Scope Title
Kilowatt-Class Fission Energy Conversion

Scope Description
NASA is considering the use of kilowatt class Fission Power Systems for surface missions to the moon and Mars. This technology directly aligns with the Space Technology Mission Directorate (STMD) roadmap for space power and energy storage. Prior work in fission power systems had focused on a 1kWe ground demonstration, however, NASA desires to scale-up the system and components for a flight demo mission to the lunar surface, so component technologies that support a 10kWe-class fission power system are sought that address the following technical challenges:

- Robust, efficient, highly reliable, and long-life thermal-to-electric power conversion in the range of 1-10kWe. Stirling, Brayton, and thermoelectric convertors that can be coupled to Kilopower reactors are of interest.
- Freeze tolerant heat pipe radiators that can operate through lunar night (-173 ºC) and day (127 ºC) temperature swings. Heat pipes must start-up from lunar night temperature and begin transferring heat within several thermal cycles.
- Radiation shield materials selection, design, and fabrication for mixed neutron and gamma environments, with consideration for mass effectiveness, manufacturability, and cost.
- Radiation tolerant generator control electronics designed to withstand an induced radiation environment in addition to the ambient environment in space. These electronics can include: source control and generation, high voltage outputs with dynamic response needed to meet power quality standards, short term heating prior to startup, shunt control to manage excess power production, and source monitoring for power management. Target dose tolerance ranges for fission power system electronics are between 1E11 to 1E13 n/cm² total neutron fluence, and between 100 kRad (Si) and 1000kRad (Si) total ionizing gamma dose. Natural space environment should also be considered, with specific attention to Single Event Effect susceptibility.

The desired deliverables are primarily prototype hardware, research, and analysis to demonstrate concept feasibility and a TRL range of 3 to 5. The prototype hardware may include one (or more) of the following:

- Power convertor (hot-end temperature = 800 ºC, cold-end temperature = 100 to 200 ºC)
- Heat pipe radiator (for up to 30 kW heat rejection)
- Radiation shield (reduce radiation down to 1E11 to 1E13 n/cm² neutron fluence and 100 to 1000 kRad TID)
at minimum mass)
  - Control electronics (capable of surviving the radiation environment that passes through the radiation shield)

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services [1]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Kilopower (https://www.nasa.gov/directorates/spacetech/kilopower [2]).


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware, Analysis, and Research

Desired Deliverables Description

We are primarily looking for component and/or breadboard hardware to demonstrate concept feasibility in a lab or relevant environment. The appropriate research and analysis required to develop the hardware are also desired.

State of the Art and Critical Gaps

Kilowatt-class fission power generation is an enabling technology for lunar and Mars surface missions that require day and night power for long-duration surface operations, and may be the only viable power option to achieve a sustained human presence. The surface assets that could benefit from a continuous and reliable fission power supply include landers, rover recharge stations, science platforms, mining equipment, ISRU (In-Situ Resource Utilization) propellant production, and crew habitats. Compared to solar arrays with energy storage, nuclear fission offers considerable mass savings, greater simplicity of deployment, improved environmental tolerance, and superior growth potential for increasing power demands. Fission power is also one of very few technologies that can be used on either the moon or Mars with the same basic design. A first-use on the moon provides an excellent proving ground for future Mars systems, on which the crew will be highly dependent for their survival and return propellant. The technology is also extensible to outer planet science missions with power requirements that exceed the capacity of radioisotope generators, including nuclear electric propulsion spacecraft that could enable certain science missions that might otherwise be impossible.
Current work on fission power systems has focused on a 1kWe design using a highly enriched Uranium-Molybdenum reactor core with a Beryllium oxide reflector. Depleted uranium, tungsten, and lithium hydride provide shielding of gamma rays and neutrons to the power conversion system, control electronics, payload, and habitat. Heat is removed from the core at approximately 800° C using sodium heat pipes and delivered to the power conversion system. Waste heat is removed from the power conversion system at approximately 100 to 200° C using water heat pipes coupled to aluminum or composite radiator panels.

Reliable, robust, and long life power conversion is highly desirable in fission systems. There are currently not enough vendors or enough long duration reliability data for power conversion technologies under these operating conditions and environments. More work is needed in this area to expand the supplier base, and to increase the TRL of power conversion technology. The reactor core must be isolated from the Martian environment to prevent oxidation. However, simply canning the core may not be an option since increased distance between the core and reflector can have large negative effects on system mass. Canning the reflector and core together is the simplest option; however, the increased temperature of the reflector results in reduced reactivity and increased mass. Innovations are necessary to provide isolation while reducing the negative effect due to the neutronics.

Total Ionizing Dose (TID) effects, Displacement Damage Dose (DDD) effects, and Single Event Effect (SEE) transients are well studied for the standard space radiation environment composed of charged particles and electromagnetic radiation of either solar or galactic origin. Aerospace electronics vendors offer high reliability product lines that have been qualified using standard irradiation testing procedures. These procedures do not typically cover the neutron environment of a nuclear fission reactor. Further qualification in a reactor radiation environment is needed for components and systems that will be used in a space fission power system.

Relevance / Science Traceability

This technology directly aligns with the STMD roadmap for space power and energy storage. This technology could be infused into the Kilopower Project to enhance performance or reliability.

Z1.05 Lunar & Planetary Surface Power Management & Distribution

Lead Center: GSFC

Participating Center(s): GSFC, JSC

Technology Area: TA15 Aeronautics

Scope Title

Innovative ways to transmit high power for lunar & Mars surface missions

Scope Description

The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA’s plans for future human-rated space missions. A major factor in this involves establishing bases on the lunar surface and eventually Mars. Surface power for bases is envisioned to be located remotely from the habitat modules and must be efficiently transferred over significant distances. The International Space Station (ISS) has the highest power (100kW), and largest space power distribution system with eight interleaved micro-grids providing power functions similar to a terrestrial power utility. Planetary bases will be similar to the ISS with expectations of multiple power sources, storage, science, and habitation modules, but at higher power levels and with longer distribution networks providing interconnection. In order to enable high power (>100kW) and longer distribution systems on the surface of the moon or Mars, NASA is in need of innovative technologies in the areas of lower mass/higher efficiency power electronic regulators, switchgear, cabling, connectors, wireless sensors, power beaming, power scavenging, and power management control. The technologies of interest would need to operate in extreme temperature environments, including lunar night, and could experience temperature changes from -153C to 123C for lunar applications, and -125C to 80C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation
levels.

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

Specific technologies of interest would need to address the lunar or Mars environment, and include:

- Application of wide bandgap electronics in DC-DC isolating converters with wide temperature (-70°C to 150°C), high power density (>2 kW/kg), high efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Low mass, highly conductive wires and terminations that provide reliable small gauges for long distance power transmission in the 1-10kW range, low mass insulation materials with increased dielectric breakdown strength and void reductions with 600 V or greater ratings, and low loss/low mass shielding.
- Power beaming concepts to enable highly efficient flexible/mobile power transfer in the 100-1,000W range, including the fusion of power/communication/navigation.

(See Z13.02 - Dust Tolerant Mechanismssubtopic to propose power connection/termination related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically-enabled high voltage connectors and/or near-field wireless power transfer in the 1-10kW range.)

References


Space Policy Directive, December 2017: [https://www.nasa.gov/topics/moon-to-mars/overview] [4]

Expected TRL or TRL range at completion of the project 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

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

State of the Art and Critical Gaps

While high power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes which will be encountered. The temperature swings will be a critical requirement on any technology developed, from power converters to cabling or power beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms.

Relevance / Science Traceability

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

Z1.06 Radiation tolerant high-voltage, high-power electronics

Lead Center: GSFC

Participating Center(s): GRC, JPL, LaRC

Technology Area: TA15 Aeronautics

Scope Description

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

- **High-voltage, high-power solutions**: Technology Area (TA) 3.3.3, Power Management and Distribution (PMAD) Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme-temperature components for power distribution systems. NASA has a core need for diodes and transistors that meet the following specifications:
  - Diodes: minimum 1200 V, 40 A, with fast recovery < 50 ns;
  - Transistors: minimum 600 V, 40 A, with < 24 mohm on-state drain-source resistance.

- **High-voltage, low-power solutions**: In support of TA 8.1 (Remote Sensing Instruments and Sensors), radiation-hardened, high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
  - Transistors: minimum 1000 V, < 40 ns rise and fall times;
  - Diodes: 2 kV to 5 kV, < 50 ns recovery time.

- **High-voltage, low- to medium-power solutions**: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
  - Transistors: minimum 600 V, < 50 ns rise and fall times, current ranging from low to > 20 A.
Successful proposal concepts should result in the fabrication of transistors and/or diodes that meet or exceed the above performance specifications without susceptibility to damage due to the heavy-ion space radiation environment (single-event effects resulting in permanent degradation or catastrophic failure). These diodes and/or transistors will form the basis of innovative, high-efficiency, low mass and volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion radiation-tolerant devices. Proposals must state the initial state of the art for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle:

- For vertical-field power devices: No heavy-ion induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface incident Linear Energy Transfer (LET) of 40 MeV-cm$^2$/mg and sufficient energy maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident Linear Energy Transfer (LET) of 75 MeV-cm$^2$/mg and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value (Bragg peak).

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

References

The following is only a partial listing of relevant references:

Expected TRL or TRL range at completion of the project: 5 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

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

State of the Art and Critical Gaps

A prior version of this subtopic, "High-Power, High-Voltage Electronics" was active in 2016-2017 and paused for two years to give time for funded proposals and a similar Early Stage Innovation topic designed to understand the radiation-induced failure mechanisms in wide bandgap semiconductors to mature. This pause has allowed these studies to mature and it is now time to re-open this subtopic to provide a means for applying the knowledge gained toward fabrication of radiation hardened power devices that are tailored to meet performance criteria of a number of NASA technology needs.

High voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial Wide Bandgap (WBG) power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed they are very susceptible to damage from the heavy ion space radiation environment (galactic cosmic rays) that cannot be shielded against. Higher voltage devices are more susceptible to these effects; as a result, to date, there are space qualified GaN (Gallium Nitride) transistors now available but these are limited to 300 V. Recent radiation testing of 600 V and higher GaN transistors have shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage. NASA
has funded modeling and experimental efforts to understand the silicon carbide's susceptibility to heavy-ion radiation. Re-opening of this topic will provide a path for development and fabrication of hardened designs based upon this research, and encourage progress in other wide bandgap technologies such as higher voltage GaN, gallium oxide, and possibly diamond.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas have been identified for spacecraft PMAD and science instrument power applications and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current PPU's (Power Processing Unit's) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), the technology of this subtopic nomination is truly enabling.

A phase I funded SBIR under the S4.04 Extreme Environments Technology, was awarded (https://sbir.nasa.gov/SBIR/abstracts/19/sbir/phase1/SBIR-19-1-S4.04-3611...) in 2019 to develop low-defect gallium oxide (Ga$_2$O$_3$) based high-voltage power diodes grown on commercially available bulk Ga$_2$O$_3$ substrates via a thin-film deposition technique. The S4.04 Subtopic Manager serves as a participating subtopic manager on this Z1 subtopic to foster good leveraging and to avoid duplication of efforts. The S4.04 subtopic solicits development of technology for extreme temperatures and high total ionizing dose radiation primarily.

