynolds numbers limits the validation of numerical simulations and predictive tools for use in design and certification by analysis. The proposed technology could possibly have application on flight vehicles and in the medical field as well.

Relevance / Science Traceability:

The Transformational Tools and Technologies Project would use this technology to provide critical data to validate computational tools at near-flight Reynolds numbers as it pursues technical challenges to realize the CFD 2030 Vision and enable new aerospace vehicles to be certified by analysis. The technology would also have application for tests supporting the Advanced Air Transport Technology Project, the Commercial Supersonic Technology Project, the Revolutionary Vertical Lift Technology Project, and the Aerosciences Evaluation and Test Capabilities (AETC) Portfolio.

References:

https://www.nasa.gov/aeroresearch/programs/aavp/aetc/ground-facilities
https://ntrs.nasa.gov/search.jsp?R=20140003093

Scope Title:

Measurement Technologies for Vertical Lift Configurations and Concepts

Scope Description:

NASA is currently evaluating new vertical lift configurations and concepts to enable Advanced Air Mobility (AAM). The measurement capabilities needed for AAM research are varied depending on whether model- or full-scale test articles are involved, whether wind tunnel or flight testing is conducted, and whether customized or off-the-shelf hardware is utilized. Nevertheless, vertical lift concepts will require new methods of providing real-time or near real-time measurements of rotor blade and vehicle performance including blade surface pressure distributions, boundary layer transition, rotor performance and blade position, rpm/phasing measurements, rotor control positions (cyclic pitch and flapping) and off-body flow field measurements for examining multiblade vortex interactions and wake/fuselage interaction. Current capabilities for obtaining these data are limited due to lower sampling rates and spatial resolutions using remote sensing. Technologies are needed to (1) increase the temporal and spatial resolutions of remotely sensed/wireless measurements and (2) bring these remotely sensed/wireless measurements onboard the vehicle or test article, where possible, to allow data to be efficiently acquired across a range of operational envelopes. Instrumentation that can be embedded in the blades and fuselage or added to off-the-shelf vehicle or model hardware with efficient data telemetry are desired.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.X Other Ground, Test, and Surface Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

Phase I: The desired deliverable would be a detailed system design to enable remotely sensed/wireless measurements of blade surface pressure distributions, boundary layer transition, rotor performance and blade position, and off-body measurements. The system should enable efficient acquisition of performance data across the operating envelope of a representative AAM vehicle or model.

Phase II: Desired deliverables for Phase II include demonstration of a prototype system on a representative AAM vehicle, model, or test stand of the offeror’s choosing or in collaboration with NASA during a Revolutionary Vertical Lift Technology- (RVLT-) sponsored test.

State of the Art and Critical Gaps:

As part of the AAM mission, NASA is seeking to develop vehicle concepts and technologies to define requirements and standards that address key challenges such as safety, affordability, passenger acceptability, noise, automation, etc. Evaluation of these concepts and technologies will inherently depend on the same type of vehicle performance data typically used to assess the performance of larger-scale vehicles. Unfortunately, the same measurement techniques used for larger-scale vehicles are not directly applicable to AAM vehicles due to the reduced scale and unique design. As such, new measurement capabilities are needed that can be applied or added to vehicles or models during and after development.

Relevance / Science Traceability:

This technology would help fulfill the vision of the Revolutionary Vertical Lift Technology (RVLT) Project to create a future where vertical takeoff and landing (VTOL) configurations operate quietly, safely, efficiently, affordably, and routinely as an integral part of everyday life. This scope has been endorsed by the RVLT Project Manager as well as the Technical Leads in RVLT for Validation Test Campaigns.

The system might also have application to other types of flight and ground-based testing within the NASA Enterprise. This would fall under the purview of the Aerosciences Evaluation and Test Capabilities (AETC) Project.

References:

https://www.nasa.gov/aam

https://www.nasa.gov/aeroresearch/programs/aavp/rvlt

A1.09 Vehicle Sensor Systems to Enable Situational Awareness (SBIR)

Lead Center: **GRC**

Participating Center(s): **AFRC, ARC, LaRC**

Scope Title:

Technologies to Enable Situational Awareness for Autonomous as well as Increasingly Autonomous Air Vehicles

Scope Description:

Achieving a vision for a safer and more efficient National Airspace System (NAS) with increasing traffic and the introduction of new vehicle types and unpiloted vehicles requires increasingly intelligent vehicle systems able to respond to complex and changing environments in a resilient and trustworthy manner. Future air vehicles, especially autonomous vehicles and those that support Advanced Air Mobility (AAM), must operate with a high degree of awareness of their own well-being, and possess the integrated intelligence to efficiently conduct operations while providing warning of off-nominal states. A vehicle's capability to independently assure safety may be the only recourse in some situations, and for piloted vehicles addresses the recurring issue of inappropriate crew response. Internal to the vehicle, predictive maintenance reduces maintenance cost and vehicle down time through improved vehicle availability and throughput. Understanding the vehicle state also has impact on vehicle performance, efficiency, and environmental impact. External to the vehicle, vehicle awareness of the environment and ability to detect potential hazards in the surrounding airspace is crucial to the overall safety of the NAS and a vehicle's ability to meet flight objectives.

This subtopic seeks technologies to enable intelligent vehicle systems, including subsystem and avoidance technologies, with an internal and external situational awareness to assure safety; optimize mission completion, efficiency and performance in nominal conditions; and respond to off-nominal conditions. The emphasis is on piloted vehicles augmented with autonomous capabilities, as well as increasingly autonomous unmanned air vehicles (including AAM). This subtopic includes vertical lift vehicles in general, but excludes sensor systems specifically designed for monitoring powertrain health; such proposals should propose to A1.06. Vertical Lift Technology and Urban Air Mobility. Situational awareness of new or alternate vehicle configurations, including distributed and hybrid electric propulsion, are also of interest. Areas of interest include:

- Sensing and perception technologies that provide the ability of the vehicle to detect and extract internal and external vehicle information.
- Information fusion technologies to integrate information from multiple, disparate sources and evaluate that information to determine health and operational state.

- Onboard hardware and software systems that are modular, scalable, redundant, high reliability, and secure with minimal vehicle impact.
- Diagnostic technologies that provide critical markers trending to unsafe state.
- Networked sensors and algorithms to provide necessary vehicle full-field state information ranging from the component level to the subsystem and system level.
- Integrated systems technologies that enable the diagnosis of multiple hazards, while effectively dealing with uncertainties and unexpected conditions.
- Approaches that enable improved in-flight vehicle state safety awareness with adaptive methods to achieve improved efficiency, performance, and reduced environmental impact.
- Methods that significantly enhance the fidelity and relevance of information provided to ground systems by the vehicle in-flight for use in on-demand maintenance.
- Perception software capabilities including multispectrum sensor fusion, real-time perception system assurance software, and wake detection.
- Low-SWaP-C (size, weight, power, and cost) detection hardware that can detect objects at far distances, e.g., 1,500 ft to 3 nmi, including visual cameras, infrared (IR) cameras, event cameras, gated camera, Lidar, radar, and sonic hardware.
- Highly reliable vehicle navigation technologies (position, orientation, and rotational and translational velocities) robust against Global Positioning System (GPS) denial/failures and responsive to the external environment.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology developments into applications.
- A technology demonstration that clearly shows the benefits of the technology developed.
- A written plan to continue the technology development and/or to infuse the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, reports, products, components, and integrated systems

Phase II deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, and a plan to infuse the technology developments into applications.
- A technology demonstration that clearly shows the benefits of the technology developed.
- There should be evidence of efforts taken to infuse the technology into applications or a clear written plan for near term infusion of the technology. This may be part of the final report.
- Resulting products can include hardware, software, demonstrations, reports, products, components, and integrated systems.

State of the Art and Critical Gaps:

It is predominately left to pilots (not the vehicle) to interpret current state and infer future states based on experience and expertise. Commercial Aviation Software Team (CAST), Federal Aviation Administration (FAA), National Transportation Safety Board (NTSB), and the National Research Council (NRC) have called for research on systems that can predict the state of the aircraft, including the state of autonomous systems, to provide notifications of trending to unsafe states. In order for there to be trust in autonomy, vehicle situational awareness needs to be tailored for independent autonomous systems without human intervention. Significant new capabilities are needed to enable safe vehicle operation in the airspace independent of human intervention. Sensing systems as intended here not only include the sensing element itself, but may also include the supporting technologies necessary to provide a meaningful measurement. Such supporting include hardware (e.g., networking capability) but also software (e.g., sensor fusion).

There has been development in internal vehicle component health management technology with some adoption; integrated subsystem/vehicle system full-field health management is limited and do not presently enable a completely autonomous vehicle system. Further, measurement and monitoring technologies need to be adapted with the introduction of new vehicle types to provide information relevant to understanding the specific vehicle state. The objective is to provide sufficient, dependable information with limited vehicle impact to enable, e.g., time appropriate cognition and decision making. [For Unmanned Aircraft Systems (UAS) vehicles, proposals involving such cognition and decision making can be submitted to Subtopic A2.02. Unmanned Aircraft Systems (UAS) Technologies.]

Relevant to AAM, current exterior perception technologies are focused on specific domains that are not relevant to AAM. AAM applications fly faster and in a less cluttered environment than automobiles. Nominal operations are expected to be at speeds between 40 and 200 mph and altitudes below 5,000 ft over a range under a few hundred miles. They also fly at a lower altitude than commercial airlines, making them more susceptible to weather conditions, while resulting in a more obstacle-rich environment. Most perception systems and software are currently focused on the auto industry where required ranges are shorter and update rates need to be faster, or they are designed for extremely low SWaP unmanned aerial vehicles (UAVs) that do not have passenger carrying safety requirements. Known gaps include the following: maintaining an aviation-grade safety assurance of perception systems, reaching the required detection distances, detection of objects in low-contrast/degraded environments, and detection and knowledge of hyperlocal weather phenomena.

Relevance / Science Traceability:

This technology development is directly relevant to the NASA Aeronautics Research Mission Directorate (ARMD) Thrust 6 Autonomy Roadmap in order to allow more intelligent vehicle systems, and has strong relevance to NASA autonomy activities. NASA also plans to have an increasing role in the expanding market of AAM. Autonomy applications will only be able to make decisions as good as the information and insight at hand. The approach is to mature technology through this subtopic for ongoing implementation into NASA missions and commercial applications. This subtopic will also help define the limits of commercially available technology to meet the needs of increasingly intelligent systems to operate autonomously and in new transportation paradigms.

Autonomy is also a core capability increasingly relevant across a range of NASA mission directorates. For Science Mission Directorate (SMD) and Space Technology Mission Directorate (STMD), autonomy is central to planetary exploration and Earth monitoring, enabling more capable missions that provide improved science without the burden of human intervention. For example, the capability of an autonomous probe to maintain operations in uncertain or unforeseen conditions without human intervention can be critical to the success of the mission. Vehicle situational awareness may be mandatory in remote missions where it is difficult for a human to be in the loop in a timely manner. Likewise, the safety of the astronauts in a manned mission may depend on appropriate vehicle response to rapidly changing conditions.

References:

1. ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation, Vision and Roadmap, M.Ballin, June 2016, https://nari.arc.nasa.gov/thrust6
2. https://www.nasa.gov/aam
3. https://www.nasa.gov/aeroresearch/programs/tacp/ttt
4. G. W. Hunter, R. W. Ross, D. E. Berger, J. D. Lekki, R. W. Mah, D. F. Perey, S. R. Schuet, D. L. Simon, and S. W. Smith, "A Concept of Operations for an Integrated Vehicle Health Assurance System," NASA TM 2013-2178 25, 2013
5. David P. Thipphavong et. al, "Urban Air Mobility Airspace Integration Concepts and Considerations" 2018 Aviation Technology, Integration, and Operations Conference AIAA AVIATION Forum, June 25-29, 2018, Atlanta, Georgia 10.2514/6.2018-3676.

T15.04 Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations (STTR)

Lead Center: **AFRC**

Participating Center(s): **ARC, GRC, LaRC**

Scope Title:

Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations

Scope Description:

NASA's Aeronautics Research Mission Directorate (ARMD) laid out a Strategic Implementation Plan for aeronautical research aimed at the next 25 years and beyond. The documentation includes a set of Strategic Thrusts that are research areas that NASA will invest in and guide. It encompasses a broad range of technologies to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation. Furthermore, the convergence of various technologies will also enable highly integrated electric air vehicles to be operated in domestic or international airspace. In response to the recently updated Strategic Thrust #4 (Safe, Quiet, and Affordable Vertical Lift Air

Vehicles), a new subtopic titled "Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations" is being introduced.

Proposals are sought in the following areas: (1) design and execution of experiments to gather research-quality data to validate aerodynamic and acoustic modeling of full-scale, multirotor eVTOL aircraft, with an emphasis on rotor-rotor interactions and (2) development and validation of scaling methods for extending and applying the results of instrumented subscale model testing to full-scale applications. This solicitation does not seek proposals for designs or experiments that do not address full-scale eVTOL applications. Full-scale (2+ passenger) is defined as a payload capacity equivalent to two or more passengers, including any combination of pilots, passengers, or ballast.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Hardware
- Analysis
- Research
- Prototype

Desired Deliverables Description:

Expected deliverables of Phase I awards may include but are not limited to:

- Initial experiment test plans for gathering experimental results related to the aerodynamic and/or acoustic characteristics of a multirotor eVTOL aircraft, with an emphasis on interactions between rotors and between the rotors and the vehicle structure for either
    - a full-scale flight vehicle
    - a subscale vehicle with fully developed methods for scaling the results to full scale
- Expected results for the flight experiment using appropriate design and analysis tools.
- Design (CAD, OpenVSP, etc.) and performance models for the vehicle used to generate the expected results.
- Preliminary design of the instrumentation and data recording systems to be used for the experiment.
- Awardee may also provide kickoff, midterm, and final briefings as well as a final report.

Expected deliverables of Phase II awards may include but are not limited to:

- Experimental results that capture aerodynamic and/or acoustic characteristics of a multirotor eVTOL aircraft, with an emphasis on interactions between rotors and between the rotors and the vehicle structure for either:
    - a full-scale flight vehicle
    - a subscale vehicle with results extrapolated to full scale
- Design (CAD, OpenVSP, etc.) and performance models for the experimental vehicle.

- Experimental data along with associated as-run test plans and procedures.
- Details on the instrumentation and data logging systems used to gather experimental data.
- Comparisons between predicted and measured results.
- Awardee may also provide kickoff, midterm, and final briefings as well as a final report.

State of the Art and Critical Gaps:

Integration of Distributed Electric Propulsion (DEP) (4+ rotors) systems into Advanced Air Mobility eVTOL aircraft involves multidisciplinary design, analysis, and optimization (MDAO) of several disciplines in aircraft technologies. These disciplines include aerodynamics, propulsion, structures, acoustics, and/or control in traditional aeronautics-related subjects. Addressing ARMD’s Strategic Thrust #1 (Safe, Efficient Growth in Global Operations), #3 (Ultra-Efficient Commercial Vehicles), and #4 (Safe, Quiet, and Affordable Vertical Lift Air Vehicles) innovative approaches in designing and analyzing highly integrated DEP eVTOL aircraft are needed to reduce the energy use, noise, emissions, and safety concerns. Due to the rapid advances in DEP-enabling technologies, the current state-of-the-art design and analysis tools lack sufficient validation against full-scale eVTOL flight vehicles. This is especially true in the areas of aerodynamics and acoustics.

Relevance / Science Traceability:

The proposed subtopic supports ARMD’s Strategic Thrust #4 (Safe, Quiet, and Affordable Vertical Lift Air Vehicles). Specifically, the following ARMD program and project are highly relevant.

NASA/ARMD/Advanced Air Vehicles Program (AAVP):

- Revolutionary Vertical Lift Technology (RVLT) project

References:

- ARMD/Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
- ARMD/Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt
- ARMD/Convergent Aeronautics Solutions (CAS) Project: https://www.nasa.gov/aeroresearch/programs/tacp/cas
- ARMD/Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt
- ARMD/University Innovation (UI) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ui
- ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy
- ARMD Urban Air Mobility Grand Challenge: https://www.nasa.gov/uamgc

Focus Area 19 Integrated Flight Systems

Lead MD: **ARMD**

Participating MD(s): **N/A**

This focus area includes technologies that contribute to the Integrated Aviation Systems Program's (IASP) objectives. IASP conducts flight-oriented, system-level research and technology development to effectively mature and transition advanced aeronautic technologies into future air vehicles and operational systems, including urban air mobility. IASP focuses on the rigorous execution of highly complex flight tests and related experiments to support all phases of NASA's aeronautics research.

A2.01 Flight Test and Measurement Technologies (SBIR)

Lead Center: **AFRC**

Participating Center(s): **ARC, GRC, LaRC**

Scope Title:

Flight Test and Measurement Technologies

Scope Description:

NASA continues to use flight research as a critical element in the maturation of technology. This includes developing test techniques that improve the control of in-flight test conditions, expand measurement and analysis methodologies, and improve test data acquisition and management with sensors and systems that have fast response, low volume, minimal intrusion, and high accuracy and reliability. By using state-of-the-art flight test techniques along with novel measurement and data acquisition technologies, NASA and the aerospace industry will be able to conduct flight research more effectively and also meet the challenges presented by NASA and industry's cutting edge research and development programs.
NASA's Flight Demonstrations and Capabilities Project supports a variety of flight regimes and vehicle types ranging from low-speed, subsonic applications and electric propulsion, through transonic and high-speed flight regimes. Therefore, this solicitation can cover a wide range of flight conditions and vehicles. NASA also requires improved measurement and analysis techniques for acquisition of real-time, in-flight data used to determine aerodynamic, structural, flight control, and propulsion system performance characteristics. These data will be used to provide information necessary to safely expand the flight and test envelopes of aerospace vehicles and components. This requirement includes the development of sensors for both in situ and remote sensing to enhance the monitoring of test aircraft safety and atmospheric conditions during flight testing. This subtopic supports innovative flight platform development for use in flight testing, science missions, and related subsystems development.
Flight test and measurement technologies proposals may significantly enhance the capabilities of major government and industry flight test facilities. Proposals may address innovative methods and technologies to reduce costs and extend the health, maintainability, communication, and test techniques of flight research support facilities to directly enhance flight test and measurement.

Areas of interest emphasizing flight test and measurement technologies include:

- High-efficiency digital telemetry techniques and/or systems to enable high data rate and high-volume telemetry for flight test. This includes air-to-air and air-to-ground communication.
- Architecture and tools for high-integrity data capture and fusion.
- Real-time integration of multiple data sources from onboard, off-board, satellite, and ground-based measurement equipment.
- Advanced in situ/onboard sensing and/or integrated secured remote services for use in real-time decision making.
- Prognostic and intelligent health monitoring for hybrid and/or all-electric propulsion systems using an adaptive embedded control system.

- Test techniques, including optical-based measurement methods that capture data in various spectra, for conducting quantitative in-flight boundary layer flow visualization, schlieren photography, near and far-field sonic boom determination, and atmospheric modeling as well as measurements of global surface pressure and shock wave propagation.
- Measurement technologies for in-flight steady and unsteady aerodynamics, juncture flow measurements, propulsion airframe integration, structural dynamics, stability and control, and propulsion system performance.
- Improved rugged wideband fiber optic sweeping laser system design for optical frequency domain reflectometry containing no moving parts, to be operated onboard NASA's wide range of aircraft. Improved development of polarization insensitive fiber measurements using optical frequency domain reflectometry.
- Wireless sensors, sensing technologies, and telecommunication methods that can be used for flight test instrumentation applications for manned and unmanned aircraft. Emphasis should be on developing a variety of specialized low-profile sensors that are capable of participating in a synchronized, high data rate and high data volume diverse wireless sensor measurement network with a capability to deliver time-stamped data to a central node. This area of technologies also includes wireless (nonintrusion) power transferring techniques and/or wirelessly powering remote sensors.
- Innovative measurement methods that utilize intelligent sensors for autonomous remote sensing in support of advanced flight testing.
- Fast imaging spectrometry that captures all dimensions (spatial/spectral/temporal) and can be used on unmanned aerial systems (UAS) platforms.
- Innovative new flight platforms and associated subsystem development for use in all areas of flight tests.

The emphasis here is for articles to be developed for flight test and flight test facility needs.

The technologies developed for this subtopic directly address the technical challenges in the Aeronautics Research Mission Directorate (ARMD) Integrated Aviation Systems Program (IASP) and the Electrified Powertrain Flight Demonstration (EPFD) and Flight Demonstrations and Capabilities (FDC) projects. The FDC Project conducts complex flight research demonstration to support multiple ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve the ARMD Strategic plan. They could also support Advanced Air Vehicle Program (AAVP) projects: Commercial Supersonic Technology (CST) and Advanced Air Vehicles Program (AAVP) - Aerosciences Evaluation and Test Capabilities (AETC) Project.

For technologies focused on ground testing or operations, please consider submitting to subtopic A1.08 Aeronautics Ground Test and Measurement Technologies, as ground testing technologies will be considered out of scope for this A2.01 subtopic.
For technologies with space-only applications, please consider submitting to a related space subtopic as space-only technologies will be considered out of scope for this A2.01 subtopic.
Proposals that focus solely on flight vehicle development rather than focusing on technologies applicable to flight test and measurement will be considered out of scope for the A2.01 subtopic.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.X Other Flight Vehicle Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For a Phase I effort, at a minimum, a report is desired that describes the effort's successes, failures, and the proposed path ahead.

For a Phase II effort, the small business should show a maturation of the idea or technology that allows for a presentation of detailed influential analysis or a thorough demonstration at least, and most ideally a delivery of a prototype that includes beta-style or better hardware or software.

State of the Art and Critical Gaps:

Current atmospheric flight systems cover a large range of uses from point-to-point drones, to high-performance small aircraft, to large transports, to general aviation. In all areas, advancements can be possible if insights can be gained, studied, and used to create new technologies. New insights will require an evolution of current testing and measurement techniques as well as novel forms and implementations. Known gaps include: wireless instrumentation for flight, advanced telemetry technique, intelligent internal state monitoring for air and space vehicles, techniques for studying sonic booms, advanced techniques for capturing all dimensions of system operation and vehicle health (spatial/spectral/temporal), and extreme environment high-speed large-area distributive sensing techniques. Along with these comes secure telemetry of data to ensure informed operation of the flight system.

