

NASA SBIR Subtopic:

S2.03

Advanced Optical Systems and Fabrication
Testing/Control Technologies for EUV/Optical and
IR Telescopes

H. Philip Stahl, Ph.D.

Sub-Topic Manager

NASA 'Optics' Award Statistics Total

	Phase 1	Phase 2
2005	21% (8/38)	71% (5/7)
2006	28% (8/29)	63% (5/8)
2007	36% (4/11)	50% (2/4)
2008	59% (10/17)	50% (4/8)
2009	56% (9/16)	50% (4/8)
2010	50% (11/22)	11% (1/9)
2011	28% (7/25)	20% (1/5)
2012	28% (8/29)	50% (4/7)
2014	54% (7/13)	33% (2/6)
2015	48% (10/21)	20% (3/8)
2016	29% (7/24)	33% (2/6)
2017	39% (11/28)	
Total	37% (100/273)	43% (33/76)

S2.03 “Advanced Optical Systems for UVO & IR”

	Phase 1	Phase 2
2015	50% (5/10)	20% (1/5)
2016	42% (3/7)	33% (1/3)
2017	70% (7/10)	
Total	56% (15/27)	25% (2/8)

S2.04 “X-Ray Mirrors, Coatings and Free-Form”

	Phase 1	Phase 2
2015	45% (5/11)	66% (2/3)
2016	24% (4/17)	33% (1/3)
2017	22% (4/18)	
Total	28% (13/46)	50% (3/6)

2016 SBIR S2.03 'Normal Incidence'

Phase I 7 Submitted 3 Funded

Additive Manufacturing of Telescope Mirrors, Arctic Slope Technical Services

Phase Reconfigurable Nulling Interferometer, Boulder Nonlinear Systems

Ultra-Stable Zero-CTE HoneySiC and H2CMN Mirror Support Structures,
Fantom Materials

Phase II 3 Submitted 1 Funded

Ultra-Stable Zero-CTE HoneySiC and H2CMN Mirror Support Structures,
Fantom Materials

NASA SBIR/STTR Technologies

S2.03-8014 - Ultra-Stable Zero-CTE HoneySiC and H2CMN Mirror Support Structures



PI: William Fischer

Fantom Materials, Inc. - Lihue, HI

Identification and Significance of Innovation

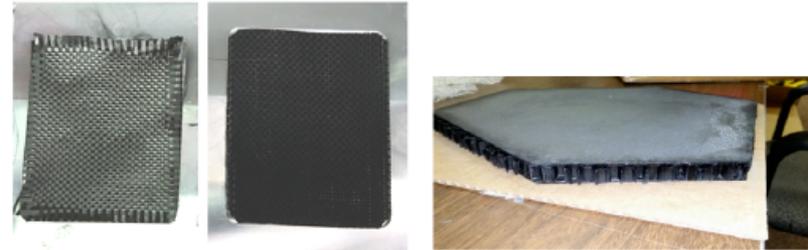
NASA MSFC/GSFC/JPL are interested in Ultra-Stable Mirror Support Structures for Exoplanet Missions. Fantom Materials proposes HoneySiC for ultra-stable mirror support structures traceable to Cosmic Origins for UVOIR/Exo/FIR telescopes, including whiffle plates, delta frames, strongbacks, tubular structures or other optical structures. HoneySiC's inherent features make it an ideal deployment hinge and latching material: 1) It's an additively manufactured Ceramic Matrix Composite (CMC) with no Coefficient of Moisture Expansion. Individually molded parts become a monolithic construct so it's possible to manufacture an entire telescope using HoneySiC, 2) It's extremely light weight; HoneySiC panels have ~1/5 density of beryllium, 3) It's extremely dimensionally stable due to a zero-CTE across a temp range of -200C to RT. The thermal conductivity can be supercharged by adding carbon nanotubes. Project objective: Collaborate with NASA MSFC/GSFC/JPL/NG to demonstrate ultra-stable HoneySiC mirror mounting materials to potentially replace all Be and M55J-954-6 parts.

Estimated TRL at beginning and end of contract: (Begin: 5 End: 6)

Technical Objectives and Work Plan

Objectives: 1) Collaborate with NASA MSFC/GSFC/JPL/NGAS to design a prototype whiffle plate, delta plate, strongback, or other optical structure using HoneySiC and/or H2CMN to support advanced telescopes, 2) Evaluate additional HoneySiC and H2CMN material properties, 3) Manufacture the prototype, 4) Plan for Phase III transition.

Task 1) Kick-Off Telecon. Task 2) Monthly Technical Meetings to establish action items and provide technical progress. Task 3) H2CMN Validation to improve H2CMN to mechanical performance levels expected in Phase I. Task 4) HoneySiC™ HCMC/H2CMN Prototype design to be defined by NASA, Fantom, NGAS and UH. Task 5) Prototype Design & Engineering – Design and performance requirements to be defined that are applicable to produce a HoneySiC™ HCMC/H2CMN component. Task 6) Scaled prototype joint specimens will replicate joint in design, application and use of fasteners/hardware for testing. Task 7) At least one joint specimen design will be tested for strength. Task 8) HoneySiC™ HCMC/H2CMN prototype to be produced based on results of Tasks 5 & 7. Task 9) Mechanical testing of prototype to be performed at UH. Task 10) Fantom will apply for a Phase II-E to continue characterization of HoneySiC™ HCMC and H2CMN, develop 3D printing processes for HoneySiC™, and design and fabricate a meter-class telescope front structure. Task 11) Phase III Plan & Final Report.



As-received T300 carbon fabric (pristine) (left).
T300 carbon fiber with CNT nanoforest grown on it (CNT) (right).

Prototype concept for HoneySiC Whiffle Plate

NASA Applications

Present state-of-the-art materials require an 8 order-of-magnitude improvement in stability. This project is the point of departure for ultra-stable mirror support structures made using 1st generation zero CTE HoneySiC (ca. 2014), and 2nd generation H2CMN (ca. 2016). Fantom Materials' promising CMCs will replace beryllium and status quo, moisture-absorbing, organic matrix composites used today. 1st and 2nd gen HoneySiC will provide low areal cost, low areal density, and ultra-stability required for future EUV, UV/O and Far-IR missions.

Non-NASA Applications

Fantom's HoneySiC has use in complex telescopes for Astronomy, Imaging and Remote Sensing applications, including surveillance, mapping and reconnaissance missions for police, paramilitary units and fire fighters, power/pipeline/NOAA monitoring, search and rescue, disaster relief and communications. The dual-use nature of complex telescopes will bring affordability to national defense missions.