Other non-NASA funded efforts include:

Vertical GaN diode development has been a focus of ARPA-E PNDIODE and (previous) SWITCHES programs. Diodes developed under the SWITCHES program were shown by Sandia National Lab to have good switching reliability, but another Italian team has found they may degrade under high current stress. Heavy-ion radiation susceptibility has not been assessed and is not expected to be robust without design alteration.

DoD (Department of Defense) has two funded Ga$_2$O$_3$ technology SBIRs that focus on development of manufacturing capabilities as opposed to device design itself.

**Relevance / Science Traceability**

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

TA 3.3.3, Power Management and Distribution (PMAD) Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme-temperature components for power distribution systems. This subtopic will serve as a feeder to the subtopic Z1.05 - Lunar & Planetary Surface Power Management & Distribution" in which wide bandgap circuits for PMAD applications are solicited. The solicited developments in this subtopic will also feed systems development for Kilopower
due to the savings in size/mass combined with radiation hardness. In addition, power
distribution for lunar and Martian habitats will benefit from power circuits adopting this
subtopic through significantly improved power efficiencies and radiation hardness.

TA 8.1, Remote Sensing Instruments and Sensors, radiation-hardened, high-voltage
transistors are needed for low-mass, low-leakage, high-efficiency applications such as
LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. These
applications are aligned with science objectives including Earth Science LIDAR needs,
Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to
planetary and asteroid research and in the search for life on other planets such as Mars
require high voltage power systems and will thus benefit from mass and power savings
from this subtopic's innovations.

Z2.01 Spacecraft Thermal Management

Lead Center: JSC

Participating Center(s): GRC, GSFC, JPL, MSFC

Technology Area: TA15 Aeronautics

Scope Description

NASA seeks new technologies that will facilitate low mass and highly reliable thermal control systems for the
exploration of our solar system. This solicitation specifically targets new technologies and methods for two-phase
mechanically pumped deployable radiators, novel three-way valves that can operate as either mix or split single
phase fluid flow passively, global access lunar lander technologies, and improved integrated human thermal
modeling. Proposed improvements are expected to demonstrate analytical and/or empirical proof-of-concept
results at the end of Phase I and delivery of a prototype (or better) at the end of Phase II.

Two-Phase Deployable Radiators:

NASA seeks novel deployable radiator designs for two-phase (vapor/liquid) mechanically pumped fluid loop system
that provide passive turn-down capability via stagnation and freeze of the ammonia working fluid in the radiator
condenser (three-phase compatible design). A stretch goal of compatibility with other working fluids is acceptable.
Proposed technologies must address all of the following design goals:

- Condensing radiators with passive, variable heat rejection turn-down capability of greater than 200:1
  achieved through partial to complete coolant freezing and built-in flow bypass
- Compatible with a segmented radiator design where panels are one-time deployable
- Mass goal of < 8 kg/m^2 including fluid and deployable hardware
- Scalable design up to 3 m^2 consisting of 1 m^2 panels
- Materials and structures should be compatible with 15-year life in environments ranging from low Lunar
  orbit, Jupiter orbit (radiation exposure), and inner to outer planet exploration (temperature exposures)
- Working pressures and freeze-tolerance turn-down technologies should assume ammonia as the working
  fluid

Passive Three-Way Valves:

NASA seeks novel three-way valves that can operate as either a mixing valve (two liquid input ports and one liquid
output port) or splitting valve (one liquid input port and two liquid output ports) that can be used to passively control
loop temperatures by the degree fraction of radiator bypass. Such miniature passive thermal control valves could
find use in a number of single-phase mechanically pumped fluid thermal control systems. Proposed technologies
must address the following design goals:

- Design shall autonomously operate without power
- <0.1% flow rate through the shut off port, with a goal of having a provision for no leakage/adjustable leakage through the use of a pre-installed orifice
- Control range of 5-10°C, with pre-adjustable set-point control
- Operational temperature limits -55°C to 90°C, non-operational limits of -55°C to 125°C
- Designs shall be compatible with FC-72 working fluid as well as those used on the ISS thermal control loops (water and ammonia). Retrofit of soft goods are acceptable.
- Mass desire <250 grams (maximum mass 500 g)
- Unit volume <50 cm³ (maximum 100 cm³)
- Leak rate 1x10⁻⁶ scc/s gHe at 200 PSIA
- Minimum 4000 full actuation cycles, desired 17,500 cycles
- Rad hard to 300 krad
- 200 psia maximum expected operating pressure, 200 psia proof pressure, 800 psia burst pressure
- Pressure drop <1.5 psi at 1.5 liters per minute of FC-72 working fluid

Global Access Lunar Technology Development:

NASA is seeking focused efforts to develop large human class lunar lander technologies. Technologies should address a gap associated to long duration habitation on the lunar surface where temperatures range from -193°C in shadow regions (including night) to 120°C at the subsolar point. System technologies should be orientation insensitive; for example, lander side mounted radiators must provide their function regardless of lunar surface temperature condition. Technologies are needed that allow a single vehicle design to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. Adding heaters can add significant vehicle mass to accommodate an additional power source and are not considered a novel architecture approach. Proposed radiator technologies should also address Micrometeoroid and Orbital Debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include: the deposition of dust on radiators leading to degraded optical properties, contamination insensitive evaporators/sublimators to enable long mission life, and self-healing coolant tubes for MMOD impact resilience.

Technologies should be suitable for use in medium sized landers that operate near 1 kW average heat dissipation capacity. Proposed technologies should also be extensible to human class landers that will have variable heat loads, and average loads between 3-6 kW. All technologies should support a minimum flight duration of 5 years and be compatible with the encountered aerospace environment.

This subtopic is different from S3.06 subtopic, which is focused on thermal control technologies for payloads and smaller robotic landers.

Human Thermal Modeling:

Human thermal analysis for space applications has primarily focused on Extravehicular Activity (EVAs), and typically utilized standalone tools for these short duration assessments. As NASA moves beyond low earth orbit to long duration missions, crew member induced loads to an exploration vehicle’s thermal control, environmental control, and life support systems need conjugate analytical assessments between crew and vehicle to determine the most mass efficient capacity for these systems. Additionally, these missions will require an exercise prescription at high metabolic rates for the crew which drives the system sizing for CO2, water (vapor and liquid), and metabolic heat removal. The provided human thermal model should be capable of interfacing with Systems Improved Numerical Differencing Analyzer (SINDA) compatible analysis tools to enable conjugate assessments of crew-induced loads and vehicle thermal control systems.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services
CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software

Desired Deliverables Description

Phase I awards are expected to provide a proof-of-concept analysis and supporting hardware/software which demonstrates the ability of the organization to meet the goals stated in the solicitation.

At the culmination of a Phase II contract, deliverables would include math modeling that has been correlated to test data, raw and reduced test data, and delivery of the new hardware or software package to NASA.

State of the Art and Critical Gaps

These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human class spacecrafts. These improvements may come through either novel hardware solutions or
modernization of software tools used to assess human vehicle interactions. The current state-of-the-art (SOA) in thermal control results in vehicle power and mass impact of greater than 25-30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.) the need for intelligent control (both actively and passively) within the thermal control system becomes more apparent. As science payloads continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be provided by traditional thermal control methods due to vehicle level impacts of mass/volume and power.

Relevance / Science Traceability

- Gateway
- Europa Clipper/Lander
- Lunar Lander
- Long duration habitats (moon, mars. etc.)

Z2.02 High Performance Space Computing Technology

Lead Center: JSC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title

Avionics Computing Support

Scope Description

The NASA State-Of-the-Art (SOA) in space computing utilizes 20-year-old technology and is inadequate for future missions. In conjunction with the United States Air Force (USAF), NASA is investing in the development of the High-Performance Spaceflight Computing (HPSC) Chiplet, a radiation-hardened multi-core processor that will improve space computing capabilities by two orders of magnitude. Another joint NASA-USAF project will develop rad-hard, high capacity, high-speed memory components that will likewise improve space computing capabilities by approximately two orders of magnitude. And yet another project, with a planned start date of FY 2019, will start developing a single board computer based on an HPSC-chiplet.

While these efforts will provide an underlying platform, they do not provide the full range of advanced computing capabilities that will be required to support missions currently in the planning stage for the mid-2020s and beyond. Topics of interest include:

- HPSC-compatible Coprocessors: General purpose neural networks and other machine learning accelerators for robotic vision, system health management, and similar applications are needed to meet performance: power requirements in future autonomous robotic systems. Initial design of this application-specific integrated circuit (ASIC) and a validated field-programmable gate arrays (FPGA) implementation of critical portions of the design is desired. A successful SBIR will potentially lead to a Phase 3 award, or alternate funding, to implement the final chiplet.

- Fault Tolerant, Real Time Linux: A flight qualifiable version of Linux for the HPSC Chiplet, capable of supporting parallel and heterogeneous processing for autonomy, robotics and science codes is desired. Initial design of a verifiably reliable, fault tolerant, real time Linux kernel is desired. A successful SBIR will potentially result in a Phase 3 award, or alternate funding, to develop a complete, qualified, operating system.

- Compilers that support Software Implemented Fault Tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for the HPSC Chiplet is desired. A successful SBIR will potentially result in a Phase 3 award, or alternate funding, to implement a complete SIFT-capable software development system.
Fault tolerant middleware to Support HPSC Chiplet Parallel Processing: Includes math and I/O libraries to support robotic capabilities, autonomy and science processing, and including library routines for Neon Single instruction, Multiple Data (SIMD) processors as well as A53 general purpose processors.

- Technology and languages to enable development of provably correct software.
- Radiation tolerant standard cell libraries for processes below 28nm that are suitable for NASA missions in the natural space environment.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: [https://www.nasa.gov/content/commercial-lunar-payload-services](https://www.nasa.gov/content/commercial-lunar-payload-services) [1]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

**References**

[1](https://www.nasa.gov/content/commercial-lunar-payload-services)

**Expected TRL or TRL range at completion of the project:** 4 to 6

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software

**Desired Deliverables Description**

For hardware elements, a preliminary design ready for detailed design, fabrication, and production.

**State of the Art and Critical Gaps**

The SOA in space qualifiable high performance computing has high power dissipation (approximately 18 W) and the SOP in TRL-9 space computing have relatively low performance (between 2 DMIPS to 200 DMIPS at 100 MHz). Neither of these systems provides the performance, power-performance ratio, or the flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements. The HPSC Chiplet, currently in development, will provide significantly enhanced capabilities but, as currently defined, lacks a broad range of coprocessors and accelerators (which are supported in the architecture but not planned for implementation) as well as software elements that will be required for use in future missions. This lack of hardware and software ecosystem elements is the focus of this nomination.

**Relevance / Science Traceability**

HPSC ecosystem is of interest to all major programs in HEOMD (Human Exploration and Operations Mission Directorate) and SMD (Science Mission Directorate). We have had discussions with program and project managers across NASA. Immediate infusion targets include Mars Fetch Rover, WFIRST/Chronograph, Gateway, and SPLICE/Lunar Lander.

Z3.03 Development of material joining technologies and large-scale additive manufacturing processes for on-orbit manufacturing and construction

Lead Center: MSFC
Participating Center(s): GSFC, LaRC

Technology Area: TA15 Aeronautics

Scope Title
Development of Material Joining Technologies for On-Orbit Manufacturing and Construction

Scope Description

Technology development efforts are required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material joining capability is an important supporting technology for the long duration, long endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space material joining capability can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex and more optimized structures. Material joining is an essential complementary capability to large scale additive manufacturing technologies being developed by NASA and commercial partners. Material joining is also a critical capability for repair scenarios (ex. repair of damage to a structure from micrometeorite impacts).