Relevance / Science Traceability:

The technologies developed for this subtopic directly address the technical and capability challenges in ARMD's IASP and FDC projects. FDC conducts complex flight research demonstrations to support different ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve ARMD Strategic plan. Also, they could support IASP and EPFD projects, and AAVP CST project and Aerosciences Evaluation and Test Capabilities (AETC) Project.

References:

https://sbir.nasa.gov/

https://www.nasa.gov/mission_pages/lowboom/index.html

https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html

https://www.nasa.gov/centers/armstrong/research/X-56/index.html

https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-108-AFRC.html

https://www.nasa.gov/centers/armstrong/features/shock_and_awesome.html

https://technology-afrc.ndc.nasa.gov/featurestory/fiber-optic-sensing

A2.02 Enabling Aircraft Autonomy (SBIR)

Lead Center: **AFRC**

Participating Center(s): **ARC, GRC, LaRC**

Scope Title:

Enabling Aircraft Autonomy

Scope Description:

The increased use of automation on aircraft offers significant advantages over traditional manned aircraft for applications that are dangerous to humans, long in duration, and require a fast response and high degree of precision. Some examples include remote sensing, disaster response, delivery of goods, industrial inspection, and agricultural support. Advanced autonomous functions in aircraft can enable more capability and promises greater economic and operational advantages. Some of these advantages include a higher degree of resilience to off-nominal conditions, the ability to adapt to dynamic situations and less reliance on humans during operations.

There are many barriers that are restricting greater use and application of autonomy in air vehicles. These barriers include, but are not limited to, the lack of methods, architectures, and tools that enable:

- Cognition and multi-objective decision making.
- Cost-effective, resilient, and self-organizing communications.
- Prognostics, survivability, and fault tolerance.
- Verification and validation technology and certification approaches.

NASA and the aviation industry are involved in research that would greatly benefit from breakthroughs in autonomous capabilities that could eventually enable the Advanced Air Mobility (AAM). A few of the areas of research and missions are listed below:

- Remote missions utilizing one or more unmanned aircraft system (UAS) would benefit from autonomous planning algorithms that can coordinate and execute a mission with minimal human oversight
- Detect and avoid algorithms, sensor fusion techniques, robust trajectory planners and contingency management systems that can enable AAM and higher levels of UAS integration into the national airspace
- Fault detection, diagnostics, and prognostics capabilities to inform autonomous contingency management systems.

This solicitation is intended to break through these and other barriers with innovative and high-risk research.

The Integrated Aviation Systems Program's FY2021 SBIR solicitation is focused on tackling these barriers to enable greater use of autonomy in NASA research, in civil aviation use, and, ultimately, in the emerging AAM market. The following four research areas are the primary focus of this solicitation, and any submissions must show a strong relevance to these areas to be considered. The primary research areas are:

- Cognition and multi-objective decision making—Technologies need to be developed that transform the raw data into actionable information and make decisions based on this information. Detect and avoid in the national airspace utilizing multiple sensors is an example of one challenge this particular research is attempting to address. Artificial intelligence-based methods such as machine learning will be considered if it provides a novel approach.

- Cost-effective, resilient, and self-organizing communications—Methods that ensure reliable, trusted-source communications with increasingly complex and interconnected systems are needed to minimize the impact of infrastructure outages (e.g., Global Positioning System (GPS) or ground station) and that are resilient against both internal and external cyberphysical attacks. Several key areas of interest are:
    - Resilient Position Navigation and Timing (RPNT) approaches for Global Navigation Satellite Systems- (GNSS-) denied or GPS-denied/degraded environments.
    - Resilient wireless communications in the presence of jamming, terrain, or weather caused interference.
    - Mesh/self-organizing networks.
    - Quantum communication technologies, in particular, quantum repeaters and quantum key distribution methods.
- Prognostics, survivability, and fault tolerance—Techniques that can understand vehicle health, critical failures, can anticipate failures, and autonomously replan or execute emergency landings safely. Prognostics technologies capable of providing accurate predictions in a computationally constrained environment, such as that expected for small vehicles. Examples include, but are not limited to, new, efficient approaches and algorithms and hybrid edge/cloud approaches.
- Verification and validation technology and certification approaches—New methods of verification, validation, and certification need to be developed which enable application of complex systems to be certified for use in the National Airspace System (NAS). Proposed research could include novel hardware and/or software architectures that enable alternate or expedite traditional verification and validation requirements. Proposals should reference material on emerging standards for autonomy certification, including ASTM autonomy guidelines and emerging Federal Aviation Administration (FAA) considerations for small aircraft, UAS, and Urban Air Mobility (UAM).

It is important to note that any proposals for UAS development will not be considered unless it can demonstrate strong relevance to aforementioned research interests.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology.

- A technology demonstration in a simulation environment that clearly shows the benefits of the technology developed.
- A written plan to continue the technology development and/or to infuse the technology. This may be part of the final report.

Phase II deliverables should include, but are not limited to:

- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology developments.
- A technology demonstration in a relevant flight environment that clearly shows the benefits of the technology developed.
- There should be evidence of infusing the technology or a clear written plan for near term infusion of the technology. This may be part of the final report.

State of the Art and Critical Gaps:

Current autonomous systems have limited capabilities, poor perception of the environment, require human oversight, and need special clearances to fly in the NAS. Future autonomous systems with higher degrees of autonomy will be able to freely fly in the NAS but will require certifiable software that ensure a high degree of safety assurance. Additionally, advanced sensors and more sophisticated algorithms that can plan around other UAS/AAM vehicles and obstacles will be needed. Therefore, the technology that will be required to advance the state of the art are as follows:

1. A certification process for complex nondeterministic algorithms.
2. Prognostics, vehicle health, and sensor fusion algorithms.
3. Decision making and cooperative planning algorithms.
4. Secure and robust communications.

Relevance / Science Traceability:

This subtopic is relevant to NASA ARMD's Strategic Thrust 5 and Strategic Thrust 6.

- https://www.nasa.gov/aeroresearch/programs/tacp
- https://www.nasa.gov/aeroresearch/programs/aosp
- https://www.nasa.gov/aeroresearch/programs/iasp

References:

https://www.hq.nasa.gov/office/aero/pdf/armd-strategic-implementation-plan.pdf

https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_aug2018_tfong_tagged.pdf

A2.03 Advanced Air Mobility (AAM) Integration (SBIR)

Lead Center: **HQ**

Participating Center(s): **LaRC**

Scope Title:

AAM Community Integration - Weather Infrastructure Testbed

Scope Description:

AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

Although limited manned, passenger-carrying UAM and other air taxi operations occur today, this market is ripe to expand as technologies such as electric propulsion and increasing autonomy converge enabling novel aircraft with enhanced capabilities. With time, the small unmanned aerial systems (sUAS) market and manned UAM and air taxi markets may converge into a broader AAM market including both manned and unmanned vehicles. To start down the path to enabling this, ARMD has proposed an organizational framework, identified a set of barriers organized according to this framework that must be overcome to enable this market, and has identified NASA's potential contributions to overcome these market impeding barriers.

The AAM framework consists of five pillars: (1) aircraft design, (2) individual aircraft operations, (3) airspace design, (4) airspace and fleet operations, and (5) community integration. This solicitation focuses specifically on the community integration pillar (Refs 1-3, 6-8). Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

- Scope 1 Weather Data Infrastructure Testbed—Weather data sensors are part of the weather infrastructure proposed in the UAM Maturity Level 4 (UML-4) ecosystem ConOps (concept of operations) (Refs 4 and 8). These sensors provide current weather conditions. The data they collect is an input into the UAM system for use by vehicle and vertiport operators and Providers of Services/UTM Supplemental Service Providers (PSUs/USSes) (Ref 6) and will also be utilized to validate forecasting models. This testbed should consider the innovative use of existing and new, fixed and mobile, and nontraditional weather sensors as part of the architecture; testing and validation of the accuracy of the sensors and data; new weather forecast techniques and/or ultrahigh spatial and temporal resolution weather forecast models tailored for UAM; and/or the assimilation of weather data from these sensors into weather models. The effort should consider the work being done by ASTM's F38 WK73142 (Ref 5) and work towards a goal of increasing measurement density and scalability while incentivizing private sector companies to install weather sensing equipment, data delivery, and receive payment for the data by local government(s) and commercial Weather Supplemental Data Service Providers (SDSP) to improve UML-4 weather situational awareness and predictions. Phase I would also identify potential localities interested in hosting and utilizing the data from this testbed. Phase II would be to build the testbed in at least one locality and market for additional customers beyond those identified in Phase I.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.X Other Ground, Test, and Surface Systems

Desired Deliverables of Phase I and Phase II:

- Software
- Hardware
- Analysis
- Research
- Prototype

Desired Deliverables Description:

Phase I of this SBIR would be focused on the development of an aviation metropolitan based weather sensing and prototype testbed architecture to support addressing the challenges associated with future UAM and AAM weather infrastructure. Phase I would also identify potential localities interested in hosting and utilizing the data from this testbed.

Phase II would be to build the testbed in at least one locality and market for additional customers beyond those identified in Phase I.

State of the Art and Critical Gaps:

The AAM marketplace is assessed at a UML-0 (see references). Technologies are needed to progress towards the desired UML-4 level where this model of travel is affordable to the general public.

Relevance / Science Traceability:

AAM Mission Office.

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) AAM Mission and the eight projects supporting that mission. Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

References:

1. NASA's National Aeronautics Committee briefings: https://www.nasa.gov/aeroresearch/aero-nac-committee
2. George Price et al., "Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations," NASA\CR—2020-5001587
3. https://www.nasa.gov/aeroresearch/one-word-change-expands-nasas-vision-for-future-airspace/
4. Reference: Urban Weather section from the UAM UML-4 ConOps https://nari.arc.nasa.gov/sites/default/files/attachments/4%203%206%20Weather--CIWG%20version.pdf
5. ASTM WK731142 https://www.astm.org/DATABASE.CART/WORKITEMS/WK73142.htm
6. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
7. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint

8. Kenneth H. Goodrich and Colin R. Theodore, "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA SciTech 2021 (to be published).

Scope Title:

AAM Community Integration - Urban Planning Simulation

Scope Description:

AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

Although limited manned, passenger-carrying UAM and other air taxi operations occur today, this market is ripe to expand as technologies such as electric propulsion and increasing autonomy converge enabling novel aircraft with enhanced capabilities. With time, the small unmanned aerial systems (sUAS) market and manned UAM and air taxi markets may converge into a broader AAM market including both manned and unmanned vehicles. To start down the path to enabling this, ARMD has proposed an organizational framework, identified a set of barriers organized according to this framework that must be overcome to enable this market, and has identified NASA's potential contributions to overcome these market impeding barriers.

Th AAM framework consists of five pillars: (1) aircraft design, (2) individual aircraft operations, (3) airspace design, (4) airspace and fleet operations, and (5) community integration. This solicitation focuses specifically on the community integration pillar (Refs 1-3, 6-8). Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

- Urban Planning Simulation – Develop or modify an existing city or urban planning gaming software to incorporate the ability to realistically simulate a multimodal transportation system that includes AAM transportation as an additional mode of transportation in a U.S. metropolitan area. (Ref 2)

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.3 Simulation

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

Phase I would focus on the identification of the specific gaming software, gaining the appropriate permissions, researching the constraints associated with UAM/AAM and planned Concept of Operations (Ref 2 and 6), planning the software modifications, and developing a schedule for updates and release of the updated software.

Phase II would be the software and graphics modification and release of the updated software in accordance with the Phase I plan.

State of the Art and Critical Gaps:

Multiple urban planning games currently exist.

Relevance / Science Traceability:

AAM Mission Office.

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) AAM Mission and the eight projects supporting that mission. Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

References:

1. NASA's National Aeronautics Committee briefings: https://www.nasa.gov/aeroresearch/aero-nac-committee
2. George Price et al., "Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations," NASA\CR—2020-5001587
3. https://www.nasa.gov/aeroresearch/one-word-change-expands-nasas-vision-for-future-airspace/
4. Reference: Urban Weather section from the UAM UML-4 ConOps https://nari.arc.nasa.gov/sites/default/files/attachments/4%203%206%20Weather--CIWG%20version.pdf
5. ASTM WK731142 https://www.astm.org/DATABASE.CART/WORKITEMS/WK73142.htm
6. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
7. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint
8. Kenneth H. Goodrich and Colin R. Theodore, "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA SciTech 2021 (to be published).

Scope Title:

AAM Community Integration

Scope Description:

AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

Although limited manned, passenger-carrying UAM and other air taxi operations occur today, this market is ripe to expand as technologies such as electric propulsion and increasing autonomy converge enabling novel aircraft with enhanced capabilities. With time, the small unmanned aerial systems (sUAS) market and manned UAM and air taxi markets may converge into a broader AAM market including both manned and unmanned vehicles. To start down the path to enabling this, ARMD has proposed an organizational framework, identified a set of barriers organized according to this framework that must be overcome to enable this market, and has identified NASA’s potential contributions to overcome these market impeding barriers.

Th AAM framework consists of five pillars: (1) aircraft design, (2) individual aircraft operations, (3) airspace design, (4) airspace and fleet operations, and (5) community integration. This solicitation focuses specifically on the community integration pillar (Refs 1-3, 6-8). Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

- The integration of AAM into a multi-modal transportation system is a complicated endeavor involving leveraging existing infrastructure, working with existing and new stakeholders in an evolving regulatory environment. The results from this SBIR would form the nucleus of a set of tools that could be utilized by local community stakeholders to support the planning, public acceptance, and analysis of various design options to incorporate AAM into the local or regional transportation system.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I would be to identify initial needed types of data sets e.g., local zoning data and existing and needed tools, a plan to assemble or build the tools and incorporate the needed datasets, and create a business plan to market a planning suite of tools to localities to assist them to develop plans and assess the potential benefits of various site selection options and demand potential for various options for integration into the existing multimodal transportation system.

Phase II would be to execute the plans developed in Phase I.

State of the Art and Critical Gaps:

NASA has developed decision support tools for the National Airspace System. This effort would leverage that experience to support local communities.

Relevance / Science Traceability:

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) AAM Mission and the eight projects supporting that mission. Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

References:

1. NASA's National Aeronautics Committee briefings: https://www.nasa.gov/aeroresearch/aero-nac-committee
2. George Price et al., "Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations," NASA\CR—2020-5001587
3. https://www.nasa.gov/aeroresearch/one-word-change-expands-nasas-vision-for-future-airspace/
4. Reference: Urban Weather section from the UAM UML-4 ConOps https://nari.arc.nasa.gov/sites/default/files/attachments/4%203%206%20Weather--CIWG%20version.pdf
5. ASTM WK731142 https://www.astm.org/DATABASE.CART/WORKITEMS/WK73142.htm
6. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
7. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint
8. Kenneth H. Goodrich and Colin R. Theodore, "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA SciTech 2021 (to be published).

Scope Title:

AAM Community Integration - Multimode Transportation Information Integration

Scope Description:

AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

Although limited manned, passenger-carrying UAM and other air taxi operations occur today, this market is ripe to expand as technologies such as electric propulsion and increasing autonomy converge enabling novel aircraft with enhanced capabilities. With time, the small unmanned aerial systems (sUAS) market and manned UAM and air taxi markets may converge into a broader AAM market including both manned and unmanned vehicles. To start down the path to enabling this, Aeronautics Research Mission Directorate (ARMD) has proposed an organizational framework, identified a set of barriers organized according to this framework that must be overcome to enable this market, and has identified NASA's potential contributions to overcome these market impeding barriers.

Th AAM framework consists of five pillars: (1) aircraft design, (2) individual aircraft operations, (3) airspace design, (4) airspace and fleet operations, and (5) community integration. This solicitation focuses specifically on the community integration pillar (Refs 1-3, 6-8). Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

- This effort would be to design and develop an innovative Multimodal Information Management System (MIMS) that includes AAM as one element of a Smart City transportation data management system.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.4 Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I would be to identify the system requirements, physical infrastructure including interfaces, data architecture and sources, security and data assurance measures needed for the system, and public and private partners.

Phase II would be to build the planned system and market it to several localities.

State of the Art and Critical Gaps:

Some systems exist e.g., Los Angeles has a scooter tracking system and app for their Department of Transportation and many localities have apps for their metros e.g. Washington DCs, Metro app. This would be a comprehensive multimodal system.

Relevance / Science Traceability:

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) AAM Mission and the eight projects supporting that mission. Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to the A3 topic.

References:

1. NASA's National Aeronautics Committee briefings: https://www.nasa.gov/aeroresearch/aero-nac-committee
2. George Price et al., "Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations," NASA\CR—2020-5001587
3. https://www.nasa.gov/aeroresearch/one-word-change-expands-nasas-vision-for-future-airspace/
4. Reference: Urban Weather section from the UAM UML-4 ConOps https://nari.arc.nasa.gov/sites/default/files/attachments/4%203%206%20Weather--CIWG%20version.pdf
5. ASTM WK731142 https://www.astm.org/DATABASE.CART/WORKITEMS/WK73142.htm
6. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
7. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint

8. Kenneth H. Goodrich and Colin R. Theodore, “Description of the NASA Urban Air Mobility Maturity Level (UML) Scale,” AIAA SciTech 2021 (to be published).

Focus Area 20 Airspace Operations and Safety

Lead MD: **ARMD**

Participating MD(s): **N/A**

This focus area includes technologies addressing both the Airspace Operations and Safety Program (AOSP), and NASA's ARMD Strategic Thrusts 1, 5, and 6. AOSP is targeting system-wide operational benefits of high impact for NextGen and beyond, both in the areas of airspace operations and safety management. The SBIR Airspace Operations and Safety Topic is focused on research and technology development for enabling a modernized air transportation system that will achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. This will include the integration of new types of vehicles such as unmanned vehicles, advanced subsonic aircraft, supersonic or commercial space vehicles; new types of business models or operations (i.e., urban air mobility); and new architectures or services for enabling these operations within the NAS.

A3.01 Advanced Air Traffic Management System Concepts (SBIR)

Lead Center: **ARC**

Participating Center(s): **LaRC**

Scope Title:

Advanced Air Traffic Management System Concepts

Scope Description:

This subtopic addresses contributions towards Air Traffic Management (ATM) systems and concepts with potential application in the near-future (2025-2030) National Airspace System (NAS). The subtopic seeks proposals that can apply novel and innovative technologies and concepts towards addressing established ATM challenges of improving efficiency, capacity, and throughput while minimizing negative environmental impact, maintaining or improving safety, and/or accelerating the implementation of NASA technologies in the current and future NAS.

Given the recent coronavirus pandemic, and the dramatic impact to the airlines and U.S. aviation industry as a whole, this solicitation also seeks proposals that can apply novel and innovative concepts, technologies, and capabilities towards enabling the U.S. air transportation system to recover from the recent negative impacts of reduced traffic demand.

The NASA technologies that are being researched and developed for the future NAS include, but are not limited to: Integrated Arrival, Departure, and Surface (IADS) capabilities, routing and rerouting around weather from ground-based and cockpit-based systems, tools enabling trajectory-based operations (TBO), and capabilities that can be integrated with a fully-realized Unmanned Aircraft Systems Traffic Management (UTM) system for a wide range of commercial and public use.

Technologies, concepts, models, algorithms, architectures and tools are sought in this solicitation to bridge the gap from NASA's research and development (R&D) to operational implementation, and should address such nearer-term ATM challenges as:

- Safe, end-to-end TBO.
- Enabling and integrating existing independent systems and domains, and increasingly diverse and unconventional operations (gradually enabling the future integration of large unmanned vehicles, unconventional commercial airline business models, space traffic management, and subsonic and supersonic vehicles).
- Applying elements of the service-based architecture concept being pioneered in the UTM domain.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance safe and efficient growth in global operations [Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal] that can be incorporated into existing and future NASA concepts.

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the R&D challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:

State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the NAS.

Critical Gaps: Significant challenges remain in integrating air transportation technologies across different domains and operators (e.g., airport surface and terminal area; airport authority and air navigation service providers; etc.), providing comprehensive, strategic scheduling and traffic management technologies, enabling concepts that will allow for increased demand and complexity of operations, and enabling recovery from the global pandemic-induced air transportation system impacts.

Relevance / Science Traceability:

Airspace Operations and Safety Program (AOSP) within ARMD.

Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the Program, and enable successful technology transfer to external stakeholders (including the Federal Aviation Administration and the air transportation industry).

References:

https://www.nasa.gov/aeroresearch/programs/aosp

A3.02 Increasing Autonomy in the National Airspace System (NAS) (SBIR)

Lead Center: **ARC**

Participating Center(s): **LaRC**

Scope Title:

Increasing Autonomy in the National Airspace System (NAS)

Scope Description:

NASA's future concepts for air transportation (2030 and beyond) will significantly expand the capabilities of airspace and vehicle management and are anticipated to increasingly rely on autonomy and artificial intelligence and machine learning to ensure safe, secure, and equitable operations. Such future concepts propose a seamless, integrated, flexible, and robust set of systems that are anticipated to include traditional as well as nontraditional vehicle types and operations, diverse airspace domains and mission types, and a service-based architecture to provide user services as those demonstrated within NASA's Unmanned Aircraft Systems Traffic Management (UTM) Project, as appropriate. Future concepts will require resilient, cyber-attack-resistant systems to ensure safe and robust operations that maintain expected levels of safety, as well as accommodate changes to environmental and operational conditions.

Human operators currently perform the most significant roles in decision making in the National Airspace System (NAS). The appropriate allocation of functions as humans team with autonomy (and even current automation) is a critical research question as more autonomous systems are introduced. To address these research challenges, this subtopic seeks proposals that will apply novel and innovative techniques, methods, and approaches to developing tools and/or technologies that will enable successful human-autonomy teaming in the future NAS.

This subtopic is focused on the human-autonomy teaming of the airspace operations in the future NAS. Proposals that do not address the human operator interaction with future NAS technologies will be rejected.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance safe and efficient growth in global operations [Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal] as well as developing autonomy applications for aviation (as under ARMD

Thrust 6).