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NON-PROPRIETARY DATA

2016 SBIR S2.04 'X-Ray & Freeform'

Phase I 17 Submitted 4 Funded

Low Coherence Wavefront Probe for Nanometer Level Free-Form Metrology,
Apre Instruments

UltraForm Finisher Optical Mandrel Fabrication, OptiPro Systems

**Zero Net-Stress, Non-Distorting Iridium Coatings for Thin-Shell X-ray
Telescope Mirrors,** Reflective X-ray Optics

Advanced X-ray Telescope Material System, Peregrine Falcon Corp

Phase II 3 Submitted 1 Funded

Low Coherence Wavefront Probe for Nanometer Level Free-Form Metrology,
Apre Instruments

PI: Artur Olszak

Apré Instruments, LLC - Tucson, AZ

Identification and Significance of Innovation

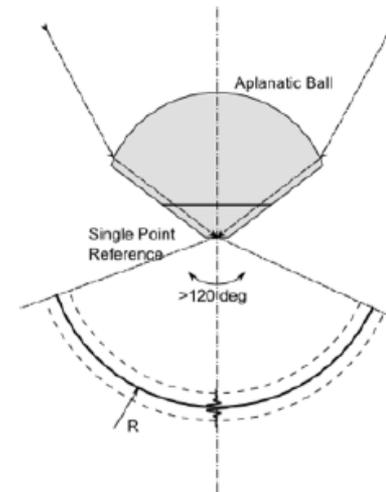
Apré Instruments proposes to bring to preproduction a novel low-coherence wavefront PROBE for the measurement of free-form optical surfaces with nanometer level PROBE measurement uncertainty over slopes up to 60 degrees. A simple 3 axis metrology frame architecture can be utilized, enabling nanometer level free-form measurement uncertainty in a surface profiler. Future NASA missions benefit from smaller, lighter optical systems with larger fields of view with better resolution and free-form optics promise these advantages. Today's metrology tools, profilers and interferometers lack the accuracy and basic capability required. This innovation will lead to readily available free-form optics.

Estimated TRL at beginning and end of contract: (Begin: 4 End: 6)

Technical Objectives and Work Plan

This Phase II moves the PROBE TRL 4 to TRL 6, which in this case is ready for market introduction. The technical objectives are:

1. Design and manufacture a production prototype of the Spectrally Modulated Source based on a digital mirror device (DMD) and package it for production
2. Design and manufacture a production prototype low coherence wavefront probe that measures slopes up to 60 degrees with measurement uncertainties of <2 nm
3. Design and manufacture a production prototype detection system with measurement rates of 10kHz and sensitivities <1 nm
4. Integrate the source/probe/detector system into a CMM/profiler and demonstrate profiling capabilities of free-form surfaces
5. Measure the measurement uncertainties of the probe and the profiling system laying the groundwork for a commercial system and a system to meet NASA's 2 nm RMS uncertainty target



NASA Applications

NASA missions with low-cost science and small-sized payloads constrained by traditional spherical form optics will benefit from this probe/metrology technology. Free-form optics provide better imaging qualities in wider field of view with higher resolution, smaller size, fewer components, and lighter weight to meet the mission requirements of small satellites such as:

- CubeSat
- SmallSat
- Visible Nulling Coronagraph (VNC)

Non-NASA Applications

Free-form optics promise to improve the performance of Imaging and illumination systems. Such as Cell phones, tablets, computer and remote cameras, surveillance cameras for research and defense, and also for illumination system from car headlamps to semiconductor process equipment. These promises are not met today due to the lack of high accuracy metrology. This PROBE promises to bridge that gap.

Firm Contacts

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2017 SBIR S2.03 ‘Normal Incidence’

Phase I

10 Submitted

7 Funded

Arctic Slope Technical Services, Additively Manufactured, Thermally Stable Telescope Mirror Substrates

CFE Services, Lightweight, Stable Optical Benches in Silicon Carbide and Beryllium

Dallas Optical Systems, Additive Manufactured Very Light Weight Diamond Turned Aspheric Mirror

Goodman Technologies, 3D Printed Silicon Carbide Scalable to Meter-Class Segments for Far-Infrared Surveyor

Mentis Sciences, Silica-Silica Mirror Substrate Fabrication Technology

Soter Technology, Rapid Fabrication of High Stability Optical Mirror Blanks

Peregrine Falcon Corp, Advanced Athermal Telescopes

Phase II

TBD Submitted

TBD Funded

PI: Tony Harrison

Arctic Slope Technical Services, Inc. - Huntsville, AL

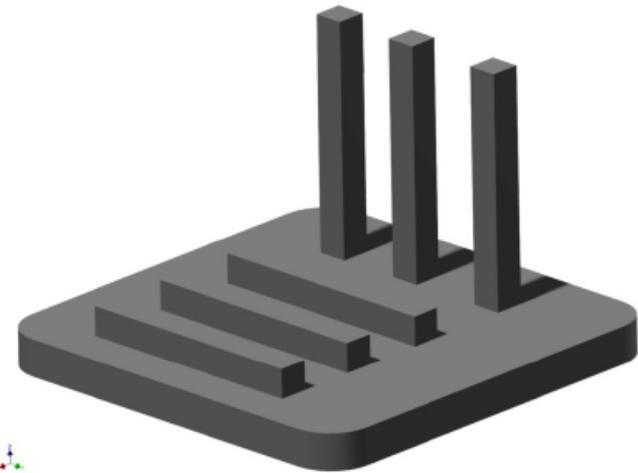
Identification and Significance of Innovation

To Demonstrate the Feasibility of:
Establishing selective laser melting (SLM) processing parameters for AlSi10Mg
Establishing a process to bind AlSi10Mg over SiC particulates to create a spheroid SiC powder for SLM processing
Fabricating a 20% and 45% by weight silicon carbide (SiC) reinforced AlSi10Mg matrix composite (SiC-AMC) using SLM processing
For all three SLM processing parameters establish SLM process having practically no voids or porosity in the material and verifying CTE is reduced as SiC-AMC ratio is increased from 20% to 45%

Estimated TRL at beginning and end of contract: (Begin: 4 End: 5)

