NASA Technology Prioritization Plans for the Journey to Mars

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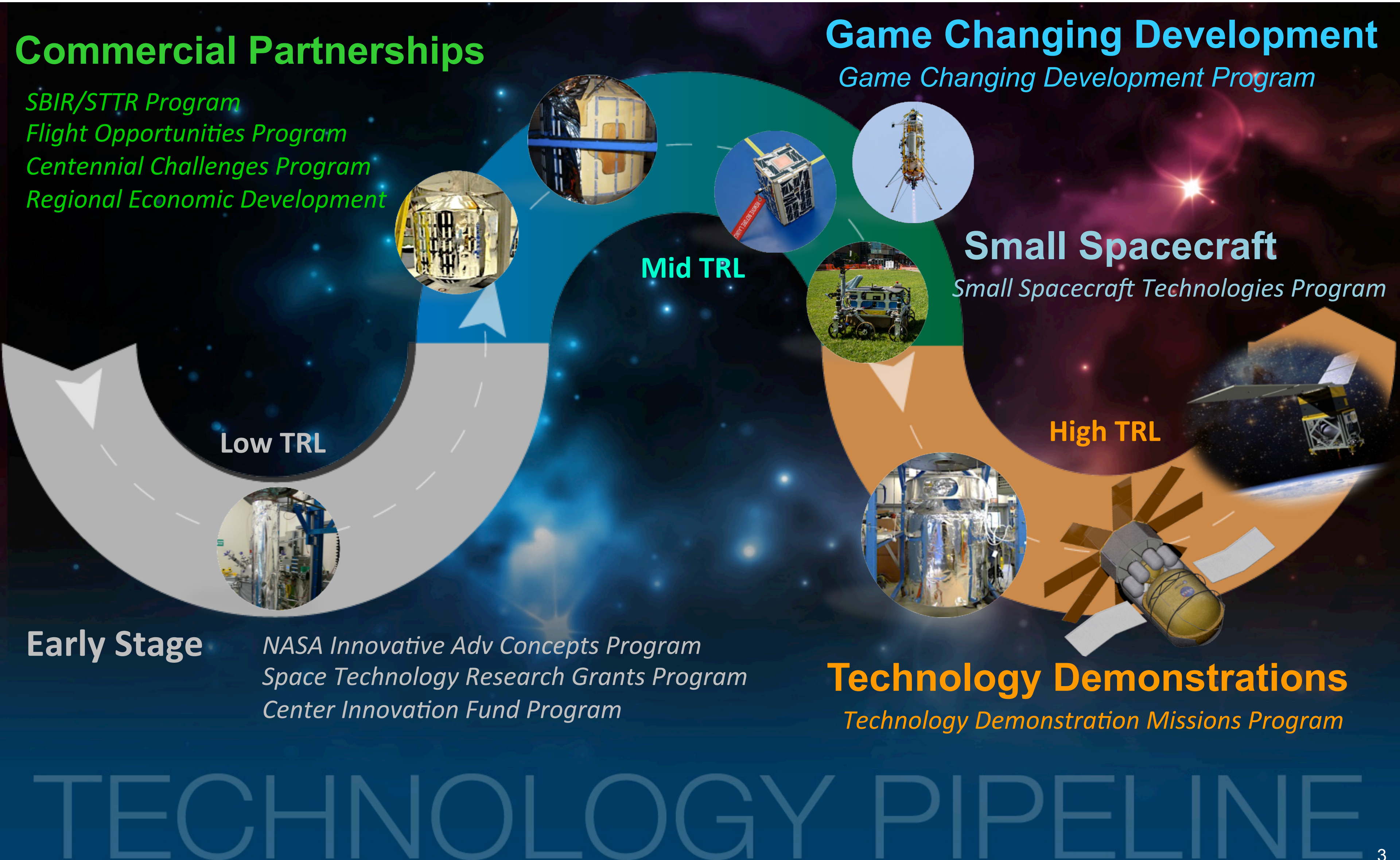
Guiding Principles of the Space Technology Programs

- **Adhere to a Stakeholder Based Investment Strategy:** NASA Strategic Plan; NASA Space Tech Roadmaps / NRC Report; NASA Mission Directorate / Commercial advocacy
- **Invest in a Comprehensive Portfolio:** Covers low to high TRL; Grants & Fellowships; SBIR & prize competitions; prototype developments & technology demonstrations
- **Advance Transformative and Crosscutting Technologies:** Enabling or broadly applicable technologies with direct infusion into future missions
- **Develop Partnerships to Leverage Resources:** Partnerships with Mission Directorates and OGAs to leverage limited funding and establish customer advocacy; Public – Private Partnerships to provide NASA resources and support to U.S. commercial aerospace interests
- **Select Using Merit Based Competition:** Research, innovation and technology maturation, open to academia, industry, NASA centers and OGAs
- **Execute with Lean Structured Projects:** Clear start and end dates, defined budgets and schedules, established milestones, lean development, and project level authority and accountability.
- **Infuse Rapidly or Terminate Promptly:** Operate with a sense of urgency; Rapid cadence of tech maturation; informed risk tolerance to implement / infuse quickly or terminate
- **Place NASA at technology's forefront – refresh Agency's workforce:** Results in new inventions, enables new capabilities and creates a pipeline of NASA and national innovators, and refreshes the agencies technical capabilities / workforce

Space Technology Mission Directorate



STMD Investment Planning

STMD Strategic Alignment Framework
- Core values, guiding principles, implementation goals flowdown

STMD Strategic Themes
- Get There, Land There, Live There, Observe There, Invest Here

Strategic Guidance
- Stakeholder input: Space Technology Roadmaps, NRC recommendations, STIP, MD roadmaps, Roundtables, etc.

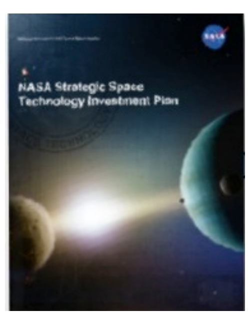
STMD Thrust Areas
- Focused areas of STMD investments

Content Generation
- Principal Technologists: Technology investment plans

Technology Portfolio Integration
- Crosscutting Investment strategy and content selection

STMD Programs
- Implementation instruments

National Science and Technology Priorities



STMD Strategic Themes

Get There
Improve the ability to efficiently access and travel through space

Land There
Enable the capability of landing more mass, more accurately, in more locations throughout the solar system

Live There
Make it possible to live and work in deep space and on planetary bodies

Observe There
Transform the ability to observe the universe and answer the profound questions in Earth and space sciences

Invest Here
Enhance the nation's aerospace capabilities and ensure its continued technological leadership

Categories of Collaboration Between Mission Directorates

- **Deliveries:** STMD matures technology and delivers to HEOMD or SMD for system-level evaluation (e.g., RCA, VOR, EVA Gloves, RPM instruments, etc.)

- **Partnerships:** STMD, HEOMD and/or SMD co-fund the development of technologies that are of mutual interest (e.g., MOXIE, MEDA, MEDLI-2, TRN, SCOR, etc.)

- **Coordination:** STMD, HEOMD and/or SMD define specific divisions of responsibility within a technical discipline (e.g., entry descent & landing, nuclear systems, synthetic biology, advanced manufacturing, etc.)

Human Space Exploration Phases From ISS to the Surface of Mars

Today

Phase 0: Exploration Systems ***Testing on ISS***

Ends with testing, research and demos complete*

Phase 1: ***Cislunar Flight Testing*** of Exploration Systems

Asteroid Redirect-Crewed Mission Marks Move from Phase 1 to Phase 2

Phase 2: ***Cislunar Validation*** of Exploration Capability

Ends with one year crewed Mars-class shakedown cruise

Phase 3: Crewed Missions Beyond Earth-Moon System

Phase 4a: Development and robotic preparatory missions

Phase 4b: Mars Human Landing Missions

Planning for the details and specific objectives will be needed in ~2020

Mid-2020s

2030

[* There are several other considerations for ISS end-of-life]

Capability Development Risk Reduction

= Plan/resources understood (green)
= Plan/resources finalization required (yellow)

	Capability \ Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration		Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND			EARTH INDEPENDENT	

Mars Exploration Capability Summary Assessment

Capabilities	Assessment
In Situ Resource Utilization & Surface Power	MOXIE is a small-scale demonstrations of oxygen production from the Mars atmosphere. Resource Prospector will demonstrate ice and other volatiles extraction in polar regions of the Moon. These would need to be significantly scaled up to support human exploration.
Habitation & Mobility	ISS is demonstrating long-duration habitation in LEO, but duration depends on resupply. Conceptual studies are underway for short duration cis-lunar habitats.
Human/Robotic & Autonomous Ops	Human/Robotic & Autonomous Ops are being demonstrated on ISS. Substantial additional work is needed to enable maintenance of human exploration systems.
Exploration EVA	Uncertain if next generation spacesuit will be ready before 2024 for demonstration on ISS.
Crew Health	Human Research Program is investigating crew health risks on ISS, and developing medical diagnostics and countermeasures. Some health risks may not be controlled by 2024.
Environmental Control & Life Support	ISS life support systems require frequent maintenance. New ECLSS technologies are being demonstrated on ISS. Long-duration, system-level ECLSS demonstration is being planned.
Radiation Safety	Characterizing LEO, cis-lunar, and Mars surface radiation environments. Improving forecast models for solar particle events. Reducing uncertainty in radiation effects on humans. Effective shielding has not been developed.
Ascent from Planetary Surfaces	Little work is being done in this area except for MAV concept studies and small LOX-methane propulsion efforts.
Entry, Descent & Landing	There are multiple EDL technology development activities for Mars robotic missions; current technology development efforts are balanced between enabling future robotic and human missions.
In-space Power & Propulsion	Developing 40 kW SEP system for ARM. Initiating ground testing of 100 kW electric thrusters. Developing small fission reactors for surface power (low funding level).
Beyond LEO: SLS & Orion	Proceeding toward first flight of SLS and Orion in 2018.
Commercial Cargo & Crew	Proceeding toward Commercial Crew IOC in 2018. Opportunities for resupply of cis-lunar habitats.
Communication & Navigation	Demonstrating high bandwidth optical communications for cis-lunar and Mars. Deep space optical comm is a candidate for demonstration on SMD missions.