This subtopic seeks innovative engineering solutions to robotically join materials, fully or semi-autonomous, for manufacturing in the external space environment. Current State-Of-the-Art (SOA) terrestrial joining methods such as laser beam, electron beam, brazing, friction/ultrasonic stir and arc welding should be modified with an effort to reduce the footprint, mass and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for external in-space manufacturing applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a damaged structure may require the need to not only join material but cut and remove material. A single process with the ability to not only join material but also cut/remove material is a priority. The Phase I effort should provide a laboratory demonstration of the joining process and its applicability to aerospace grade metallic materials and/or thermoplastics, focusing on joint configurations which represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios: for example, repair of a metal panel following micrometeorite damage, longitudinal joining of two metal curved panels, and joining of a truss to an adjacent truss. The Phase I should also provide an assessment of the proposed process operational capabilities (for example: classes of materials which can be welded with the process, joint configurations which can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under the phase I. Concepts for ancillary technologies such as post-process inspection, in-situ monitoring, or robotic arms for manipulation of structures to be joined may also be included in the Phase I effort.

Phase I requires a demonstration/proof of concept that: a) the process selected enables high-value applications of in-space welding for repair and assembly and b) system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on ISS, Gateway, Restore-L or as a free-flyer.

References


External in-space manufacturing has primarily focused on fabrication of structures in the space environment. Material joining is an essential supporting technology to these capabilities. Research on joining tapered off to some extent following the cancellation of the In-Space Welding Experiment (ISWE) for space shuttle. With the emergence of the OSAM initiative, a renewed interest and focus on manufacturing structures in the space environment as an enhancing capability for long duration missions and as a way to remove design constraints imposed by payload fairings and launch loads, additional work on development of an in-space material joining capability should be a priority. In-space joining represents an essential complementary technology to in-space fabrication techniques.

Relevance / Science Traceability

ISS, Gateway, Restore-L, ISAT, IRMA

Scope Title
Development of Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing and Construction

Scope Description
Technology development efforts are required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

The ability to additively manufacture large scale structures in-space in an enabling capability needed to fully realize the game changing impacts of on-orbit servicing, assembly and manufacturing. Current state of the art on-orbit manufacturing systems are constrained to a build volume similar to terrestrial additive manufacturing processes with a build volume. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. A large-scale, free-form additive manufacturing capabilities can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex and more optimized structures.
This subtopic seeks innovative engineering solutions to robotically fabricate and/or repair large structures, fully or semi-autonomous, in the external space environment. Current SOA terrestrial large-scale additive manufacturing processes such as wire-fed directed energy deposition and additive friction stir should be modified with an effort to reduce the footprint, mass and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic large-scale additive manufacturing process and system for external in-space manufacturing applications. Targeted applications for this technology include fabrication of truss structures, build-up of structural material for retrofitting spent tanks to habitat modules, and/or solar arrays back planes. Additional targeted applications include the repair of structures such as spacecrafts and/or payloads damaged during the ascent stage, habitat modules with micrometeoroid impact, and out-of-service components due to unforeseen circumstances and/or scheduled repairs. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace grade metallic materials, focusing on structures which represent the priority in-space manufacturing applications identified above. Work under Phase I will inform preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment. The Phase I should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design and concept of operations are also deliverables under the Phase I. Concepts for ancillary technologies such as post-process inspection, in-situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase I requires a demonstration/proof of concept that: a) the process selected enables high-value applications of in-space fabrication of large-scale structures and b) system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on ISS, Gateway, Restore-L or as a free-flyer.

References


Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Phase I: laboratory demonstration/proof of concept of large-scale additive manufacturing system for external in-space manufacturing, initial design of system

Phase II: ground-based prototype system including autonomous capability

Phase III: flight demonstration (Gateway, IRMA, Restore-L or free-flyer)

State of the Art and Critical Gaps

External in-space manufacturing has primarily focused on fabrication of 3D printed truss structures and beams. The In-Space Robotic Manufacturing and Assembly Project funded by the STMD (Space Technology Mission Directorate) Technology Demonstration Mission Program is planning the demonstration of 3D printed truss structures and beams. The technology advancement to multiple degrees of freedom, large-scale fabrication of
structures is a priority for on-orbit manufacturing.

Relevance / Science Traceability

ISS, Gateway, Outpost, IRMA, Restore-L

Z3.04 Autonomous Modular Assembly Technology for OSAM

Lead Center: MSFC

Participating Center(s): MSFC

Technology Area: TA15 Aeronautics

Scope Title
Autonomous Modular Assembly Technology for On-Orbit Servicing, Assembly and Manufacturing (OSAM)

Scope Description

As NASA seeks to extend its presence into deep space, ground-based human intelligence applied to supervision, control, and intervention of operations will no longer be viable due to system and mission complexity and communication delays. Therefore, trusted and certified-safe autonomous systems with machine intelligence and robotic capabilities of responding to both nominal and unexpected situations will be needed. These systems should be capable of:

- Sensing and perception
- Acquiring measurements on-orbit or on planetary surfaces
- Achieving situational awareness
- Making decisions
- Taking action
- Teaming with humans and other machine agents
- Using experiential data to update capabilities
- Verifying autonomy algorithms and behavior
- Validating as-assembled structure shape and interface integrity

As such, autonomy, system modularity, metrology, and modeling & simulation are four critical aspects required to enable On-Orbit Servicing, Assembly, and Manufacturing (OSAM). The hardware and software components of an in-space assembled structure must be modular to facilitate servicing, component replacement, and reconfiguration of the spacecraft. Assembly by autonomous robots can reduce the workload on astronauts and ground crew as well as mitigate inefficiencies due to communication delays associated with teleoperation. The OSAM paradigm requires multiple autonomous agents to collaborate in a complex, dynamic environment. These agents will need to accurately perceive both their environment (the worksite) and each other in order to efficiently allocate tasks, plan trajectories, and respond to disturbances all in the presence of uncertainties such as unknown payload characteristics and unmodeled effects.

Modular structures will increase ease of access to space. Modular platforms could host flight hardware and share power, data, Guidance, Navigation and Control (GN&C), and thermal regulation capabilities. Under this paradigm, technology demonstrations could be carried out without the need to design and operate an entire spacecraft. Modules could simply occupy space on the already existing platform. This constitutes a plug-and-play architecture which will require a common interface between modules such that required structural loads can be supported as well as power, data, and other services.

Modeling & simulation of structures and assembly agents is necessary for verifying autonomous agent algorithms and behavior used for structures that cannot be assembled on the ground.

Accurate sensing of complex and uncertain environments is necessary to provide autonomous agents with
situational awareness to accomplish assembly tasks. Validation of the autonomous system behavior and in-space assembled structure accuracy in-situ will require in-space metrology capabilities.

The scope of this subtopic includes modular hardware and software systems:

- **Element 1**: Algorithms and software for sensing, planning and control of both autonomous robots and mission/task management agents
- **Element 2**: Novel hardware designs (modular robots and structures)
- **Element 3**: Hardware and software for global (worksit scale) metrology systems for accurately sensing agent and structure pose within an on-orbit or lunar assembly worksite
- **Element 4**: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections and independent verification and validation for dynamics-based rigid multi-body mathematical models

Specific subjects to be considered include

- **Heterogeneous multi-agent planning and control**: Algorithms for collaboration on shared tasks for assembly of large modular space structures; task allocation amongst multiple agents; trajectory planning through the worksite and real-time updating of tasks and trajectories to respond to unplanned scenarios; robust and adaptive control for guaranteed performance or graceful degradation of performance for robotic manipulators and/or novel assembly agents; teaming of humans and machines for planning, validation, and post-assembly analysis

- **Strategies and solutions for error detection and correction during the assembly process**: Perception systems and/or classification algorithms independent from the assembly agent for verifying assembly steps and characterizing assembly errors. Fault/anomaly detection, diagnosis, and response to restore nominal operations or derive an acceptable alternative goal

- **Metrology systems**: Global metrology systems or sensing tools that can map a worksite to facilitate agent and structure assembly path-planning for real-time task management and situational awareness and facilitate verification and validation of assembly tasks. A scalable system that can accurately measure structures at an in-space (orbital or surface) worksite with a focus on minimal supporting infrastructure is desired. Concepts with potential for integration and repurposing after construction are favored.

- **Modular structures, systems, and tools**: Deployables that are rigidizable by an accompanying in-situ system (i.e. trusses or functional modules), can be serviced (due to modularity), are capable of moving along truss structures of variable geometries, and/or can interface with agents or be stored/stowed at a worksite where the agent mostly acts as a driver for a mobility system. Of particular interest are approaches to efficiently connect truss modules together. Hardware concepts that support the interconnection of modules in the 100 – 5,000 kg range using some form of space robotics. The objective is to minimize the parasitic mass of the completed spacecraft from the modularity features that are required for inter-module assembly. Features can be added and removed to reduce this parasitic mass. Proposals are preferred that include features to connect both electrical (power and data) and structural features, noting that the connections can occur sequentially. Joining strategies that support fluid connections are of interest but not necessary to be responsive to this subtopic area. The structural connection should occur at a minimum of 3 discrete locations fixing the rigid body motion of the 2 modules in all 6 degrees of freedom while isolating (minimizing) forces resulting from thermal induced strain between the modules consistent with a LEO orbit. The three (or more) connections do not have to occur simultaneously.

- **Modeling & simulation**: Novel approaches to dynamics-based mathematical modeling for complex rigid-body connections with nonlinear effects (for example, slider, ball, or slot connections) and independent verification and validation for dynamics-based rigid multi-body mathematical models. Of particular interest are accurate dynamics-based models for joining of modules on-orbit or in planetary environments.

References

- NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/
Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware, Software

Desired Deliverables Description

- Software implementations and documentation verifying the efficacy of the designed algorithms
- Physical prototypes and documentation for the designed hardware

State of the Art and Critical Gaps

As humans venture into deeper space, communication latency will increase to the point that autonomous operations are crucial. Current technologies for autonomous robots are low TRL, application specific, and fragile with respect to environmental uncertainties. To enable OSAM, these technologies must be made more resilient. Many interesting ideas exist in academia, but have yet to be made into a viable product.

Existing interfaces for modular trusses are purely structural. A critical gap is the development of interfaces that can exchange power, data, and other services over the interface.

Relevance / Science Traceability

Achieving a robust and resilient autonomous solution for OSAM requires the intersection of many disciplines including mechanical and electrical systems, robotics, dynamics modeling, control theory, and computer science. NASA goals that would directly benefit from this work are future lunar exploration missions, including sustained human presence on the moon and persistent space platforms.

Z3.05 Satellite Servicing Technologies

Lead Center: MSFC

Participating Center(s): LaRC, MSFC

Technology Area: TA15 Aeronautics

Satellite servicing technology developments are needed to enable robotic science and human exploration missions that are sustainable, affordable, and resilient and may not be realizable based on current approaches to space systems design, launch, and operations. The focal areas for technology development are remote inspection, refueling, repair, replacement of equipment, and augmentation of existing on-orbit assets. The intended application for these technology developments are servicing, assembly, exploration, sample return, and mission extension.