Technical Objectives and Work Plan

Optimize the AlSi10Mg SLM process parameters: Optimize the SLM processing to achieve maximum material density of the AlSi10Mg metal using our Concept Laser MLab.
Incorporate 20% SiC into AlSi10Mg Powderbed base: Acquire SiC-AMC spheroid powder from Plasma Processes, Inc at 45% SiC by weight, add appropriate AlSi10Mg powder to achieve 20% SiC-AMC by weight, and then optimize the SLM processing to achieve maximum material density of the SiC-AMC metal using our Concept Laser MLab. Obtain CTE test results from Thermtest of ASTS SLM produced samples
Incorporate 45% SiC into AlSi10Mg Powderbed base: Acquire SiC-AMC spheroid powder from Plasma Processes, Inc at 45% SiC by weight and then optimize the SLM processing to achieve maximum material density of the SiC-AMC metal using our Concept Laser MLab. Obtain CTE test results from Thermtest of ASTS SLM produced samples
Analyze CTE Data and Produce Final Report: ASTS shall prepare the Phase I final report, which will include the SLM process development data that guided process-setting decisions



NASA Applications

- Relatively small aperture mirrors that are launched on NASA sounding rockets or on balloon missions.
- NASA's Medium Class Explorers (MIDEX) TESS mission
- NASA's Gondola for High Altitude Planetary Science (GHAPS)
- Structural casing/jacket over a copper lined combustion device to support a MARS Ascent Vehicle, 2nd stage engine, or reaction control system using green propellants

Non-NASA Applications

A near zero coefficient of thermal expansion (CTE) or targeted CTE SiC-AMC material can be applied to a structural casing/jacket over a copper lined combustion device for DOD rocket and missiles engines. Unmanned aerial vehicles (UAV) mirrors supports applications in the agriculture industry, in the transportation industry, and in DOD land based military industry.

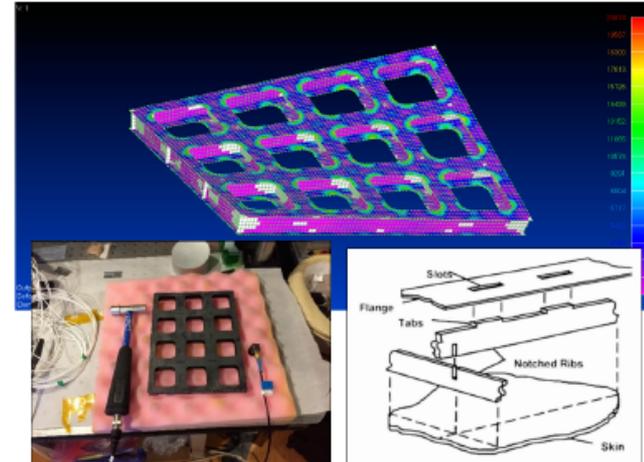
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PI: Brian Catanzaro
CFE Services - San Diego, CA

Identification and Significance of Innovation

As the world community, has become aware that exoplanets exist in abundance, it has inspired new observatories in search of Earth-like worlds. Technology development studies have highlighted the need for structures with extraordinary dimensional stability. Advanced materials such as silicon carbide and beryllium are costly and time consuming to manufacture. Using methods pioneered in carbon fiber composites, sandwich panels from silicon carbide and beryllium are proposed for lightweight, stiff, ultra-stable optical benches for instruments on new observatories such as LUVOIR and WFIRST. Assembled from flat stock and waterjet machined, the panels are extremely lightweight. A prototype panel is shown whose stiffness is a close match to the FEA. Fittings machined from Invar 39 for silicon carbide and AlBeMet for beryllium can be bonded to the panels to provide interfaces to optical mounts and optical components.



Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

There are four objectives. The first is to describe a series of reference designs which are candidates for this new optical bench technology. Second is to design and analyze the stability and stiffness of sandwich panels made from silicon carbide and beryllium using a spectrometer, coronagraph, or imager as a case study. The third is to demonstrate test panels of both silicon carbide and beryllium. Finally, the produce a test plan that can be used to evaluate the technology's stiffness, strength and dimensional stability. The work plan includes a team with expertise in silicon carbide and the manufacture of lightweight sandwich panels made from carbon fiber composites.

NASA Applications

Potential NASA applications include the use of this technology for lightweight and ultra-stable optical benches for spaceflight or balloon borne instruments including LUVOIR and WFIRST.

Non-NASA Applications

Potential non-NASA applications include:

- Military systems with similar requirements.
- Commercial robotic systems that require high speed operation (e.g. gantry, assembly, pick-and-place, wafer handling).

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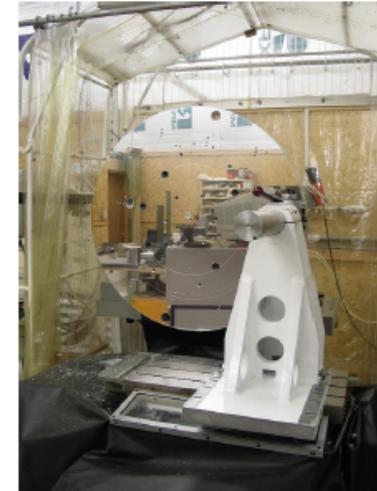
Identification and Significance of Innovation

- Very stable dia. turned additive manufactured on-axis Al mirrors.
- § Low cost, ultra-light and off-axis mirrors of hexagon mirrors.
- § Laser weld Al₁₀SiMg mirrors to make 0.5 meter assembly.
- § Manufacture of an aluminum 0.5 meter segmented spherical mirror made of a diamond turned central hexagonal segment surrounded by six diamond turned off-axis hexagonal spherical mirrors.

Estimated TRL at beginning and end of contract: (Begin: 4 End: 5)

Technical Objectives and Work Plan

- DOS will design the mirrors to be additively manufactured to optimize strength, stiffness and areal density consistent with very low cost.
- Work closely with Stratasys(SDM), to build ultra lightweight on-axis and off-axis aluminum segments for a diamond turned 0.6 meter mirror made of one on-axis spherical hexagonal mirror surrounded by six off-axis spherical hexagonal mirror segments.
- Precision robotic GTAW and laser welding will be investigated to join AM mirror segments. Welded test mirrors will be diamond turned to evaluate effects of welding on diamond turned finish and optical contour accuracy.
- Optical testing of the assembled spherical mirror is much easier and less expensive than aspheres.
- Demonstration of a combination process of AM technology, robotic welding and large diameter diamond turning for building ultra light aluminum aspherical mirrors will be done.
- A team of three small businesses will design and plan a robotic welding
- DOS will diamond turn and optically test robotically welded Al₁₀SiMg mirrors



NASA Applications

NASA's mission in space research includes such far-reaching projects as Deep Space Optical Communication (DSOC), Advanced Technology Large Aperture Telescope (ATLAST), Terrestrial Planet Finder, Orbiting Wide Angle Light Collector, Cosmic Microwave Background Polarization (CMB-Pol), the Single Aperture Far-IR (SAFIR), the Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) and Wide Field InfraRed Space Telescope (WFIRST).