Selected Critical Time Frames and Decisions

DECISIONS MADE & IMPLEMENTATION UNDERWAY	DECISIONS TO BE MADE IN NEXT FEW YEARS, IN WORK NOW	DECISIONS TO BE MADE IN THE NEXT DECADE, FED BY STUDIES IN PROGRESS
• **Extended ISS operations to at least 2024 and implementing HRP and ECLSS capability development plans** • **Pursued an evolvable SLS via Exploration Upper Stage and then advanced solid rocket boosters** • **Selected an ARM baseline mission to return an asteroidal boulder to lunar orbit for subsequent crew rendezvous and exercise high-power SEP** • **Defined and initiated key technology developments and EMC and SMT studies**	• **Allocate Flight Test and Proving Ground objectives to post-EM2 missions** • **Develop an exploration EVA suit for use on Orion missions** • **Define initial deep-space habitation capability** • **Select in-space transportation systems** • **Identify future Mars robotic precursor missions beyond Mars 2020**	• **Select initial human missions beyond the Proving Ground** • **Identify the role of ISRU in the overall logistics strategy** • **Demonstrate higher mass EDL and round trip capability** • **Define and develop robotic Mars preparatory missions** • **Design Mars surface habitats** • **Develop Mars surface power generation**

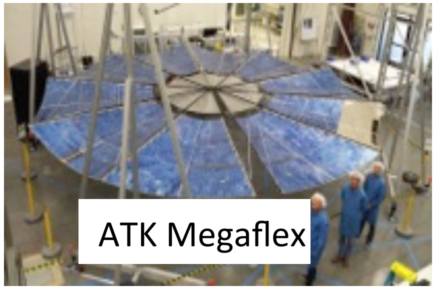
Proving Ground Phase 1 Flight Test Objectives
Mapping of ongoing technology development activities in Backup

#	CATEGORY	FLIGHT TEST OBJECTIVE
P1-1	Transportation	Demonstrate Orion's capability to extract co-manifested payload from SLS fairing.
P1-2	Transportation	Determine Orion's ability to support missions with at least 4-Crew longer than 21 days in conjunction with additional elements.
P1-3	Transportation	Evaluate Orion's depress/repress for EVA contingency operations.
P1-4	Transportation	Evaluate Orion's off-axis (tail-to-sun) performance.
P1-5	Transportation	Evaluate EUS TLI Performance with Orion plus Co-Manifested Payload.
P1-6	Transportation	Evaluate high-power electric propulsion systems.
P1-7	Transportation	Evaluate high-efficiency, high-power solar arrays in deep space.
P1-8	Transportation	Demonstrate Earth-independent deep space navigation.
P1-9	Operations Working in Space	Demonstrate transition between crewed and uncrewed operations, including configuration for remote/dormant operations and reactivation for crewed support.
P1-10	Operations Working in Space	Demonstrate human spacecraft operations in the presence of communications latency.
P1-11	Operations Working in Space	Demonstrate independent (on-board) mission and trajectory design/planning capability.
P1-12	Operations Working in Space	Evaluate stowage strategies to handle logistics and trash within available stowage volume for deep space missions.
P1-13	Operations Working in Space	Demonstrate side-by-side human and robotic operations.
P1-14	Exploration Working in Space	Demonstrate collection and return of geologic asteroid samples.
P1-15	Exploration Working in Space	Demonstrate research sample acquisition, handling, analysis, and curation requiring environmentally controlled conditions with no cross-contamination permitted.
P1-16	Habitation Staying Healthy	Demonstrate crew accommodations for Beyond-LEO conditions.
P1-17	Habitation Staying Healthy	Evaluate the performance of electrical components in a deep-space radiation environment.
P1-18	Habitation Staying Healthy	Evaluate cislunar transit habitat airlock and EVA system servicing accommodation for ability to support contingency EVA operations.
P1-19	Habitation Staying Healthy	Evaluate cislunar transit habitat airlock and EVA system servicing accommodation for ability to support nominal deep space mission EVA operations.
P1-20	Crew Health Staying Healthy	Demonstrate/evaluate space radiation protection and monitoring.
P1-21	Crew Health Staying Healthy	Demonstrate/evaluate human health, performance, and environmental health in a hostile and closed environment.
P1-22	Crew Health Staying Healthy	Evaluate the effects of deep space on complex organisms, plants, food, medicines, and animal models.

Space Technology Contributions to Asteroid Redirect Mission

Objective: Demonstrate high-power solar electric propulsion
(~50 kW; ~1/4 needed for human-class Mars cargo mission w/SEP)

- Developing magnetically-shielded, high-power Hall thrusters and power processing units to be provided to ARM as GFE
  - Applicable to all-electric commercial satellites and other gov't uses
- Developed two advanced solar arrays to TRL-6; available for commercial bus providers to meet ARM requirements
  - DSS integrated Rollout Solar Array (ROSA) being infused in SSL commercial spacecraft (CDR completed); targeting GEO satellites launching in 2018.
  - Orbital ATK flew Ultraflex array on Cygnus cargo spacecraft in December 2015 that employed STMD-sponsored technology.
- Contributing to SEP bus development w/HEO



Electric Propulsion System Procurement (Hall Thrusters & PPUs)
- RFP released in July 2015, final proposals received
- Anticipated award in May 2016

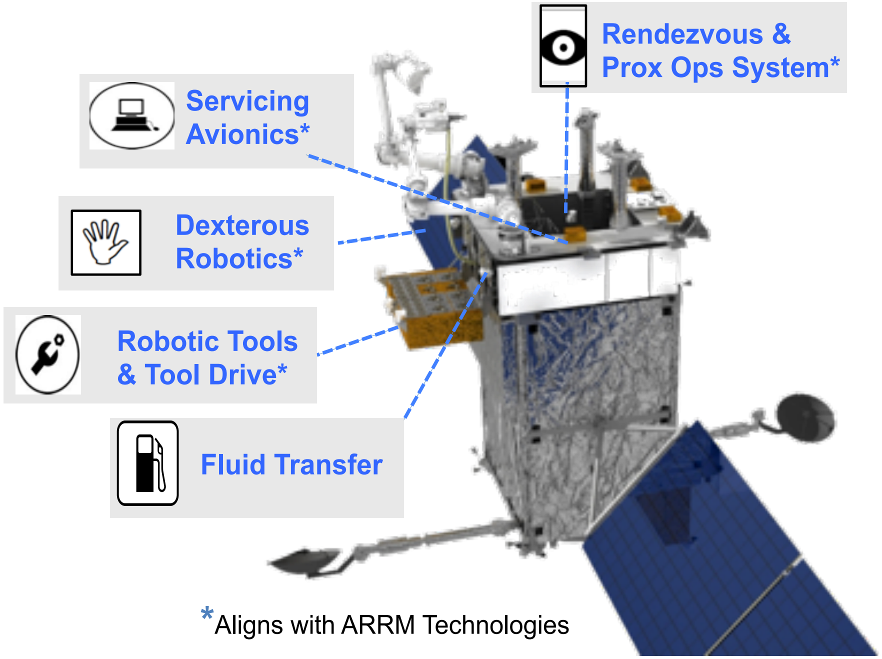
FY15	FY16	FY17	FY18	FY19
RFP Issued – July Proposals Due - Sept	Contract Award - May EDU Design Begins	EDU Fabrication & Testing	Flight Unit Fabrication & Testing	Flight Units Delivered

Space Technology Contributions to Asteroid Redirect Mission (cont.)