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the research and development (R&D) challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:

State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the NAS. Autonomy is the focus of increased ARMD interest as evidenced in Thrust 6, Assured Autonomy for Aviation Transformation. Airspace Operations and Safety Program (AOSP) research is increasingly applying autonomous technologies and capabilities towards air transportation challenges. These technologies and capabilities may address limited solutions to targeted problems.
Critical Gaps: The growth of data sciences and autonomy/artificial intelligence technologies continue to have great potential to benefit the development of a more autonomous air transportation system. This is needed to accommodate the increasing demand and diversity of air transportation missions and operations. The interpretation and use of data science-based information by human operators and decision makers, continues to be of interest.
This subtopic is focused on the human-autonomy teaming of the airspace operations in the future NAS. Proposals that do not address the human operator interaction with future NAS technologies will be rejected.

Relevance / Science Traceability:

Airspace Operations and Safety Program (AOSP).
Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the Program. The technologies also introduce new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application, and show where such approaches are/are not appropriate to advance airspace operations.

References:

https://www.nasa.gov/aeroresearch/programs/aosp

A3.03 Future Aviation Systems Safety (SBIR)

Lead Center: **ARC**

Participating Center(s): **LaRC**

Scope Title:

Future Aviation Systems Safety

Scope Description:

Public benefits derived from continued growth in the transport of passengers and cargo are dependent on the improvement of the intrinsic safety attributes of the Nation’s and the world’s current and future air transportation system. Recent developments to address increasing demand include: increased use of automation and autonomy to enhance system capabilities, airspace systems with tightly coupled air and ground functions, cloud computing-based technologies used to perform functions or services, other widely distributed functions across ground, air, and space environments, increasingly integrated aircraft systems, and novel vehicles and mission types, such as Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM). These revolutionary changes are leading to greater system complexity, and current methods of ensuring that airspace and vehicle designs meet desired safety levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). The Airspace Operations and Safety Program (AOSP) is addressing this challenge with a major area of focus on In-Time System-Wide Safety Assurance (ISSA). Understanding and predicting system-wide safety concerns of the airspace system and the vehicles flying in it, as envisioned in future aviation systems, is paramount. Thus, a proactive approach to managing system safety requires that once a new system, technology, procedure, or training is introduced, that operators have: (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors through health monitoring of system-wide functions; and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks. Specifically, AOSP's System-Wide Safety (SWS) Project is developing an In-Time Aviation Safety Management System (IASMS), to address aviation system safety needs. Based on ISSA building blocks, its functional capabilities are architecturally structured to "Monitor—Assess—Mitigate" operational safety risks. One application area of high interest is monitoring, assessing, and mitigating cybersecurity vulnerabilities and attacks. Innovative approaches and methods are sought that monitor/assess/mitigate vulnerabilities before they can be exploited by malicious actors. Proposed innovations are sought that can be easily incorporated into the IASMS. Proposals that lack a technology/function that can be integrated into IASMS will be rejected.

Specifically, this subtopic seeks the following types of proposals, whose technologies can be integrated into IASMS:

- Proposals to address the safety-critical risks identified in beyond visual-line-of-sight (BVLOS) operations in small and large UAS, including but not limited to risks such as:
    - Flight outside of approved airspace.
    - Unsafe proximity to people/property.
    - Critical system failure [including loss of command and control (C2) link, loss or degraded Global Positioning System (GPS), loss of power, and engine failure].
    - Loss-of-control (i.e., outside the envelope or flight control system failure).
    - Any potential cybersecurity or cyber-physical attack affecting any or all operations within the UAS airspace system.
- Proposals supporting the research and development of ISSA objectives:
    - To detect and identify system-wide safety anomalies, precursors, and margins.
    - To develop the safety-data-focused architecture, data exchange model, and data collection mechanisms.
    - To enable simulations to investigate flight risk in attitude and energy aircraft state awareness.
- Proposals supporting safety prognostic decision support tools, automation, techniques, strategies, and protocols:
    - To support real-time safety assurance (including in-time monitoring of safety requirements).
    - That consider operational context, as well as operator state, traits, and intent.

    - For integrated prevention, mitigation, and recovery plans with information uncertainty and system dynamics in a UAS and trajectory-based operations (TBO) environment.
    - To enable transition from a dedicated pilot in command or operator for each aircraft (as required per current regulations) to single pilot operations.
    - To enable efficient management of multiple unmanned and AAM aircraft in civil operations.
    - To assure safety of air traffic applications through verification and validation (V&V) tools and techniques used during certification and throughout the product lifecycle.
- Cybersecurity resiliency requiring availability and integrity of critical functions including:
    - Rapid detection of incidents to enable remediation.
    - Automatic remediation actions to restore sufficient network or application services to support mission essential functions.
    - Information resilience for shared airspace status.
    - Reliable delivery and authentication of important messages.
    - Security management systems, security management frameworks or information security management systems.
    - Resilient voice, data, and precision navigation and timing.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.1 Safe All Vehicle Access

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance the goals of safe air transportation operations that can be incorporated into existing and future NASA concepts.

Desired deliverables for Phase I include development of multiple concepts/approaches, tradeoffs analyses, and proof-of-concept demonstrations.

Desired deliverables for Phase II include development of functional prototypes, integration of prototypes into existing and future NASA concepts, and demonstration of the prototype in a realistic environment.

State of the Art and Critical Gaps:

State of the Art: Recent developments to address increasing air transportation demand are leading to greater system complexity, including airspace systems with tightly coupled air and ground functions as well as widely distributed and integrated aircraft systems. Current methods of ensuring that designs meet desired safety

levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). AOSP is addressing this challenge with a major area of focus on ISSA.
Critical Gaps: A proactive approach to managing system safety requires: (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors after new technologies, procedures, and training are introduced and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks. Also, with the addition of Urban Air Mobility (UAM)/AAM concepts, and increasing development of UAS Traffic Management (UTM), the safety research needs to expand to include these various missions and vehicles.

Relevance / Science Traceability:

Successful technologies in this subtopic will advance the safety of the air transportation system. The AOSP safety effort focuses on proactively managing safety through continuous monitoring and extracting relevant information from diverse data sources and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies towards those objectives.

References:

https://www.nasa.gov/aeroresearch/programs/aosp

https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/aero-rdplan-2010.pdf

A3.04 Nontraditional Airspace Operations (SBIR)

Lead Center: **ARC**

Participating Center(s): **LaRC**

Scope Title:

Nontraditional Airspace Operations

Scope Description:

NASA is exploring airspace operations incorporating unmanned vehicles and novel operations occurring in all airspaces (controlled and uncontrolled), with a goal to safely and efficiently integrate with existing operations and mission types. NASA's research to enable unmanned vehicles to be safely and fully integrated into existing airspace structures (or lack thereof) has already demonstrated the potential benefits and capabilities of a service-based architecture [such as developed for the Unmanned Aircraft Systems Traffic Management (UTM) Research and Development (R&D) evaluations], and has led to new procedures, equipage and operating requirements, and policy recommendations, to enable widespread, harmonized, and equitable execution of diverse unmanned missions.

This subtopic seeks proposals to continue to adapt the UTM concept elements for application to Urban Air Mobility (UAM)/Advanced Air Mobility (AAM), including:

- Service-based architecture designs that enable dense and/or increasingly complex UAM operations.
- Dynamic route planning that considers changing environmental conditions, vehicle performance and endurance, and airspace congestion and traffic avoidance.
- Dynamic scheduling for on-demand access to constrained resources and interaction between vehicles with starkly different performance and control characteristics.

- Integration of emergent users with legacy users, large commercial transport, including pass-through to and from ultrahigh altitudes and interactions around major airports.
- Operational concepts for fleet and network management, market need and growth potential for future operations, and airspace integration.
- Identification of potential certification approaches for new vehicles operations (such as electric vertical takeoff and landing).

Future service-based architectures also require resiliency to cyberattacks to ensure safe and robust operations that maintain expected levels of safety, as well as accommodating changes to environmental and operational conditions. Therefore, proposals incorporating cyber-resiliency methods, tools, or capabilities, or address cyber-resiliency as part of the proposed effort are also being solicited.

New this year, this solicitation is focused on UAM/AAM airspace operations only, and is not accepting proposals specific to other nontraditional operations. In addition, proposals that focus only on cyber-resiliency solutions without proposing specific UAM/AAM services, will be rejected.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance safe and efficient growth in global operations [Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal] as well as developing autonomy applications for aviation (as under ARMD Thrust 6), that are specifically applicable to UAM operations, and address post-pandemic recovery, as appropriate.

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the R&D challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:

Current state of the art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the National Airspace System and has been applying this expertise, as well as a service-based architecture and concepts pioneered for UTM towards UAM/AAM.
Critical gaps: Significant challenges remain to fully develop the UAM/AAM airspace concept of operations, including integrating air transportation technologies across different domains and operators, providing comprehensive, strategic scheduling and traffic management technologies, and enabling concepts that will allow for scaling demand and complexity of operations.
This subtopic is focused on the Airspace Operations of the UAM/AAM concept only. Proposals must have clear

application to UAM/AAM airspace operations. Proposals that focus on UAM/AAM vehicle capabilities, or onboard vehicle technologies or systems, will be rejected. Proposals that are specific to other nontraditional operations (such as, but not limited to, space traffic management, automated air cargo, UTM, and ultrahigh altitude), without clear application to UAM/AAM, will be rejected.

Relevance / Science Traceability:

Airspace Operations and Safety Program (AOSP).

Air Traffic Management-eXploration (ATM-X) Project.

Successful technologies in this subtopic will help NASA pioneer UAM concepts and technologies. The technologies also incorporate new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application.

References:

https://www.nasa.gov/aeroresearch/programs/aosp

https://www.aviationsystemsdivision.arc.nasa.gov/publications/index.shtml
https://www.aviationsystemsdivision.arc.nasa.gov/index.shtml

https://www.nasa.gov/aeroresearch/strategy

Focus Area 21 Small Spacecraft Technologies

Lead MD: **STMD**

Participating MD(s): **N/A**

NASA is pursuing rapid identification, development, and testing of capabilities that exploit small spacecraft platforms and responsive launch capabilities to increase the pace of space exploration, scientific discovery, and the expansion of space commerce. These emerging capabilities have the potential to enable new mission architectures, enhance conventional missions, and promote development and deployment on faster timelines. This will, in turn, allow NASA and other space mission operators to achieve their objectives at significantly lower programmatic risk and cost than traditional approaches.

Small spacecraft are typically defined as those weighing 180 kg or less and are often designed using standardized form factors and containerized deployment (e.g. CubeSats). Small spacecraft and responsive launch capabilities are proving to be disruptive innovations for exploration, discovery, and commercial applications. NASA seeks technical innovations that enable small spacecraft to rival the capabilities of their larger more expensive counterparts, while also striving to make them cheaper and quicker to build, and easier to launch and operate. NASA also seeks innovations to help further expand the reach of small spacecraft beyond Low Earth Orbit. Greatly improved capabilities are needed for lunar exploration missions, lunar communications and navigation infrastructure, and exploration at Mars and other deep space destinations. Technology and capability investment will be needed to meet these upcoming mission needs while keeping overall costs low, mission cadence high, and retaining the agile aerospace approach that has fueled what has been termed the “smallsat revolution”.

Specific improvements required are: long-range high-bandwidth optical and RF communications; novel navigation devices and navigation references for use well beyond Earth; improved power management; and robust tolerance of the harsher thermal and radiation environment of deep space. Propulsion technologies with improved performance are sought for Trans Lunar Injection (TLI), lunar orbit insertion and maintenance, return-to-Earth and Earth entry and descent mechanisms. Transfer stages that host small spacecraft are also sought. Innovations are wanted to increase economic and rapid production and availability; modular designs will facilitate reliable assembly and test of singly- or batch-produced small spacecraft. Specifically needed technologies include wirelessly interconnected sensors and modules and commercially available "stock" optics in place of expensive, long-lead custom designs. Affordable powerful computing hardware and intelligent software tools and infrastructure are needed for autonomous operation of distant spacecraft or for cooperation of spacecraft groups, minimizing human-in-the-loop bottlenecks. NASA's Small Spacecraft Technology Program will consider promising SBIR technologies for spaceflight demonstration missions and seeks partnerships to accelerate spaceflight testing and commercial infusion.

The following references discuss some of NASA's small spacecraft technology activities:

- https://www.nasa.gov/directorates/spacetech/small_spacecraft/index.html
- www.nasa.gov/smallsats https://www.nasa.gov/smallsat-institute

Another useful reference is the Small Spacecraft Technology State of the Art Report at:

- http://www.nasa.gov/sites/default/files/atoms/files/small_spacecraft_technology_state_of_the_art_2015_tagged.pdf

T5.05 Solar and Electric Sail Embedded Technologies for Communications, Control, or Ancillary Functions (STTR)

Lead Center: **MSFC**

Participating Center(s): **ARC, GRC, JPL**

Scope Title:

Solar and Electric Sail Control Systems Modeling and/or Development

Scope Description:

One of the challenges with higher performance solar sails remains to be a highly resilient yet low-resource and low-complexity control system. Traditional solar sail options under consideration have previously considered impulsive systems (chemical and electric), mechanical systems (translation tables, guy wires, and moving masses), reflective control devices, and advanced diffractive metafilms. Further electric solar wind sail (E-sail) control systems are lower maturity and require new modeling and analysis tools for higher fidelity performance assessment. This solicitation seeks either embedded sail control technologies for traditional solar sails or the development of advanced modeling capabilities for E-sail control systems.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

For a traditional solar sail, the anticipated final product would be a prototype-tested control solution with potential to enable high performance for long-duration (>10-year) missions. For Phase I, the final deliverable must include very clear Key Performance Parameters (KPPs) of the control system approach based on preliminary proof-of-concept testing and/or analysis. The proposal must indicate anticipated KPPs for system-level implementation for a known design reference mission (e.g., Solar Polar Imager). The Phase II product must contain hardware development with laboratory performance testing to validate anticipated KPPs.

For an E-sail, the anticipated final product would be a high-fidelity modeling tool for performance assessment of solar sail control system performance. The Phase I product must include the identification and assessment of the key driving elements for total control system performance and control system performance uncertainty in addition to the approach to mitigate flight system performance uncertainty in the Phase II development. The Phase II product must include the delivery of a fully functional control system modeling tool suitable for high-fidelity performance assessment applied to missions of interest (e.g., Solar Polar Imager and Interstellar Probe).

State of the Art and Critical Gaps:

State-of-the-art solar sail systems use translating masses (so-called AMT (Active Mass Translator)) and reflective control devices. Solar sail thrust, though miniscule in size, can produce large-velocity deltas over a multiyear mission. These small forces also create disturbance torques caused by misalignment in the center of mass (CM) and center of pressure (CP). NEAScout (current NASA Sail mission) estimates that the CP/CM offset is large enough to overload control systems and requires a mechanical system to adjust the CM and trim the spacecraft—the AMT. However, the scalability of the AMT to larger sail missions, such as the Interstellar Probe is currently unknown.

Attitude can also be controlled by varying solar radiation pressure directly on the sail itself. So-called reflectivity control devices (RCDs) were demonstrated on JAXA's first solar sail mission, IKAROS, and are currently being investigated by NASA and academic partners. A typical RCD utilizes a polymer-dispersed liquid crystal whose optical properties can be adjusted via an applied electric voltage. These devices show promise, although challenges exist in yielding control in all three axes. Further, space environments survivability in extreme environments, especially the hot thermal of a high-inclination Solar Polar Imager, for example, also remains a challenge.

E-sails have low-fidelity simulations for control systems. Multitethered bodies coupled with varying plasma environments throughout the mission profiles, spacecraft charging, tether dynamics, and the like, are critical gaps.

Relevance / Science Traceability:

The resulting product should improve the performance or lower the subsystem mass for a solar-sail-based spacecraft optimized for the high-inclination Solar Polar Imager, advanced generation Solar Storm Warning systems, as well as the interstellar probe.

References:

- Overview of NEAScout Sail mission with AMT: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170012287.pdf
- AMT Translation Table Development at NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160008126.pdf
- SOA RCDs being evaluated by NASA: https://drum.lib.umd.edu/bitstream/handle/1903/19291/Ma_umd_0117E_17785.pdf?isAllowed=y&sequence=1
- SOA RCDs at JAXA: https://www.semanticscholar.org/paper/Optimal-Design-of-Advanced-Reflectivity-Control-for-Hirokazu-Shida/cfbc675862ca232e0d52b5cfd0173fcc969d7c7c
- Summary of NASA E-Sail Investigation:

- https://www.researchgate.net/publication/322310672_A_Summary_of_Recent_NASA's_Electric_Sail_Propulsion_System_Investigations
- E-Sail Control: https://arxiv.org/abs/1406.6847
- Advanced Diffractive MetaFilms: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190025234.pdf

Scope Title:

Lightweight Deployable (Solar Sail) Embedded Interplanetary Communication Solutions

Scope Description:

The Mars Cube One (MarCO) mission demonstrated the potential of SmallSat spacecraft to perform interplanetary missions. SMD is continuing to invest in technologies and interplanetary missions due to the high science value enabled by SmallSat spacecraft; several of those being solar-sail-based missions. However, MarCO was extremely limited in communication rates. Also, future interplanetary missions will be carrying science instrumentation with higher data requirements. This solicitation is seeking deployable embedded technology solutions for higher gain, enabling higher data rate communications for interplanetary spacecraft with an emphasis on applicability to solar sail missions (very low SWaP-C (Size, Weight, Power, and Cost)). The NEAScout solar sail architecture can be used as a sample design reference for the proposed technologies. However, the proposed technologies should be extensible to solar sails in general (that is, not be tied to NEAScout-specific requirements) as well as to stand-alone devices (that is, to be applicable to nonsolar sail missions).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis

Desired Deliverables Description:

The anticipated Phase I product of this solicitation would be a proof-of-concept demonstration of the technology with determination of the Key Performance Parameters by test and/or analyses leading to a higher fidelity prototype(s) and relevant environmental demonstrations in Phase II.

State of the Art and Critical Gaps:

The current state of the art for SmallSat/CubeSat missions is led by ISARA (Integrated Solar Array and Reflectarray Antenna) flown on MarCO. Using a combination reflectarray and patch array, it demonstrated an 8-kbps X-band downlink from Mars orbit with a 28-dB-gain design in a small form factor of <1 kg and 272 cm^3 at 5 W. For reference, the Mars Reconnaissance Orbiter is a large spacecraft communicating from aproximately the same distance as MarCO with a 46.7-dB 3-m dish that varies from 500- to 4,000-kbps X-band downlink at 100 W.

Outside of ISARA, various arrays of 16 patch antennas or fewer are available from places like Endurosat and Clyde Space with gains from 11.5 to 16 dB. Thin-film solutions such as the Lightweight Integrated Solar Array and anTenna (LISA-T) are in development. However, the ultimate scalability (mechanically, mass, stowage volume, etc.) is limited. Thus, a critical technology gap exists in higher data rate communication solutions for SmallSats outside Earth orbit. The current NASA Small Spacecraft Strategic Technology Plan states this need in several ways including large deployable apertures. This gap is especially critical for deployable solar sail missions such as interstellar probe and potentially for second- and third-generation space weather monitoring platforms. In short, low SWaP-C, high-gain communication techniques that will push small spacecraft data rates towards their larger spacecraft brothers and sisters are needed. To enhance future solar sail missions, these concepts should be amenable if not directly embedded onto the solar sail itself.

Relevance / Science Traceability:

The SIMPLEX solicitation opportunities would benefit significantly from higher data rate communication solutions for SmallSat missions. Further specific solar sail mission such as the high-inclination Solar Polar Image mission and second- and third-generation space weather monitoring missions would be enhanced by this technology, and specific solar sail missions such as the interstellar probe would be enabled by this technology.

References:

- Review of CubeSat Antenna for Deep Space: https://pureadmin.qub.ac.uk/ws/portalfiles/portal/174234474/IEEE_Magazine.pdf
- LISA-T: https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxqb2huYW50aG9ueWNhcnJ8Z3g6YzcxMGZjY2Y4MDYwMmJl

Z8.02 Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO) (SBIR)

Lead Center: **GRC**

Participating Center(s): **ARC, GSFC, JPL**

Scope Title:

End-to-End Deep Space Communications

Scope Description:

Develop enabling communications technologies for small spacecraft beyond LEO. These technologies will be required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in communications technologies for distributed small spacecraft are essential to fulfill the envisioned science missions within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture [Ref. 11], it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include data relay from lunar surface to surface, data relay to Earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

Technologies for specific lunar architecture are especially needed. For example, landers near the lunar South Pole may not have—and landers on the far side of the Moon will not have—direct line-of-sight to Earth-based ground stations and will need to send data through a relay satellite (or Gateway) to return data to Earth. Small surface systems (including rovers or astronauts on extravehicular activities (EVAs)) on the Moon will likely not have the necessary system resources to close a direct link to Earth. Human surface operations may require surface-to-surface over-the-horizon communications through an orbital relay. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space.

Considerations of extension of the technologies and capabilities to the martian domain and other deep space applications are also solicited.

Interspacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP-C hardware for radio-frequency (RF) and optical cross links. While network protocols developed for interoperable communications relays may be interchangeable with those for distributed missions, relay networks may not be scalable to very large scale sensor webs of small spacecraft. As such, addressing interspacecraft networking gaps may require investment in both hardware cross links and networking protocols that scale to hundreds of nodes, and require robustness for loss of nodes or as new nodes enter the network.

An end-to-end system needs to be considered for the application of small satellites for deep space missions as described in preceding paragraphs. Therefore, enabling technologies also include non-NASA ground services that keep the operations cost commensurate with the lower costs of the small satellites themselves. Automation of the ground services as well as the small satellite constellations are needed.

Communications solutions can operate in optical or various RF bands; however, considerations must be given to bandwidth, public and Government licensing, and compatibility with referenced candidate architectures.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.2 Radio Frequency

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I: Identify and explore options for the deep space small-satellite missions, including ground services. Conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of communication technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Small-spacecraft missions beyond Earth require compact, low-power, high-bandwidth radios for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio (0.5U, 1.2 kg, and 35 W) [Ref. 12] that has been operationally used at Mars, and there is no known affordable, readily available competitor. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, Ka-band, and optical), and can reach uplink and downlink speeds in excess of 20 Mbps. Spectral, modulation, information layer, and protocol compatibility with current technologies (Space Communications and Navigation (SCaN)); licensing and spectrum approval; and planned Government or commercial deep space communication architecture must all be considered.