This subtopic seeks two specific technologies that will enhance satellite servicing by: 1) providing improved sensing/perception during close proximity robotic manipulator operations; and 2) providing a mechanical swivel for use with liquid hypergolic oxidizer propellant.
Scope 1 Title: Development of low mass low power proximity sensor for satellite servicing

The first technology scope covers small robot proximity range sensor which can be mounted at the end of a robotic arm and provide mm-class range performance inside of a few cm, for measurement of range from the sensor to an arbitrary object. Restore-L autonomous capture utilizes only cameras for this operation, a sensing modality which cannot enable “capture before contact” or soft-capture of a legacy vehicle. A direct ranging sensor, operating at high frequency (>10Hz) would greatly enhance this operation, and enable many other autonomous robotic operations.

Phase 1 proposals are expected to identify options, or develop prototypes, and test potential sensor options in laboratory demonstrations at various distances from centimeters to contact, and with typical satellite external surface materials including multi-layer insulation blankets, launch vehicle interfaces (marman rings), and other materials found on or near space grapple or grasp fixtures. Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

Scope 2 Title: Mechanical swivel for liquid hypergolic oxidizer propellant

The second technology scope concerns the selection or development of materials, and subsequent design and test of mechanisms capable of introducing a mechanical swivel in the fluid lines of a liquid hypergolic oxidizer propellant system. While Restore-L does not plan to transfer Oxidizer, other refueling missions will need to do so. One option for this transfer includes a flexible hose with no dynamic seals, and therefore limited dexterity and ability to accommodate a large variety of clients (for example, imagine an automobile gas station hose with no swivel – filling the tank with a more than one specific vehicle would be very challenging). Introduction of a dynamic seal and swivel would greatly expand the ability of such a system to accommodate multiple clients and fluid coupler locations. This flexibility is essential for the commercial refueling business case, which must amortize the cost of the refueler over many clients and configurations.

Phase 1 proposals are expected to develop a mechanical swivel joint that can be utilized for fluid transport with flow rates in the range of 2-20 kg / min and maximum expected operating pressure of 500 psia with a low quantity of dynamic cycles (<10) with exposure to liquid hypergolic oxidizer propellant (N2O4 MON-3), and also varying degrees of prior accelerated radiation exposure to softgoods to assist with determining possible on-orbit life cycle use estimates. Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

References

Fourth Technology Transfer Industry Day; Plan to Facilitate Commercial On-Orbit Robotic Servicing, Assembly and Manufacturing (OSAM) - Federal Business Opportunities: Opportunities, National Aeronautics Space Administration, 30 July 2019, www.fbo.gov/index.php?s=opportunity&mode=form&id=1f59d52003a1a1538aba9975a854ec9e&tab=core&tabmode=list& [15].


Expected TRL or TRL range at completion of the project: 2-4

Desired Deliverables Description

Scope 1: Proximity sensor with mass < 0.25 kg, range 20 cm to 0.5 cm, precision better than 0.5 mm, power less than 3 W at 10 hz update rate.

Scope 2: A mechanical swivel joint that can be utilized for fluid transport with flow rates in the range of 2-20 kg / min and maximum expected operating pressure of 500 psia with a low quantity of dynamic cycles (<10) maintaining a leak rate better than 1x10^-5 sscs gHe with exposure to liquid hypergolic oxidizer propellant (N2O4 MON-3), and also varying degrees of prior accelerated radiation exposure to softgoods to assist with determining possible on-orbit life cycle use estimates. Laboratory demonstration would involve determining top material selection (metal and latest available Teflon or polymer), fabrication of small test unit, and post-exposure GHe precision leak testing utilizing as much of existing standardized testing infrastructure as possible (NASA STD 6001 Test 15, etc.).
State of the Art and Critical Gaps

Scope 1: Mass is critical at the end of robotic arms during autonomous capture. Having knowledge of the distance from the end of the arm to the adjacent free flying satellite would reduce the risk of a collision or missed capture.

Scope 2: Dynamic seals exist today for chemical fuel propellants (hydrazine, monomethyl hydrazine, etc.), however there is no known oxidizer seal that can meet the requirements listed above.

Relevance / Science Traceability

Restore-L, ISS, Gateway, Artemis, iSAT, commercial refueling.

Each of the technologies are considered key for satellite servicing. These technologies could be applicable to the Restore-L mission as well as other potential servicing missions, platform demonstrations, or smallsats. These technologies could also be applicable to refueling at Artemis.

Z4.04 Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes

Lead Center: LaRC

Participating Center(s): MSFC

Technology Area: TA15 Aeronautics

Scope Title

Development of Real Time Defect Detection, Identification and Correction in Wire-Feed Additive Manufacturing Processes

Scope Description

Additive Manufacturing (AM) (also referred to here as 3D printing) offers the ability to build light-weight components that are optimally suited for use in aerospace applications. Significant strides have been made in the development of AM with 3D printed components now being part of active aircraft and spacecraft\(^1,2,3\). While the use of AM has enabled non-traditional designs and decreased part counts, full inspection of each component is typically required post-build to determine fitness for the final application. Complex geometries, rough as-built surface finishes, and porosity can hinder inspection. If 100% inspection is not possible, proof test logic or some other method of proving fitness for use must be applied\(^4\). Defects that occur can force a complete reprint. The ultimate promise of AM is to enable on-demand production of customized unique components. For utility in space applications, printed parts have to be fully functional with zero to minimal post processing. Ideally, parts need to be built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service. To enable the full realization of the potential of 3D printing, a capability for closed loop control of the process that integrates \textit{in situ} monitoring, real-time defect detection and identification, & print parameter modification is required.

Wire-feed or extrusion type AM, with its relative simplicity, wide range of feedstocks and build volume flexibility is a popular 3D printing technique that is well suited to space applications\(^6\). Fused Filament Fabrication (FFF) and Electron Beam Free Form Fabrication (EBF\(^3\)) are useful examples of wire-feed processes to illustrate the limitations placed on AM by presently available design and process control tools. After designing an object using 3D modeling software, the geometry is passed to a slicing and tool path planning code, which generates the list of instructions needed by the printing hardware. Once received by the printer, no further modifications or corrections can be made, and the process continues to completion.

Proposals are invited to advance the manufacturing technology by incorporating an \textit{in situ} defect detection and correction capability into wire-feed or extrusion type metallic, plastic or composite AM.
In Phase I, contractors should prove the feasibility of integrating sensor feedback with appropriate software tools and computation resources to be able to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects to the part performance and the correction of those defects. Solutions sought include the software that can be integrated into the 3D printing workflow, hardware requirements to run that software for real-time data processing and sensors capable of operating in the build environment to provide data also in real time. The proposed approach should be demonstrable at least on the coupon scale for shapes such as circles or boxes.

Phase II, should demonstrate the feasibility of Phase I concepts to arrive at closed loop solutions to build parts in which information on the processing generated from gathering and analyzing sensor data is used for the prediction of part performance, unique to each individual part, as it is being built. Incorporation of defect correction during fabrication, rather than requiring a print to be scrapped and restarted should be demonstrated on sample parts.

References

7. https://cdn.eos.info/839090ec135565bc/b6a6ac17dca9/EOS_Whitepaper_Monitoring_and_Control_3D_Printing.pdf [22] [Lukas Fuchs, Christopher Eischer, EOS GmbH Whitepaper - “In-process monitoring systems for metal additive manufacturing”]

Expected TRL or TRL range at completion of the project: 2 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

In Phase I, concept studies documenting the feasibility of incorporating sensor data feedback and appropriate software tools and computation resources to be used to detect defects during fabrication of parts with complex geometries, evaluating the potential impact of the defects on the performance of the parts and the correction of those defects.

Phase II, scale demonstration of a printer with closed loop control that incorporates defect detection, identification and correction during fabrication. The complexity of defects that are detected and corrected as well as the size of the parts should demonstrate the challenges that would come up in full-scale use of the control processes. Printed part sizes should be at least 10 cm per side for cubes with detectable defects down to the mm scale or smaller. The defects should have a demonstrable effect on the part performance, such as a decrease in mechanical properties that is then corrected for by the process.
State of the Art and Critical Gaps

Additive Manufacturing is seeing rapidly expanding applications in many areas including in aerospace. Despite this growth in AM, fulfilling its full potential has always been limited by quality control issues and certification of the manufactured parts as each component that is built is unique\textsuperscript{6}. Some work has begun to add defect detection and correction to powder based manufacturing processes such as Direct Metal Laser Sintering (DMLS)\textsuperscript{7,8} and wire-feed AM\textsuperscript{9}. There has however not been the requisite advance in ensuring that defect detection and identification is coupled with the real-time correction of those defects and ensuring final performance of the manufacturing part in a particular application.

Gap: Real-time defect detection, identification and correction in AM processes, which would ensure the performance of the as-printed parts without relying on post production inspection processes, with parts built with acceptable form, fit, and function the first time, with sufficient documentation to allow direct entry into service has not been demonstrated.

Relevance / Science Traceability

This topic fits under STMD (Space Technology Mission Directorate). It supports Advanced Manufacturing of Lightweight Structures. Enhancing quality control in AM opens up its use in many industrial applications as well as for NASA use. In particular, in-space use of AM in future Gateway, Lunar and Mars exploration missions will require that parts that are produced are ready for use as-produced since there will be limitations in availability of material for re-printing as well as crew time and equipment for post-printing inspection.

Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis

Lead Center: LaRC

Participating Center(s): ARC, GSFC

Technology Area: TA15 Aeronautics

Scope Description

NASA’s Non-Destructive Evaluation (NDE) SBIR subtopic will address a wide variety of NDE disciplines. These disciplines include but are not limited to Structural Health Monitoring (SHM), Novel NDE Sensor Development and NDE Modeling and analysis. All of these three disciplines can be used on aerospace structures and materials systems including but not limited to Inconel, Titanium, Aluminum, Carbon Fiber, Avcoat, ATB-8, Phenolic Impregnated Carbon Ablator (PICA) and thermal blanket structures. Sensor systems, SHM and modeling can target any set of these materials in common aerospace configurations such as Micro-Meteoroids and Orbital Debris (MMOD) shielding, Truss Structures and Stiffened Structures. In addition NDE can target material and material systems in a wrought state, in process and NDE techniques that could be used to inspect additively manufactured components would be favored. Current NDE computational tools do not have sufficient resolution to provide representation on the order of Finite Element Model (FEM) models allowing for Digital Twin. Depending on the size of the critical flaw in the material system / structure this resolution can range from 500nm to 100cm realistically. As NDE tool resolution grows larger volumes of data are created and thus new computational tools are required. At the same time, low cost emerging computational hardware, such as Graphics Processing Units (GPUs), is enabling the growing use of advanced physics based models for improved NDE inspection and for advanced data analysis methods such as Machine Learning. In addition as NASA strives to go deeper and longer new tools need to be developed in order to support long duration space flight.

NDE sensors and data analysis:

Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.
Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multi-wall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) Radiators or aerospace structural components.

Additionally, techniques for quantitative data analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material Foreign Object Debris (FOD) and/or defects and evaluation of bondline and in-depth integrity for light-weight rigid and/or flexible ablative materials are sought. Typical internal void volume detection requirements for ablative materials are on the order of less than 6mm and bondline defect detection requirements are less than 25mm.