ARM Objectives:

- **Demonstrate advanced autonomous proximity operations in deep space and with a natural body**
- **Demonstrate integrated crewed/ robotic vehicle operations in deep space**

- Restore-L mission uses robotic technology to rendezvous with and refuel a government-owned satellite in low Earth orbit, autonomously and via remote control.
- Restore-L technologies being developed to be common/synergistic with ARM needs
  - Non-cooperative autonomous rendezvous capability
  - Robotic capture and servicing
- Restore-L propellant transfer demonstration represents key technology for human exploration needs



Restore-L Satellite Servicing

Preliminary schedule:

- FY 2016: MCR and KDP-A
- FY 2017: SRR/MDR and KDP-B
- CY 2019: Launch Readiness Date (to be validated by KDP-C)

Key Space Technology Contributions "Select In-Space Transportation Systems"

- **Solar Electric Propulsion:** Development of SEP (thrusters, PPUs, solar arrays, bus) to support ARM provides foundation for continued human exploration needs.
- **Green Propellant Infusion Mission (GPIM):** Flight demonstration to validate the on-orbit performance of a complete AF-M315E propulsion system (w/AFRL)
  - Significantly reduced toxic handling concerns and 40% greater efficiency than hydrazine.
  - Ready to be integrated into USAF STP-2 flight targeted CY 2017 Q1.
- **Nuclear Thermal Propulsion:** Three year project initiated in FY16 focused on determining whether NTP is viable as a Mars transportation system to enable faster crew transit (lower crew radiation hazards), reduced architectural mass (fewer SLS launches), and decreased sensitivity to mission departure and return dates. Tasks include:
  - Design, develop, and manufacture low enriched uranium (LEU) fuel element segments
  - Evaluate NTP engine design utilizing LEU fuel elements
  - System-level assessment and cost estimate for a potential future NTP development and demonstration effort
- **Entry, Descent & Landing Architecture Study:** Determine an appropriate strategy to land large payloads on the surface of Mars to support future human exploration
  - Evaluate the risks of the candidate EDL concepts
  - Identify risk mitigation strategies (i.e., benefits of flight demonstration at Mars relative to terrestrial test, modeling, and analysis, and at what scale these should be performed)
  - Provide recommendations to focus near-term EDL investments
  - Integrated with in-space transportation and Mars Evolvable Campaign assessments

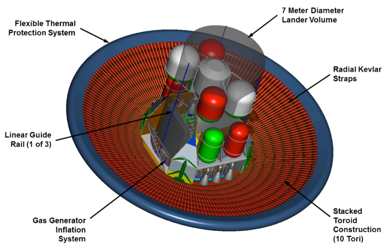
Mars Human Exploration EDL Architecture Study
“Demonstrate higher mass EDL …”

Entry Configurations Considered

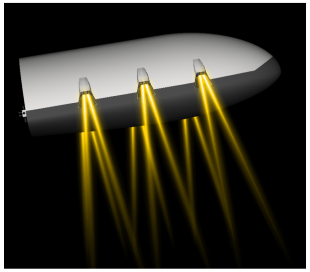
Low Ballistic Number (β)

High Ballistic Number (β)

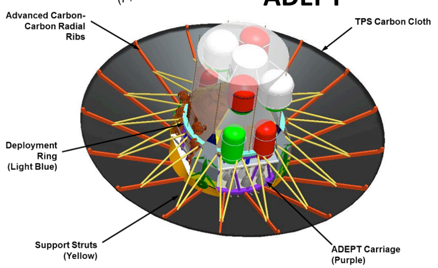
HIAD



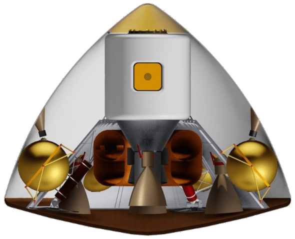
Mid L/D



ADEPT



Heritage Capsule



EDL Risks Common to All Architectures

Supersonic Retro Propulsion
- Heatshield integration of thrusters is a major concern (plug jettison vs doors)
- Interactions between aero / flight dynamics / controllability / propulsion system
- Aero / aerothermal vehicle interactions with plumes
- Plume / ground interactions (creates landing hazards, plume ejecta, and sensor interference)

Vehicle Integrated Performance
- Controllability schemes and aerocapture
  - Major concern for low β options - sufficient force (lift vector control and some minimum L/D) to meet landing accuracy requirements
  - High β options will need to prove robust margins to packaging sensitivities on Cg

Propulsion Development
- Long duration cryofluid management for minimizing propellant loss
- Highly throttleable, LOX/Methane engine that is common with other mission elements
- Integrated RCS fed by low pressure main tanks

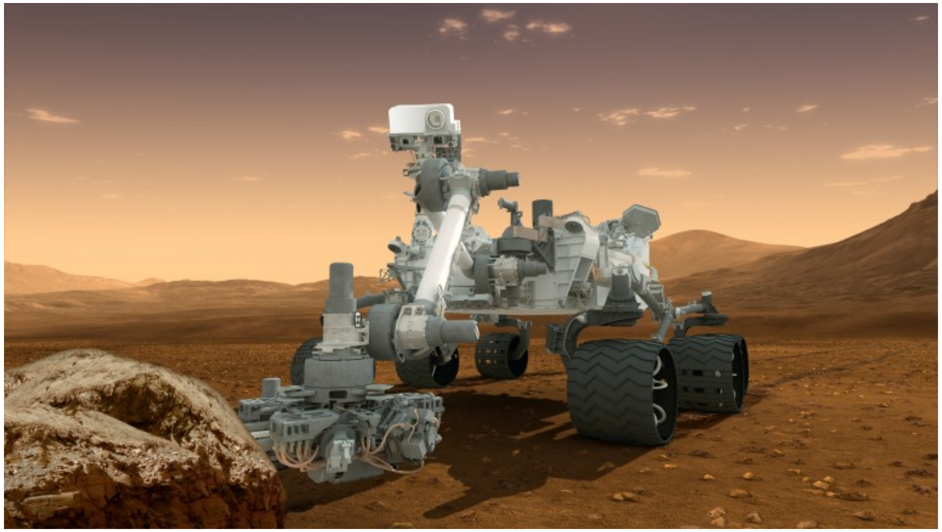
Safe, Precision Landing (SPL)
- Terrain Relative Navigation (TRN) beginning prior to SRP for elimination of entry dispersions
- Real-time Hazard Detection and Avoidance (HDA) during approach to the landing target to resolve surface roughness and slopes

- **Continuing EDL Architecture Study through FY16**
- **Utilizing results to shape investment strategy**
  - Particular focus on risks common to all EDL architectures (e.g., supersonic retro propulsion, safe precision landing, etc.)
- **Identifying partnership opportunities to leverage investments**

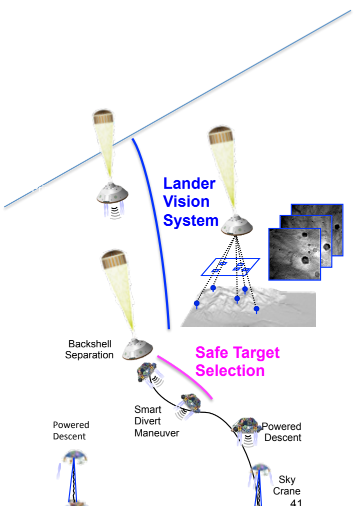
Key Space Technology Contributions
"Identify future Mars robotic precursor missions …"

- **Actively working across Mission Directorates and with potential OGA/Commercial Partners to identify leveraged opportunities to demonstrate technology critical to Mars human exploration.**
- **Mars 2020:** Baselined Exploration technology demonstrations:
  - **Terrain Relative Navigation (TRN)** (SMD/STMD): Provide the capability to avoid large scale landing hazards during entry, descent, and landing operations
  - **Mars Entry, Descent, & Landing Instrumentation (MEDLI-2)** (HEOMD/STMD): Temperature and pressure sensors on heat shield to validate aerothermal models.
  - **Mars Oxygen ISRU Experiment (MOXIE)** (HEOMD/STMD): Demonstrate production of oxygen from Mars atmosphere.
  - **Mars Environmental Dynamics Analyzer (MEDA)** (HEOMD/STMD): Surface weather station
- **Discovery 2014:** Provided opportunity for proposers to utilize exploration technologies without being penalized for technical risk during evaluation
  - **Deep Space Optical Communications (DSOC)**: 4 of 5 candidate missions
  - **Heatshield for Extreme Entry Environment TPS (HEEET)**: Backup technology for one candidate mission
- **Additional Candidate Technology Demonstrations on Precursors Being Considered:**
  - Extreme Environments Technologies, including:
    - High Performance Spaceflight Computing (w/AFRL, SMD): More capable radiation-hard general purpose multi-core fault-tolerant processor for low power space applications.
    - Extreme Environment Solar Panel (w/SMD): low temp, low intensity, high radiation
    - Ultra Low-Temperature Batteries
  - Real-Time Hazard Detection and Avoidance integrated with TRN

Robotic Precursors: Mars 2020 Payloads

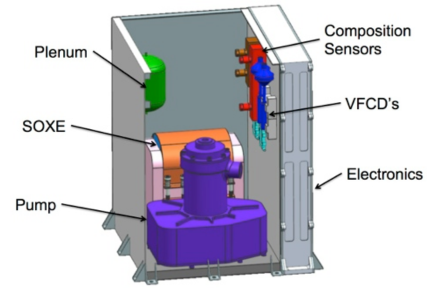


Mars 2020 payloads to demonstrate key technologies and address Strategic Knowledge Gaps for human missions.