Communications among spacecraft in a distributed spacecraft mission (DSM) configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (10s to 100s of km apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- Uplinks (Earth-to-space) and downlinks (space-to-Earth): Alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth. Each spacecraft cannot rely on its own dedicated Earth link, consuming valuable ground infrastructure and operators.
- Integrated communications payload: Hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration. Spacecraft communication SWaP-C should be reduced by at least 25% from a non-DSM spacecraft.
- Small-spacecraft antennas: Development of antennas optimized for either intersatellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. SWaP-C should be reduced from state of the art, such as the recent 6U CubeSat MarCO mission, which used a 0.2m^2 X-band reflectarray to achieve 29 dBic gain and 42% efficiency [Refs. 13, 14]. Operations compatible with NASA's space communications infrastructure [Ref. 9] and Government exclusive or Government/non-Government-shared frequency spectrum allocations is required [Refs. 6, 7, 8].
- Compatibility and interoperability with lunar communications and navigation architecture plans [Refs. 1, 2, 3]. Application of the emerging lunar standards includes frequency allocations per link functionality, modulation, coding, and networking protocol standards. Ka-band frequencies and above are highly desired.

Relevance / Science Traceability:

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, Commercial Lunar Payload Services (CLPS); Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE); human exploration (Artemis) landing site and resource surveys; lunar communications and navigation infrastructure, including LunaNet, Mars communications relay, etc. Commercial and NASA small spacecraft, lunar surface assets, and manned vehicles in cislunar space and beyond will multiply within the decade. All of these missions will depend on small-spacecraft communications relays, time reference transmissions, and navigation capabilities.

References:

[1] International Communication System Interoperability Standard (ICSIS): https://www.internationaldeepspacestandards.com

[2] Interagency Operations Advisory Group (IOAG): https://www.ioag.org/

[3] Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030: https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf

[4] NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn

[5] "Delay-tolerant networking: an approach to interplanetary internet." IEEE Communications Magazine 41, no. 6 (2003): 128-136.

[6] National Telecommunications and Information Administration Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

[7] National Telecommunications and Information Administration Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html

[8] NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html

[9] NASA Space Communications and Navigation networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html

[10] NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview

[11] LunaNet: A Flexible and Extensible Lunar Exploration communications and Navigation Infrastructure: https://esc.gsfc.nasa.gov/news/_LunaNetConcept https://esc.gsfc.nasa.gov/news/_LunaNetConcept

[12] IRIS Radio: https://www.jpl.nasa.gov/cubesat/missions/iris.php

[13] N. Chahat et al.: "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review." IEEE Antennas and Propagation Magazine, vol. 61, no. 5, pp. 37-46, Oct. 2019, doi: 10.1109/MAP.2019.2932608.

[14] Mars Cube On (MarCO) mission overview: https://www.jpl.nasa.gov/cubesat/missions/marco.php

[15] NASA/TP-2018-220027, State of the Art Small Spacecraft Technology Report: https://www.nasa.gov/smallsat-institute/sst-soa

Scope Title:

Relative and Absolute Deep Space Navigation

Scope Description:

Develop enabling technologies for beyond low Earth orbit (LEO) relative and/or absolute position knowledge. This situational awareness allows for autonomous control of small spacecraft as well as determining and maintaining position within a swarm or constellation of small spacecraft. In addition, timing distribution solutions for the SmallSats are important. Earth-independent and Global Positioning System- (GPS-) independent navigation and timing are enabling capabilities required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in navigation technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative stationkeeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small-spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft requires sensors and maneuvering systems that are low in mass, volume, power consumption, and cost.

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Exploration mission operations that involve multiple-element distributed-mission architectures may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Access to DSN ranging may not be available for multiple concurrent missions, may be blocked by terrain for surface operations, or may be limited by the radio capabilities of smaller missions. In concert with other available signals of opportunity and landed beacons, small spacecraft can provide relative ranging or triangulation to aid lunar navigation. Knowledge at the spacecraft of relative (between-spacecraft) situational awareness is needed for real-time stationkeeping/relative position control where required rapid reaction speeds preclude human-in-the-loop operation.

Future small-spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions and for distributed missions composed of small spacecraft beyond Earth. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g., dual use of star-tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser rangefinding to other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost (SWaP-C) constraints of the platforms.

Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Improvements in chip-scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate reference sources are not available or feasible. The vast majority of current commercial interests and Government missions operate in near-Earth orbits. To date, both NASA and the commercial spaceflight industry have enjoyed strong investment in near-Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grows and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.

Primary applications include navigational aids to lunar surface and orbiting users. Distributing these capabilities across multiple SmallSats may be necessary because of limited SWaP, but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the martian domain are also solicited. Navigation solutions for deep space distributed spacecraft missions (DSMs) may be addressed via hardware or software solutions or a combination thereof.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I: Identify and explore options for the deep space navigation technology, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated navigation payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated navigation system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of navigation technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Science measurements of distributed satellite missions (DSMs) are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft are involved. State of the art (SOA) for attitude is the Jet Propulsion Laboratory's ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U CubeSat demonstrated pointing stability of 0.5 arcsec (0.1 microdeg) rms over 20 min using guide stars. For position knowledge, missions still primarily use ranging transponders relying on a two-way Earth link. Examples of SOA for this ranging are the Iris transponder and the Small Deep Space Transponder (SDST) [Ref. 13].

Global navigation satellite services like the United States' Global Positioning System (GPS) provide very limited services beyond Geostationary Earth Orbit distances, and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs. Critical areas for advancement are:

- Long-term, high-accuracy attitude determination: In particular, low-SWaP absolute attitude determination using star trackers, etc., to achieve sub-arcsec accuracy.
- Optical navigation: Solutions are sought for visual-based systems that leverage advances in optical sensors (e.g., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. Opportunities for innovation include methods that do not require the execution of satellite maneuvers and/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various lunar and deep space mission operations concepts are of interest.
- Other novel navigation methods: Stellar navigation aids, such as navigation via quasars, x-rays, and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters and provide control for individual spacecraft.

Opportunities for innovation include the application of optimization techniques that are feasible for small satellite platforms and do not assume particular orbit eccentricities. State-of-the art in this area is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), the first spacecraft to attempt to navigate to and maintain a near-rectilinear halo orbit around the Moon as a precursor for Gateway [Ref. 11]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 12].

NOTE: Small-spacecraft propulsion technologies are not included in this subtopic.

Relevance / Science Traceability:

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of distributed spacecraft missions (DSMs) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, CLPS; human exploration (Artemis) landing site and resource surveys; and lunar communication and navigation infrastructure, including LunaNet, Mars communications relay, etc. All of these missions will benefit from improved communications and navigation capabilities.

References:

[1] International Communication System Interoperability Standard (ICSIS): https://www.internationaldeepspacestandards.com

[2] Interagency Operations Advisory Group (IOAG): https://www.ioag.org/

[3] Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030: https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf

[4] NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn

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[6] National Telecommunications and Information Administration Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

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[8] NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html

[9] NASA Space Communications and Navigation networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html

[10] NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview

[11] Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)https://www.nasa.gov/press-release/nasa-funds-cubesat-pathfinder-mission-to-unique-lunar-orbit

[12] On-Orbit Demonstration of Surface Feature-Based Navigation and Timing: https://www.nasa.gov/feature/ames/nasa-selects-universities-for-collaborative-development

[13] NASA/TP-2018-220027, State of the Art Small Spacecraft Technology Report: https://www.nasa.gov/smallsat-institute/sst-soa

Z8.08 Technologies to Enable Cost and Schedule Reductions for Optical System for CubeSats (SBIR)

Lead Center: **ARC**

Participating Center(s): **GSFC, JPL**

Scope Title:

Technologies to Enable Cost and Schedule Reductions for Optical System for CubeSats

Scope Description:

Concepts for optical systems are sought that will enable larger apertures or longer focal lengths than currently available systems, to be deployed from within small spacecraft. Relatively inexpensive small spacecraft offer several advantages over larger, more expensive spacecraft: small spacecraft can perform inspection and repair of larger spacecraft, several can be deployed for more frequent revisit rates over Earth's surface or planetary objects, and multiple craft can achieve affordable mission reliability through redundancy. To date, the utility of small spacecraft in missions involving remote sensing (in any spectral band) has been constrained by their low budget and compact size; optical sensitivity is limited in proportion to the diameter of a telescope's aperture, and magnification is limited by the effective focal length. The cost to produce one-of-a-kind optical assemblies is disproportionate and the production times too long to incorporate into the tight budgets and schedules typical of small-spacecraft missions.

The objective of this subtopic is to receive proposals that articulate a demonstrable ability to manufacture, test, and control ultra-low-cost observing systems that can meet the reference mission performance requirements (including infrastructure issues) within a time frame and budget compatible with a small-spacecraft development cycle. For the purposes of this subtopic, small spacecraft are defined as CubeSats of 12U volume. Proposals are sought that will

- Specify observing systems figures of merit for a potential small-spacecraft mission, for example:
    - Earth resource management (commercial).
    - Maritime traffic monitoring.
    - Observations for agricultural industry.
    - Fire, flood, or other emergency monitoring.
    - Lunar exploration precursors or observation of human activity at the Moon.
    - Remote spacecraft health inspection.
    - Near-Earth object detection.
    - In-space or lunar-to-Earth optical communications.
    - Other reference mission to be specified by proposer.
- Include discussion of current state of the art for telescope optical parameters (sensitivity, resolution, and magnification within a spectral band).
- Include production cost and schedule significantly improved by the proposed system design.

Significant areas for proposals are:

- Concept systems that are modular in nature that can be produced in quantities larger than the single-unit production typical of spaceflight hardware builds (for instance, batch or lot production yielding flight units in the quantity range of 30 to 50).
- Concepts that will enable large deployable apertures (optical and related, such as sun shades enabling larger apertures) and/or longer focal lengths than currently available systems that can be implemented from within a 12U small spacecraft. The concepts of large deployable optical apertures and focal lengths for small spacecraft address the fact that small spacecraft are inherently size constrained.

Requirements to be addressed in the project should include specific needs for each wavelength application region, for example:

- For UV/Optical:
    - Wavefront Figure <5 nm rms
    - Wavefront Stability <1 nm/10 min
    - First Mode Frequency >500 Hz
    - Actuator Resolution <1 nm rms
- For EUV:
    - Slope <0.1 microrad

Also needed is ability to fully characterize surface errors and predict optical performance.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:

Prototype optical system appropriate for inclusion in a 12U CubeSat with up to 8U available for optics. A CubeSat-class precision optical system with an undeployed aperture constrained by a 0.2-m diameter (fits within a 12U volume). For Phase I, deliverables should include a design reference mission relevant to the optical system design, with key performance parameters identified. Identification of key relevant subcomponents of a telescope system that require a prototype demonstration for fabrication, test, or control technology required for a successful Phase II delivery of a prototype.

Ideally, Phase I includes a reviewed preliminary design and manufacturing plan that demonstrates production feasibility, appropriate material behavior, process controls, and optical performance. Mounting/deploying issues, especially with consideration to small spacecraft, should be resolved and demonstrated. While final manufacturing and assembly will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analysis will be done to show compliance with proposed performance measures, survival of the launch environment, and performance in the space environment (Earth orbiting or deep space).

In Phase II, the project could build a prototype and complete environmental qualification testing of the optical system (or a single node in the case of a multi-element system), including measuring optical figure before and after vibration testing, acoustic testing, and thermal cycling. It would also demonstrate that the telescope maintains optical figure in a reference thermal environment including thermal gradients.

A successful mission-oriented Phase II would yield a credible plan to deliver (in Phase III) flight hardware within the allocated budget for a fully assembled and tested telescope assembly that can be integrated into the potential mission. This plan would demonstrate an understanding of how the engineering specifications of their system meet the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis). Cost and schedule goals and optical performance goals are listed under State of the Art and Critical Gaps.

Requirements to be addressed in the deliverables should include specific needs for each wavelength application region, for example:

- For UV/Optical:
    - Wavefront Figure <5 nm rms
    - Wavefront Stability <1 nm/10 min
    - First Mode Frequency >500 Hz
    - Actuator Resolution <1 nm rms
- For EUV:
    - Slope <0.1 microrad

Also needed is ability to fully characterize surface errors and predict optical performance.

State of the Art and Critical Gaps:

Technical Challenges
Ultrastable, normal incidence mirrors with low mass-to-collecting area ratios, affordably produced and delivered, modular and readily integrated into CubeSat-class form-factor, are desired.

Affordably Manufactured, Easily Integrated, Readily Available

After performance, affordability is the most important metric for an advanced optical system, and long telescope fabrication times add significant program cost. Current normal incidence space telescopes in the 0.2- to 0.5-m aperture class have lead times of 12 to 18 months and cost $1 million to $5 million. This research effort seeks a 10× reduction in schedule and cost for precision optical components: a lead time of 4 to 6 months and a cost of $100K to $500K for a 0.2- to 0.5-m aperture-class telescope. Options should be offered for modular and easy installation into a CubeSat-style payload enclosure, with considerations for maximizing aperture sizes, reliable deployment (if required), and reliable optical alignment.

Large Deployable Apertures for Small Spacecraft

Small spacecraft are inherently size constrained. Given the tight volume constraints of CubeSats and other small spacecraft, deployable systems for these platforms need to be highly volumetrically efficient and may employ novel configurations or deployment mechanisms relative to their larger brethren. Systems that can deploy a larger aperture then nominally available in a fixed system can address this constraint.

Affordably Manufactured, Easily Integrated, Readily Available

To accomplish NASA CubeSat-class missions, the mirrors and even entire optical assemblies must be delivered on CubeSat-class schedules after they have been specified. Earth-observing missions and astronomical applications often involve assembling and testing one or many spacecraft within a matter of months from concept to delivery. Optics that can be quickly procured as "catalog items" upon specification must be fabricated and ready for installation—preferably as an assembled module including optics bench and mounting hardware "plug and play" ready—or risk not being available on time for the tight mission schedules.

Relevance / Science Traceability:

A new class of low-cost, optically stable, wide-spectral-range telescopes designed specifically for small spacecraft have application in a variety of exploration, commercial, and science missions. Existing missions can be accomplished in novel and more affordable ways with small spacecraft, and new missions will be enabled by high-performance telescopes in small spacecraft. A few examples include:

- Earth resource management.
- Maritime traffic monitoring.
- Observations for agricultural industry from low Earth orbit.
- Satellite optical crosslinks or lunar satellite-to-Earth optical communications.
- Lunar exploration in situ resource utilization (ISRU) or landing site surveyors or manned surface mission operations observation.
- Remote spacecraft health inspection/monitoring.
- Near-Earth object detection or exoplanet transit detection in deep space.

References:

Types of large sparse systems are described in this SPIE paper: Large sparse aperture space optical systems, Aden B. Meinel, Marjorie P. Meinel, 1 August 2002, Optical Engineering, 41(8), (2002). https://doi.org/10.1117/1.1490557

Nautilus Observatory: a space telescope array based on very large aperture ultralight diffractive optical elements, Dániel Apai, Tom D. Milster, Dae Wook Kim, Alex Bixel, Glenn Schneider, Benjamin V. Rackham, Rongguang Liang, Jonathan Arenberg, Proceedings Volume 11116, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II; 1111608 (2019). https://doi.org/10.1117/12.2529428

Z8.09 Small Spacecraft Transfer Stage Development (SBIR)

Lead Center: **MSFC**

Participating Center(s): **AFRC, GRC**

Scope Title:

Small Spacecraft Transfer Stage Development

Scope Description:

NASA and industry represent prospective customers for sending small-spacecraft payloads in the near term to the cislunar environment, with longer term potential for farther destinations such as near-Earth objects, Mars, or Venus. The lunar destinations in this case include the lunar surface, with specific interest in the South Pole, low lunar and frozen lunar orbits, and cislunar space, including Earth-Moon LaGrange points (e.g., E-M L3) and the lunar Near Rectilinear Halo Orbit (NRHO) intended for Gateway. In future missions, NASA may transport small spacecraft to Venus for scientific discovery, to Mars to serve as precursors and infrastructure for human (and scientific) exploration, and on small-spacecraft missions to near-Earth objects for science measurements needed to understand prospective threats to Earth, and perhaps even for resource extraction and return to Earth. The ultimate goal is to exploit the advantages of low-cost and rapidly produced CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, by enabling them to reach these locations. Due to the current limits of SmallSat propulsion capabilities and the constraints of rideshare opportunities, NASA has an interest in the development of a low-cost transfer stage to guide and propel small spacecraft on trajectories to the vicinity of the Moon, then enable their insertion into the above-referenced orbits with the transfer stage or within sufficient proximity to achieve and maintain final orbit under their own power. These same capabilities and others will later need to be extended for small spacecraft to explore nearby planets.

Transfer stage architectures and designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching imminently. Proposals shall identify one or more relevant small launch vehicles, describe how their designs fit within the constraints of those vehicles, and define the transfer capability of the proposed system (i.e., from low Earth orbit (LEO), geosynchronous transfer orbit (GTO), etc., to low lunar orbit (LLO), NHRO, E-M L3, etc.). Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication in order to complete the mission. Any and all propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy one or more SmallSat payloads into the target trajectory or orbit. Innovations such as novel dual-mode systems that enable new science missions or offer improvements to the efficiency, accuracy, and safety of lunar missions are of interest. Concepts that can demonstrate improvements in cost and reliability and those that reduce requirements (thermal, power, etc.) on the payload are also highly desired.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium- or heavy-lift launch vehicles (e.g., Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.

Lunar design reference mission:

- Launch on a small launch vehicle (ground or air launch).
- Payload (deployable spacecraft) mass: at least 25 kg.
- Provide sufficient delta V and guidance to enter into Trans Lunar Injection (TLI) orbit after separation from small launch vehicle. An example mission is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)/NRHO Pathfinder 12U (25 kg) CubeSat that requires a TLI orbit with a C3 of -0.6 km^2/s^2.
- (Alternative) Provide sufficient delta V and guidance to place a 25- to 50-kg spacecraft directly into lunar NHRO or E-M L3 orbit.
- Deploy spacecraft from transfer stage.
- Safe and disposal of transfer stage.

A stretch goal is extensibility of the design for planetary design reference missions: Similar to the above, for Venus, Mars, or near-Earth object destinations.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.1 Chemical Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

- Analysis

Desired Deliverables Description:

A Phase I effort should provide evidence in the feasibility of key elements of cost, assembly, integration, and operations through fabrication or testing demonstrations. A prototype system should reach a "near CDR" level during Phase I with a mapping of key performance parameters (mass, power, cost, etc.) from the prototype to the flight design, along with potential opportunities for technology demonstration and commercialization.

It is highly desired that the Phase II deliverable include demonstration test of the prototype system along with detailed metrics (mass, power, cost, etc.) traceable to a flight design for the reference mission. Efforts leading to Phase II delivery of integrated prototype systems that could either be ground- or flight-tested as part of a post-Phase II effort are of particular interest.

State of the Art and Critical Gaps:

Many CubeSat/SmallSat propulsion units are designed for low delta-V maneuvers such as orbit maintenance, stationkeeping, or reaction control. Larger delta-V systems are employed for larger satellites and science/exploration missions, but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bipropellant storables with electric systems also viable for very small systems. Rocket Lab has recently introduced an upgraded version of their monopropellant kick stage, which includes a bipropellant engine, advanced attitude control, and power subsystems. This system will be used for the first time for NASA's CAPSTONE mission and is suggested to have capability for orbits beyond the lunar environment. At the component level, Aerojet Rocketdyne and Moog, Inc. are prominent suppliers of state-of-the-art (SOA) thrusters, including commonly used variants of the R-4D engine, while companies like Blue Canyon Technologies offer spacecraft bus solutions absent dedicated propulsion elements. Advanced manufacturing, electric pumps and actuators, nontoxic propellants, and electrospray thrusters all offer potential improvements in the flight capabilities of small propulsion systems. System concepts that enable improved spacecraft performance and control, such as dual-mode systems, provide potential advancements to the current SOA, especially those that enable new science missions and those that offer potential improvements to the efficiency, accuracy, and safety of future lunar manned missions. While many of these component technologies are reasonably mature, no integrated system capability has been developed and implemented specifically as a rapid, low-cost solution for translunar or cislunar mission designs.

Relevance / Science Traceability:

This subtopic extends the capabilities of the Flight Opportunities Program and Launch Services Program by seeding potential providers to establish lunar/cislunar transfer capabilities. The Small Spacecraft Technology Program (SSTP) also seeks demonstrations of technical developments and capabilities of small spacecraft to serve as precursor missions (such as landing site investigation or in situ resource utilization (ISRU) prospecting) for human exploration, and as communications and navigation infrastructure for follow-on cislunar missions. SSTP CAPSTONE is an example mission.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight testbeds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors. Sound rocket capabilities are being improved with options financed through this topic.

Small launch vehicles provide direct access for a small spacecraft to the destination or orbit of interest at a time of the small spacecraft mission’s choosing. In support of exploration, science, and technology demonstration missions, further expansion of these vehicle’s reach beyond LEO is needed. To expand the risk-tolerant small spacecraft approach to deep space missions, frequent and low-cost access to destinations of interest beyond Earth is required.

In the longer term, technical capabilities of small spacecraft at Venus, Mars, or NEO destinations will be demonstrated by SSTP, and ultimately new kinds of transfer vehicles derived from these capabilities may be needed to propel them there.