Additive manufacturing is rapidly becoming a manufacturing method targeting fracture critical components and as such NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and it effect on diffracting energy sources. Additive manufacturing also offers an additional chance for in-process inspection. Development of NDE techniques, sensors and methods addressing these issues would be highly desired. But techniques addressing weld inspection will also be considered. Most of the aerospace components will be metallic in nature and critical flaws are on the range of 1mm or smaller and can be volumetric or fracture like in nature.

Structural Health Monitoring (SHM):

Future manned space missions will require spacecraft and launch vehicles that are capable of monitoring the structural health of the vehicle and diagnosing and reporting any degradation in vehicle capability. This subtopic seeks new and innovative technologies in Structural Health Monitoring (SHM) and Integrated Vehicle Health Management (IVHM) systems and analysis tools.

Techniques sought include modular/low mass-volume systems, low power, low maintenance systems, and systems that reduce or eliminate wiring, as well as stand-alone smart-sensor systems that provide processed data as close to the sensor as practical and systems that are flexible in their applicability. Examples of possible system are: Surface Acoustic Wave (SAW)-based sensors, passive wireless sensor-tags, flexible sensors for highly curved surfaces direct-write film sensors, and others. Damage detection modes include leak detection, ammonia detection, micrometeoroid impact and others. Reduction in the complexity of standard wires and connectors and enabling sensing functions in locations not normally accessible with previous technologies is also desirable. Proposed techniques should be capable of long term service with little or no intervention. Sensor systems should be capable of identifying material state awareness and distinguishing aging related phenomena and damage related conditions. It is considered advantageous that these systems perform characterization of age-related degradation in complex composite and metallic materials. Measurement techniques and analysis methods related to quantifying material thermal properties, elastic properties, density, microcrack formation, fiber buckling and breakage, etc. in complex composite material systems, adhesively bonded/built-up and/or polymer-matrix composite sandwich structures are of particular interest. Some consideration will be given to the IVHM /SHM ability to survive in on-orbit and deep space conditions, allow for additions or changes in instrumentation late in the design/development process and enable relocation or upgrade on orbit. System should allow NASA to gain insight into performance and safety of NASA vehicles as well as commercial launchers, vehicles and payloads supporting NASA missions. Inclusion of a plan for detailed technical operation and deployment is highly favored.

NDE Modeling:

Technologies sought under this SBIR include near real-time realistic NDE and SHM simulations and automated data reduction/analysis methods for large data sets. Simulation techniques will seek to expand NASA’s use of physics based models to predict inspection coverage for complex aerospace components and structures and to utilize inverse methods for improved defect characterization. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space flight structures and components, and may involve methods such as machine learning, domain transformation, etc. NASA’s interest area is light weight structural materials for space flight such as
composites and thin metals. Future purposes will include application to long duration space vehicles, as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction (i.e., NDE) simulations for high-strength lightweight material systems and include energy interaction with realistic damage in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, laser, Microwave, Terahertz, Infrared, X-ray, X-ray Computed Tomography, Fiber Optic, backscatter X-Ray and eddy current. It is assumed that any data analysis methods will be focused on NDE techniques with high resolution high volume data. Modeling efforts should be physics based and it is desired they can account for material aging characteristics and induced damage, such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. It is advantageous to use co-processor/accelerator based hardware [e.g., GPUs, Field Programmable Gate Arrays FPGA)] for simulation and data reduction. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

References:


**Expected TRL or TRL range at completion of the project:** 1 to 6

**Desired Deliverables of Phase II**

Working prototype or software of proposed product, along with full report of development, validation, and test results.

**Desired Deliverables Description**

**Phase I Deliverables** - For NDE sensors focused proposals, lab prototype and feasibility study or software package including applicable data or observation of a measurable phenomenon on which the prototype will be built. For NDE modeling focused proposals, feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (TRL 2-4). Inclusion of a proposed approach to develop a given methodology to Technology Readiness Level (TRL) of 2-4. All Phase I's will include minimum of short description for Phase II prototype/software. It will be highly favorable to include description of how the Phase II prototype or methodology will be applied to structures.

**Phase II Deliverables** - Working prototype or software of proposed product, along with full report of development, validation, and test results. Prototype or software of proposed product should be of Technology Readiness Level (TRL 5-6). Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

**State of the Art and Critical Gaps**

NDE Tools for flight still do not have sufficient resolution to provide representation on the order of Finite Element Models (FEM) allowing for Digital Twin. Also as NDE tools grow and sensors get faster larger volumes of data are created and thus new computational tools are required. At the same time, low cost emerging computational hardware, such as GPUs, is enabling the growing use of advanced physics based models for improved NDE inspection and for advanced data analysis methods such as Machine Learning. Development of new techniques are enabling Orion to meet its 100% inspected mission directive. In addition as NASA strives to go deeper and longer new tools need to be developed in order to support long duration space flight.

**Relevance / Science Traceability**

Several missions could benefit from technology developed in the Area of nondestructive evaluation. Currently NASA is returning to manned space flight. The Orion/Space Launch System and Artemis program has continuing to have inspection difficulties and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently Orion is using several techniques and prototypes that have been produced under the NDE SBIR topic. Space Launch System is NASA’s next heavy lift system. Capable of sending hundreds of metric tons into orbit. Inspection of the various systems is on-going and will continue to have challenges such as verification of the friction stir weld on the fuel tanks. As NASA continues to push in deeper space smart structures that are instrumented with structural health monitoring system can provide real time mission critical information of the status if the structure.

**Z5.04 Technologies for Intra-Vehicular Activity Robotics**

Lead Center: ARC

Participating Center(s): JSC
Technology Area: TA15 Aeronautics

Scope Title

Improve the capability or performance of intravehicular activity robots

Scope Description

To support human exploration beyond Earth orbit, NASA is preparing to develop the "Gateway", which will be an orbiting facility near the Moon. This facility would serve as a starting point for missions to cis-lunar space and beyond. This facility could enable assembly and servicing of telescopes and deep-space exploration vehicles. This facility could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.

In contrast to the ISS (International Space Station), which is continuously manned, the Gateway is expected to only be intermittently occupied by humans – perhaps only 1 month per year. Consequently, there is a significant need for the Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking, particularly when astronauts are not present. Intra-Vehicular Activity (IVA) robots can potentially perform a wide variety of tasks including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and ops.

The objective of this subtopic, therefore, is to develop technologies that can improve the capability or performance of IVA robots to perform payload operations and spacecraft caretaking. Proposals are specifically sought to create technologies that can be integrated and tested with the NASA Astrobees or Robonaut 2 robots in the following areas: (1) Sensors and perception systems for interior environment monitoring, inspection, modeling and navigation; (2) Robotic tools for manipulating logistics and stowage or performing maintenance, housekeeping or emergency management operations (e.g. fire detection & suppression in multiple constrained locations or cleaning lunar dust out of HEPA (High-Efficiency Particulate Air) filters; and (3) Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.), increase robot autonomy (planning, scheduling, and task execution), or improve human-robot teaming (software architecture, remote operations methods, etc.).

References


What is a Robonaut? - https://www.nasa.gov/robonaut2 [26]


Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II
Desired Deliverables Description

Prototype components or subsystems. Proposals must describe how the technology will make a significant improvement over the current state of the art, rather than just an incremental enhancement, for a specific IVA robot application.

State of the Art and Critical Gaps

The technology developed by this subtopic would both enable and enhance the Astrobot free-flying robot and Robonaut 2 humanoid robot, which are the SOA for IVA robots. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVA tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2020 SBIR awards can be tested with these robots in ground testbeds at ARC and JSC during the SBIR period of performance. On-orbit testing on ISS may be possible during Phase 2 and beyond (Phase 2-E, 2-X, 3, etc.).

The technology developed by this subtopic would also fill technical gaps identified by the proposed GCD (Game Changing Development) "Integrated System for Autonomous and Adaptive Caretaking" (ISAAC) project, which will mature autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability

This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

- Astrobot free-flying robot – GCD
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC) – GCD
- Deep Space Smart Habitats – Space Technology Research Institutes (STRI)

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:

- SPHERES/Astrobot facility – ISS
- Robonaut 2 humanoid robot – ISS
- Gateway program – Advanced Exploration Systems (AES)
- Logistics Reduction project – AES

Autonomous Systems Operations project – AES

Z5.05 Lunar Rover Technologies for In-situ Resource Utilization and Exploration

Lead Center: ARC

Participating Center(s): ARC, GRC, KSC

Technology Area: TA15 Aeronautics

Scope Title

Enabling Rover Technologies for Lunar Missions

Scope Description
The objective of this subtopic is to innovate lunar rover technologies that will enable In-Situ Resource Utilization (ISRU) and exploration missions. In particular, this subtopic will develop ideas, subsystems components, software tools, and prototypes that contribute to more capable and/or lower-cost lunar robots.

A potential lunar ISRU application is the prospecting, characterization, and collection of volatiles that could be processed to produce oxygen, fuel, etc. Recent remote sensing measurements, modeling, and data from LCROSS (Lunar Crater Observation and Sensing Satellite) indicates that there may be an abundance of volatiles (e.g., hydrogen) near the lunar poles. However, the distribution of the volatiles at and under the surface is unknown. The Lunar Rover Technologies for In-situ Resource Utilization and Exploration subtopic seeks new robotic technology that will enable rover technologies for lunar missions to support ISRU activities. This does not include new ISRU technology (which is solicited by subtopics T2.05 - Advanced Concepts for Lunar and Martian Propellant Production, Storage, Transfer, and Usage for the STTR solicitation and S4.02 - Robotic Mobility, Manipulation and Sampling for the SBIR solicitation).

The expected environment at the lunar poles involves all the challenges observed during the Apollo mission (thermal extremes, vacuum, radiation, abrasive dust, electrostatic dust) plus the addition of low sun angles, potentially less consolidated regolith, and permanently shadowed regions with temperatures as low as 40K. This subtopic seeks new technology to address these challenges.

Phase I success involves technical feasibility demonstration through analysis, prototyping, proof-of-concept, or testing. Phase II success will advance TRL to a level of 4-5. Of specific interest are:

- Mobility architectures, including novel mobility mechanisms and lunar dust tolerant mechanisms.
- Cryo-capable actuators capable of operating at extremely cold temperatures (in environments as cold as -230C). Preferably solutions will not include heaters as they significantly increase the power draw for normal operations during the lunar day. Novel materials capable of maintaining metallurgical properties at cryogenic temperatures will be considered. Also desired are cryo actuators featuring dust tolerances and the ability to operate at high temperatures as well (approaching 150C).
- Magnetic gearing applications for space. NASA and others are developing relatively low ratio (less than 25:1 per stage) concentric magnetic gearing for aeronautics applications. Space applications demand high speed-reduction ratio (often more than 1000:1) and high specific torque (>50 Nm/kg), operation in environmental temperatures down to -230C (40K), operation in low-atmosphere or hard vacuum, with high reliability and energy efficiency. Phase I work would include identifying the most suitable magnetic gear topologies to meet these space application needs, defining the technology development challenges including thermal and structural issues, advancing the most critical aspects of the technology, and producing a low-fidelity prototype to prove the feasibility of the concept(s).
- Perception systems and algorithms with a path toward flight for the lunar surface capable of operating in the harsh lighting conditions that might include high dynamic range, shadowed regions, low angle illumination, and opposition effects
- Lunar regolith terramechanical modeling tools and simulations, especially tools that integration with existing commercial and open source robotic analysis and simulation tools.
- Rover embedding and entrapment detection and escape approaches including slip monitoring, regolith sensing/modeling, low ground pressure wheels and soft soil tolerant mobility architectures.