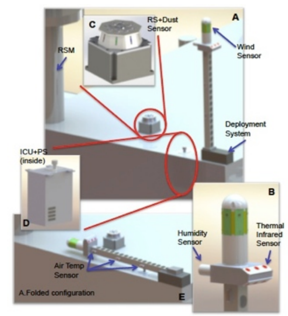
Terrain Relative Navigation (TRN):

- Enables safe access to scientifically compelling landing sites
- Provides capability to land near pre-deployed assets
- Reduces post-landing surface drive distances
- All current human and robotic precursor mission architectures for Mars exploration require TRN.
- Preliminary design is complete and moving into detail design phase
- SMD and STMD



Mars Oxygen ISRU Experiment (MOXIE):

- Demonstrating production of oxygen from Mars atmosphere.
- Completed PDR in Jan. 2016.
- HEOMD/AES and STMD



Mars Environmental Dynamics Analyzer (MEDA):

- Surface weather station.
- Completed PDR in Nov. 2015.
- HEOMD/AES and STMD

Mars Entry, Descent, & Landing Instrumentation (MEDLI-2):

- Temperature and pressure sensors on heat shield to validate aerothermal models.
- Completed SRR in Sep. 2015
- HEOMD/AES and STMD

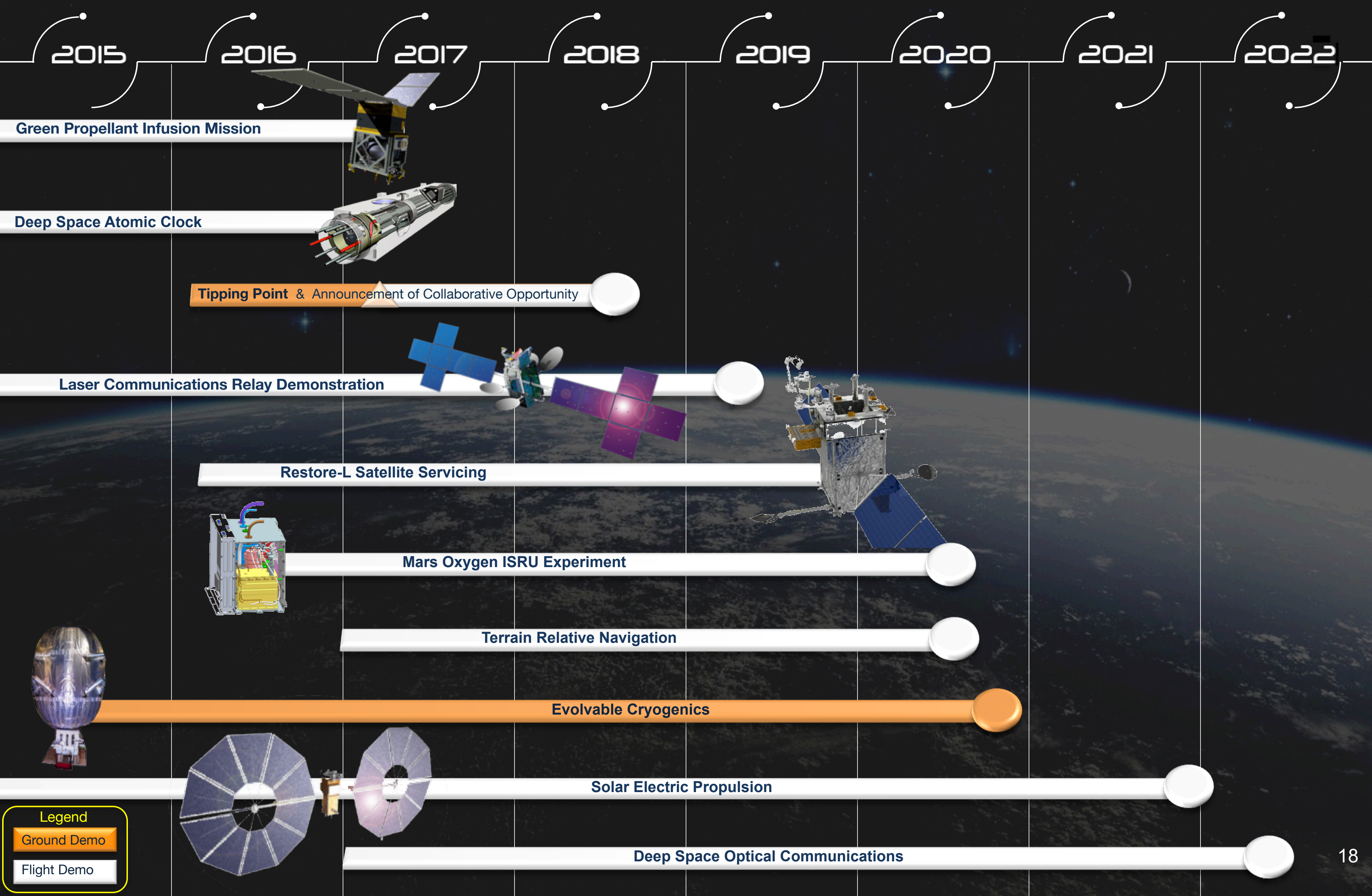
"Define Initial Deep-Space Habitation Capability"
"Develop an Exploration EVA Suit for Use on Orion Missions"

- **Ensuring crew health and operations (including EVA) are among the most critical Exploration technologies to demonstrate on ISS, and then in cis-lunar space during Proving Ground activities**
- **Space Technology supports HEOMD led activities – "deliveries" more common approach.**
- **Examples include:**
  - Spacecraft Oxygen Recovery: recover at least 75% of the oxygen from spacecraft atmosphere revitalization
  - Advanced Radiation Protection: Analytical and empirical effort to validate the radiation shielding efficiency of spacecraft materials
  - EVA Gloves: Developing actuated and counter-pressure gloves with improved dexterity.
  - EVA Portable Life Support components: variable oxygen regulator, rapid cycle amine
  - Phase Change Material Heat Exchanger

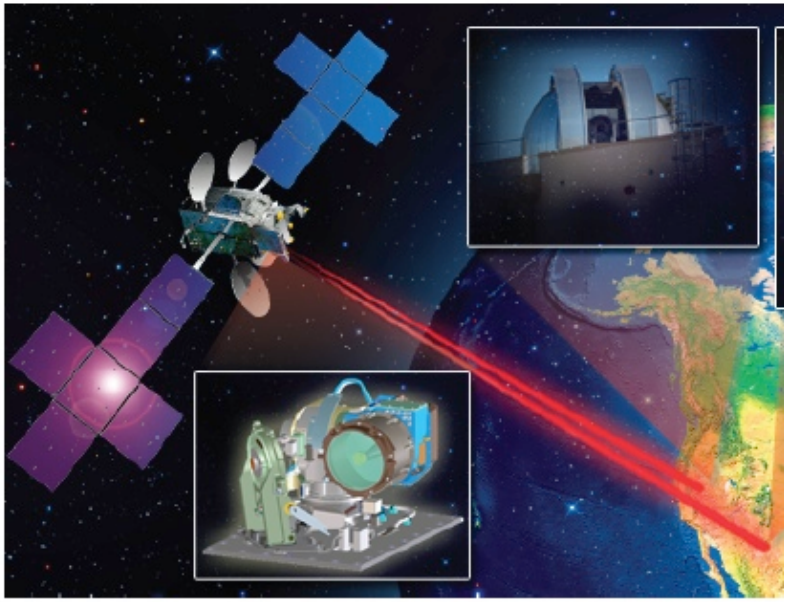
Key Habitat and ECLSS technology demonstrations planned on ISS (HEO led):

- **Bigelow Expandable Activity Module (BEAM)**: April 8 launch
- **Saffire-1**: First of six fire safety experiments investigating spread of fires in microgravity, and demonstrating technologies for combustion products monitoring and post-fire cleanup. Launched on OA-6 (March 22, 2016); will be activated on May 20 after Cygnus departs from ISS
- **Long Duration Sorbent Test Bed**: improved sorbents for CO2 removal (Feb. 2016)
- **Organic Water Monitor**: measuring organic contaminants in ISS water system (Apr. 2016)
- **Aerosol Sampler**: Quantitative data on ambient air quality (Apr. 2016)
- **Brine Processor**: Ionomer Membrane Water Processor to purify and recover 86% of the available water from brine (Dec. 2017)
- **Spacecraft Atmosphere Monitor**: Miniature mass spectrometer for detecting trace gas contaminants in ISS air (Feb. 2018)
- **Universal Waste Management System**: Common compact toilet for ISS and Orion (Oct. 2018)
- **Primary Wastewater Processor**: Cascade Distillation System for wastewater processing (Feb. 2019)
- **High Pressure High Purity Oxygen Generation**: Demonstration of a High Pressure/High Purity Oxygen generation system to support future EVA and emergency medical needs (Sep. 2019)
- **Oxygen Recovery**: Demonstration of Plasma Pyrolysis Assembly to convert up to 90% of the oxygen from carbon dioxide. (Oct. 2019)
- **CO2 Removal**: Demonstration of the next generation CO2 removal system that can operate for extended durations without maintenance. (Sep. 2021)

STMD Technology Demonstrator Portfolio



Laser Communication Relay Demonstration



Demo Description (STMD/HEOMD):

- Two-year flight demonstration to advance optical communications technology toward infusion into operational systems while growing the capabilities of industry

Objectives:

- Demonstrate bidirectional optical communication between GEO and Earth
- Measure and characterize system performance over a variety of conditions
- Provide on-orbit capability for test and demonstration of standards for optical relay communications
- Transfer laser communication technology to industry for future missions
- DoD Partnership to add encryption capability

Anticipated Benefits:

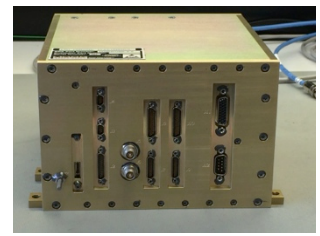
- A reliable, capable, cost effective optical comm technology for infusion into future operational systems

Anticipated Mission Use:

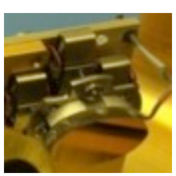
- Next-gen TDRS and near-earth science; ISS & human spaceflight
- LCRD project is taking major steps toward commercialization and infusion into industry

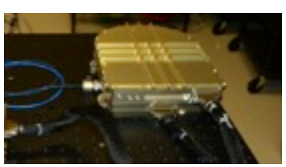
Optical Communication for Deep Space

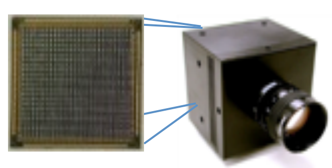
FY15	FY16	FY17	FY18	FY19
Engineering Model Assembly & Test & Flight Units Fabrication	Flight Units Assembly & Test	Complete Flight Unit Assembly & Test	Flight Payload Integration & Test	Mission Integration & Test & Hosted Spacecraft Notional Launch Readiness



FY15	FY16	FY17	FY17+
Complete Laboratory Testing of Photon Counting Camera	Deliver Optics and Laser Transmitter Assembly	Ground Demo of DSOC System	TDM DSOC: Targeted for Discovery 2014







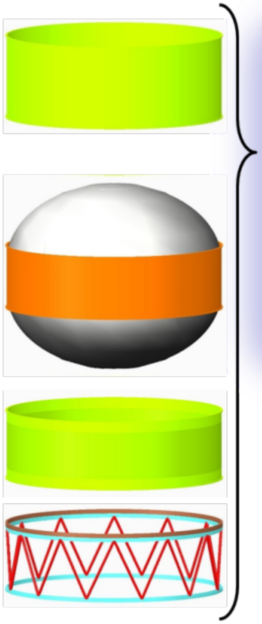
Evolvable Cryogenics

Metallic forward skirt with heaters and Vapor Cooling

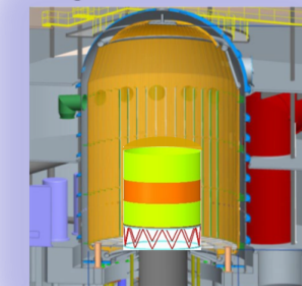
4m diameter liquid hydrogen tank, insulated with SOFI and MLI

Aft skirt

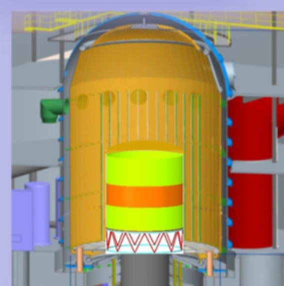
Support structure



Thermal performance testing in B-2:



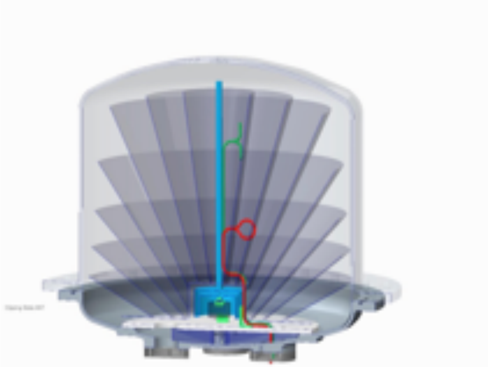
Acoustic vibration test at RATF:



Repeat thermal performance testing in B-2

Integrated Vehicle Fluid (IVF) System Assessment for SLS

SHIIVER Test



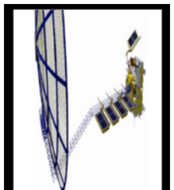
Radio Frequency Mass Gauge (RFMG)

eCryo develops, integrates and validates cryogenic fluid management (CFM) technologies at a scale relevant to and meeting the mission needs for SLS Stages and Exploration Systems

- Testing ranges from components to entire systems
- Ground-based project leveraging CFM competencies and facilities at GRC and MSFC

STMD Public-Private Partnerships

- **Market research revealed two categories of Industry-led Space Technologies**
  - Those at a “tipping point”, where a final demonstration or validation would result in rapid adoption and utilization – “STMD Tipping Point Solicitation”
  - Those that could directly benefit from NASA’s unique experience, expertise, facilities – “STMD Announcement of Collaboration Opportunity (ACO)”
- **Tipping Point and ACO solicitation released May 2014**
  - Topics: Robotic In-Space Manufacturing, Small Spacecraft Systems, Remote Sensing Instrumentation, Advanced Thermal Protection, Launch Systems Development
  - Nine Tipping Point and Thirteen ACO industry-led projects selected across all topics
  - Three Robotic In-Space Manufacturing projects selected for Phase 1 activities



- **Space Systems Loral** (Palo Alto, California): “Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors” - will modify existing antenna/robotic equipment to perform a high fidelity antenna assembly ground demonstration to provide next generation of performance advancements in GEO ComSats
- **Orbital ATK** (Dulles, Virginia): “Public-Private Partnership for Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures” - will perform an integrated ground demonstration including robotically deployed rigid backbone and upgraded TALISMAN system
- **Made in Space, Inc.** (Moffett Field, California): “Versatile In-Space Robotic Precision Manufacturing and Assembly System” - will utilize the Archinaut in-space additive manufacturing and assembly system in a space environment test

Game Changing Development Program*

AEDL

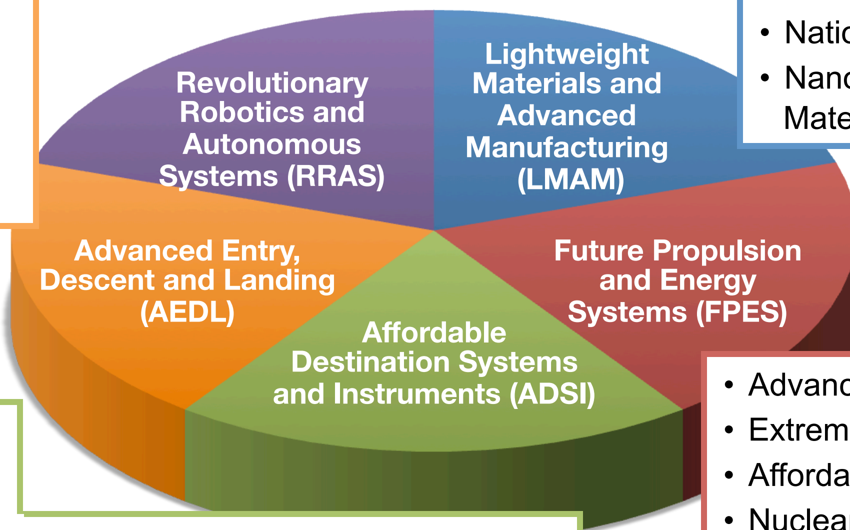
- Entry Systems Modeling
- Mars Entry Descent and Landing Instrument (MEDLI-2)
- Propulsive Descent Technology
- Heatshield for Extreme Entry Environment TPS (HEEET)
- Conformal Ablative TPS
- Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
- Adaptable, Deployable Entry Placement Technology (ADEPT)

RRAS

- Resource Prospector Rover
- National Robotics Initiative
- Pop-Up Flat Folding Explorer Robotics (PUFFER)
- Astro Bee
- Autonomous Cryo Loading Operations

LMAM

- Low Cost Upper Stage
- Additive Construction for Mobile Emplacement
- Bulk Metallic Glass
- Manufacturing Initiative
- Materials Genome Initiative
- National Center for Advanced Manufacturing
- National Nanotechnology Institute
- Nanotechnology: Ultra-light Core Materials; Wires and Cables



ADSI

- High Performance Spaceflight Computing (HPSC)
- Ultra-Low Temperature Batteries
- Ultra-Low Temperature Radiation Hard Electronics
- Station Explorer for X-Ray Timing and Navigation Technology (SEXTANT)
- Landing Guidance Navigation and Control
- Icy Body Mobility
- Thick Gamma Cosmic Ray Shield
- SpaceCraft Oxygen Recovery
- High Performance EVA Gloves
- TPS Phase Change Material
- High-Capacity Cryocooler
- Synthetic Biological Membrane

FPES

- Advanced Energy Storage Systems
- Extreme Environment Solar Power
- Affordable Vehicle Avionics
- Nuclear Thermal Propulsion
- Iodine Hall Thruster
- DESLA Upper Stage Engine Testing
- Design & Manufacture Cryo Prop Tank for Air Launched Liquid Rocket
- Flight Qualification of Busek's 5N Green Monopropellant Thruster

* Not a complete project list

Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR)

SBIR/STTR topics chosen and managed to advance small business and also support NASA's mission needs

Provides the small business sector and research institutions with an opportunity to compete for funding to develop technology for NASA and commercialize that technology to spur economic growth.

- **Annual Solicitations for Phase I awards**
- **Phase II proposed 6 months later**
  - Phase II Extended: Cost sharing opportunity to promote extended R&D efforts of current Phase II contracts.
- **Phase III: Infusion of SBIR/STTR technologies to NASA missions.**
  - Contract funded from sources other than the SBIR/STTR programs and may be awarded without further competition.