References:

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- https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010585.pdf
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- https://www.rocketlabusa.com/photon/
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- https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop2sided.pdf

Z8.10 Wireless Communication for Avionics and Sensors for Space Applications (SBIR)

Lead Center: **ARC**

Participating Center(s): **GRC, JPL, LaRC, MSFC**

Scope Title:

Modular and Flexible Wireless Avionics Architectures and Wireless Sensing and Integrated Avionics for Space Applications

Scope Description:

The Wireless Communication for Avionics and Sensors for Space Applications subtopic solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for small spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. These can range from developmental and flight instrumentation systems used for qualification and diagnostics on large spacecraft to full-up wireless avionics for small spacecraft. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the size, weight, and power consumption (SWaP) and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems, and software across multiple spacecraft and missions while reducing production and operating costs.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system, and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems, including software incorporating functions compatible with common spacecraft components. This means being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks, allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other nonrelated components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through the use of innovative methods such as the use of flexible materials and additive manufacturing. For example, the use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines, and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats, including ESPA-class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter)) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include cislunar, lunar orbiting, lunar landed, and exploration precursor missions; low Earth orbit (LEO) “swarms” for Earth science and heliophysics; and disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:

1. Improve the reliability and applicability of wireless avionics for small spacecraft with significant improvements in subsystem size, mass, and volume, particularly if the technology can simplify the spacecraft fabrication, test, and integration process.
2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small-satellite missions.
3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address developmental and flight instrumentation use.
4. Use innovative techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors, or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.
5. Use additive manufacturing of wireless components such as antennas, sensors, and processing elements to create new components that may be smaller and lighter than current products. These new components could possibly be embedded into materials and structures that enable in situ structural health management, contributing to the development of smart structures and materials.
6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the Moon, Mars, or other celestial bodies.

Key performance parameters (KPPs) would include improvements of at least a factor of 2 over existing technology in size, mass, and power consumption for sensors and associated components for a wireless instrumentation system. Improvements of sensor network throughput greater than 5× the current 2-Mbps performance is desired, along with reduction of latency and incorporation of timing information.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description:

Possible deliverables include benchtop hardware systems that demonstrate reliable wireless interconnectivity of two or more modules with a host flight central processing unit (CPU), or payload/developmental flight instrumentation (DFI) processor, inside a CubeSat or small-satellite form-factor bus. This system need not be flight ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Gateway and other Artemis projects.

Specific Phase I deliverables include:

- Methods of improving reliability of wireless avionics technology.
- Redundancy methods to broaden mission applicability.
- Improvements in tolerance to extreme environments including radiation.
- Novel avionics architecture definition and demonstration.
- Software support for redundant modular avionics.
- Plug-and-play methods for handling dynamic changes to avionics configuration.
- Fault detection and recovery for wireless avionics.
- Improvements in spacecraft production.
- Improvements in spacecraft integration and test.
- Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
- Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near- to mid-range time frames.

Phase II deliverables should build upon the work completed in Phase I to demonstrate the new technology at a higher Technology Readiness Level (TRL) with alignment to NASA mission needs:

- Demonstration showing the key innovations of the developed technology.
- Demonstration of specific new mission capabilities.
- Delivery of prototype hardware for NASA evaluation.

State of the Art and Critical Gaps:

Development of small satellites missions benefit from a growing number of users worldwide. This means there may be a large pool of COTS components available for a specific mission (depending on the type and class of mission). A variety of command and data handling (C&DH) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the onboard computer, memory, electrical power system (EPS), and the ability to support a variety of input and output (I/O) for the CubeSat class of small spacecraft.

Wireless networks have been incorporated as crew support aboard the International Space Station (ISS). Wireless sensor networks have been flown as demonstrations. Dynamic self-configuring wireless networks have been evaluated in the lab. AIAA has defined the Space Plug-and-Play (SPA) standard, and flight demonstrations are planned.

The maturation of additive manufacturing and 3D-printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multifunctional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management in future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent, such as parachutes and inflatable structures.

Relevance / Science Traceability:

NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred on any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

References:

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Fly-by-Wireless Update (2012): https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120010669.pdf

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NASA Armstrong Patent: https://technology.nasa.gov/patent/DRC-TOPS-42

NASA Trade Study:

https://pdfs.semanticscholar.org/b7d6/e6d92ec78b6bee4cffd5a7f613b90b4508b8.pdf?_ga=2.244696965.1804159109.1563897519-1127952606.1563032260

Passive Wireless Sensor Technology Workshops: https://attend.ieee.org/wisee-2019/program/workshops/

Z8.11 Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control (SBIR)

Lead Center: **ARC**

Participating Center(s): **GSFC, JPL**

Scope Title:

Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control

Scope Description:

Constellations of small spacecraft currently provide unprecedented persistent coverage of the Earth's surface, but the use of distributed missions for exploration infrastructure and multipoint scientific measurements beyond Earth will require new approaches to operational efficiency. Current commercial constellations use ground-based semiautonomous scheduling and orbital maintenance to decrease the need for spacecraft-by-spacecraft human-in-the-loop decision making. However, each spacecraft is still individually commanded by the ground-based system. For missions operating beyond Earth, the spacecraft will need to be operated as a single unit. Enabling command and control capabilities within the flight element of the distributed mission will allow control of an otherwise impractical number of small spacecraft as well as decreased operational costs for missions with fewer spacecraft.

NASA intends to expand the exploitation of small spacecraft swarms (or potentially constellations) in support of exploration and science missions. Multiple numbers of SmallSats, working in concert, offer unique capabilities and benefits to space researchers and satellite operators. For instance, some of these advantages embedded in fractionalized architectures, such as fault-tolerance and continuous repair and upgrades enabling dynamic, agile, adaptable mission plans, are better able to deal with the unplanned and unexpected. However, as the number of spacecraft grows, and destinations of interest move farther away from traditional low Earth orbit (LEO) orbits, operational challenges created by managing large numbers of agents along with significant space-to-ground communication latencies and bandwidth issues require alternative architectures that are able to make time-critical decisions and operate within the maneuvering limitations of each swarm member. Innovative technologies such as AI/ML can contribute significantly to the success of these deep space, multi-spacecraft missions by providing local control less reliant on the ground, as well as optimal use of propulsion.

Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously. These sensor-driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well as the detection and reaction to transient events for observation.

This subtopic is interested in software agents and architectures that enable relative stationkeeping, multi-spacecraft orbit determination and prediction, autonomous reactive operations, and interspacecraft timing and communications to enable the above. Proposals should address software applications and/or network applications that enable:

- Efficient information exchange between individual spacecraft.
- Minimal reliance on ground commanding.
- Efficient use of space-qualified computing architectures.
- High-precision swarm navigation and control.
- Asymmetric use of ground assets (emphasizing space side over ground side).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype

Desired Deliverables Description:

Phase I Deliverables:

1. Software architecture design, including figures of merit (FOMs) for performance.
2. Test-bed environment for software development and testing (identify requirements or develop/describe test bed).
3. Plan to continue through Phase II.
4. Phase I report.

Phase II Deliverables:

1. Software suitable for testing on test-bed environment.
2. Software description/documentation.
3. Final report, including test results.

State of the Art and Critical Gaps:

Currently, the operation of each small spacecraft is individually planned, scheduled, and commanded. Signals from each individual small spacecraft are acquired by ground stations individually. Volumes of unprocessed raw data demand high bandwidth, and this becomes even less practical for greater numbers of cooperative small spacecraft operating at farther distances. As SmallSats are deployed to the Moon, Mars, near-Earth objects (NEOs), and other distant locations, it is costly—in terms of antenna time and human labor—and impractical due to time-of-flight delays at long distance and the fast dynamics of formation flight and cooperative operations to command and control each spacecraft individually, to react to dynamic situations at very remote destinations, and to change the focus of observations, data acquisition, and sample manipulation as areas of interest are discovered at the target. Very little has been done with true swarms of SmallSats, especially in deep space or even lunar locales. Flight processors are becoming more capable, but advanced software, autonomous processes, and adaptive systems that take advantage of increased processing power for SmallSats lag behind. Intelligent, adaptive behaviors and autonomous decision making in reaction to changing conditions at the target, with minimal dependence on Earthbound operators, is needed.

Relevance / Science Traceability:

The Small Spacecraft Technology Program is very interested in developing and demonstrating this technology for a broad list of crosscutting applications within the Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD). Examples include:

- Fault-tolerant swarms composed of individual assets capable of reassigning their function to compensate for loss of an individual spacecraft.
- Spacecraft capable of decisions and tactical adaptation for acquiring, preprocessing, and transmitting scientific information (rather than raw data) at distant science or exploration destinations.

- Cooperative groups of spacecraft capable of disaggregated inspection, repair, resource resupply, and other functions autonomously and cooperatively at cislunar or more remote destinations.

Small spacecraft conducting science will need to make observations, process dynamic conditions, make decisions, and adapt their performance without manual intervention (for example, sampling the eruption of a plume at Enceladus).

Suggested use cases:

- Investigation of near-Earth asteroids (NEAs) – Orbit determination and maneuvering around an asteroid.
- Coordinated sensor operations (remote sensing, etc.) between multiple spacecraft at planetary destinations.
- Coordinated observation of distant objects (stars, planets) using multiple sensor platforms.
- Autonomous formation flying and inspection of other space assets.

References:

Achieving Science with CubeSats: Thinking Inside the Box. Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, 2016. Committee Chair: Thomas Zurbuchen. (https://doi.org/10.17226/23503)

Mission Design for Deep Space CubeSats. NASA Technical Reports, ARC-E-DAA-TN43486, October 30, 2017. (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010358.pdf)

Operating Multiple Satellites as a Single Entity: Introducing SODA. (https://digitalcommons.usu.edu/smallsat/2017/all2017/100/)

Z8.12 Modular and Batch-Producible Small Spacecraft (SBIR)

Lead Center: **ARC**

Participating Center(s): **MSFC**

Scope Title:

Modular Open Systems Architectures for Small-Spacecraft Platforms

Scope Description:

This suptopic requests advances within modular open systems architectures for small spacecraft. As the most accessible spacecraft platform logistically and financially, small spacecraft benefit from a heritage based on rapid deployment and cost-effective missions. To further the state of the art (SOA) of both of these considerations, further cost savings may be found by standardizing the system architectures that drive the subsystems for these platforms. Such a realization would enable modular, hot-swappable spacecraft subsystems to accommodate the ever-increasing need for a wider definition of what small spacecraft are capable of and utilized for.

The development of standardized, hot-swappable interfaces should be compliant with and cognizant of NASA spacecraft standards. Of particular interest are designs acquiescent to the Agency standards existing between grounding, thermal, software, and data transfer interfaces.

The adaptability introduced by an open and modular, interchangeable commercial-off-the-shelf (COTS) architecture furthers the ability to tailor current spacecraft designs for novel applications without requiring significant modifications to existing platforms. Also of interest are advances in modules that minimize complexity in spacecraft manufacturing (such as deterring geometrical modifications by virtue of manufacturing). Advances in additive manufacturing may enable critical enhancements to the performance of small-spacecraft systems by embedding otherwise impractical internal features (such as through holes and cavities for electronics integration).

Systems that are applicable to small spacecraft (CubeSats up to Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class), but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include:

- Cislunar, lunar orbiting, lunar landed, and exploration precursor.
- Low Earth orbit (LEO) “swarms” for Earth science and heliophysics.
- Disaggregated cooperative ensembles and sustained infrastructure for human exploration.

New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in open modular architectures for small spacecraft and may include technologies that:

1. Provide interchangeable hardware and software with standardized interfaces.
2. Enable spacecraft to be built up from “plug and play” components.
3. Improve the state of the art of open interfacing platforms suitable for small spacecraft, leveraging COTS wherever possible.
4. Leverage novel manufacturing-in-the-loop considerations for small-spacecraft design standardization.
5. Increase the reliability and durability of small-spacecraft hardware and software by integrating subsystem considerations directly into the design process at the architectural level.
6. Demonstrate expanded adaptivity for small spacecraft, allowing for platforms to be rapidly varied with respect to altering objectives and variable risk postures.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Promising platform architectures that enable the standardization of COTS hardware and software could be demonstrated through benchtop setups validating numerous protocols and compliance with existing NASA design standards for small spacecraft. A demonstration of ease of hot-swapping would be ideal, demonstrating how rapidly such a system could be adapted for altered requirements with new instrumentation and subsystems.

The deliverables should address improvements for ease of integration of varied hardware and software, plug-and-play integration of small-spacecraft subsystems, increased assembly speed of small spacecraft, utilization of advanced manufacturing for ease of integration, automated error assessment for targeted repairability of subsystems, reduced small-spacecraft design complexity, and reduction of small-spacecraft development cost through standardized COTS.

Phase I Deliverable:

Trade study for and demonstration of how NASA small-spacecraft standards, such as thermal, grounding, and software/data normalizations, could be implemented into hot-swappable, modular architecture.

These architectures must be cognizant of:

- NASA thermal interface standards to demonstrate necessary conductivity and respective thermal isolation.
- NASA grounding interface standards to mitigate unwanted currents through single- or multiple-point grounding framework.
- NASA software and data interfacing standards, complying with Unified S-Band (USB) or Consultative Committee for Space Data Systems (CCSDS) standards.

Phase II Deliverable:

A benchtop hardware demonstration of open and modular architectures at work, exhibiting the standards within Phase I being conserved. The components should take advantage of supply-chain-compliant, heritage-relevant COTS whenever possible.

State of the Art and Critical Gaps:

The current SOA leverages COTS and compiled standards for integrating small spacecraft into a functional system meeting varied mission requirements. A number of in-house developments within NASA have complemented progress in academia and private industry to develop the infrastructure required to expand and normalize the definition of small-spacecraft-compliant subsystems and instrumentation. An issue arises with the software and hardware architecture regulating the agreement of these subsystems with NASA standards. Commercial vendors offering plug-and-play components are often only compliant with a limited number of subsystems, and consequently there exists a need to address this with an open modular architecture to enable more rapid, compliant, and consequently cost-effective small spacecraft that meet NASA's standards. Notable standardization gaps exist within communication gaps (such as wireless systems) and interconnectivity protocols, including but not limited to sustainable (and commonly grounded) power and data transfer with respect to manufacturability considerations.

Relevance / Science Traceability:

NASA and other space agencies are exploring the application of SmallSats for deep space missions. Modular architectures would enable a hot-swap adaptivity to altering mission requirements and serve as low-cost, rapid solutions for emerging destinations as they arise. Modular components allow easier reconfiguration and late additions to any design. Small-spacecraft modularity can be analogous for larger systems as well by virtue of defining and standardizing interconnectivity of universal COTS systems, enabling new objectives to be realized with a wide variety of instrumentation with a wide scope of requirements.

References:

- NASA Common Instrument Interface Project. Hosted Payload Guide for Proposers. Document Number: HPIG0001, Version: Initial. 22 March 2018.
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Scope Title:

Batch-Producible Small Spacecraft

Scope Description:

The Batch-Producible Small Spacecraft subtopic requests proposals to address the need for industry collaboration to manufacture 30 to 100 small spacecraft for a wide variety of missions, addressing objectives ranging from heliophysics to constellation demonstrations and sensor web applications. The ability to fabricate relatively large "batches" of spacecraft will play an important role with regard to the throughput required for addressing the needs of the mission objectives listed above. As an advent in tandem with small-spacecraft swarms, batch-producible spacecraft are an increasing need as larger spacecraft are replaced with many smaller spacecraft, distributing sensing and collaboratively accomplishing objectives enabled novelly by variable topologies and network-based considerations.

Advances in batch producibility are in tandem with standardization of rapid manufacturing of small spacecraft by private industry and will likely take advantage of advances in throughput-favorable fabrication methods. The manufacturability of batch-producible small spacecraft would need to consider the required throughput of manufacturing as a factor intrinsic to the small-spacecraft design itself. These systems must still remain compliant with existing NASA small-spacecraft protocols for thermal, electrical, communications, and redundancy considerations. However, batch-producible spacecraft should leverage design methodologies that would decrease the cost and increase the compatibility of these standardized requisites by virtue of the manufacturing process itself, exhibiting design-for-standardization through the engineering process.

Such a batch-producible set of small spacecraft should leverage supply chain considerations wherever possible and should integrate commercial-off-the-shelf (COTS) components and instrumentation into the design of spacecraft architecture. The end result of rapidly manufacturable batches of spacecraft should demonstrate a significant reduction in manufacturing costs for 30 to 100 buses, with quicker turnaround times than otherwise possible over a range of NASA-relevant projects.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverable

An overview and technical description of methods for batch producibility of small spacecraft within the range of 30 to 100 buses, demonstrating the integration of COTS as part of the framework. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- A standardized high-throughput manufacturing method to enable the fabrication of small spacecraft in batches of 30 to 100 buses (within the scope of CubeSats, up to and including ESPA-class spacecraft).
- A systematic decision tree that addresses fabrication turnaround-time considerations as a factor of spacecraft complexity.
- Demonstrated cost decreases for spacecraft batches with respect to the current state of the art (SOA).
- The integration and normalization of COTS relevant for batch production of small spacecraft as a function of supply chain availability and vendor capabilities.

Phase II Deliverable

Integrating small-spacecraft standards into batch production and demonstrating an infrastructure that is batch-compliant. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- The integration of common NASA small-spacecraft standards (such as thermal, grounding, communications) directly into batch producibility.
- A method for rapid assembly of batch-produced small spacecraft that accounts for manufacturability directly into the architecture of common subsystems (such as power, communications, etc.).

State of the Art and Critical Gaps:

The current SOA of batch-produced small spacecraft relies heavily on the industry-demonstrated heritage of COTS for small-satellites. These systems have limited throughput considerations and are currently inappropriate for meeting future mission requisites pertaining to small spacecraft requiring the fabrication and integration of 30 to 100 spacecraft at a time (such as those relevant to heliophysics missions, network demonstrations, and swarm considerations).

Relevance / Science Traceability:

Partnership with industry on batch production of spacecraft will be required for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications architectures, constellations, and sensor web applications; planned heliophysics missions call for 30 to 100 spacecraft. Technology development missions would also benefit from low-cost and shorter lead-time standardized bus platforms.

References:

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- Le Moigne, Jacqueline, John Carl Adams, and Sreeja Nag. "A new taxonomy for distributed spacecraft missions." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13 (2020): 872-883.

Focus Area 22 Low Earth Orbit Platform Utilization and Microgravity Research

Lead MD: **HEOMD**

Participating MD(s): **N/A**

The Human Exploration and Operations Mission Directorate (HEOMD) provides mission critical space exploration services to both NASA customers and to other partners within the U.S. and throughout the world: operating the International Space Station (ISS); ensuring safe and reliable access to space; maintaining secure and dependable communications between platforms across the solar system; and ensuring the health and safety of astronauts. Additionally, the HEOMD is chartered with the development of the core transportation elements, key systems, and enabling technologies required for beyond-Low Earth Orbit (LEO) human exploration that will provide the foundation for the next half-century of American leadership in space exploration. In this topic area, NASA is seeking technologies that address how to improve and lower costs related to use of flight assets; maximize the utilization of the ISS for in-situ research; and utilize the ISS as a platform for in-space commercial science and technology opportunities.

NASA seeks to accomplish these objectives by achieving following goals:

- Investing in the near- and mid-term development of highly-desirable system and technologies that provide innovative ways to leverage existing ISS facilities for scientific payloads
- Increasing investments in research to prepare for extended duration missions in near Earth space and beyond
- Enabling U.S. commercial spaceflight opportunities and technology development to support the commercialization of low Earth orbit (LEO)

Through the potential projects spurred by this topic, NASA hopes to incorporate SBIR-developed technologies into current and future systems to contribute to the expansion of humanity across the solar system while providing continued cost-effective ISS operations and utilization for its customers, with a high standard of safety, reliability, and affordability.

References:

- Space Station Research &Technology: https://www.nasa.gov/mission_pages/station/research/experiments/explorer

- Center for the Advancement of Science in Space: https://www.iss-casis.org/

Low-Earth Orbit Economy: https://www.nasa.gov/leo-economy/low-earth-orbit-economy/

H8.01 Low Earth Orbit (LEO) Platform Utilization to Foster Commercial Development of Space (SBIR)

Lead Center: **JSC**

Participating Center(s): **ARC, GRC, JPL, KSC, LaRC, MSFC**

Scope Title:

Use of the International Space Station (ISS) to Foster Commercialization of LEO Space

Scope Description:

This subtopic seeks proposals that advance NASA's objective of leveraging the unique ISS capabilities (microgravity and exposure to space) to catalyze markets leading to a broad commercial demand for LEO. Of specific interest are proposals that could lead to valuable terrestrial applications and foster a scalable and sustainable demand for commercial markets in LEO. Use of the ISS will facilitate validation of these applications and enable development of the minimal viable product required to significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: in-space manufacturing, regenerative medicine, bioengineering, and advanced materials production.

Expected TRL or TRL Range at completion of the Project: 3 to 7
Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For Phase I, as a minimum, a written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware and software demonstration in orbit. Bench or lab-level demonstrations are desirable.

Desired deliverables at the end of Phase II would be engineering development units and/or software packages for NASA-sponsored testing that could be turned into proof-of-concept systems suitable for flight demonstrations.

State of the Art and Critical Gaps:

The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy.

Relevance / Science Traceability:

This subtopic is in direct support of NASA's recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development.

References:

- Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
- Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org/(link is external)
- LEO Economy: https://cms.nasa.gov/leo-economy/low-earth-orbit-economy

Focus Area 23 Digital Transformation for Aerospace

Lead MD: **STTR**

Participating MD(s): **N/A**

Digital Transformation is the strategic transformation of an organization's products, processes, and capabilities, driven and enabled by rapidly advancing and converging digital technologies, to dramatically enhance the organization's performance and efficiency. These advancing digital technologies include software, cloud computing, data management and analytics, artificial intelligence, mobile access, Internet of Things (IoT), and others. Their convergence is producing major transformations across industries - media and entertainment, retail, advertising, publishing, health care, travel, transportation, etc. Through digital transformation, organizations seek to gain or retain their competitive edge by becoming more aware of and responsive to both customer and employee interests, more agile in testing and implementing new approaches, and more innovative and prescient in pioneering the next wave of products and services.

Central to the success of digital transformation is the pervasive (and often automated) collection and use of data about everything that impacts success--the organization's infrastructure, processes, activities, competencies, products and services, customers, partners, industry, and so on. Organizations can mine this massive, complex, and often unstructured data to develop accurate insights into how to improve organizational performance and efficiency. An organization may also use this data to build models of systems in order to refine operations, or to train machine learning algorithms to automate processes, provide recommendations, or enhance customer experiences. The digital technologies listed above are essential to generate, collect, transform, mine, analyze, and utilize this data across the enterprise. NASA is undertaking a digital transformation journey to enhance mission success and impact. NASA is engaging digital transformation to:

- Accelerate innovation and knowledge growth
- Support data-informed decisions
- Achieve more complex missions
- Enable pervasive collaboration
- Enhance cost-effectiveness
- Build a digital-savvy workforce

Through this focus area, NASA is seeking to explore and develop technologies that are essential for the Agency's successful digital transformation. Specific innovations being sought in this solicitation are:

- Intelligent digital assistants that reduce the cognitive workload of NASA personnel, from scientists and engineers to operations and administrative staff to space mission crews.
- Model-based enterprise, which seeks to create digital models or twins of any aspect of NASA's enterprise, to enable decision-making with increased insight and velocity.