For all the above, it is desired to have been demonstrated in, or have a clear path to operating in, the lunar environment. NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services [1]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References
NASA is still formulating its approach to future lunar science and exploration. The current plan is to start with small commercial landers (<100kg) beginning as early as 2019, with relatively high launch cadence (2+ launches/year). In the future, NASA seeks to build mid-to-large landers, with an eye on human-rated landers with a first mid-sized lander planned for 2022.

Further information can be found at the following:

- Apollo Experience Report - Thermal Design of Apollo Lunar Surface Experiments Package: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf) [29]
- The Lunar Environment: [https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter03.pdf](https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter03.pdf) [30]
- Commercial Lunar Payload Services - CLPS: [https://www.fbo.gov/index?s=opportunity&mode=form&id=46b23a8f2c06da6ac08e1d1d2ae97d35&tab=core&cview=0](https://www.fbo.gov/index?s=opportunity&mode=form&id=46b23a8f2c06da6ac08e1d1d2ae97d35&tab=core&cview=0) [31]
- Survive and Operate Through the Lunar Night Workshop: [https://www.hou.usra.edu/meetings/survivethenight2018/](https://www.hou.usra.edu/meetings/survivethenight2018/) [32]
- NASA Exploration Campaign: [https://www.nasa.gov/sites/default/files/thumbnails/image/nasa-exploration-campaign.jpg](https://www.nasa.gov/sites/default/files/thumbnails/image/nasa-exploration-campaign.jpg) [34]

Additional information on NASA's interest in landers that might host the rovers can be found at the following:

- Lunar Surface Transportation Capability Request for Information (RFI) ([https://govtribe.com/project/lunar-surface-transportation-capability-request-for-information-rfi](https://govtribe.com/project/lunar-surface-transportation-capability-request-for-information-rfi) [36])

Magnetic gearing references:


**Expected TRL or TRL range at completion of the project:** 3 to 5

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software

**Desired Deliverables Description**

Example deliverables coming from a successful phase II within this subtopic, might including some of the following:

- Designs of cryo-capable or dust tolerant mechanisms motor controllers with test data and prototypes
- Prototype rovers or scale versions of prototype rovers showing novel mobility architecture for escaping entrapment in regolith
• Software algorithms including demonstrating slip detection or image processing in harsh lunar lighting conditions
• Software packages either standalone or integrated with commercially available or open-source robotic simulation packages (preferred).

NASA is also interested in technologies demonstrations that could serve as payloads on commercial landers at the end of phase II.

State of the Art and Critical Gaps

Current state of the art in robotic surface mobility is the MER/MSL (Mars Exploration Rover/Mars Science Laboratory) rovers for Mars and the Chinese Chang’e on the moon. Since the end of the NASA Constellation program in 2011, there has been only small pockets of technology development for the lunar surface within NASA and other space agencies, plus the small business/academic communities.

The specific areas noted above for targeted development (mechanisms, cryoactuators, magnetic gearing, perception systems, terramechanics simulations and novel mobility architectures) are all of specific interest as they are specific challenges unique to the lunar surface and lunar poles specifically.

Magnetic gearing has become practical in recent years due to the availability of high energy density magnets and design topologies that conserve volume. As a result, there has been an exponential growth in R&D for Earth applications like wind/wave energy generators and hybrid vehicle power-trains.

Relevance / Science Traceability

This SBIR resides within STMD as a vehicle for development of technology objectives. It is expected that successful projects would infuse technology into either the STMD Game Changing Development (GCD) or Technology Demonstration Missions (TDM) programs. Technology could also be infused into joint efforts involving STMD's partners (other mission directorates, other government agencies, and the commercial sector). Flights for these technology missions could be supported on small commercial lunar landers (SMD) or possibly mid-size NASA lunar landers (HEOMD).

Potential customers:

• Autonomy and robotics
• Robotic ISRU missions
• Payloads for Commercial Lunar Payload Services landers
• Commercial vendors

Future prospecting/mining operations

Z7.01 Entry Descent & Landing Sensors for Environment Characterization, Vehicle Performance, and Guidance, Navigation and Control

Lead Center: ARC

Participating Center(s): JPL, JSC, LaRC

Technology Area: TA15 Aeronautics

Scope Description

NASA human and robotic missions to the surface of planetary or airless bodies require Entry, Descent, and Landing (EDL). For many of these missions, EDL represents one of the riskiest phases of the mission. Despite the criticality of the EDL phase, NASA has historically gathered limited engineering data from such missions, and use of the data for real-time Guidance, Navigation and Control (GN&C) during EDL for precise landing (aside from
Earth) has also been limited. Recent notable exceptions are the Orion EFT-1 flight test, Mars Entry, Descent, & Landing Instrument (MEDLI) sensor suite, and the planned sensor capabilities for Mars 2020 (MEDLI2 and map-relative navigation). NASA requires EDL sensors to: a) understand the in-situ entry environment b) characterize the performance of entry vehicles, and c) make autonomous and real-time onboard GN&C decisions to ensure a precise landing.

This subtopic describes three related technology areas where innovative sensor technologies would enable or enhance future NASA EDL missions. Proposers may submit solutions to any of these scope areas:

1) High Accuracy, Light Weight, Low Power Fiber Optic or Recession Sensing System for Thermal Protection Systems.

2) Miniaturized Spectrometers for Vacuum Ultraviolet & Mid-wave Infrared In-Situ Radiation Measurements during Atmospheric Entry.


NASA seeks innovative sensor technologies to enable and characterize entry, descent and landing operations on missions to planetary and airless bodies. This subtopic describes three related technology areas where innovative sensor technologies would enable or enhance future NASA EDL missions. Candidate solutions are sought that can be made compatible with the environmental conditions of deep spaceflight, and the rigors of landing on planetary bodies both with and without atmospheres. Proposers may submit to scope areas 1, 2 or 3 below.

1) HIGH ACCURACY, LIGHT WEIGHT, LOW POWER FIBER OPTIC OR RECESSION SENSING SYSTEM FOR THERMAL PROTECTION SYSTEMS.

Current NASA state-of-the-art EDL sensing systems are very expensive to design and incorporate on planetary missions. Commercial fiber optic systems offer an alternative that could result in a lower overall cost and weight, while actually increasing the number of measurements. Fiber optic systems are also immune to Electro-magnetic Interference (EMI) which reduces design and qualification efforts. This would be highly beneficial to future planetary missions requiring Thermal Protection Systems (TPS). In addition, as NASA looks to the future of science missions to the Outer Planets, extreme entry environments will require the new, 3-D woven Heatshield for Extreme Entry Environment Technology (HEEET) TPS recently matured within the Agency. Gathering flight performance data on this new material will be key, particularly the measurement of recession, which was so very important on the Galileo probe mission to Jupiter. Minimizing the sensor intrusion of the outer mold line is critical in this case, because the extreme environment dictates that the TPS be as aerothermally monolithic as possible. In applications to planetary entry vehicles greater than about 1 m diameter, however, the HEEET TPS is expected to contain seams that might be used for accommodating instrumentation. Recession measurements in carbon fiber/phenolic TPS systems like Phenolic Impregnated Carbon Ablator (PICA) and AVCOAT are also of interest. When ablation is not severe and/or rapid, accurate measurements have proven difficult with the historic Galileo-type sensor, which was based on the differential resistance resulting from sensor materials that have charred.

The upcoming Mars 2020 mission will fly the Mars Entry, Descent, and Landing Instrumentation II (MEDLI2) sensor suite consisting of a total of 24 thermocouples, 8 pressure transducers, 2 heat flux sensors, and a radiometer embedded in the TPS. This set of instrumentation will directly inform the large performance uncertainties that contribute to the design and validation of a Mars entry system. A better understanding of the entry environment and TPS performance could lead to reduced design margins enabling a greater payload mass fraction and smaller landing ellipses. Fiber optic sensing systems can offer benefits over traditional sensing system like MEDLI and MEDLI2, and can be used for both rigid and flexible TPS. Fiber optic sensing benefits include, but are not limited to; sensor immunity to EMI, the ability to have thousands of measurements per fiber using Fiber Bragg Grating (FBG), multiple types of measurements per fiber (i.e. temperature, strain, and pressure), and resistance to metallic corrosion.

To be considered against NASA state-of-the-art TPS sensing systems for future flight missions, fiber optic systems must be competitive in sensing capability (measurement type, accuracy, quantity), and Sensor Support Electronics (SSE) mass, size and power. Therefore NASA is looking for a fiber optic system that can meet the following requirements:

Sensing Requirements
• TPS Temperature: Measurement Range: -200 to 1250°C (up to 2000°C preferred), Accuracy: +/- 5°C desired.
• Surface Pressure: Measurement Range: 0-15 psi, Accuracy: < +/-0.5%

Sensor Support Electronics Requirements (including enclosure):

• Weight: 12 lbs or less,
• Size: 240 cubic inches or smaller,
• Power: 15W or less,
• Measurement Resolution: 14-bit or Higher,
• Acquisition Rate per Measurement: 16 Hz or Higher.
• Compatibility with all sensors types, e.g., Temperature, Pressure, Heat Flux, Strain, Radiometer, TPS recession.

For recession measurements in extreme entry environments requiring 3-D woven TPS, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

• Up to 5000 W/cm² heat flux,
• Up to 5 atmospheres of pressure on the vehicle surface,
• Recession measurement accuracy within +/- 1 mm.

For recession measurements in moderate entry environments requiring carbon fiber/phenolic TPS systems, NASA is seeking novel concepts that fit into the sensor/electronics architecture described above, and meet the following requirements:

• Up to 150-2000 W/cm² heat flux,
• Up to 1 atmosphere of pressure on the vehicle surface,
• Recession measurement accuracy within +/- 1 mm.

2) MINIATURIZED SPECTROMETERS FOR VACUUM ULTRAVIOLET & MID-WAVE INFRARED RADIATION IN-SITU MEASUREMENTS DURING ATMOSPHERIC ENTRY

The current state-of-the-art for flight radiation measurements includes radiometers and spectrometers. Radiometers can measure heating integrated over a wide wavelength range (e.g. MEDLI2 Radiometer), or over narrow-wavelength bands (COMARS+ ICOTOM at 2900 nm and 4500 nm). Spectrometers gather spectrally resolved signal and have been developed for Orion EM-2 (combined Ocean Optics STS units with a range of 190-1100 nm). A spectrometer provides the gold standard for improving predictive models and improving future entry vehicle designs.

For NASA missions through CO2 atmospheres (Venus and Mars), a majority of the radiative heating occurs in the Midwave Infrared range (MWIR: 1500 nm - 6000 nm) [Brandis]. Similarly, for entries to Earth, the radiation is dominated by the Vacuum Ultraviolet (VUV) range (VUV: 100 - 190 nm) [Cruden]. Both of these ranges are outside of those detectable by available miniaturized spectrometers. While laboratory-scale spectrometers and detectors are available to measure these spectral ranges, there are no versions of these spectrometers which would be suitable for integration into a flight vehicle due to lack of miniaturization. This SBIR calls for miniaturization of VUV and Mid-Wave Infrared (MWIR) spectrometers to extend the current state of the art for flight diagnostics.