FY 2015 Awards:

- SBIR Awards: 325 Phase I and 119 Phase II; 7 Phase I Selects and 10 Phase II Selects
- STTR Awards: 50 Phase I and 21 Phase II
- Phase II-E Awards: 31 SBIR/STTR Phase II-Es were awarded, leveraging $5.36 M funds from non-SBIR sources

FY16 Topics

Small Business Technology Transfer

- Launch Propulsion Systems
- In-Space Propulsion Technologies

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Human Exploration and Operations

- In-situ Resource Utilization (ISRU)
- Space Transportation
- Life Support and Habitation Systems
- Extra-Vehicular Activity (EVA)
- Lightweight Structures and Materials
- Autonomous and Robotic Systems
- Entry, Descent, and Landing
- High Efficiency Space Power
- Space Communications and Navigation
- Ground Processing
- Radiation Protection
- Human Re
- Non-Destr
- Internation & Develop Tec

Aeronautics

- Air Vehicle Technology

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Science

- Sensors, Detectors and Instruments
- Advanced Telescope Systems

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Technologies

Space Technology

- Power & Energy Storage
- Thermal Management
- Advanced Manufacturing
- Lightweight Structures and Materials
- Robotics and Autonomous Systems
- Wireless Technology

Space Technology Research Grants (STRG)

NASA Space Technology Research Fellowships (NSTRF)

- Graduate student research in space technology; research conducted on campuses and at NASA Centers and not-for-profit R&D labs

Early Career Faculty (ECF)

- Focused on supporting outstanding faculty researchers early in their careers as they conduct space technology research of high priority to NASA's Mission Directorates

Early Stage Innovations (ESI)

- University-led, possibly multiple investigator, efforts on early-stage space technology research of high priority to NASA's Mission Directorates
- Paid teaming with other universities, industry and non-profits permitted

> - ECF-16 proposals due: April 1
> - ESI-16 solicitation release: May
> - Establish Virtual Institutes in FY17

Recent ECF and ESI Topics (# Awards)

ECF-16

- Advanced In-Space Propulsion Technologies (TBD)
- Effective Human-Robot Interaction (HRI) for Space Exploration (TBD)
- Verification and Validation of Autonomous Systems (TBD)
- Cryogenic Actuator Technology (CAT) Development (TBD)

ESI-15

- Robotic Mobility Technologies for the Surfaces of Icy Moons (2)
- Payload Technologies for Assistive Free-Flyers (4)
- Integrated Photonics for Space Optical Communication (5)
- Atmospheric Entry Modeling Development Using Orion EFT-1 Flight Data (2)
- Computationally Guided Structural Nanomaterials Design (2)
- High Voltage PMAD Electronics for Space Applications (0)
- Discrete Cellular Materials Assembly, Repair, and Reconfiguration (0)

ECF-15

- High Temperature Solar Cells (2)
- Dynamic Tensegrity Technologies for Space Science and Exploration (1)
- Synthetic Biology Technologies for Space Exploration (2)
- Fundamental Aerothermodynamic Model Development (3)

Space Technology Drives Exploration

- Delivering on today's commitments
- Utilizing architecture assessments to drive investment strategy
- Leveraging across Mission Directorates and Centers to enhance technology development activities
- Identifying partnership opportunities to leverage resources
- Maintaining a comprehensive portfolio to ensure innovative concepts have opportunity to solve tomorrow's challenges
- Putting the pieces in place to enable human exploration of Mars

National Aeronautics and
Space Administration

Technology Drives Innovation

www.nasa.gov/spacetech

Backup Material

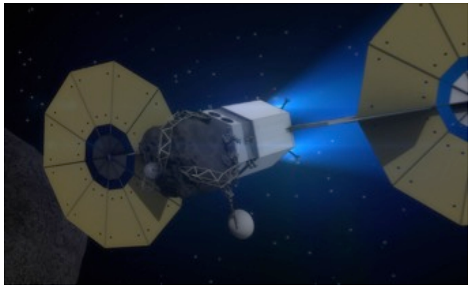
Summary of Ongoing Technology Development Activities

In-Space Power & Propulsion

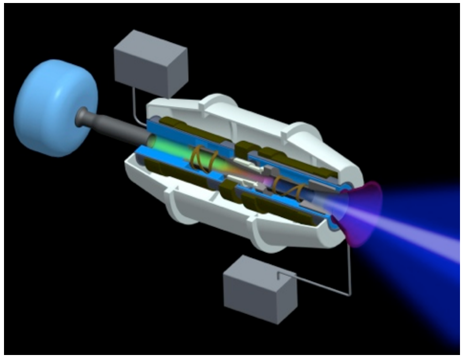
(P1-x) refers to Proving Ground Phase 1 Flight Test Objective

- **Objectives**
  - Develop 100 kW-class solar electric propulsion systems for transporting cargo to Mars.
  - Develop technologies for nuclear thermal propulsion to enable rapid transport of crew to Mars.

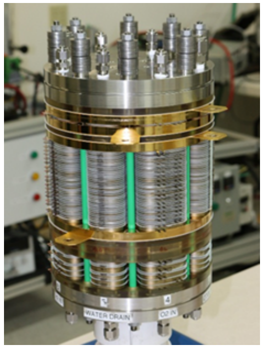
- **Current Activities**
  - **Solar Electric Propulsion (SEP):** Develop 40 kW SEP system for Asteroid Redirect Mission (ARM). (STMD) (P1-6)
  - **Next Space Technologies Exploration Partnerships (NextSTEP):** Develop 100 kW electric propulsion systems and testing for 100 continuous hours. (AES) (P1-6)
  - **Green Propellant Infusion Mission (GPIM):** Demonstrate on-orbit performance of an alternative fuel to hydrazine to improve propellant efficiency and reduce toxic handling concerns. (STMD)
  - **Nuclear Thermal Propulsion (NTP)**: Develop fuel elements, engine design, and perform system assessment of NTP viability for human exploration transportation. (STMD)
  - **Advanced Solar Arrays:** Develop 50 kW solar arrays for SEP and in-space power generation. (STMD) (P1-7)
  - **Extreme Environment Solar Power**: Develop advanced solar power capable of operating in deep space environments (low temperature, low intensity, and high radiation). (STMD/SMD) (P1-17)
  - **Energy Storage**: Develop high energy density batteries for space suits and fuel cells for SLS. (AES/STMD) (P1-19)



SEP for ARM



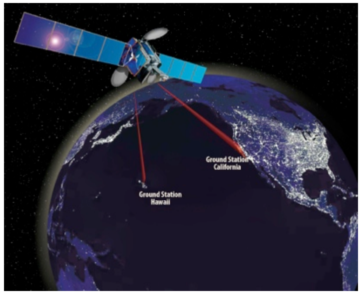
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)



1 kW fuel cell

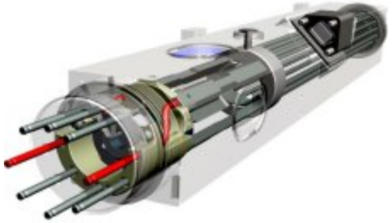
Communication & Navigation

- **Objectives**
  - Develop high-data rate communications infrastructure to support deep space missions.
  - Develop new technologies for precise deep space navigation.
- **Current Activities**
  - **Laser Communications Relay Demonstration (LCRD)**: Flight test of optical communications between ground and GEO. (SCAN/STMD)
  - **Deep Space Optical Communications (DSOC)**: Perform technology demonstration of deep-space optical communication capable of high bandwidth downlinks from outside cis-lunar space for 10x improvement. Provide hardware to SMD's Discovery for demo. (SCAN/STMD)
  - **Ka-Band Objects Observation & Monitoring (KaBOOM):** Demonstrating antenna arrays with atmospheric disturbance compensation for future space communications and radar applications. (AES) (P1-10)
  - **Disruption Tolerant Networking (DTN):** Infusion of store and forward communications protocols into NASA and international missions. (AES) (P1-10)
  - **Deep Space Atomic Clock:** Flight test of ultra-precise atomic clock for deep space navigation. (STMD) (P1-8)
  - **NICER/SEXTANT**: Demonstration of deep space navigation using X-ray pulsars. (STMD) (P1-8)
  - **High Performance Spaceflight Computing:** More capable radiation-hard general purpose multi-core processor for low power space applications. (STMD/SMD) (P1-17)



LCRD

KaBOOM at KSC



Deep Space Atomic Clock

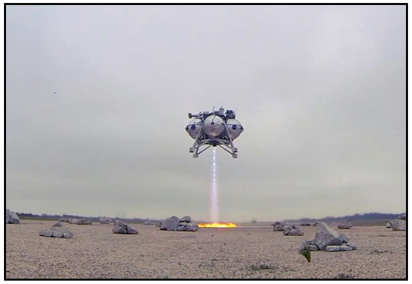
Entry, Descent, and Landing (EDL)

- **<u>Objectives</u>**
  - Develop the capability to land science and human exploration payloads (> 18 mt) on Mars.