Details about these applications of digital transformation technologies are in the respective subtopic descriptions.

H6.04 Model-Based Systems Engineering for Distributed Development (SBIR)

Lead Center: **ARC**

Participating Center(s):

Scope Title:

Model-Based Systems Engineering for Distributed Development

Scope Description:

Systems Engineering technology is both a critical capability and a bottleneck for NASA human exploration development. NASA looks to a sustainable return to the Moon to enable future exploration of Mars, components such as Lunar Gateway and Artemis will require partnerships with a wide variety of communities. Building from the success of the international partnerships for International Space Station (ISS), space agencies from multiple governments are looking for roles on the Gateway. A particular focus has been made to include the rapidly growing commercial space industry to provide an important role in supporting a sustained presence on the Moon. All of these potential partners will have their own design capabilities and their own development processes and internal constituencies to support. Integrating and enabling disparate systems built in different locations by different owners to all work cohesively together will require a significant upgrade to the core-systems engineering capabilities.

In the last decade, Model-Based Systems Engineering (MBSE) technology has matured as evidenced by the development of Systems Modeling Language (SysML) tools and frameworks that support engineers in development efforts from requirements through hardware and software implementation. MBSE holds considerable promise for accelerating, reducing overhead labor, and improving the quality of systems development. However, a remaining bottleneck is the coordination and integration of system development across distributed organizations, such as the multiple partners developing Lunar Gateway and eventual Mars exploration. This subtopic seeks technology to fill this gap.

Areas of particular need include:

- Methodologies that support integration among tools and exchange of information between multidisciplinary artifacts using automated intelligent reasoning.
- The definition of open interface standards and tools to enable inspection of distributed models across engineering domains.
- Tools or systems that allow models to be shared across development environments and trace the resulting system model back to contributions from multiple partners while maintaining information

security [International Traffic in Arms Regulations (ITAR), Export Administration Regulations (EAR), sensitive but unclassified (SBU)] and protecting intellectual property.

- Modeling visualization environments that facilitate user interaction from multiple stakeholders perspectives with varying expertise in MBSE.
- Executable requirements specification with precise semantic links disparate development sources.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

Phase I: Prototype software to demonstrate proof of concept.

Phase II: Functional software that is ready to be tested in an operational environment by end users.

State of the Art and Critical Gaps:

For distributed development, the state of the art tends to be laboriously negotiated interface control documents and manual integration processes that are inherently slow and labor intensive. In an effort to overcome these challenges, MBSE and SysML in particular has seen significant adoption at NASA (Gateway, Resource Prospector, Europa Clipper, Space Communications and Navigation [SCaN], Space Launch System [SLS]) especially after the MBSE Pathfinder (2016/2017) and MBSE Infusion And Modernization Initiative (MIAMI, 2018/2019) studies. However, these pilot programs and a survey of NASA's use of MBSE conducted by NASA Independent Verification & Validation (IV&V) and Ames Research Center identified critical challenges and factors of concern, including:

- Sharing and version control of models and information contained in the models.
- Integration of MBSE tools with domain specific tools.
- Steep learning curve for users with limited MBSE experience.
- Testing, verification, and validation with SysML have limited use.
- No tools exist for formally specifying requirements and linking to model properties.

With programs such as Gateway and Artemis that require coordination among multiple NASA centers, international space agencies, and commercial partnerships these challenges will be amplified and should be considered when addressing the scope of this subtopic. Tool infrastructures that enable integrated support of requirements tracing, design reference points, intelligent reasoning of data, and interface constructs are generally not available except within proprietary boundaries. We need tools that support integrated development and model sharing across development environments and that support use across multiple vendors.

Relevance / Science Traceability:

This subtopic would be of relevance to all Human Exploration and Operations Mission Directorate (HEOMD) missions, but of particular interest will be Gateway and Artemis development. Those systems have already adopted the use of MBSE tools and tools sought to help reduce potential system integration bottlenecks. Over the next 3 to 5 years, there will be considerable opportunity for small business contributions to be matured and integrated into the support infrastructure as Gateway evolves from concept to development program. Longer term plans for human exploration, including a sustained lunar presence and manned Mars missions, would benefit from disruptive innovations that improve the entire project life-cycle including mission design, acquisition, development, and deployment.

References:

General references:

- NASA's assessment of the state of the art for MBSE: https://www.nasa.gov/nesc/articles/se-mbse-state-of-the-discipline
- SysML: http://www.omgsysml.org

Areas of specific interest with references:

- Ensuring information exchange of digital artifacts are transferable and up to date among multiple stakeholders.
  - Digital Engineering Information Exchange Working Group (DEIX WG)
  - CCSDS Electronic Data Sheets
- Computational tools to augment human decision making and reasoning on complex systems with large amounts of data from disparate sources
  - Augmented Intelligence for Systems Engineering challenge team (AI-SECT)
  - Chami, M., Zoghbi, C., Bruel, JM. "A First Step towards AI for MBSE: Generating a Part of SysML Models from Text Using AI", (2019).
- Web-based interfaces including CRUD (create, read, update, delete) operations and digital review sign-offs for models particularly for reviews required in NPR 7123.1 System Engineering Requirements.
  - Open-MBEE: https://openmbee.org
  - OSLC: https://open-services.net/
- Formal requirements specification and test case generation with traceability to a single source of truth.
  - ReqIF: https://www.omg.org/reqif/
  - FMI: https://fmi-standard.org
  - OpenCAESAR: https://opencaesar.github.io
  - Digital Thread for Smart Manufacturing

T11.04 Digital Assistants for Science and Engineering (STTR)

Lead Center: **LaRC**

Participating Center(s): **ARC, JPL, JSC, MSFC**

Scope Title:

Digital Assistants for Science and Engineering

Scope Description:

NASA is seeking innovative solutions that combine modern digital technologies (e.g., natural language processing, speech recognition, computer vision, machine learning, artificial intelligence, virtual reality, and augmented reality) to create digital assistants. These digital assistants can range in capability from low-level cognitive tasks (e.g., information search, information categorization and mapping, information surveys, and semantic comparisons), to expert systems, to autonomous ideation. NASA is interested in digital assistants that reduce the cognitive workload of its engineers and scientists so that they can concentrate their talents on innovation and discovery. NASA is also interested in digital assistants for operators and crew to improve safety and efficiency of facilities and vehicles. Digital assistant solutions can target tasks characterized as research, engineering, operations, data management and analysis (of science data, ground and flight test data, or simulation data), and business or administrative. Digital assistants can fall into one of two categories: productivity multipliers and new capabilities. Productivity multipliers reduce the time that the engineer, scientist, facility operator, and vehicle crew member spend on tasks defined by NASA policies, procedures, standards and handbooks, on common and best practices in science and engineering domains within the scope of NASA's missions, on standard operating procedures, on maintenance and troubleshooting, or on search and transformation of scientific and technical information. Proposals for productivity multipliers should demonstrate an in-depth understanding of NASA workflows and information needs for science, engineering, or operations. New capabilities are disruptive transformations of NASA's engineering, science, facility, or vehicle environments that enable technological advances infeasible or too costly under current paradigms. Proposals for new capabilities should show clear applicability to NASA's missions. Moreover, proposals relying on natural language processing (NLP) of scientific and technical information should demonstrate capability or define a work plan to train NLP algorithms for technical and scientific terms that are in common use within NASA or within a science and engineering discipline. Proposals targeting digital assistants for crew must be deployable to hardware meeting space, weight, and power (SWaP) constraints typical for the vehicle(s) of interest. Furthermore, digital assistants for spacecraft must execute all functions onboard and cannot rely on ground systems to function. Additionally, digital assistants should be hands free especially for activities where crew are wearing spacesuits or are using their hands such as performing maintenance tasks. Examples of potential digital assistants include but are not limited to:

- A digital assistant that uses the semantic, numeric, and graphical content of engineering artifacts (e.g., requirements, design, and verification) to automate traces among the artifacts and to assess completeness and consistency of traced content. For example, the digital agent can use semantic comparison to determine whether the full scope of a requirement may be verified based on the description(s) of the test case(s) traced from it. Similarly, the digital assistant can identify from design artifacts any functional, performance, or nonfunctional attributes of the design that do not trace back to requirements. Currently, this work is performed by project system engineers, quality assurance personnel, and major milestone review teams.
- A digital assistant that can identify current or past work related to an idea by providing a list of related government documents, academic publications, and/or popular publications. This is useful in characterizing the state of the art when proposing or reviewing an idea for government funding. Currently, engineers and scientists accomplish this by executing multiple searches using different combinations of keywords from the idea text, each on a variety of search engines and databases; then the engineers read dozens of documents and returns to establish relevance. This example looks for digital assistive technologies to reduce this workload substantially.
- A digital assistant that can highlight lessons learned, suggest reusable assets, highlight past solutions or suggest collaborators based on the content that the engineer or scientist is currently working on. This example encourages digital solutions that can parse textual and/or graphical

information from an in-progress work product and search Agency knowledge bases, project repositories, asset repositories, and other in-progress work products to identify relevantly similar information or assets. The digital assistant can then notify the engineer of the relevant information and/or its author (potential collaborator).

- A digital assistant that can recommend an action in real time to operators of a facility or the crew of a vehicle. Such a system could work from a corpus of system information such as design artifacts, operator manuals, maintenance manuals, and operating procedures to correctly identify the current state of a system given sensor data, telemetry, component outputs, or other real-time data. The digital assistant can then use the same information to autonomously recommend a remedial action to the operator when it detects a failure to warn the operator when their actions will result in a hazard or loss of a mission objective, or to suggest a course of action to the operator that will achieve a new mission objective given by the operator.
- A digital assistant that can create one or more component or system designs from a concept of operations, a set of high-level requirements, or a performance specification. Such an agent may combine reinforcement learning techniques, generative-adversarial networks, and simulations to autonomously ideate solutions.
- An expert system that uses a series of questions to generate an initial system model (e.g., using Systems Modeling Language (SysML)), plans, estimates, and other systems engineering artifacts.
- Question and answer (Q&A) bots: A digital agent that can answer commonly asked questions on "how to" for scientists and engineers (e.g., what resources (grounds facilities, labs, media services, and IT) are available; where to get site licenses for software packages; who to contact for assistance on a topic; answers for general business procedures such as procurement, travel, time and attendance, etc.).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.4 Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase I deliverable can be a detailed architecture for a digital assistant with supporting analysis or a set of individual or integrated software functions that substantiate features of the digital assistant considered key or high risk.

Phase II would conclude with a demonstration (prototype) or a deployable digital assistant with quantifiable reduction in time or cost of an activity typically performed by NASA scientists, engineers, or operators.

State of the Art and Critical Gaps:

Digitally assistive technologies currently permeate the consumer market with products like the Amazon Echo, Apple devices with Siri, Google devices with Google Assistant, and Microsoft devices with Cortana. Though Apple, Google, and Microsoft are also moving their assistive technologies into the enterprise space, these developments are largely focused on reducing information technology costs. Some cities and college campuses have also acted as early adopters of smart city or smart campus technologies that include digital assistants. However, application of these assistive technologies to engineering and science has largely been limited to university research. Moreover, most assistive technologies exercise no more cognition than a Q&A bot or executing simple commands. The emergence of improved natural language processing brings the possibility of digital assistants that can perform low-level cognitive tasks. This subtopic aims not only to bring commercially available assistive technologies to the engineering environment, but also to elevate their cognitive capabilities so that engineers and scientists can spend more time innovating and less time on low-level cognitive work that is laborious or repetitive.

Relevance / Science Traceability:

This subtopic is related to technology investments in the NASA Technology Roadmap, Technical Area 11 Modeling, Simulation, Information Technology, and Processing under sections 11.1.2.6 Cognitive Computer, 11.4.1.4 Onboard Data Capture and Triage Methodologies, and 11.4.1.5 Real-Time Data Triage and Data Reduction Methodologies. This subtopic is seeking similar improvements in computer cognition more generally applied to the activities performed by engineers and scientists and made more easily accessible through technologies like speech recognition.

References:

- CIMON "Crew Interactive Mobile Companion"
    - https://www.nasa.gov/mediacast/space-to-ground-meet-cimon-07062018
    - https://www.space.com/41041-artificial-intelligence-cimon-space-exploration.html(link is external)
- NASA TM–2016-219361 Big Data Analytics and Machine Intelligence Capability Development at NASA Langley Research Center: Strategy, Roadmap, and Progress https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170000676.pdf
- NASA/TM-2016-219358 Machine Learning Technologies and Their Applications for Science and Engineering Domains Workshop—Summary Report https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170000679.pdf
- Rohaidi, N., "How NASA Uses AI on Mars," GovInsider, https://govinsider.asia/security/tom-soderstrom-jpl-nasa-digital-assistants-curiosity-rover/(link is external), January 31, 2018
- Soderstrom, T., "A peek at artificial intelligence in action at NASA Jet Propulsion Laboratory," The Enterprisers Project, https://enterprisersproject.com/article/2019/5/artificial-intelligence-jpl-nasa(link is external), May 9, 2019

T11.05 Model-Based Enterprise (STTR)

Lead Center: **ARC**

Participating Center(s): **HQ, LaRC, MSFC, SSC**

Scope Title:

Model-Based Enterprise, Digitally interacting comprehensive frameworks and models, and Automated Decision-Making for Agency Operations

Scope Description:

Model-based enterprise targets the use of models in any function, from engineering to safety to finance to facilities and more (i.e., Model-based "Anything" or MBx), to enable high-complexity decision making embodying agile processes to achieve efficiency, accuracy, confidence, and adaptability in support of NASA's mission, programmatic development, and institutional activities.

Consider the implementation of Model-based Institutional Management, as an example, where outputs from one functional model become real-time inputs to another functional model, resulting in a digital workflow for knowledge transfer and holistic decision making; thus enabling transformative gains in engineering, institutional, and management practices. Ultimately, functional area models will be digitally integrated to form a model-based enterprise.

NASA is seeking specific innovative, transformational, model-based solutions in the area of "Digital Twin" Institutional Management of Health/Automated Decision Support of Agency Facilities that would greatly enhance operational efficiencies, the quality and robustness and trustworthiness of information, the ability to identify and analyze risks earlier, and the overall velocity and robustness of knowledge transfer and decision making across the Agency, including interactions with internal/external partners and supply chain that are made possible through overarching an MBx Digital Twin Enterprise model(s).

Health/Automated Decision Support of Agency Facilities represents an opportunity to make revolutionary changes in how our Agency conducts business by investing in nascent technologies. The Agency's newly minted Digital Transformation Office is interested in how this initiative can help reposition and accelerate the modernization of digital systems that support modern approaches to managing the Agency's aging infrastructure.

Recent initiatives in "smart city" technologies focus on condition-based/preventive maintenance, smart buildings and smart lighting, autonomous transportation and traffic management, industrial automation, etc. As we mature our understanding and make progress toward these ends at individual centers, we need to align our efforts and share lessons learned to help expedite NASA's learning curve.

Smart city technologies often rely on interconnected systems and interoperability of those systems, making it all the more important that we have a common approach and standards (e.g., around information technology (IT)/operational technology (OT) network architecture, communication protocols, and data management) to ensure interoperability of systems within and across centers. Without a cohesive approach, we risk limiting what NASA can achieve in terms of economies of scale and affordability, as well as interorganizational data integration.

The STTR vehicle offers the small business community an opportunity to have a hand in this process towards repositioning and accelerating the modernization of digital systems supporting the Agency's aging infrastructure to:

- Save energy costs due to water and electricity usage that is poorly measured and managed.
- Enable the deployment of nascent technological trends in data-driven decision making and support tools based upon statistical methods to help streamline and improve the efficiency of facility operations and maintenance activities.
- Explore recent technologies in modeling (e.g., digital twin techniques).
- Explore how we can take advantage of the proliferation of emerging technologies, use a structured measurement and verification technique in and aim to vet them to determine if

they will bring sufficient value, and broadly deploy them across the Agency if proven effective.

- Set up a "proving ground," model, in the same spirit as GSA's emerging building technologies program.
- Determine how well technologies using this model can be broadly deployed across NASA.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables—Reports identifying use cases, proposed tool views/capabilities, identification of NASA or industry leveraging and/or integration opportunities, test data from proof-of-concept studies, and designs for Phase II.

Phase II Deliverables—Delivery of models/tools/platform prototypes that demonstrate capabilities or performance over the range of NASA target areas identified in use cases. Working integrated software framework capable of direct compatibility with existing programmatic tools.

State of the Art and Critical Gaps:

Outside of NASA, industry is rapidly advancing Model-Based Systems Engineering (MBSE) tools and scaling them to larger, more complex development activities. Industry sees scaling as a natural extension of their ongoing digitization efforts. These scaling and extension efforts will result in reusable, validated libraries containing models, model fragments, patterns, contextualized data, etc. They will enable the ability to build upon, transform, and synthesize new concepts and missions, which has great attraction to both industry and government alike. Real-time collaboration and refinement of these validated libraries into either “single source” or “authoritative sources” of truth provide further appeal as usable knowledge can be pulled together much more quickly from a far wider breadth of available knowledge than was ever available before.

One example of industry applying MB/MBe/MBSE is through Digital Thread™, a communication framework that helps facilitate an integrated view and connected data flow of the product's data throughout its life cycle. In other words, it helps deliver the right information at the right time and at the right place. Creating an “identical” copy (sometimes referred to as a "digital twin") is another use, a digital replica of potential and actual physical assets, processes, people, places, systems, and devices that can be used for various purposes. These twins are used to conduct virtual cost/technical trade studies, virtual testing, virtual qualification, etc., that are made possible through an integrated model-based network. Given the rise of MBSE in industry, NASA will need to keep pace in order to continue to communicate with industry, manage and monitor supply chain activities, and continue to provide leadership in spaceflight development.

Within NASA, our organization is faced with increasingly complex problems that require better, timelier, integration, and synthesis of both models and larger sets of data, not only in the systems engineering or MBSE realm, but in the broader MB Institution, MB Mission Management, and MB Enterprise Architecture. NASA is challenged to sift through and pull out the particular pieces of information needed for specific functions, as well as to ensure requirements are traced into designs, tested, and delivered; thus, confirming that the Agency gets what it has paid for. On a broader cross-agency scale, we need to ensure that needed information is available to support critical decisions in a timely and cost-effective manner. All of these challenges are addressed through the benefits of model-based approaches. Practices such as reusability, common sources of data, and validated libraries of authoritative information become the norm, not the exception, using an integrated, model-based environment. This model-based environment will contribute to a diverse, distributed business model encompassing multicenter and government-industry partnerships as the normal way of doing business.

Relevance / Science Traceability:

MBx solutions can benefit all NASA Mission Directorates and functional organizations. NASA activities could be dramatically more efficient and lower risk through MBx support of more automated creation, execution, and completion verification of important agreements, such as international, supply chain, or data use.

References:

1. https://www.sae.org/standards/content/as9100/

2. https://www.nasa.gov/offices/FRED

3. https://www.omg.org/

4. https://OpenMBEE.org

5. https://sercuarc.org/project/?id=64&project=Formal+Methods+in+Resilient+Systems+Design+using+a+Flexible+Contract+Approach

6. Keady, R.A.: Equipment Inventories for Owners and Facility Managers: Standards, Strategies, and Best Practices. Wiley Press, 2013

7. GSA's Emerging Building Technologies Program: https://www.gsa.gov/governmentwide-initiatives/sustainability/emerging-building-technologies

Focus Area 24 Dust Mitigation

Lead MD: **STMD**

Participating MD(s): **N/A**

A number of space exploration missions to planetary bodies have noted significant deleterious effects due to fine particulates. This fine dust can foul mechanisms, alter thermal properties, and obscure optical systems. It can abrade textiles and scratch surfaces. With near term goals to return to the Moon, lunar dust is of particular concern. It has the potential to negatively affect every lunar architecture system. The goal of this focus area is to develop dust mitigation technologies that can be incorporated into space exploration systems.

All planetary exploration missions require a proactive strategy to lessen the effects of dust. Dust mitigation approaches include active and passive technologies and informed engineering design. Much of the dust can be mitigated through operational constraints and architecture consideration early on in the system design lifecycle. However, passive, and active technologies and novel engineering design are also needed to form a complete dust mitigation strategy. Proposed research may focus on development of new technologies, but there is particular interest in technologies that are approaching readiness for space environment testing.

Exploration systems require dust mitigation technologies within the following capability areas:

- Optical Systems – Viewports, camera lenses, solar panels, space suit visors, mass spectrometers, other sensitive optical instruments.
- Thermal Surfaces – Thermal radiators, thermal painted surfaces, thermal connections.
- Fabrics – Space suit fabrics, soft wall habitats, mechanism covers.
- Mechanisms – Linear actuators, bearings, rotary joints, hinges, quick disconnects, valves, linkages.
- Seals and Soft Goods – Space suit interfaces, hatches, connectors, hoses; and,
- Gaseous Filtration – Atmosphere revitalization and ISRU processes.

Specific dust mitigation innovations being sought in this solicitation will be outlined in the subtopic descriptions.

Z13.01 Active and Passive Dust Mitigation Surfaces (SBIR)

Lead Center: **KSC**

Participating Center(s): **JSC, LaRC**

Scope Title:

Advanced Technologies for Active Dust Mitigation

Scope Description:

Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations, or other means to keep vital surfaces clean under space conditions. Self-cleaning surfaces that require minimal effort by astronauts are highly desired. Proposers are expected to show an in-depth understanding of the current state of the art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- Brushing: A self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power, or temperature activated, such as shape memory alloys.
- Electrostatic removal: Methods to use direct-current (DC) electric fields to remove dust from surfaces, either internal to the surface (embedded) or external using a removed high-voltage source.
- Liquid removal: A jet of liquid is applied to the surface that traps particles and removes them from the surface.
- Vacuum: Methods to remove particles from surfaces using suction of gases.
- Jets: High-velocity gas jet that blows dust particles from surfaces.
- Spinning surfaces: Surface rotates in a manner that does not allow collection of dust on it.
- Vibrational surfaces: Vibrating surface bounces the particles off of the surface.