Advancements in either VUV or MWIR measurements are sought, preferably for sensors with:

• Self-contained with a maximum dimension of ~10 cm or less,
• No active liquid cooling,
• Simple interfaces compatible with spacecraft electronics, such as RS232, RS422, or Spacewire,
• Survival to military spec temperature ranges [-55 to 125°C],
• Power usage of order 5W or less.
3) NOVEL SENSING TECHNOLOGIES FOR EDL GN&C AND SMALL BODY PROXIMITY OPERATIONS

NASA seeks innovative sensor technologies to enhance success for EDL operations on missions to other planetary bodies (including Earth's Moon, Mars, Venus, Titan, and Europa). Sensor technologies are also desired to enhance proximity operations (including sampling and landing) on small bodies such as asteroids and comets.

Sensing technologies are desired that determine any number of the following:

- Terrain relative translational state (altimetry/3-axis velocimetry).
- Spacecraft absolute state in planetary/small-body frame (either attitude, translation, or both).
- Terrain characterization (e.g., 3D point cloud) for hazard detection, absolute and/or relative state estimation, landing/sampling site selection, and/or body shape characterization.
- Wind-relative vehicle state and environment during atmospheric entry (e.g., velocity, density, surface pressure, temperature).

Successful candidate sensor technologies can address this call by:

- Extending the dynamic range over which such measurements are collected (e.g., providing a single surface topology sensor that works over a large altitude range such as 1m to >10km, and high attitude rates such as greater than 45° /sec).
- Improving the state-of-the-art in measurement accuracy/precision/resolution for the above sensor needs.
  * Substantially reducing the amount of external processing needed by the host vehicle to calculate the measurements.
- Significantly reducing the impact of incorporating such sensors on the spacecraft in terms of Size, Weight, and Power (SWaP), spacecraft accommodation complexity, and/or cost.
- Providing sensors that are robust to environmental dust/sand/illumination effects.
- Mitigation technologies for dust/particle contamination of optical surfaces such as sensor optics, with possible extensibility to solar panels and thermal surfaces for Lunar, asteroid, and comet missions.
- Sensing for wind-relative vehicle velocity, local atmospheric density, and vehicle aerodynamics (e.g. surface pressures and temperatures).

NASA is also looking for high-fidelity real-time simulation and stimulation of passive and active optical sensors for computer vision at update rates greater than 2 Hz to be used for signal injection in terrestrial spacecraft system test beds. These solutions are to be focused on improving system-level performance Verification and Validation during spacecraft assembly and test.

References


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Depending on the type of technology submissions, hardware demonstrations of sensors or applicable support
hardware (e.g. EDL sensors), or software simulations/analysis of simulated environments (simulation environments for passive and active optical sensors) are acceptable.

State of the Art and Critical Gaps

Active and passive GN&C EDL sensor technologies have been in development over the past decade. Infusion of these capabilities into spaceflight missions requires additional technology advancements to enhance operational performance and dynamic envelop, reduce size, mass, and power, and to address the process of space qualification.

The EDL community has a need to understand the specific contributors to aftbody radiation (especially in CO2 and air); a spectrometer is the next logical step beyond the current state-of-the-art radiometers for EFT-1 and MEDLI2. NASA now requires instrumentation on SMD competed missions involving EDL, and these cost- and mass-constrained missions cannot use the SOA instrumentation. The specific need is for miniaturized spectrometers for in-situ measurements with sensitivity in the VUV or MWIR regions where NASA predicts significant radiation for Earth, Venus, and Mars entries. VUV spectrometers require window operation under vacuum conditions with UV-grade windows for detection of the vacuum ultraviolet. The window materials become increasingly exotic as lower wavelengths are sought. The dispersion of wavelength becomes reduced as spectrometers shrink, which may become an issue for closely spaced features at lower wavelength. Extending the range of miniaturized spectrometers into the MWIR may be limited by the need for extensive cooling and as long wavelengths approach the diffraction limit.

Relevance / Science Traceability

EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation and in-flight performance of planetary entry systems. Improved understanding of entry environments and TPS performance could lead to reduced design margins enabling a greater payload mass-fraction and smaller landing ellipses. Improved real-time measurement knowledge during entry could also minimize the landing dispersions for placing advanced payloads onto the surface of atmospheric and airless bodies.

NASA Science missions are frequently proposed, that include high-speed Earth return (New Frontiers, Discovery, and Mars Sample Return) and Venus and Mars entry. Capsules used for these missions must withstand both convective and radiative aeroheating, and NASA now requires EDL instrumentation for these missions. Current radiative measurement techniques (radiometers) provide only an integrated heating over limited wavelength range; past interpretation of such flight data [Johnston] show the need for spectrally resolved measurements from spectrometers. For Earth and Venus, the radiative component may be the dominant source of heating, and emission comes from the VUV, that NASA currently has no capability to measure. For Mars and Venus, the aftbody radiation is dominated by MWIR. Again, NASA does not have a method to measure MWIR radiation in flight; the current radiometers integrate across several band systems. Miniaturized spectrometers that can measure in VUV and MWIR would have immediate application to SMD planetary missions. Such spectrometers may also inform what ablation species are emitted from the heatshield and backshell during entry.

Z7.03 Deployable Aerodynamic Decelerator Technology

Lead Center: ARC

Participating Center(s): ARC

Technology Area: TA15 Aeronautics

Scope Title
Deployable Aerodynamic Decelerator Technology

Scope Description

Background: NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, Titan, as well as payload return to Earth from Low Earth Orbit.
The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system is not constrained by the launch vehicle shroud. It has the flexibility to more efficiently use the available shroud volume, and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology enables delivery of very large (20 metric tons or more) usable payload, which may be needed to support human exploration. The technology also allows for reduced cost access to space by enabling the recovery of launch vehicle assets. This subtopic area solicits innovative technology solutions applicable to deployable entry concepts. Specific technology development areas include:

1) Advancements in textile manufacturing technologies that can be used to simplify production, reduce the mass, or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their flexible thermal protection system. Thermal protection concepts can also lead to improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1200 C). Concepts can be either passive or active dissipation approaches. For smaller scale inflatable systems, less than 1.5 meters in diameter, thin-ply or thin-film manufacturing approaches that can be used to reduce the minimum design gauge are of particular interest for inflatable structures. Focus of Phase 1 development can be subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase 2 manufacturing scale-up for applications related to Mars entry, Earth return, launch asset recovery, or the emergent small satellite community.

2) Concepts designed to augment the drag or provide guidance control for any class of entry vehicle. Concepts can be either deployable or rigid design systems that are suitable to deployable vehicle designs, including methods that modulate vehicle symmetry or adjust lift for active flight control to improve landing accuracy. Designs that decrease the ballistic coefficient by a factor of two to three times are to be considered. Of particular interest are concepts that can be used to modulate the lift or drag of a vehicle for enhanced control. Phase 1 proof of concept and preliminary design efforts that will lead to, or can be integrated into, flight demonstration prototypes in a Phase 2 effort are of interest.

3) High temperature capable structural elements to support mechanically deployable decelerators that surpass the performance capability of metallic ribs, joints, and struts. Anticipated systems would include composite elements or hybrid approaches that combine metallic structures with high temperature capable interface materials to improve thermal performance. Phase 1 development can be subscale component demonstrations that lead to Phase 2 scale-up and testing in relevant environments.

References


Expected TRL or TRL range at completion of the project: 1 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Subscale manufacturing demonstration articles for Phase I that can lead to Phase II manufacturing scale up.

State of the Art and Critical Gaps

The current state of the art for deployable aerodynamic decelerators is limited due to novelty of this technology.
Developing more efficient, lighter, and thinner flexible thermal protection system component materials with higher temperature capability could potentially enable more efficient designs and extend the maximum range of use of the concepts. Development of efficient guidance control and drag enhancements concepts for deployable vehicles is enabling technology. Novel and innovative high temperature structural concepts are needed for the mechanically deployed decelerator.

Relevance / Science Traceability

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, Titan, as well as payload return to Earth from Low Earth Orbit. HEOMD (Human Exploration and Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

Z7.04 Lander Systems Technologies

Lead Center: ARC

Participating Center(s): GRC, LaRC

Technology Area: TA15 Aeronautics

Scope Description

Plume/Surface Interaction Analysis & Ground Testing

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to model and predict the extent to which regolith is transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in close proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere, gravitational field, and the characteristics of the regolith are different for the Moon, the tools and analysis capability to characterize plume/surface interactions on the Moon will feed forward to Mars.

Therefore, NASA is seeking support in the following areas:

1. To increase analysis capability to model and predict the plume/surface interaction and nature and behavior of the ejecta, for NASA and commercial landing. Currently, there are negligible amounts of data collected from planetary robotic landings to develop and validate plume/surface interaction analysis tools. However, the limited data increase the understanding of various parameters, including the various types of surfaces that lead to different cratering effects and plume behaviors. Additionally, the information influences lander design and operations decisions for future missions. Ground testing (“unit tests”) is also used to provide data for tool validation. Innovative non-intrusive diagnostic development to measure critical parameters in this discipline are also severely lacking and are needed to advance prediction capability. The current post-landing analysis of planetary landers (on Mars) is of limited applicability in reducing risk to future landers, as it is limited to comparisons with only partially empirically-validated tools. Flight test data do not yet exist in the environments of interest.

2. The community needs ground test and flight test data, together with comprehensive Computational Fluid Dynamics (CFD) tools and methods, to devise validated models for different conditions that are applicable to a variety of landing missions. A consistent tool set is important for assessing risk and is useful to both the commercial sector and NASA.

3. Solutions are sought to alleviate the plume-surface interaction environment. Solutions should provide novel approaches for propulsion cluster placements, surface ejecta damage tolerant systems, mitigation shielding, etc. These solutions must be mass-efficient and have minimal interference with vehicle operations.
4. Validation data and diagnostic techniques at relevant scales, environments, and degrees of system integration are sought to reduce uncertainties in predicted plume-induced environments and subsequently reduce risk to landers and other surface assets. Critical parameters include near-field and far-field particle velocity, trajectories and concentration, erosion rates and transient crater profiles. There are large uncertainties associated with these parameters. Plume-induced environments include cratering, ejecta, aerodynamic destabilization, and elevated convective heating.

Mission needs to consider, in proposing these solutions, include landers with single and multiple engines, both pulsed and throttled systems, landed masses from 400 to 40,000 kg, and both Lunar and Mars destinations.

Innovations for Vehicle Structures

The development of more efficient lander structures and components are sought to improve the mass efficiency of in-space stages and landers. This may include the adoption and utilization of advanced lightweight materials, especially as used in combination with advanced manufacturing to enable reliable, conformal, and lightweight design innovations. Of interest are systems for actively alleviating flight loads and environments, reduce integration complexity, or improve system life, enable reusable landing systems, allow restowage and redeployment of solar arrays for multiple mission usage, and develop mechanisms and couplings for continuous use in the lunar dust environment. Approaches for achieving multifunctional components, repurposing structure for post-flight mission needs, and incorporating design features that reduce operating complexity are also of interest.

Lunar Dust Mitigation

Lunar dust, as experienced during the Apollo program, can have a wide range of deleterious effects on lander subsystems and the people using them. As we head back to the moon with robotic and human landers, the need for effective prevention and/or mitigation measures is needed to ensure long term, nominal operation of lander and surface systems and mission operations. Numerous studies have been performed to characterize dust deposition and potential impacts. Proposals are sought that build on previous studies to better characterize the deposition and impact of dust (see Z13.02 - Dust Tolerant Mechanisms).