- **<u>Current Activities</u>**
  - **EDL Architecture:** Studying EDL architecture alternatives for a mission to Mars in 2026 to test subscale EDL system for human missions. (EMC/STMD)
  - **Low Density Supersonic Decelerator (LDSD):** Flight test of supersonic aerodynamic decelerator and supersonic ring sail parachute for future robotic missions to Mars. (STMD/SMD) – *Under Review*
  - **Supersonic Retro Propulsion**: Evaluate SpaceX flyback booster tests data to validate models. (STMD)
  - **Hypersonic Inflatable Aerodynamic Decelerator (HIAD):** Conducted sounding rocket flight tests of subscale HIAD. (STMD)
  - **Adaptable Deployable Entry & Placement Technology (ADEPT):** Deployable, semi-rigid aeroshell. (STMD)

LDSD flight hardware

HIAD engineering model

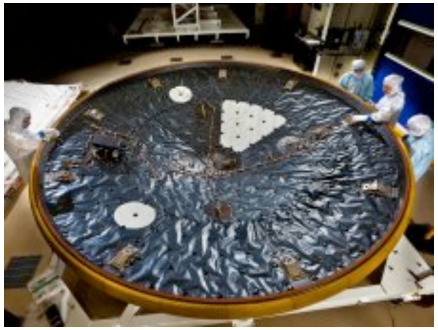


ALHAT testing on Morpheus lander

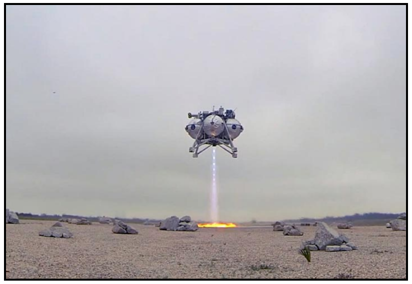
Entry, Descent, and Landing (EDL) (cont.)

- **<u>Objectives</u>**
  - Develop the capability to land science and human exploration payloads (> 18 mt) on Mars.

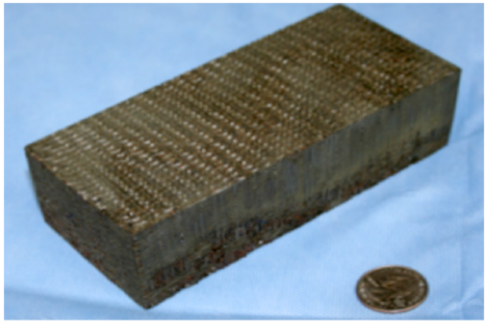
- **<u>Current Activities (cont.)</u>**
  - **Entry Systems Modeling:** Updating and improving computational fluid dynamics codes to reduce design uncertainties for future missions. (STMD)
  - **Mars Entry, Descent, & Landing Instrumentation (MEDLI-2):** Measuring temperatures and pressures on Mars 2020 heat shield to validate aerothermal models. (AES/STMD)
  - **Advanced Thermal Protection System (TPS) materials**: Developing woven and high heat flux TPS materials. (STMD)
  - **Terrain Relative Navigation (TRN):** Greatly improve targeting accuracy to enable exploring high-value landing sites near hazards for Mars 2020. (SMD/STMD) (P1-11)
  - **Autonomous Landing & Hazard Avoidance Technology (ALHAT):** Flight test of ALHAT system on Morpheus lander. (AES)



MEDLI Instrumentation



ALHAT testing on Morpheus lander

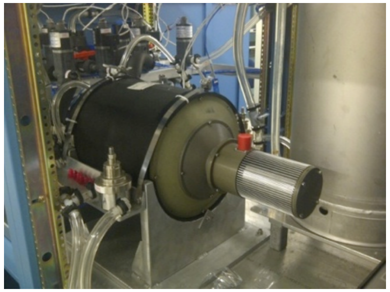


Woven TPS

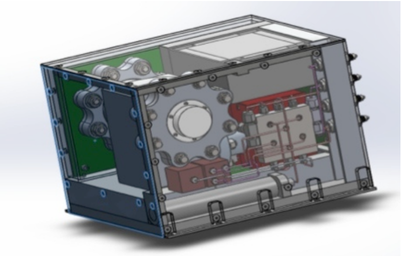
Environmental Control & Life Support

- **Objectives**
  - Develop highly-reliable life support systems that recycle air, water, and waste to reduce consumables.
  - Demonstrate next generation life support systems with integrated ground-based testing and ISS flight experiments.

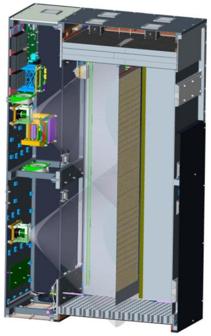
- **Current Activities**
  - **Spacecraft Oxygen Recovery**: Developing technologies to recover at least 75% of the oxygen from a spacecraft atmosphere revitalization system. (STMD) (P1-2, P1-16)
  - **Sorbents for CO_2 Removal:** Developing new sorbents that do not generate dust. (AES) (P1-2, P1-16)
  - **High Pressure Oxygen Generation:** Providing oxygen supply for replenishing space suits. (AES) (P1-19)
  - **Waste Water Processing**: Developing green pre-treatments, Cascade Distillation System, and Biological Water Processor. (AES/STMD) (P1-2, P1-16)
  - **Spacecraft Atmosphere Monitor:** Instrument for detecting trace gas contaminants in ISS air. (AES) (P1-2, P1-16)
  - **PCM Heat Exchanger**: Developing a large-scale Phase Change Material heat exchanger to maintain the crew cabin within safe/comfortable temperatures throughout exploration missions. (STMD) (P1-2, P1-16)
  - **Spacecraft Fire Safety:** Saffire experiments will investigate the spread of fires in microgravity. Also developing technologies for fire suppression, combustion products monitoring, and post fire clean-up. (AES) (P1-2, P1-16)
  - **Next Space Technology Exploration Partnerships (NextSTEP):** Developing advanced CO_2 removal technologies, modular ECLSS, and hybrid biological and chemical life support systems. (AES) (P1-2, P1-16)



Cascade Distillation System



Spacecraft Atmosphere Monitor

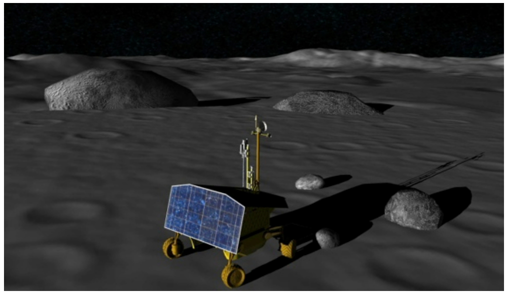


Saffire Fire Safety Experiment

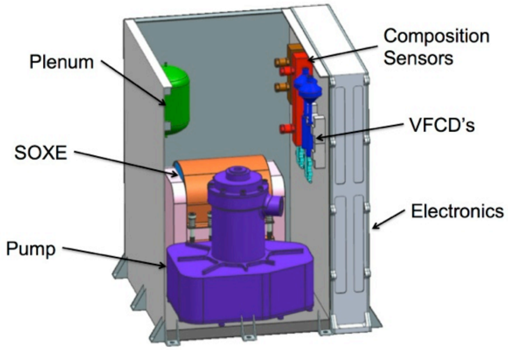
In Situ Resource Utilization & Surface Power

- **<u>Objectives</u>**
  - Reduce logistical support from Earth by utilizing local resources to produce water, oxygen, propellants, and other consumables.
  - Generate abundant power for surface systems.

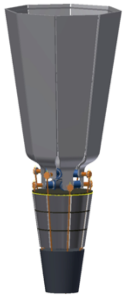
- **<u>Current Activities</u>**
  - **Resource Prospector**: Formulating robotic mission to prospect for ice and other volatiles in polar regions of the Moon. (AES/STMD)
  - **Mars Oxygen ISRU Experiment (MOXIE)**: Demonstration of oxygen production from the Mars atmosphere on the Mars 2020 mission. (AES/STMD)
  - **Fission Surface Power:** Ground demonstration of Stirling power conversion technology and small nuclear reactors for 1-10 kW modular surface power systems. (STMD) – *Under Review*



Resource Prospector



MOXIE



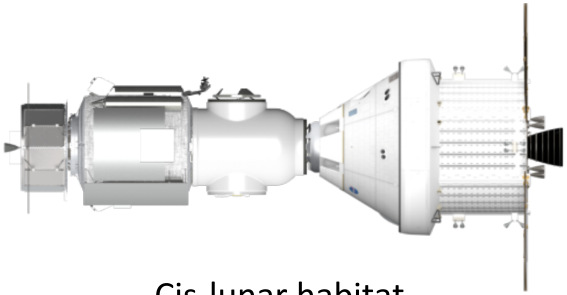
Kilopower fission surface power system

Habitation & Mobility

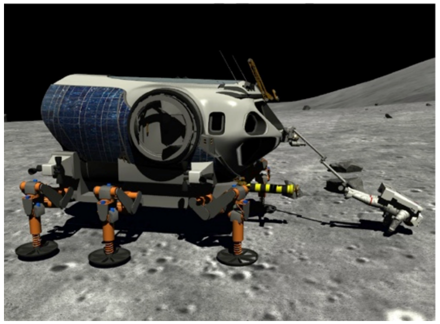
- **Objectives**
  - Develop a deep space habitat that will enable a crew to live in deep space on missions lasting 1,000 days.
  - Develop surface mobility systems that will allow the crew to explore regions beyond the immediate vicinity of the landing site.