Non-NASA Applications

This innovative mirror manufacturing technology is applicable to all these projects as well as any military, scientific or commercial application requiring low cost light weight mirror optical components

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NASA SBIR/STTR Technologies

S2.03-9933 - 3D Printed Silicon Carbide Scalable to Meter-Class Segments for Far-Infrared Surveyor

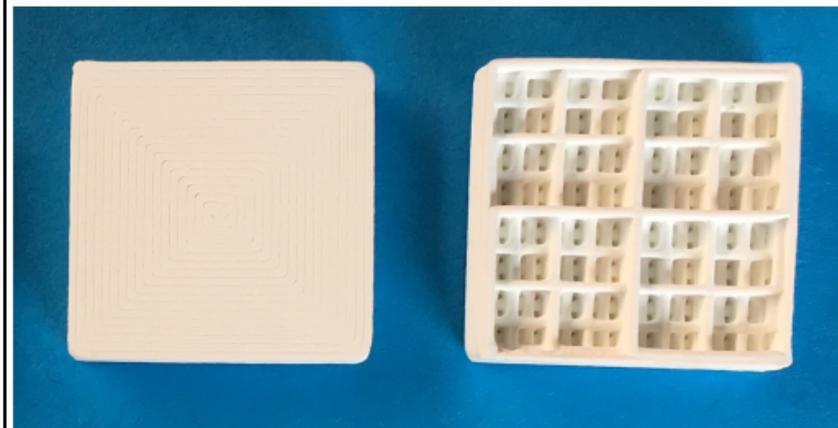
PI: William Goodman

Goodman Technologies LLC - Albuquerque, NM



Identification and Significance of Innovation

Our 3D printed 1.5-meter hexagonal silicon carbide segments will meet or exceed all NASA requirements for the primary mirror of a Far-IR Surveyor such as the Origins Space Telescope (OST), and may also provide a solution for the LUVOIR Surveyor. Our analysis and internal research and development show that we will achieve an areal density of 7.75 kg/m² (~39% of a JWST beryllium segment), a cost to print of \$60,000/segment, and an optical surface that has nanometer-scale tolerances. Our encapsulated lattice construction provides a uniform CTE throughout the part for dimensional stability, incredible specific stiffness, and the added benefit of cryo-damping. Our process will also allow for direct embedding of electronics for active structures and segments, and the potential for actively cooling with helium for unprecedented low emissivity and thermal control. Finally, the particulate paste extrusion process may be very suitable for printing mirrors in the zero gravity of space.



Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

The overarching objectives of the tasks performed during the Phase I, II and III projects are directly responsive to filling the COR PATR technology capabilities gaps. Phase I objectives are: 1)To develop and demonstrate silicon carbide particulate pastes to be used in Robocaster machines. One group of particulate paste formulations will consist of preceramic polymer as the liquid phase, and will be loaded with variable volume fractions of silicon carbide powders of various sizes. Another formulation will use water and other proprietary additives to make a quick drying silicon carbide paste that deposits as a greenbody (like a chalky clay), and which is then subsequently sintered to a ceramic. Viscosity, rheology, drying and shrinkage are all key aspects of the particulate paste development. 2)To demonstrate 3D printing of ultralightweight mirror structures using robocasting, a particulate paste printing technique. Using the newly created preceramic polymer particulate pastes we will 3D print greenbody mirror substrates. We shall be using our proprietary methodology and will do both open and closed back coupons. 3)We shall document and mature a Phase II and III technology roadmap and program plan which results in meter-class segments by the 2020 Decadal Survey. This shall include the 1.2x1.2-meter Robocaster machine.

NASA Applications

The NASA Astrophysics Division Roadmap Enduring Quests – Daring Visions builds on the 2010 Decadal Survey and includes near-term, formative (10-20 years – notional Surveyor missions) and visionary (20+ years – notional Mapper missions). Assuming a 20-m aperture Far-Infrared Surveyor (Origins Space Telescope), a 16-m aperture LUVOIR Surveyor, and 500 square-meter collection area for the ExoEarth Mapper, then at least 1015 square-meters of mirrors are required by NASA in the next 30 years.

Non-NASA Applications

Potential non-NASA applications include complex telescopes for astronomy, imaging and remote sensing applications, ISR missions for police and paramilitary units, fire fighters, power and pipeline monitoring, search and rescue, atmospheric and ocean monitoring, resource management, disaster relief and communications, and national defense missions such as airborne, shipborne and land-based lasers.

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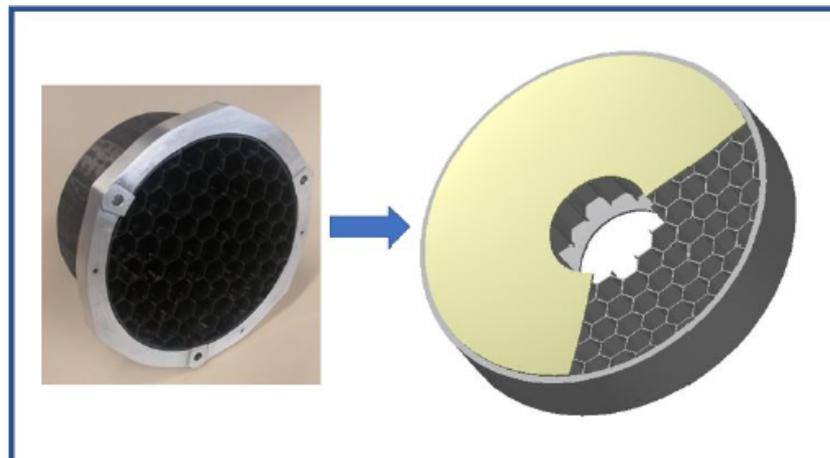
NON-PROPRIETARY DATA

PI: Robert Lumpkins

Mentis Sciences, Inc. - Manchester, NH

Identification and Significance of Innovation

Mentis Sciences, Inc. Proposes to develop a thin walled Silica-Silica composite that can be used as part of a honeycomb core sandwich panel that will form a mirror substrate that has a low coefficient of thermal expansion that is matched in all directions



Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

Mentis will work to develop the processing steps to create a silica-silica composites starting with Quartz polysiloxane and using Tetraethyl orthosilicate as a silica precursor. At the conclusion of this Task One Mentis will have met Technical Objective I - Identify and refine the manufacturing steps required to create a silica-silica composite.