- Electrodynamic removal: The surface contains embedded electrodes with varying high-voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be *combined* with the SOA of passive dust mitigation technologies. For example, passive dust mitigation strategies include:

- Electrostatic discharge (ESD) coatings and films: Statically dissipative coatings are less likely to accumulate charge, and hence dust, in dry environments.
- Superhydrophobic coatings: Materials with a very high contact angle can lower the adhesion of water-based contaminants, not allowing the capillary forces to take hold.
- EVA and robotic-compatible dustproof electrical, fluid, and gas connectors.
- Dustproof bearings and mechanical spacesuit connectors.
- Dust-tolerant or dust-resistant hatches.
- Docking systems, including suitport docking systems and pressurized rover and habitat docking systems.
- Lotus leaf coating: Microscopic nanostructures used to limit the van der Waals force of adhesion.
- Peel-away coating: Removable surface coatings.

Strong proposals are those that identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above. Strong proposals will also include a brief description of an infusion plan to support a potential flight demonstration after completion of the Phase II effort and how the prototype(s) developed under the Phase II effort could support that goal.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.3 Mechanical Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype

Desired Deliverables Description:

A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be a device showing the desired method working in a laboratory environment, removing and/or keeping dust from adhering to a surface. The "dust" utilized in these experiments must be an appropriate simulant with justification for the source and size distribution related to the intended application and lunar location. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed.

Phase I deliverables shall consist of a final report. Samples or prototypes can also be delivered if available.

Phase II deliverables shall consist of a final report and a prototype demonstrating surface dust mitigation.

State of the Art and Critical Gaps:

All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA, and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield (EDS), which lifts and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references.

The EDS can be incorporated into a variety of configurations addressing many of NASA's needs. However, several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- Miniaturized high-voltage three-phase power supply: The current SOA for the EDS power supply is approximately 10 × 5 × 3 cm. It is highly desired to have smaller power supplies both in size and power to drive the EDS waveform for a variety of applications.
- High dielectric breakdown strength for both glues/epoxies and the coating material: The efficiency of dust removal for the EDS is limited to amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- Flexible transparent surfaces with high current capabilities: The optically transparent version of the EDS uses indium tin oxide (ITO) as the main conductive medium for its electrode. Although the EDS is not a high-current DC device, the displacement current (I dV/dt) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.
- The EDS technology also works on fabrics. However, high-voltage flexible wires that can be used as threads are unavailable. The electrodes would need to be low profile and sufficient to withstand up to +10 kV DC before breakdown. A unique feature of the EDS on fabrics is that it needs to be a multilayer system, as most space fabrics are. One layer would have to support electrical grounding to protect the astronaut, but intermediate layers would have withstand high-voltage breakdown. The top layer would house the high-voltage wire system composed of the EDS requirements.
- Electrical attachment: Most EDS systems have issues with the electrical connections between the high-voltage power supply (HVPS) and the electrodes. Any possibility of arcing and/or sparking as a result of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key issue for attaching high-voltage wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of materials such as copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT), and graphene, to name a few. Likewise, these and other electrodes are usually resting on or embedded into a substrate such as glass, polyimide (Kapton), clothing fibers, polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), nylon, acrylic, Lucite, and other surfaces.
- Minimizing electromagnetic interference (EMI): Most EDS designs can generate electrical noise that would be disadvantageous if it were to be incorporated into a system. Methods to reduce electrical noise and EMI would be highly sought.
- Safety: With all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- Smart EDS technology: As with all dust mitigation technologies, methods to include adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary, and if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:

- Effective and scratch-resistant brushing techniques. Apollo astronauts used brushes that are largely ineffective for large surface areas and tended to scratch sensitive equipment, such as astronaut visors.
- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

Relevance / Science Traceability:

This subtopic's focus on adhesion of granular materials and technologies that address mitigation of this adhesion will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, and mechanical properties and the particle’s surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, on the Apollo missions, every mechanical seal was compromised over the course of 3 days due to the exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will improve our survival on dusty surfaces in space.

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Mackey, P. J., et al.: Electrodynamic Dust Shield for Space Applications. ASCE Earth & Space Conference, Orlando 2016.

Calle, C. I., et al.: Reduced gravity flight demonstration of the dust shield technology for optical systems. 2009 IEEE Aerospace conference. IEEE, 2009.

Kawamoto, H., and Inoue, H.: Magnetic cleaning device for lunar dust adhering to spacesuits. Journal of Aerospace Engineering 25.1 (2011): 139-142.

Vangen, S., et al.: International Space Exploration Coordination Group Assessment of Technology Gaps for Dust Mitigation for the Global Exploration Roadmap. AIAA SPACE 2016. 2016. 5423.

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Wohl, C., Belcher, M., Ghose, S., Hopkins, J., Connell, J.: Topographical modification of materials for mitigation of lunar dust adhesion. In 40th Lunar and Planetary Science Conference, The Woodlands, TX United States, 2009.

Gaier, J. R., Meador, M. A., Rogers, K. J., Sheehy, B. H.: Abrasion of Candidate Spacesuit Fabrics by Simulated Lunar Dust. National Aeronautics and Space Administration, 2009, TM-215800.

Scope Title:

Advanced Technologies for Passive Dust Mitigation

Scope Description:

This call seeks unique research proposals focused on passive approaches (i.e., those that do not require external stimuli) that will minimize the potential impact lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system). Novel materials may include high-performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous, and rough or smooth, with topography imparted by any number of approaches, including (but not limited to) lithography, embossing, roll-to-roll processing, etc. However, spacesuit garment-related technologies should refer to the Lunar Dust Mitigation Technology for Spacesuits SBIR subtopic. Surfaces can incorporate strategies for mitigation of adhesion contributions from van der Waals interactions, electrostatic forces, and/or chemically reactive or mechanical interactions. Both the material and surface modification approach must be demonstrated to be scalable and must exhibit a dramatic reduction (>90% relative to a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as lunar dust simulant. The simulant utilized in these experiments must be an appropriate material with justification for the source and size distribution related to the intended application and lunar location.

Strong proposals will seek to demonstrate the efficacy of lunar dust adhesion mitigation and the durability to retain these properties in a simulated environment. Strong proposals will also include a brief description of an infusion plan to support a potential flight demonstration after completion of the Phase II effort and how the prototype(s) developed under the Phase II effort could support that goal.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm.

At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated to remove adhered dust or prevent dust adhesion in a laboratory environment simulating some aspects of lunar environmental conditions. Durability of the material surface toward lunar dust abrasion, thermal cycling, and other environmental considerations should also be addressed. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

State of the Art and Critical Gaps:

Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants, but these relatively soft materials would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications. Triboelectrification of an insulating material, however, would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment. Refer to the Advanced Technologies for Active Dust Mitigation scope for a description of several state-of-the-art active dust mitigation technologies.

Relevance / Science Traceability:

This subtopic's focus on adhesion of granular materials and technologies that address mitigation of this adhesion will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, and mechanical properties and the particle’s surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, on the Apollo missions, every mechanical seal was compromised over the course of 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will improve our survival on dusty surfaces in space.

References:

Gaier, J., et al. Evaluation of surface modification as a lunar dust mitigation strategy for thermal control surfaces. 41st International Conference on Environmental Systems. 2011.

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Proctor, M. P., Dempsey, P. Survey of Dust Issues for Lunar Seals and the RESOLVE Project. 2006, NASA/TM-0010457.

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Gaier, J. R., Meador, M. A., Rogers, K. J., Sheehy, B. H. Abrasion of Candidate Spacesuit Fabrics by Simulated Lunar Dust. National Aeronautics and Space Administration, 2009, TM-215800.

Z13.02 Dust-Tolerant Mechanisms (SBIR)

Lead Center: **KSC**

Participating Center(s): **GRC, JSC, LaRC**

Scope Title:

Dust-Tolerant Joints

Scope Description:

A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth’s economic sphere will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar exploration have identified significant lunar dust-related problems that will challenge future mission success. Lunar dust is composed of regolith particles ranging in size from tens of nanometers to microns, and lunar dust concerns are a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the Moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that will protect from or tolerate dust intrusion in the following areas:

- Rotary joints (steering, suspension, hinges, bearings, etc.).
- Linear joints (latches, shafts, restraint systems, landing gear, etc.).
- Static joints (quick disconnects, covers, airlocks, sample tools, etc.).

Successful solutions will enable operation in a lunar environment for 10 to 100 months with limited or no maintenance.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables: Research, identify, and evaluate candidate technologies or concepts for dust-tolerant mechanisms. Simulations or laboratory-level demonstrations are desirable. Deliverables must include a report to document findings.

Phase II Deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results, and other associated documentation. Deliverable of a functional prototype is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a Technology Readiness Level (TRL) of 6 or higher.

State of the Art and Critical Gaps:

Previous solutions used in the Apollo program did not address the current need of long-term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Rotary joints.
    - Seals: Rotary joints are very common for actuation in dusty environments because of the widespread availability of rotary seals. Most of these seals, however, use elastomers that

would off-gas and become brittle in a lunar environment. Solutions are needed that employ materials or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).

  - Bearings: Regolith getting past the protective seals of rotary joint bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
  - Successful technologies will have operational lifetimes on the order of millions of cycles in a relevant lunar environment.
- Linear joints.
  - Seals: Linear joints are less common in dusty environments because of the challenge of sealing the sliding joints. Similar to rotary seals, linear joint seals are often made from elastomers and would need to be modified to operate in a lunar environment. Solutions are needed that employ materials or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of linear joint bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.
  - Successful technologies will have operational lifetimes on the order of hundreds of thousands of cycles in a relevant lunar environment.
- Static joints.
  - Operations on the lunar surface will include assembly, construction, and extravehicular activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination.
  - Successful technologies will have operational lifetimes on the order of thousands of cycles in a relevant lunar environment.

Relevance / Science Traceability:

Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.

References:

Dust Mitigation Gap Assessment Report, International Space Exploration Coordination Group (ISECG): https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Z13.03 Lunar Dust Mitigation Technology for Spacesuits (SBIR)

Lead Center: **JSC**

Participating Center(s):

Scope Title:

Garment Protection

Scope Description:

The multilayered fabric system (layup) that protects the structure of the suit from the extremes of the space environment is called the Exploration Extravehicular Mobility Unit (xEMU) environmental protection garment (EPG). The EPG, especially the environment-facing EPG shell fabric, is the suit's first line of defense against the extreme environment of the lunar surface. The EPG system must not only survive the environment but must perform per requirements and offer a level of protection to the underlying pressure garment system (PGS), portable life support system (PLSS), and informatics system.

The EPG is subjected to the following extreme environments:

1. Thermal

- Extreme hot (260 °F, 127 °C).
- Extreme cold (-280 °F, -173 °C).
- Possible exposure to permanently shadowed regions (PSRs) (-373 °F, -225 °C).

2. Lunar regolith/dust

- Highly abrasive.
    - Durability in the dust environment is a key requirement. The spacesuit must operate over prolonged exposure to and operation in the dusty regolith environment. This includes kneeling on the ground, thousands of walking cycles, and cleaning before ingressing the vehicle.
- Electrostatically charged.
    - The suit is also required to severely limit the amount of dust brought into the vehicle. Therefore, materials that are easily cleaned and/or dissipative so that dust does not adhere to the suit are sought.

3. Radiation

- The material must be able to be durable over hundreds of hours of ultraviolet (UV) radiation exposure. It is primarily only the environment-facing layer (outmost layer) of the EPG that must be resistant to degradation from the UV environment.
- To prevent damage from discharges, NASA is considering materials that support an EPG that is dissipative.

4. Enriched oxygen atmosphere of the lunar lander in the Artemis program

- The lunar lander in the Artemis program will have an atmosphere of 34±2% oxygen at a pressure of 8.2 psi (56.5 kPa). During the period the astronauts reside in the lander, they will need nonflammable materials for the outer layer of their lunar spacesuits.

5. Suit penetration protection

- Lunar secondary ejecta.
- Microgravity impact.
- Low Earth orbit (LEO) micrometeroids.

6. Plasma

- Charged environment in contact with the suit.

In addition to the extreme environments, other requirements include the following:

1. Optical properties

- The EPG shall have an average ratio of solar absorptivity to infrared emissivity (α/ε) of 0.21 (TBR).
- The EPG shall have an average solar absorption of 0.18 (TBR).

2. Mass

- Using the current fabric layers, as a component the EPG weighs on the order of 16 lb. EMU layup mass (with seven layers aluminized Mylar) = 30.84 oz/yd^2 (1.92 lb/yd^2). Orthofabric = 14.0 oz/yd^2 + 1.0 - 0.5. Aluminized Mylar = 1.12 oz/yd^2 maximum. Neoprene-coated nylon = 9.0 oz/yd^2 maximum.
- NASA has a goal of a 25% weight reduction.

3. Mobility impacts

- While it is understood that the layered materials of the EPG will increase torque in the spacesuit joint by a small amount, the EPG cannot significantly affect mobility of the suit. This requires that the individual materials and the combination of the fabric layers of the EPG allow for joint mobility, such as bending of the elbow. The fabrics themselves must be flexible, and they must be flexible during exposure to the other environmental extremes, such as extreme low temperature and vacuum.
- Within the environment listed above, the EPG must be flexible and low mass while meeting all other architectural, functional, interface, structural, and design and construction requirements imposed on the xEMU and EPG system.

Past program solutions do not meet the requirements of the Artemis program sustaining missions.

Beta fabric, the glass fiber fabric used in the Apollo spacesuit, addressed only the high flammability risk in the Apollo Lunar Module (LM) atmosphere of 100% oxygen at 4.8 psi (33 kPa). The three extravehicular activities (EVAs) in the last Apollo mission, with an average combined duration of 22 hr, resulted in damage to the outer fabric of the Apollo spacesuits, and the suits could not have endured more EVAs. The glass fiber developed for NASA was the first-ever textile microfiber (3.8-µm fiber diameter) that would not burn in a 100% oxygen atmosphere, but it did not have the mechanical properties to withstand abrasion from the lunar regolith.

In the EMU program for the Space Shuttle and International Space Station, the shell fabric was designed for LEO, a significantly different environment from the lunar South Pole. The most notable difference is the absence of abrasives in LEO—no lunar dust. Orthofabric, the three-fiber shell fabric developed for the Space Shuttle suit outer layer, was designed for the Shuttle airlock oxygen concentration of 30% at 10.2 psi (70.3 kPa) and for durability. While the Orthofabric does not support combustion in an exploration environment of 36% oxygen atmosphere at 8.2 psi, it is a woven fabric. The interstices of the weave (gaps between yarns) allow for some amount of lunar dust to penetrate, and therefore it is a poor barrier to dust. In addition, the GORE-TEX expanded polytetrafluoroethylene (ePTFE) film is easily abraded by the dust. Although GORE-TEX is a PTFE (Teflon) and inert, it can accumulate a charge.

In short, NASA is without adequate softgoods/textile solutions for the outermost layer of the EPG system that covers the xEMU suit system. NASA is looking for innovative materials solutions, likely requiring a layup of materials, to address all of the requirements listed above.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables: Delivery of technologically mature hardware, including components, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps:

Good environment-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability:

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit Project (xEMU), which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:

Note to Offeror:

No specific reference is available at this time. Under a Phase I contract, a Technical Monitor who is a subject matter expert will be assigned to the project and will be available for consultation upon award. Also, for the purpose of this solicitation, offerors may consider lunar dust simulants such as OB-1A and NU-LHT 2M for planning purposes.

Scope Title:

Venting Portable Life Support System (PLSS) Covers

Scope Description:

For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust's electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to provide the capability to mate and demate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

There are several spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. These components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. PLSS Shell Vent Ports: The PLSS shell has two ports to allow evaporated water from the Spacesuit Water Membrane Evaporator (SWME) and its backup, the Mini-Membrane Evaporator (Mini-ME), to escape. The operation of these components is dependent on a low back pressure, and each of the vent ports must have a flow-through area of at least 7 in^2 to maintain the appropriate pressure for evaporation within the PLSS shell. The vents need to accommodate a water-vapor mass flow of at least 2.6 lb/hr. The total area available for the vent ports is approximately 10 by 2.5 in. on either side.
2. PLSS Rapid Cycle Amine (RCA) System Vent Quick Disconnect (QD): The RCA system for water vapor and carbon dioxide (CO_2) removal requires vacuum access for the desorption of these constituents. This is accomplished via a QD on the PLSS backplate. For efficient desorption, the pressure in the vacuum access line needs to decrease quickly and allow the flow of 0.65 L of ullage gas to the environment. The ullage gas can be assumed to be 100% oxygen (O_2) at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 sec. After the ullage gas has dissipated, the desorbed gas consists of CO_2 and water (H_2O) with a mass flow of 325 to 360 g/min depending on the bed loading and metabolic rate of the crew member. Between 210 to 230 g/min of that flow is CO_2. The rapid decompression of the vacuum line is essential for efficient operation of the RCA, as is the following diffusion of desorbed gas away from the absorber beds, both of which must not be impeded by the specialized dust cover.
3. Suit Purge Valve (SPV) and Low-Flow Purge Valve (LFPV): The SPV is located on top of the display and control unit and is used during nitrogen purge operations in the airlock. The LFPV is used during off-nominal operations to ensure sufficient CO_2 washout in the helmet and to provide some gas flow through the pressure garment. While similar in design, both valves require different flow rates. The SPV requires 3.15 to 3.38 lb/hr and the LFPV requires 1.55 to 1.69 lb/hr of O_2 flow rate at 3.5 psi. Both valves are exposed on the outside of the spacesuit to enable crew member access and thus need specialized covers in order to tolerate large amounts of dust exposure.
4. Positive and Negative Pressure Relief Valves (PPRV and NPRV): The PPRV and NPRV are located on the hard upper torso (HUT) and exposed to vacuum and dust. The full-open flow rate requirement for the PPRV is 7.49 lb/hr of dry O_2 at 70 °F with suit internal pressure of 10.1 psia and vacuum as the external reference. The requirement for the NPRV is 60.4 lb/hr of dry air at 70 °F, with the airlock pressure at 4.15 psia and a suit pressure at 3.65 psia. Specialized covers are needed in order to tolerate dust exposure.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables: Delivery of technologically mature hardware, including components, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps:

Good dust-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability:

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:

Note to offeror:

- PLSS schematics and hardware drawings shall be provided if offeror is selected for award.
- Dust simulant characteristics shall be provided if offeror is selected for award.

For further information on lunar regolith simulant materials, offerors may access NASA Technical Publication 2006-214605, Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage: https://www.nasa.gov/sites/default/files/atoms/files/nasa_tp_2006_214605.pdf

Scope Title:

Nonventing Portable Life Support System (PLSS) Covers

Scope Description:

For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust's electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to provide the capability to mate and demate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

Two other connectors are on the exterior of the suit that do not need vacuum access and are nominally covered during an extravehicular activity (EVA). However, they need to be accessed at the conclusion of an EVA, at which point they may be covered in dust. Specialized covers for these connectors are needed to protect the connectors from dust intrusion during the EVA as well as during the removal of the covers. The connectors are as follows:

1. An 85-pin receptacle that serves as the battery charge connector and is located on the bottom corner of the PLSS.
2. The spacesuit common connector (SCC) contains high-pressure oxygen lines, water lines, an electrical connector, and mechanical mounting features. The SCC is located on the front of the

spacesuit and is integrated with the display and control unit (DCU). The connector is flat and has a surface area of approximately 2.5 by 4 in.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof of concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables: Delivery of technologically mature hardware, including components, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

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Appendices

Appendix A: Technology Readiness Level (TRL) Descriptions

The Technology Readiness Level (TRL) describes the stage of maturity in the development process from observation of basic principles through final product operation. The exit criteria for each level document that principles, concepts, applications, or performance have been satisfactorily demonstrated in the appropriate environment required for that level. A relevant environment is a subset of the operational environment that is expected to have a dominant impact on operational performance. Thus, reduced gravity may be only one of the operational environments in which the technology must be demonstrated or validated in order to advance to the next TRL.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard	A medium fidelity system/component brassboard is built and	End-to-end software elements implemented and interfaced with existing	Documented test performance demonstrating

	validation in relevant environment.	operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Definitions

Brassboard: A medium-fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Breadboard: A low-fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Engineering Unit: A high-fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

Mission Configuration: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

Operational Environment: The environment in which the final product will be operated. In the case of spaceflight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward spaceflight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Prototype Unit: The prototype unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment

Relevant Environment: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Appendix B: SBIR/STTR and the Technology Taxonomy

NASA's technology development activities expand the frontiers of knowledge and capabilities in aeronautics, science, and space, creating opportunities, markets, and products for U.S. industry and academia. Technologies that support NASA's missions may also support science and exploration missions conducted by the commercial space industry and other Government agencies. In addition, NASA technology development results in applications for the general population, including devices that improve health, medicine, transportation, public safety, and consumer goods.

The 2020 NASA Technology Taxonomy is an evolution of the technology roadmaps developed in 2015. The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is composed of 17 distinct technical-discipline-based taxonomies (TX) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area that is the title of that area. Level 2 is a list of the subareas The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments.

Details on the 2015 NASA Technology Roadmaps remain accessible here: (https://www.nasa.gov/offices/oct/home/roadmaps/index.html), and information on the new 2020 NASA Technology Taxonomy can be found at: (https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf).

The research and technology subtopics for the SBIR program are identified annually by mission directorates and center programs. The directorates identify high-priority research and technology needs for respective programs and projects. Research and technology subtopics for the STTR program are aligned with needs associated with the research interests and core competencies across NASA centers and aligned with the Technology Taxonomy. Both programs support a broad range of technologies defined by a list of subtopics that vary in content within each annual solicitation.

The table on the following pages relates the current SBIR/STTR subtopics to the Technology Taxonomy.