- **Current Activities**
  - **Bigelow Expandable Activity Module (BEAM)**: Demonstration of inflatable habitat on ISS. (AES) (P1-2, P1-16)
  - **Next Space Technology Exploration Partnerships (NextSTEP):** Commercial partnerships to develop concepts for cis-lunar habitats that are extensible to Mars transit habitats. (AES) (P1-2, P1-16)
  - **Phobos Exploration Vehicle:** Developing concept for hopper to transport crew in a pressurized cabin. (EMC)

BEAM flight hardware



Cis-lunar habitat

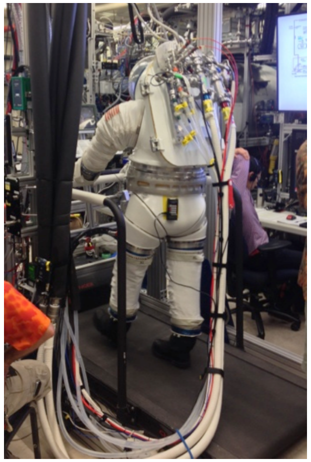


Phobos Exploration Vehicle

Exploration EVA

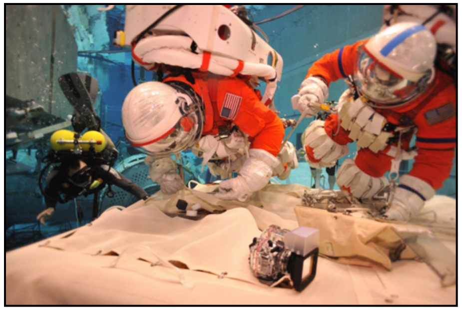
- **Objectives**
  - Enable the crew to conduct "hands-on" surface exploration and in-space operations.
  - Demonstrate advanced space suit on ISS.

- **Current Activities**
  - **Portable Life Support System (PLSS)**: Developing next generation PLSS with new technology components for carbon dioxide removal, pressure regulation, thermal control, and energy storage. (AES/STMD) (P1-18, P1-19)
  - **Z-Suit:** Developing advanced space suit with improved mobility for surface exploration. (AES)
  - **Modified Advanced Crew Escape Suit (MACES):** Conducting neutral buoyancy tests of short duration space suit for Asteroid Redirect Mission. (AES) (P1-18, P1-19)
  - **EVA Gloves:** Developing actuated and counter-pressure gloves with improved dexterity. (STMD) (P1-18, P1-19)



Human-in-the-loop testing of PLSS 2.0

Z-2 suit



MACES testing in Neutral Buoyancy Lab

Crew Health

- **Objectives**
  - Keep the crew healthy on missions lasting up to 1,000 days.

- **Current Activities**
  - **1-year mission on ISS**: Studying the effects of long missions on crew health and performance. (ISS)
  - **Human Health Countermeasures**: Developing countermeasures such as exercise and pharmaceuticals for mitigating the detrimental effects of spaceflight on human physiology. (HRP)
  - **Exploration Medical Capability:** Developing medical technologies for in-flight diagnosis and treatment. (HRP)
  - **Synthetic Biology**: Developing genetically engineered bacteria to produce bionutrients to supplement the crew's diet. (AES)

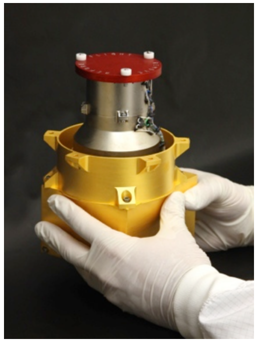
1-year mission on ISS

Exercising on ISS

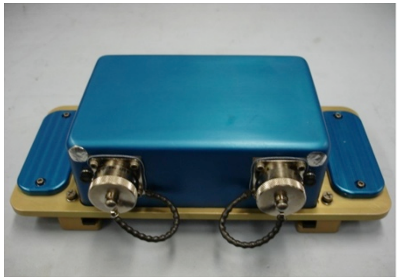
Radiation Safety

- **Objectives**
  - Characterize the radiation environments of potential destinations for human exploration.
  - Understand the biological effects of space radiation.
  - Develop shielding and countermeasures to protect crew from harmful space radiation.

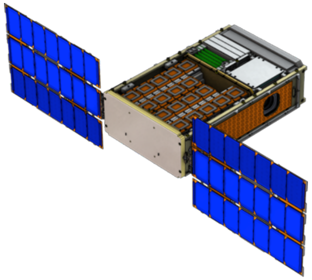
- **Current Activities**
  - **Radiation Assessment Detector (RAD)**: Characterizing Mars surface radiation environment on Mars Science Laboratory mission. (AES) (P1-20, P1-21)
  - **Radiation Environment Monitors:** Measuring radiation environments on Orion and ISS. (AES) (P1-20, P1-21)
  - **BioSentinel:** CubeSat that will investigate the effects of deep space radiation environment on yeast DNA. (AES) (P1-21, P1-22)
  - **Radiation Forecasting:** Developing improved models to predict solar particle events. (AES) (P1-20, P1-21)
  - **Advanced Radiation Protection:** Combined analytical and empirical effort to validate the radiation shielding efficiency of spacecraft materials to ultimately develop a minimal mass vehicle design. (STMD) (P1-20, P1-21)
  - **NASA Space Radiation Laboratory**: Particle beam testing at Brookhaven National Laboratory to investigate the effects of galactic cosmic radiation on rodents and to validate radiation transport models for shielding design. (HRP) (P1-20, P1-21)



Radiation Assessment Detector



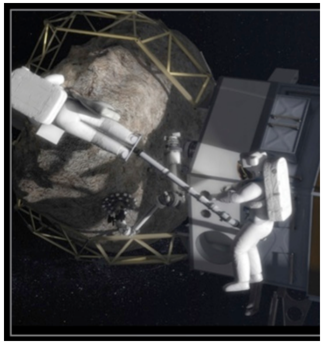
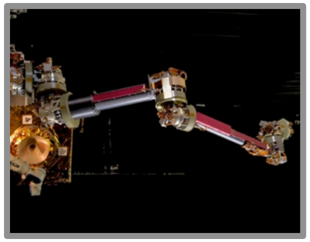
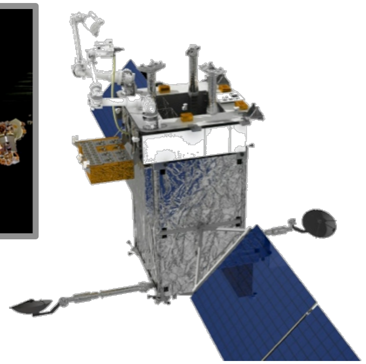
Radiation Environment Monitor flown on EFT-1



BioSentinel CubeSat

Human/Robotic & Autonomous Operations

- **Objectives**
  - Advance technologies critical for spaceflight infrastructure, including non-cooperative autonomous rendezvous, robotic capture and servicing, refueling, crew interactions
- **Current Activities**
  - **Asteroid Redirect Mission (ARM):** Robotic mission to visit a large near-Earth asteroid, collect a multi-ton boulder from its surface, and redirect it into a stable orbit around the moon. (HEOMD/STMD/SMD) (P1-6, P1-7, P1-8, P1-10, P1-11, P1-13, P1-14, P1-15, P1-18, P1-19)
  - **Restore-L**: Autonomous rendezvous and refuel a government-owned satellite in low Earth Orbit. Common rendezvous & proximity operations sensors, robotics technologies with ARM. (STMD) (P1-13, P1-14, P1-18)
  - **In-Space Robotic Manufacturing and Assembly of Space Structures**: Three new projects that advance space technologies with industry at tipping point in their development. (STMD) (P1-13)


Human/Robotic & Autonomous Operations (cont.)

- **Objectives**
  - Develop robotic assistants to support human exploration.
  - Reduce the crew's dependence on ground-based mission control.
  - Automate ground operations to reduce cost.

- **Current Activities**
  - **Robonaut-2:** Anthropomorphic robotic assistant on ISS to support crew with IVA and EVA. (STMD) – *Under Review* (P1-9, P1-13)
  - **Astrobee free flyer**: Next generation IVA free flyer on ISS will demonstrate autonomous logistics management. (STMD) (P1-9, P1-12, P1-13)
  - **Autonomous Mission Ops**: Developing software tools for vehicle systems monitoring and fault diagnosis, automated scheduling of maintenance tasks, and automated procedure execution. Demonstrating capabilities on Orion and ISS. (AES) (P1-2, P1-11)
  - **Automated Propellant Loading**: Demonstrating autonomous fueling of launch vehicles with cryogenic propellants. (AES)

Robonaut-2 on ISS

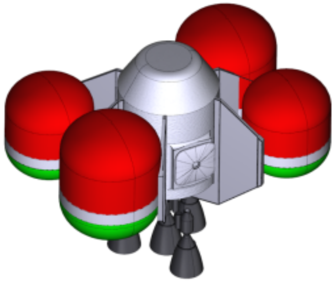
Astrobee free flyer

Crew-centric mission ops

Ascent from Planetary Surfaces

- **Objectives**
  - Develop concepts and propulsion technologies for Mars Ascent Vehicle (MAV).

- **Current Activities**
  - **MAV Concepts**: Developing MAV concepts for Mars Sample Return and human missions. (EMC)
  - **LOX-Methane Propulsion:** Developing rocket engines that can use propellants produced from Mars resources. (AES)



MAV concept

LOX-methane engine test