In Task Two Mentis will conduct material testing to provide preliminary data on some of the material properties that are critical to mirror design. This will include cte, thermal conductivity and testing to determine the modulus. Completing this task will meet Technical Objective II – Quantify Material Properties that are critical to mirror design.

To Demonstrate the economic and technological feasibility Mentis will use an existing model to compare the performance of silica-silica composites with different mirror materials that are currently used for NASA missions. In addition, a top-level economic feasibility study for the mirror concept will be conducted that will include production estimates.

Mentis will build a small scale, proof-of-concept mirror substrate to meet Technical Objective IV. This small article will demonstrate that the honeycomb manufacturing process is feasible with the quartz-polysiloxane and that the conversion process will work on more complicated geometries than the flat specimen used for testing.

NASA Applications

Silica-Silica composites, can be fabricated into low cte, lightweight, and affordable sandwich panels using unique manufacturing techniques developed at Mentis. The resulting structures would be suitable for use as mirror substrates. These mirror substrates have potential applications as components on NASA UV/Optical Telescopes.

Non-NASA Applications

Two potential applications would be integration into the optics train on a missile interceptor or use as part of the Gun-launched Tactical Satellite System (GLTSS). Performance optics with a low weight are critical to both applications and the unique ability to affordably manufacture sandwich panels from the silica-silica material make this material a true contender for insertion on these systems.

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The Peregrine Falcon Corporation - Pleasanton, CA

Identification and Significance of Innovation

This proposed innovative athermal telescope design uses advanced lightweight and high-stiffness material of Beryllium-Aluminum (Be-38Al). Peregrine's expertise with Be-38Al, Electroless Nickel and Liquid Interfaced Diffusion (LID) Bonding leveraged by Rochester Institute of Technology's experience with Optical Systems for sounding rocket instruments will provide synergy in this visionary development. Be-38Al seamlessly joined through our proficiency in LID Bonding will produce an athermal telescope that can fully operate in any in-situ environment whether in the laboratory or on-orbit while maintaining alignment. A "monolithic" metering structure of Beryllium-Aluminum used within an athermal telescope design would give sounding rocket applications and in-situ telescopes for high altitude balloons and space the ability to align telescopes at ambient temperatures and also have those positional alignments maintained through launches and their entire mission life.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)

Technical Objectives and Work Plan

Objectives: 1.) Process low temperature telescopes that are athermal maintaining their precision alignment from ambient to low temperatures to allow for angular resolutions to <1 m RMS. 2.) Telescopes that can be operated in in-situ environments down well below 200K and maintain stability 3.) Low cost design 4.) High stiffness designs with first modes over 250 to 500Hz. 5.) Low mass 6.) Rapid delivery / easy to fabricate design

Work Plan for Phase I includes: Task 1: Kickoff Meeting and Definition, Task 2: Design of an Athermal Telescope, Task 3: Fabricate a Demonstration Athermal Telescope Subscale Coupon, Task 4: Detailed Plan for Follow-on Effort, Task 5: Final Report



NASA Applications

Potential uses are for applications current under consideration for NASA's small science missions.

- Space based observatories
- High altitude balloon telescopes
- Sounding rocket telescopes

Non-NASA Applications

Non-NASA Applications may include: 1.) Optical instruments for industrial measurements, 2.) Improve and maintain ground based telescopes, 3.) Improve precision of robotic arms by maintaining alignment over wider temperature ranges, 4.) UAV based instruments and telescopes

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PI: David Strafford

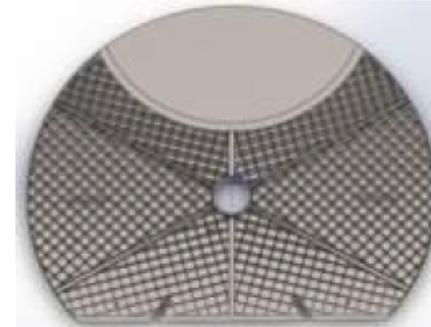
Soter Technology, LLC - Ashburn, VA

Identification and Significance of Innovation

Soter Technology offers a technology to reduce cost and schedule of the blanks for high stability, diffraction limited visible wavelength mirrors by an order of magnitude. FEA predictions indicate that this mirror blank construction technique will have thermal stabilities, in a space telescope shroud, that exceed that of a ULE mirror, while maintaining or decreasing the areal density.

This program will demonstrate a subscale (100 mm) mirror in Phase I and a 0.2 m compact flat field TMA in Phase II. The mirror and the telescope will both be FEA modeled and then thermos-optically tested. Both optical deformations and temperatures will be compared to the FEA.

The goal of these technologies is to produce aspheric mirrors which are 10 nm RMS global surface figure, 5 nm RMS mid-spatial frequency errors, 1 nm RMS surface roughness.



Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)

Technical Objectives and Work Plan

In Phase I, this SBIR will demonstrate the blank fabrication technology. It will design, model, and construct a 100 mm diameter plano mirror. The program will optically test the mirror, while applying heat loads representative of those seen by a mirror in a telescope shroud and will compare the deformation and thermal results to the FEA models.

In Phase II, this SBIR will construct a very compact, flat field, diffraction limited 0.2 m TMA that fits in a 12U cubesat.

NASA Applications

In the 2010 Decadal Survey, NASA identified needs for next generation space telescopes in TA08. Of the top technical challenges, rapid time scale development was identified as the first need, both in order to explore innovative ideas and to fit the exploration within an Explorer or a Discovery class mission. The number two need was high performance, stable, low areal density optics normal incidence optics that could be manufactured at lower cost. These three technologies address both NASA needs. Non-NASA Application

Non-NASA Applications

Commercial remote sensing satellite mirrors are very similar to NASA UVO mirrors, including large DigitalGlobe and small SkyBox systems. The long lead time of current mirrors for telescopes leads to spiraling costs. To protect a long lead, critical path item programs add quality oversight, which can add 60% to the cost. This technology program addresses the mirror blank portion of these costs.