TA Number	TA Mapping Level 1	TA Mapping Level 2	Subtopic Number	Subtopic Title	2020 Technology Taxonomy
TA01	1.0.0 - Launch Propulsion Systems	1.3.0 - Air Breathing Propulsion Systems	A1.03	Low Emissions/Clean Power - Environmentally Responsible Propulsion	TX01 - Propulsion Systems
TA02	2.0.0 - In-Space Propulsion Technologies	2.1.0 - Chemical Propulsion	Z9.01	Small Launcher Lunar Transfer Stage Development	
		2.2.0 - Non-Chemical Propulsion	Z8.06	DragSails for Spacecraft Deorbit	
			Z10.03	Nuclear Thermal Propulsion	
			Z10.04	Manufacturing Processes Enabling Lower-Cost, In-Space Electric Propulsion Thrusters	
		2.4.0 - Supporting Technologies	T2.05	Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage	
			Z10.01	Cryogenic Fluid Management	
TA03	3.0.0 - Space Power and Energy Storage	3.1.0 - Power Generation	S3.02	Dynamic Power Conversion	TX03 - Aerospace Power and Energy Storage
			S3.01	Power Generation and Conversion	
			Z1.03	Kilowatt-Class Energy Conversion for Small Fission Reactors	
		3.2.0 - Energy Storage	S3.03	Energy Storage for Extreme Environments	
		3.3.0 - Power Management and Distribution	Z1.05	Lunar & Planetary Surface Power Management & Distribution	
			Z1.06	Radiation Tolerant High-Voltage, High-Power Electronics	
TA04	4.0.0 - Robotics, Telerobotics and Autonomous Systems	4.1.0 - Sensing & Perception	T4.01	Information Technologies for Intelligent and Adaptive Space Robotics	TX04 - Robotic Systems
			T13.01	Intelligent Sensor Systems	
		4.2.0 - Mobility	S4.04	Extreme Environments Technology	
			S3.05	Terrestrial Balloons and Planetary Aerial Vehicles	
			Z5.05	Lunar Rover Technologies for In-situ Resource Utilization and Exploration	
		4.3.0 - Manipulation	S4.02	Robotic Mobility, Manipulation and Sampling	
		4.5.0 - Autonomy	A2.02	Unmanned Aircraft Systems (UAS) Technologies	
			H10.02	Autonomous Operations Technologies for Ground and Launch Systems	
			S5.05	Fault Management Technologies	
			T4.03	Coordination and Control of Swarms of Space Vehicles	
			Z5.04	Technologies for Intra-Vehicular Activity Robotics	

		4.6.0 - Autonomous Rendezvous and Docking	Z3.05	Satellite Servicing Technologies	
		4.7.0 - RTA Systems Engineering	S4.05	Contamination Control and Planetary Protection	
TA05	5.0.0 - Communication and Navigation	5.1.0 - Optical Comm. And Navigation	H9.01	Long Range Optical Telecommunications	TX05 - Communications, Navigation, and Orbital Debris Tracking/ Characterization Systems
		5.2.0 - Radio Frequency Communications	T5.02	Electric Field Mapping and Prediction Methods within Spacecraft Enclosures	
			Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond LEO	
		5.3.0 - Internetworking	Z8.10	Wireless Communication for Avionics and Sensors for Space Applications	
		5.4.0 - Position, Navigation, and Timing	H9.03	Flight Dynamics and Navigation Technology	TX17 - Guidance, Navigation, and Control (GN&C)
			S3.04	Guidance, Navigation, and Control	
		5.5.0 - Integrated Technologies	H9.07	Cognitive Communication	TX05 - Communications, Navigation, and Orbital Debris Tracking/ Characterization Systems
		5.6.0 - Revolutionary Concepts	H9.05	Transformational Communications Technology	
			T5.04	Quantum Communications	
TA06	6.0.0 - Human Health, Life Support and Habitation Systems	6.1.0 - Environmental Control Life Support & Habitation Systems	H3.02	Microbial Monitoring for Spacecraft Cabins	TX06 - Human Health, Life Support, and Habitation Systems
			H3.03	Lunar Dust Management Technology for Spacecraft Atmospheres and Spacesuits	
			H3.01	Advancements in Carbon Dioxide Reduction: Critical Subsystems and Solid Carbon Repurposing	
			T6.06	Spacecraft Water Sustainability through Nanotechnology	
		6.2.0 - Extravehicular Activity Systems	H4.05	Liquid Cooling and Ventilation Garment Connector Upgrade and Glove Humidity Reduction	
			H4.01	Exploration Portable Life Support System Component Challenges	
		6.3.0 - Human Health and Performance	H12.01	Radioprotectors and Mitigators of Space Radiation-induced Health Risks	
			H8.01	Utilization of the International Space Station (ISS) to Foster Commercial Development of Low-Earth Orbit (LEO)	
			H12.05	Autonomous Medical Operations	
		6.5.0 - Radiation	T6.05	Testing of COTS Systems in Space Radiation Environments	
TA07		7.1.0 - In-Situ Resource Utilization	Z12.01	Extraction of Oxygen from Lunar Regolith	TX07 - Exploration Destination Systems

	7.0.0 - Human Exploration Destination Systems	7.2.0 - Sustainability & Supportability	T6.07	Space Exploration Plant Growth	
		7.3.0 - Advanced Human Mobility Systems	Z13.02	Dust Tolerant Mechanisms	
		7.6.0 - Cross-Cutting Systems	Z13.01	Active and Passive Dust Mitigation Surfaces	
TA08	8.0.0 - Science Instruments, Observatories & Sensor Systems	8.1.0 - Science Instruments	S1.10	Atomic Interferometry	TX08 - Sensors and Instruments
			S1.11	In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection	
			S1.12	In Situ Instruments/Technologies for Heliophysics	
			S1.07	In Situ Instruments/Technologies for Lunar and Planetary Science	
			S1.06	Particles and Fields Sensors & Instrument Enabling Technologies	
			S2.02	Precision Deployable Optical Structures and Metrology	
			S2.01	Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets	
			S1.04	Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter	
			S1.02	Technologies for Active Microwave Remote Sensing	
			S1.03	Technologies for Passive Microwave Remote Sensing	
			S2.05	Technology for the Precision Radial Velocity Measurement Technique	
			S2.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics	
			T8.06	Quantum Sensing and Measurement	
			Z11.01	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis	
			Z8.08	Technologies to Enable Cost & Schedule Reductions for Ultra-Stable Normal Incidence Mirrors for CubeSats	
		8.2.0 - Observations	S2.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope	
		8.3.0 - Sensor Systems	S1.09	Cryogenic Systems for Sensors and Detectors	
			S1.05	Detector Technologies for UV, X-Ray, Gamma-Ray Instruments	

			S1.01	Lidar Remote Sensing Technologies	
			S1.08	Suborbital Instruments and Sensor Systems for Earth Science Measurements	
			T8.04	Metamaterials and Metasurfaces Technology for Remote Sensing Applications	
TA09	9.0.0 - Entry, Descent and Landing Systems	9.1.0 - Aeroassist & Entry	Z7.05	3D Weaving Diagnostics	TX09 - Entry, Descent, and Landing
			Z7.06	Diagnostic Tools for High Enthalpy and High Temperature Materials Testing and Analysis	
			Z7.01	Entry Descent & Landing Sensors for Environment Characterization, Vehicle Performance, and Guidance, Navigation and Control	
		9.4.0 - Vehicle Systems Technology	Z7.03	Deployable Aerodynamic Decelerator Technology	
			Z7.04	Lander Systems Technologies	
TA11	11.0.0 - Modeling, Simulation, Information Technology and Processing	11.1.0 - Computing	H6.22	Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition	TX11 - Software, Modeling, Simulation, and Information Processing
			S5.03	Accelerating NASA Science and Engineering through the Application of Artificial Intelligence	
			S3.08	Command, Data Handling, and Electronics	
			S5.01	Technologies for Large-Scale Numerical Simulation	
			Z6.01	High Performance Space Computing Technology	
		11.2.0 - Modeling	H6.04	Model Based Systems Engineering for Distributed Development	
			S5.04	Integrated Science Mission Modeling	
			S5.06	Space Weather R2O/O2R Technology Development	
		11.4.0 - Information Processing	T4.04	Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway	
			T11.04	Digital Assistants for Science and Engineering	
			T11.03	Distributed Digital Ledger for Aerospace Applications	
TA12	12.0.0 - Materials, Structures, Mechanical Systems and Manufacturing	12.1.0 - Materials	T12.06	Extensible Modeling of Additive Manufacturing Processes	TX12 - Materials, Structures, Mechanical Systems, and Manufacturing
			T12.01	Thin-Ply Composite Technology and Applications	
		12.2.0 - Structures	H5.02	Hot Structure Technology for Aerospace Vehicles	

			H5.01	Lunar Surface Solar Array Structures	
			Z3.04	Autonomous Modular Assembly Technology for OSAM	
		12.4.0 - Manufacturing	T2.04	Advanced In-Space Propulsion	
			T12.05	Deposition and Curing of Thermoset Resin Mixtures for Thermal Protection	
			Z3.03	Development of Material Joining Technologies and Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing and Construction	
			Z4.04	Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes	
TA13	13.0.0 - Ground and Launch Systems Processing	13.1.0 - Technologies to Optimize the Operational Life-Cycle	H10.01	Advanced Propulsion Systems Ground Test Technology	TX13 - Ground, Test, and Surface Systems
TA14	14.0.0 - Thermal Management Systems	14.2.0 - Thermal Control Systems	S3.06	Thermal Control Systems	TX14 - Thermal Management Systems
			Z2.01	Spacecraft Thermal Management	
TA15	15.0.0 - Aeronautics	15.1.0 - Safe, Efficient Growth in Global Aviation	A3.01	Advanced Air Traffic Management System Concepts	TX16 - Air Traffic Management and Range Tracking Systems
			A3.02	Increasing Autonomy in the National Airspace System (NAS)	
			A3.04	Non-Traditional Airspace Operations	
			A1.02	Quiet Performance - Aircraft Propulsion Noise	TA15 - Flight Vehicle Systems
			A1.09	Inflight Icing Hazard Mitigation Technology	
		15.2.0 - Innovation in Commercial Supersonic Aircraft	A1.01	Aeroelasticity and Aeroservoelastic Control	
		15.3.0 - Ultra-Efficient Commercial Vehicles	A1.05	Computational Tools and Methods	
			A1.06	Vertical Lift Technology and Urban Air Mobility	
			A1.08	Aeronautics Ground Test and Measurement Technologies	
			A1.07	Propulsion Efficiency - Turbomachinery Technology for High Power Density Turbine-Engines	
			T15.04	Integration of Airframe with Distributed Electric Propulsion (DEP) System	
		15.4.0 - Transition to Low-Carbon Propulsion	A1.04	Electrified Aircraft Propulsion	
			T15.03	Electrified Aircraft Propulsion Energy Storage	

		15.5.0 - Real-Time System-Wide Safety Assurance	A3.03	Future Aviation Systems Safety	TX16 - Air Traffic Management and Range Tracking Systems
		15.7.0 - Other	A2.01	Flight Test and Measurement Technologies	TX15 - Flight Vehicle Systems
			A1.10	Hypersonic/High Speed Technology - Seals and Thermal Barriers	

Appendix C: Potential Transition and Infusion Opportunities

Below is a listing of all the subtopics by focus area and a designation if there are potential transition and infusion opportunities that exist within each subtopic. Proposers should think of this as a guide while understanding that NASA is not placing any priority on subtopics or awards that fall under these specific opportunities. Proposers that submit a proposal under a subtopic that is aligned with these opportunities do not increase their chance for an award.

Subtopic #	Subtopic Title	Moon to Mars	CLPS	Flight Opps	ISS
FA1 In-Space Propulsion Technologies (Lead: STMD)					
Z10.01	Cryogenic Fluid Management	Yes			Yes
Z10.03	Space Nuclear Propulsion		Yes	Yes	
Z10.04	Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters		Yes	Yes	
FA2 Power Energy and Storage (Lead: STMD, Participating: SMD)					
S3.01	Power Generation and Conversion				
S3.02	Dynamic Power Conversion				
S3.03	Energy Storage for Extreme Environments				
Z1.05	Lunar and Planetary Surface Power Management and Distribution	Yes			
Z1.06	Radiation-Tolerant High-Voltage, High-Power Electronics	Yes			
Z1.07	Dynamic Energy Conversion for Space Nuclear Power and Propulsion				
FA3 Autonomous Systems for Space Exploration (Lead: HEOMD, Participating: SMD, STTR)					
H6.22	Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition	Yes			Yes
H6.23	Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration	Yes			Yes
S5.05	Fault Management Technologies				
T10.03	Coordination and Control of Swarms of Space Vehicles	Yes	Yes	Yes	Yes
T10.05	Integrated Data Uncertainty Management & Representation for Trustworthy and Trusted Autonomy in Space	Yes	Yes	Yes	Yes
T10.04	Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway	Yes	Yes		Yes
FA4 Robotic Systems for Space Exploration (Lead: STMD, Participating: SMD, STTR)					
S4.02	Robotic Mobility, Manipulation and Sampling				
Z5.04	Technologies for Intravehicular Activity Robotics	Yes			Yes

Subtopic #	Subtopic Title	Moon to Mars	CLPS	Flight Opps	ISS
T7.04	Surface Construction	Yes	Yes	Yes	
FA5 Communications and Navigation (Lead: HEOMD, Participating: SMD, STTR)					
H9.01	Long Range Optical Telecommunications	Yes			
H9.03	Flight Dynamics and Navigation Technologies			Yes	
H9.05	Transformational Communications Technology	Yes			
H9.07	Cognitive Communication	Yes			Yes
S3.04	Guidance, Navigation, and Control				Yes
T5.04	Quantum Communications	Yes	Yes	Yes	Yes
FA6 Life Support and Habitation Systems (Lead: HEOMD, Participating: STTR)					
H3.02	Microbial Monitoring for Spacecraft Cabins	Yes			Yes
H3.05	Additive Manufacturing for Adsorbent Bed Fabrication	Yes			Yes
H3.07	Flame Retardant Textiles for Intra-Vehicular Activities (IVA)	Yes			Yes
H4.05	Advancements in Water and Air Bladder Assemblies and Technology	Yes			Yes
T6.06	Enabling Spacecraft Water Monitoring through Nanotechnology	Yes		Yes	Yes
T6.07	Space Exploration Plant Growth	Yes	Yes	Yes	Yes
FA7 Human Research and Health Maintenance (Lead: HEOMD)					
H12.01	Radioprotectors and Mitigators of Space Radiation-induced Health Risks	Yes			Yes
H12.03	Portable Spatial Disorientation Simulator - Trainer	Yes			
FA8 In-Situ Resource Utilization (Lead: STMD, Participating: STTR)					
Z12.01	Extraction of Oxygen and Water from Lunar Regolith	Yes			
T14.01	Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage	Yes	Yes	Yes	Yes
FA9 Sensors, Detectors and Instruments (Lead: SMD, Participating: STTR)					
S1.01	Lidar Remote Sensing Technologies				
S1.02	Technologies for Active Microwave Remote Sensing				
S1.03	Technologies for Passive Microwave Remote Sensing				
S1.04	Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter				
S1.05	Detector Technologies for UV, X-Ray, Gamma-Ray Instruments				
S1.06	Particles and Fields Sensors & Instrument Enabling Technologies			Yes	
S1.07	In Situ Instruments/Technologies for Lunar and Planetary Science	Yes			
S1.08	Suborbital Instruments and Sensor Systems for Earth Science Measurements				
S1.09	Cryogenic Systems for Sensors and Detectors				
S1.10	Atomic quantum sensor and clocks				
S1.11	In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection				
S1.12	Remote Sensing Instrument Technologies for Heliophysics			Yes	

Subtopic #	Subtopic Title	Moon to Mars	CLPS	Flight Opps	ISS
T8.07	Photonic Integrated Circuits	Yes	Yes	Yes	Yes
T8.06	Quantum Sensing and Measurement	Yes	Yes	Yes	
FA10 Advanced Telescope Technologies (Lead: SMD)					
S2.01	Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets				
S2.02	Precision Deployable Optical Structures and Metrology				
S2.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope				
S2.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics				
S2.05	Technology for the Precision Radial Velocity Measurement Technique				
FA11 Spacecraft and Platform Subsystems (Lead: SMD, Participating: STMD)					
S3.05	Terrestrial Balloons and Planetary Aerial Vehicles				
S3.08	Command, Data Handling, and Electronics				
S4.03	Spacecraft Technology for Sample Return Missions				
S4.04	Extreme Environments Technology				
S4.05	Contamination Control and Planetary Protection				
Z2.02	High-Performance Space Computing Technology				
FA12 Entry, Descent, and Landing Systems (Lead: STMD, Participating: HEOMD, STTR)					
H5.02	Hot Structure Technology for Aerospace Vehicles			Yes	
Z7.01	Entry, Descent, and Landing Flight Sensors and Instrumentation	Yes		Yes	
Z7.03	Entry and Descent System Technologies			Yes	
Z7.04	Landing Systems Technologies	Yes	Yes	Yes	
Z7.06	Entry, Descent, and Landing (EDL) Terrestrial Testing Technologies				
T9.02	Rapid development of advanced high-speed aerosciences simulation capability	Yes			
FA13 Information Technologies for Science Data (Lead: SMD)					
S5.01	Technologies for Large-Scale Numerical Simulation				
S5.03	Accelerating NASA Science and Engineering through the Application of Artificial Intelligence				
S5.04	Integrated Science Mission Modeling				
S5.06	Space Weather R2O/O2R Technology Development				
FA14 On-orbit Servicing, Assembly, and Manufacturing (OSAM) (Lead: STMD, STTR)					
Z3.03	Development of Advanced Joining, Large-Scale Additive Manufacturing Processes, and Metal Recycling Technologies for On-Orbit Manufacturing				Yes
Z3.04	Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly, and Manufacturing (OSAM)			Yes	
Z3.05	Satellite Servicing Technologies			Yes	
T12.06	Extensible Modeling of Additive Manufacturing Processes	Yes			
FA15 Materials, Materials Research, Structures, and Assembly (Lead: STMD, Participating: STMD, STTR					

Subtopic #	Subtopic Title	Moon to Mars	CLPS	Flight Opps	ISS
H5.01	Lunar Surface Solar Array Structures				
Z4.04	Real-Time Defect Detection, Identification, and Correction in Wire-Feed and Fused-Filament Additive Manufacturing				
Z4.05	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis				
Z4.06	Manufacturability Assessment as a Design Constraint for Advanced Tailorable Composites				
T12.05	Use of Additive Manufacturing for Thermal Protection Systems	Yes		Yes	
T12.07	Design Tools for Advanced Tailorable Composites	Yes			
FA16 Ground & Launch Processing (Lead: HEOMD, Participatng: STTR)					
H10.01	Advanced Propulsion Systems Ground Test Technology	Yes			
H10.02	Autonomous Operations Technologies for Ground and Launch Systems	Yes			
T13.01	Intelligent Sensor Systems	Yes	Yes	Yes	Yes
FA17 Thermal Management Systems (Lead: STMD, Participating: SMD)					
S3.06	Thermal Control Systems	Yes	Yes	Yes	
Z2.01	Spacecraft Thermal Management	Yes			
FA18 Air Vehicle Technology (Lead: ARMD, Participating: STTR)					
A1.01	Aerodynamic and Structural Efficiency - Integration of Flight Control with Aircraft Multidisciplinary Design Optimization				
A1.02	Quiet Performance - Airframe Noise Reduction				
A1.03	Propulsion Efficiency - Propulsion Materials and Structures				
A1.04	Electrified Aircraft Propulsion				
A1.05	Computational Tools and Methods				
A1.06	Vertical Lift Technology and Urban Air Mobility				
A1.07	Electric Power Generation Via Thermionic Conversion for Hypersonic Applications				
A1.08	Aeronautics Ground Test and Measurement Technologies				
A1.09	Vehicle Sensor Systems to Enable Situational Awareness				
T15.04	Full-Scale (2+ Passenger) Electric Vertical Takeoff and Landing (eVTOL) Scaling, Performance, Aerodynamics, and Acoustics Investigations			Yes	
FA19 Integrated Flight Systems (Lead: ARMD)					
A2.01	Flight Test and Measurement Technologies				
A2.02	Enabling Aircraft Autonomy				
A2.03	Advanced Air Mobility (AAM) Integration				
FA20 Airspace Operations and Safety (Lead: ARMD)					
A3.01	Advanced Air Traffic Management System Concepts				
A3.02	Increasing Autonomy in the National Airspace System (NAS)				
A3.03	Future Aviation Systems Safety				
A3.04	Nontraditional Airspace Operations				
FA21 Small Spacecraft Technologies (Lead: STMD, Participating, STTR)					

Subtopic #	Subtopic Title	Moon to Mars	CLPS	Flight Opps	ISS
Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)	Yes	Yes	Yes	
Z8.08	Technologies to Enable Cost and Schedule Reductions for Ultrastable Normal Incidence Optical System for CubeSats		Yes	Yes	
Z8.09	Small Spacecraft Transfer Stage Development		Yes	Yes	
Z8.10	Wireless Communication for Avionics and Sensors for Space Applications	Yes	Yes	Yes	Yes
Z8.11	Artificial Intelligence (AI)/Machine Learning (ML) for Small Spacecraft Swarm Trajectory Control	Yes			
Z8.12	Modular and Batch-Producible Small Spacecraft			Yes	
T5.05	Solar and Electric Sail Embedded Technologies for Communications, Control, or Ancillary Functions				
FA22 Low Earth Orbit Platform Utilization and Microgravity Research (Lead: HEOMD)					
H8.01	Low Earth Orbit (LEO) Platform Utilization to Foster Commercial Development of Space				Yes
FA23 Digital Transformation (Lead: STTR, Participating: HEOMD)					
H6.04	Model-Based Systems Engineering for Distributed Development	Yes			Yes
T11.04	Digital Assistants for Science and Engineering	Yes		Yes	Yes
T11.05	Model-Based Enterprise				
FA24 Dust Mitigation (Lead: STMD)					
Z13.01	Active and Passive Dust Mitigation Surfaces	Yes	Yes		
Z13.02	Dust-Tolerant Mechanisms	Yes	Yes		
Z13.03	Lunar Dust Mitigation Technology for Spacesuits	Yes			