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2017 SBIR S2.04 'X-Ray, Freeform & Coating'

Phase I 18 Submitted 4 Funded

Applied Sciences, Pyramid Nanostructured Coatings for Stray Light Suppression,

Mindrum Precision, Pre-Collimator Chemical Milling for X-ray Telescopes,

Voxel, Freeform Optics for Optical Payloads with Reduced Size and Weight

ZeCoat, Battery-Powered Process for Coating Telescope Mirrors in Space

Phase II TBD Submitted TBD Funded

PI: Carla Lake

Applied Sciences Inc - Cedarville, OH

Identification and Significance of Innovation

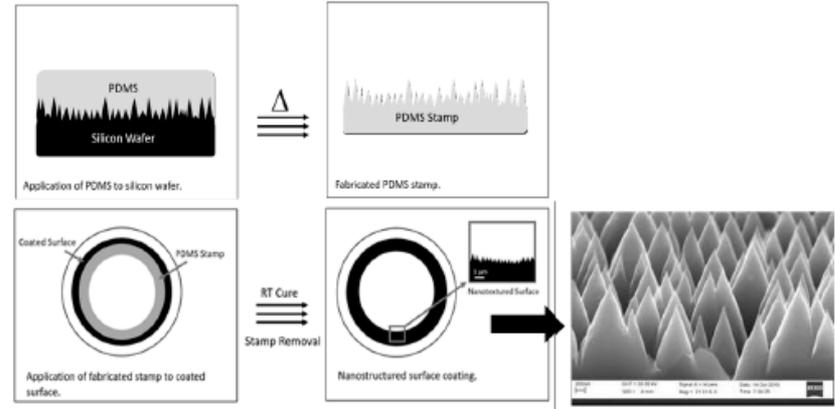
Telescopic imaging and other optical instrumentation can be polluted by stray light, which inevitably reduces the quality of the images or measurement, respectively. While treatments to reduce the impact of stray light exist, the effectiveness of these treatments have limitations thereby reducing the range and reliability of astrophysical telescopic imagery. NASA is seeking a scalable, highly effective solution to reduce and/or eliminate the impact of stray light. Applied Sciences proposes to develop a solution for stray light suppression that utilizes non-reflective/ nano-structured polymer coatings combined with a proven and scalable process that yields a light trapping nano-textured surface. Stacked-cup carbon nanotubes will provide additional absorptive properties to technology currently-used aerospace qualified resin (legacy material). A non-reflecting surface will be fabricated by plasma etching and replication into pyramidal nanostructures for broadband absorption with efficiency at or better than 99.9%. This new approach comes at a much lower cost and is readily scalable.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 6)

Technical Objectives and Work Plan

The goal of this Phase I effort is to optimize the legacy coating technology with nanostructured materials and fabricate a non-reflecting surface by plasma etching and replication, that absorbs 99.9% of all stray light. In order to achieve this, the following technical objectives are to be completed. Modify and optimize the legacy polyurethane paint with carbon nanostructured materials to enhance its absorption without compromising key mechanical and rheological properties; stamp fabrication on a silicon wafer etched with nano-structured pyramid shaped spikes; successfully transfer the silicon nano texture to the nano-enhanced polyurethane via a flexible PDMS stamp; evaluate and characterize the manufactured pyramidal structure via SEM; evaluate optical properties of the coating by hemispherical reflectance, on flat and contoured shaped coupon substrates of NASAs materials of choice. Determination of the effect of angle and spacing between nano-textured pyramids on the coatings stray light suppression is also important, especially when applied to contoured geometries. Given the vibration, acoustic and thermal loads that space flight instruments undergo, adhesion, flexibility and thermal stability of the developed coatings will be evaluated in order to meet NASA's specifications.

Non-reflective pyramid nanostructured coating for stray light suppression



NASA Applications

The proposed technology is aimed for stray light suppression in spaceflight instruments. The non-reflective nano-pyramid shaped carbon nanotube coating is designed for application on components such as baffles, entrance aperture, tubes and stops. Black-body masks and terrestrial telescopes could also benefit from the proposed technology.

Non-NASA Applications

The proposed innovation comes at a much lower cost than the current state of the art, and is readily scalable. Commercial applications include optical apertures, binoculars, night vision goggles, analytical instrumentation and other devices that benefit from stray light suppression.

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Mindrum Precision, Inc. - Rancho Cucamonga, CA

Identification and Significance of Innovation

Using **Chemical Milling** with wire **Electrical Discharge Machining (EDM)**, **Mindrum Precision** will build a **precollimator (PC)** faster and more cost effective than current methods.

Space-based x-ray telescopes currently involve the use of a PC to shield the optics from stray light. Each PC requires extensive build time from highly skilled technicians. This hands-on "place/weld/measure and repeat" process is ineffective for the thousands of ribs.

Eliminating the hands-on time with CNC unattended wire EDM automates the build, but can't reach the thin walls required. Chemical milling of this large, complex structure is an innovation which will bring fast and affordable PC to market.



Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)

Technical Objectives and Work Plan

Complex Chemical Milling Phases:

- Design and Modeling – test coupons in SolidWorks.
- Electric Discharge Machining – rough blank.
- Chemical Milling – Hydrofluoric acid etch test coupons.
- Inspection and Review – Evaluate, provide feedback, and document.

The Final Report will include:

1. New acid etching techniques to uniformly etch each slot for PC.
2. Integrate wire EDM cutting techniques with Chemical Milling to automate rapid build.
3. Determine ideal wall thickness for ease of manufacturing & strength/structural integrity.

NASA Applications

Some telescopes are unable to afford a precollimator due to budget or weight constraints. This limitation handicaps the telescopes' ability to see farther with greater clarity. Decreasing the build time from 12 months down to 1-2 months will greatly reduce cost and time constraints for future telescopes. Chemical milling has the potential to also reduce the overall weight of titanium or aluminum precollimators.

All future XRT missions that utilize a PC would all benefit, samples of these NASA missions include NuSTAR, WHIMEX and SMART-X.

Non-NASA Applications

There is a chronic need for PC for all space-based x-ray telescopes and thus this innovation would potentially support all of them with an entirely new way of manufacturing the stray-light shielding structure. Non-NASA missions that would be positively affected would be ones like ESA's Athena and JAXA's ASTRO-EII, ASTROH, DIOS and FFAST, all of which are XRT missions that utilize a precollimator.

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Identification and Significance of Innovation

To address NASA's need for robust optics compatible with space platforms of constrained size and weight, freeform optics that combine the benefits of freeform surfaces and volumetric freeform gradient-index (GRIN) optical materials will be demonstrated. The gradient-index contours of the volumetric freeform GRIN materials can be used to implement optical power and reduce geometric and chromatic aberrations. And, when freeform surfaces are included, heretofore unavailable degrees of design freedom are made available. The new degrees of freedom can be used to implement complex high-order polynomial optical functions, allowing reductions in the size and weight of the system, with machining tolerances that are relaxed due to the freeform homogeneous optical elements. As the 3D-GRIN optics are capable of achromatic performance, they can replace freeform mirrors. By virtue of the nanofillers used in the nanocomposite 3D-GRIN optics, they are hard, strong, easy to polish and machine, robust to temperature variation, and can be made radiation tolerant.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

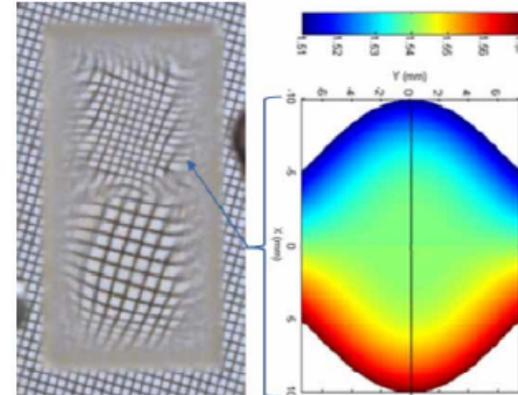
Technical Objectives and Work Plan

Technical Objectives:

- Gradient index contrast of $n \Rightarrow 0.2$ (> 0.3 goal),
- Demonstration of scatterless transparent from 400 nm to 2000 nm
- Characterization of refractive index over the -50 oC to 100 oC temperature range
- Demonstration of high-order radially variable and axially variant lenses, 1-mm to 100-mm (f/2 to f/20)
- Demonstration of high-order polynomial functions in planar 3D-GRIN optical elements
- Demonstration of high-order polynomial functions in hybrid freeform-surfaced 3D-GRIN elements

Work Plan:

1. Systems engineering and requirements definition
2. Optical design and multi-variant optimization
3. Optimization and characterization of nanocomposite inks and films
4. Demonstration of temperature stability of symmetric radially and axially varying GRIN lenses
5. Characterization of high-order polynomial optical functions implemented in: 3D-GRIN and freeform-surfaced 3D-GRIN elements
6. Temperature testing



Planar 3D GRIN profiles implementing two bicubic phases- one the inverse of the other

NASA Applications

- Adaptive optics
- Phase correctors
- Telescopes
- Optical communications
- Small-satellite optics

Non-NASA Applications

Camera lens, laser optics, rifle sight, computational imaging, contact lens, endoscope, industrial inspection, photovoltaics, solid state lighting.

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ZeCoat Corporation - Torrance, CA

Identification and Significance of Innovation

ZeCoat Corporation will develop a battery-powered, aluminum deposition process for making broadband reflective coatings in space (wavelength range: 30-nm to 2500-nm). The process uses an array of evaporation filaments powered by batteries. The vacuum coating process is scalable for large mirrors several meters in diameter, but is applicable to any size mirror. By placing iridium (or a multi-layer interference coating) on the mirror initially (coated on earth), followed by a fresh coat of aluminum in space, the broadband response of the telescope could be extended down to 30-nm. Current coating technologies limit the reflectance response to 90-nm because of the absorbing fluoride coating which protects the aluminum from oxidation on earth. To achieve future wavefront requirements over a large primary mirror, it is likely that many evaporation sources will be required. In Phase I, we will demonstrate feasibility of the process. In Phase II, miniaturized battery-powered units will be designed and manufactured, and the coating process tested in a simulated space environment.

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

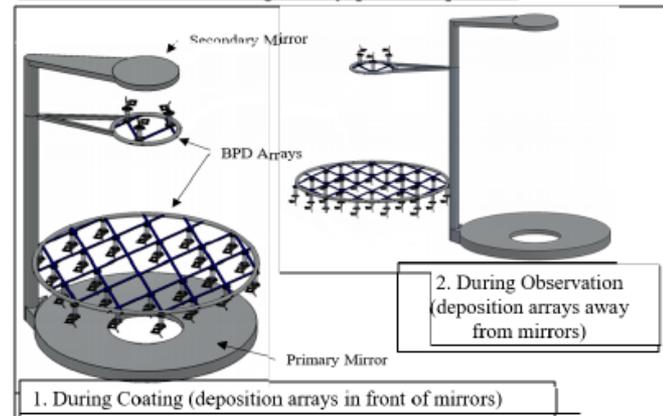
Objectives

- Demonstrate the feasibility of making a high UV reflective aluminum coating by a battery-powered filament evaporation process in a simulated space environment
- Demonstrate an aluminum over-coated iridium reflective coating design
- Demonstrate the feasibility of using LiFePO₄ (or other battery chemistry) in a simulated space environment after relevant thermal cycling
- Define mathematical solutions for creating flat coatings, which minimize wavefront error, using evaporation plume data and an array of filaments
- Validate the math models by demonstrating uniform coatings, measured over large areas, with minimal impact on WFE.

Tasks

- NRE- experimental design, documentation
- Prepare pre-melted aluminum filaments
- Battery trade study
- Fabricate iridium-coated mirrors
- Map the plume and use computer model
- Passivate aluminum with ionized NF₃
- Coat subscale mirror
- Design miniaturized BPD unit

Sketch of how a large coating array might be deployed for coating and for observations using battery-powered process



NASA Applications

- Coating mirrors in space for broadband mirrors into the EUV
- Repair of coatings in space
- Coating FUV-quality aluminum large mirrors on the ground for use in space

Non-NASA Applications

- High-quality UV-aluminum coatings for large ground-based mirrors
- Coatings for large aircraft simulator mirrors

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Any Questions?

NASA 2017 SBIR Subtopic:

S2.03 “Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope”

H. Philip Stahl, Ph.D.

Sub-Topic Manager

New for 2018

- Added need for a compact coherent LIDAR space telescope.
- Planetary Telescope needs either a complete telescope or a primary mirror assembly
- Continued interest in technology for 1.5-m class segments for a Far-IR

Generic Instructions to Proposer

Define a customer or mission or application and demonstrate that you understand how your technology meets their science needs.

Propose a solution based on clear criteria and metrics

Articulate a feasible plan to:

- fully develop your technology,
- scale it to a full size mission, and
- infuse it into a NASA program

Deliver Demonstration Hardware not just a Paper Study, including :

- documentation (material behavior, process control, optical performance)
- mounting/deploying hardware

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope

Subtopic solicits solutions in the following areas:

- **Components and Systems for potential EUV, UV/O or Far-IR missions**
- **Technology to fabricate, test and control potential UUV, UV/O or Far-IR telescopes**
- **Telescopes that enable sub-orbital rocket or balloon missions.**

Subtopic's emphasis is to mature technologies needed to affordably manufacture, test or operate complete mirror systems or telescope assemblies.

Ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters, or a relevant sub-component of a system, or a prototype demonstration of a fabrication, test or control technology. Phase 1 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.

Successful proposals will demonstrate an ability to manufacture, test and control ultra-low-cost optical systems that can meet flight 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.

Metrics

The most important metric (after performance) is affordability. Current normal incidence space mirrors cost \$4 million to \$6 million per square meter. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than \$1M to \$100K/m².

Technology Metrics:

Aperture for all wavelengths

- Monolithic: 1 to 8 meters
- Segmented: > 12 meters

For UV/Optical

- Areal Cost < \$500k/m²
- Wavefront Figure < 5 nm rms
- Thermally Stable < 10 pm/10 min (for Coronagraphy)
- Dynamic Stability < 10 pm (for Coronagraphy)
- Actuator Resolution < 1 nm rms (for UV/Optical)
- **First Mode Frequency 250 to 500 Hz**

For Far-IR

- Areal Cost < \$100k/m²
- Cryo-deformation < 100 nm rms

For EUV

- Slope < 0.1 micro-radian

Optical Components/Systems for potential UV/O missions

Potential UV/Optical missions require 4 to 16 meter 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, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pico-meters RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4 meter and larger telescope. To meet this requirement requires active thermal control systems, ultra-stable mirror support structures, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m² for a 5 m fairing EELV vs. 150 kg/m² for a 10 m fairing 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 m² of collecting area) should have an areal cost of less than \$2M/m². And, a 16-m class mirror (with 200 m² of collecting area) should have an areal cost of less than \$0.5M/m².

Optical Components/Systems for potential UV/O missions

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 that are ultra-stable 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 ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical modeling.

Optical Components/Systems for potential UV/O missions

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, nano-particle 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 meter (or larger) precision quality components.

Potential solutions for achieving the 10 pico-meter wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology, passive, and active thermal control.

Ultra-Stable Telescopes and Telescope Structures

Potential balloon and space missions require complete optical telescope system with 0.5 meter or larger of collecting aperture:

- 1-m class balloon-borne telescopes have flown successfully, however, the cost for design and construction of such telescopes can exceed \$6M, and the weight of these telescopes limits the scientific payload and duration of the balloon mission. A 4X reduction in cost and mass would enable missions which today are not feasible.
- Space-based gravitational wave observatories (eLISA) need a 0.5 meter class ultra-stable telescope with an optical path length stability of a picometer over periods of roughly one hour at temperatures near 230K in the presence of large applied thermal gradients. The telescope will be operated in simultaneous transmit and receive mode, so an unobstructed design is required to achieve extremely low backscatter light performance.

Balloon Planetary Telescope

Stratospheric balloon platform offers numerous advantages for planetary science. 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 band and in the infrared 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.

Required is a 1-m class telescope 500 nm diffraction limited performance or Primary Mirror System that can maintain < 10 nm rms surface figure error for elevation angles ranging from 0 to 60 degrees over a temperature range from 220K to 280K.

Phase I will produce a preliminary design and report including initial design requirements such as wave-front error budget, mass allocation budget, structural stiffness requirements, etc., trade studies performed 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 sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc) and performance assessment over the specified operating range.

Additional information about Scientific Balloons is at <https://www.csbf.nasa.gov/docs.html>

Planetary Mission Specifications

Telescope Specifications:

- **Diameter** > 1 meter
- **System Focal Length** 14 meter (nominal)
- **Diffraction Limit** < 500 nm
- **Mass** < 300 kg
- **Shock** 10G without damage
- **Elevation** 0 to 60 degrees
- **Temperature** 220 to 280 K

Primary Mirror Assembly Specifications:

- **Diameter** > 1 meter
- **Radius of Curvature** 3 meters (nominal)
- **Surface Figure Error** < 10 nm rms
- **Mass** < 150 kg
- **Shock** 10G without damage
- **Elevation** 0 to 60 degrees
- **Temperature** 220 to 280 K

Optical Components/Systems for potential IR/Far-IR missions

Potential Infrared and Far-IR missions require 8 to 24 meter class monolithic or segmented primary mirrors with $\sim 1 \mu\text{m}$ rms surface figures which operate at $< 10 \text{ K}$.

There are three primary challenges for such a mirror system:

- **Areal Cost of $< \$100\text{K}$ per m^2 .**
- **Areal Mass of $< 15 \text{ kg}$ per m^2 substrate ($< 30 \text{ kg}$ per m^2 assembly)**
- **Cryogenic Figure Distortion $< 100 \text{ nm}$ rms**

Infrared Interferometry Mission Telescope

A balloon-borne interferometry mission requires 0.5 meter class telescopes with siderostat steering flat mirror. There are several technologies which can be used for production of mirrors for balloon projects (aluminum, carbon fiber, glass, etc.), but they are high mass and high cost.

NIR LIDAR Beam Expander Telescope

Potential airborne coherent LIDAR missions need compact 15-cm diameter 20X magnification beam expander telescopes.

Potential space based coherent LIDAR missions need at least 50-cm 65X magnification beam expander telescopes.

Candidate LIDAR systems (operating with a pulsed 2-micrometer laser) have a narrow, almost diffraction limited field of view, close to $0.8 \lambda/D$ half angle. Aberrations, especially spherical aberration in the telescope can decrease the signal.

Additionally, the telescope beam expander should maintain the laser beam's circular polarization.

The incumbent telescope technology is a Dahl-Kirkham beam expander.

Technology advance is needed to make the beam expander more compact while retaining optical performance, and to demonstrate the larger diameter.

Fabricate, Test & Control Advanced Optical Systems

Finally, this sub-topic also encourages proposals to develop technology which makes a significant advance the ability to fabricate, test or control an optical system, including cryogenic alignment mechanisms and wavefront sensing and control systems.

Any Questions?