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: [https://www.nasa.gov/content/commercial-lunar-payload-services](https://www.nasa.gov/content/commercial-lunar-payload-services) [1]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

Lander Technologies: [https://www.nasa.gov/content/lander-technologies](https://www.nasa.gov/content/lander-technologies) [37]


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Deliverables of all types can be infused into the prospect missions due to early design maturity.

State of the Art and Critical Gaps

The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model plume/surface interactions on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools, for validation purposes. The validation data set, as well as the expertise, grows as a result of each mission, and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability, to provide data for tool validation.

The current post-landing analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically-validated tools, because there has been no dedicated fundamental research investment in this area. Flight test data does not exist, in the environments of interest.

Relevance / Science Traceability

Current and future lander architectures such as:

- Artemis
- Commercial robotic lunar landers
- Planetary mission landers

Z7.05 3D Weaving Diagnostics

Lead Center: ARC

Technology Area: TA15 Aeronautics

Scope Title

3D Weaving Diagnostics for Validation of Uniform Weaving Processes

Scope Description

NASA is utilizing 3D woven materials to develop Woven Thermal Protection Systems (W-TPS). Examples of recent 3D woven Thermal Protection Systems (TPS) projects include: 3D Multifunctional Ablative TPS (3D-MAT) for compression pads on Orion, Adaptive Deployable Entry Placement Technology (ADEPT) looking at a mechanically deployable aeroshell (similar to an umbrella) that utilizes 3D woven carbon fabric between the ribs, and Heatshield for Extreme Entry Environment Technology (HEEET), containing dual-layer 3D weaves to provide mass efficient TPS solutions for extreme entry environment missions such as to Venus, Saturn and the outer planets. The specialized equipment used to weave 3D woven preforms is based on standard textile equipment that is
substantially modified to allow hundreds of layers to be interwoven together. As these complex woven structures are scaled up, it is critical to understand the dynamics of the 3D weaving equipment/hardware and how interactions between different components affect the unit cell of the woven structure and ultimately the material properties.

This subtopic area solicits innovative technology solutions applicable to 3-D woven materials. Specific technology development areas include:

1. Advancements in the understanding of the impact of weaving parameters on the properties of the final weave itself. Looking at developing methods to associate measured weave diagnostics (such as warp tension and beat up force) to understand the effects of woven material parameters (such as fiber volume fraction and yarn crimp), to develop tools to predict the impacts of changes in weaving parameters on final material properties (such as stiffness and strength).

2. Understand what damage may be introduced into the yarns during the weaving operation and the impact of that damage on material performance (such as strength). Objective is to further improve the understanding of how/if key aspects/parameters in the weaving operation (warp tension, beat up force, warp or fill yarns per inch) lead to damage of the yarns and develop methods to reduce weaving damage and/or guidelines to reduce the level of damage induced in the yarns.

References

More info for 3D-MAT, ADEPT, HEEET can be found at: https://gameon.nasa.gov/publications/ [38]

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis

Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques
Phase II: Prototype instrument demonstration on a weaving machine demonstrating increased control capability

State of the Art and Critical Gaps

NASA is investing in woven thermal protection systems, both rigid and mechanically deployable, which both come from a 3D weave. The mechanical/structural properties of these weaves are a strong function of nuances in the resultant weave microstructure; nuances such as fiber volume fraction and the level of crimp in warp versus weft direction or damage induced in the yarns during weaving. An enhanced understanding of the effects of the weaving operation parameters on the final weave itself would better enable scale-up of weaving processes (thickness and width) and tailoring of weaves to meet specific mission needs (how does a change in warp tension to reduce fiber volume fraction manifest itself in changes to crimp or other parameters). There is also value in understanding if/where the weaving operation induces damage into the yarn and its impact on material properties. The current state of the art is very empirical for understanding the effects of weaving parameters on material performance/damage. For example, it is recognized that increasing crimp can decrease stiffness in a material, but there are not good tools to predict the impacts of changes in weave parameters (such as warp tension) on the crimp level in a weave and how that will impact the properties of the final material. This makes it difficult to predict the impacts of changes in weave on properties and understand how sensitive the relationships are. The end result is that this lack of knowledge limits the flexibility end users have, and requires substantial amounts of testing to understand if a given change is important or not.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have Entry and Descent (ED)/ Entry, Descent and Landing (EDL) architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. With few exceptions, entry vehicle TPS (Thermal Protection System) for these missions will be composed of materials currently under development and without certification heritage.
NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic.

**Z7.06 Diagnostic tools for high enthalpy and high temperature materials testing and analysis**

Lead Center: ARC

Participating Center(s): LaRC

**Technology Area: TA15 Aeronautics**

**Scope Title**
Optical imaging diagnostics for validation of conventional instrumentation and simulation used to characterize high enthalpy, arc-heated ground test facilities

**Scope Description**
Advances and new technologies are sought for optical-spectroscopic imaging techniques for NASA’s high enthalpy aeroheating test facilities, specifically the Ames Research Center’s Arc Jet Complex and Langley Research Center’s Hypersonic Materials Environmental Test System (HyMETS). These facilities are used for evaluation of entry system thermal protection materials and structures. Experimental methods for arc jet facility characterization strive to quantify thermodynamic and gas dynamic properties of arc jet flows and serve multiple purposes, such as verification of test conditions (facility operations), validation of arc heater and flow field simulations, and measurement of incident/boundary conditions for material response simulations.

Foremost among these methods are instrumented stream probes and shaped test articles. They are routinely used to measure local heat flux and surface pressure and are tightly integrated with facility operations. Concerns over systematic errors in heat flux measurements have, to date, not been adequately addressed due to a lack of relevant data for validation of the underlying metrology principle – namely the interpreted response of a heat flux sensor to a nominally stable, but unsteady and highly dissociated, gas stream. Development of specialized diagnostic tools which can acquire these validation data, in situ, is the goal of this subtopic scope.

**References**


**Expected TRL or TRL range at completion of the project:** 3 to 6

**Desired Deliverables of Phase II**

Prototype, Hardware
Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques
Phase II: Prototype instrument demonstration in relevant environment with hardware delivery to NASA

State of the Art and Critical Gaps

Heat flux is undoubtedly the most critical measurement of every arc jet test program as it is used for facility operations, flow field simulation validation, and materials response analyses. Diminished – or unwarranted – confidence in conventional heat flux gauge measurements influences uncertainty in test results and ultimately adds risk to TPS (Thermal Protection System) qualification programs.

In highly dissociated arc jet flows, convective, catalytic, and radiative heat fluxes simultaneously contribute to a heat flux gauge’s response. However, response interpretation may not properly account for the microscopic thermodynamic and spatiotemporal characteristics of the incident stream and gas-surface interactions that ultimately govern the response. Potential sources of error and bias are incident flow property unsteadiness and catalytic efficiency uncertainties.

Perturbations and instabilities within the arc heater can persist through nonequilibrium expansion within the nozzle and into the test chamber, possibly resulting in fluctuating flow properties, gradients, and atom fluxes at article surfaces. As flow property gradients are the driving potentials for catalysis, property fluctuations could influence the magnitude of catalytic heat flux. Departures from modeled interpretation cannot be discerned without direct observation, potentially resulting in unknown error and bias in heat flux measurements.

Also contributing to error and bias is the uncertainty in the sensor’s catalytic efficiency. A reduction or augmentation from an assumed value creates an undetectable bias in heat flux measurements with consequences that may not be conservative. Coupled with the potential influence of property gradient fluctuations on catalysis, the modeling assumptions of heat transfer to catalytic surfaces in dissociated flows cannot be validated without additional, independent data sources.

Time-resolved gas property measurement along the stagnation streamline would enable evaluation of the key assumptions of NASA’s heat flux measurement approach. Quantities of particular interest are atomic and molecular species concentrations and temperature. The profiles and statistical variations could verify the conformance to, or reveal the departure from, the modeled theories. The ultimate benefit will be greater confidence in NASA’s use of heat flux gauges.

The above requirements strongly indicate the use of kHz rate, species-selective, ultrafast pulsed laser spectroscopic imaging techniques to advance the state-of-the art. NASA’s current nanosecond laser-induced fluorescence capabilities are inadequate due to insufficient sensitivity for quantitative planar imaging in the highly luminous shock layer ahead of a test model.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have Entry and Descent (ED)/ Entry, Descent and Landing (EDL) architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. With few exceptions, entry vehicle TPS for these missions will be composed of materials currently under development and without certification heritage. Arc jet testing at conditions relevant for certification will invariably be required for each of these proposed missions. Ground testing at more extreme environments for future missions will challenge existing capabilities. There is a compelling need now to bring research-level diagnostic technologies forward to ensure that facility operations can credibly demonstrate required performance to TPS technology projects.

Conventional instrumentation will continue to be the primary source of facility characterization data. The purposes of the advanced techniques are to provide validating evidence for the conventional instrumentation, reveal error and bias in interpretation of heat flux measurements, and ultimately reduce uncertainty in facility performance data provided to test programs.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. The first-line project is STMD’s (Space Technology Mission Directorate) Entry Systems Modeling Project.
Scope Title
Advanced instrumentation for NASA's shock tube and ballistic range facilities

Scope Description

NASA is seeking innovative imaging and spectroscopic measurement techniques for NASA's two specialized-use impulse facilities: the Electric Arc Shock Tube (EAST) and the Hypervelocity Free Flight Aerodynamic Facility (HFFAF). The EAST facility replicates shocked gas environments encountered by entry vehicles transiting planetary atmospheres at hypersonic velocities. Spectroscopic instrumentation is used to characterize the absolute radiance and gas kinetics behind a traveling shock wave. The HFFAF is used for the study of dynamically similar supersonic and hypersonic aerodynamics, transition to turbulence, and laminar and turbulent convective heat transfer. Optical imaging instrumentation is used to characterize aerodynamic forces and moments of scaled models launched through the range. Thermographic and spectral imaging instrumentation is used to characterize spatially resolved heating rates to scaled models.

New electro-optic products and methods enable measurement of quantities beyond current capabilities and improve current practices.

References


Many journal papers, conference proceedings, and technical reports describing the NASA Ames EAST and HFFAF test facilities and research are available in the open literature.

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Phase I: Assessment study of potential diagnostic techniques or technology upgrades
Phase II: Prototype instrument demonstration in relevant environment (preferably w/hardware delivery to NASA)

State of the Art and Critical Gaps

The EAST facility's instrumentation acquires data for shocked gas phenomenology and facility performance characterization. Measurements of radiance, absorbance, electron density, and temperature are used for validation of comprehensive radiation transport simulations of planetary atmospheres. Those measurements are primarily acquired using calibrated optical-spectroscopic instruments with sufficient temporal and/or spatial resolution to correlate observed magnitudes with localized, spectrally resolved absolute radiant fluxes or columnar property densities (including electron densities). Ancillary instrumentation is used to measure shock arrival times and transient pressures at the tube wall to establish shock speeds adjacent to the science instruments.

Measurement techniques that correlate observables to atomic and molecular state populations and radiance magnitudes enable validation of radiance models. Emission spectroscopy techniques, which capture the transient characteristics of excited atomic and molecular state populations, have reached a high degree of maturity and efficacy.

However, post-shock electron and ground or other dark state population dynamics also influence shock radiance. Measurement of these states rely on more complicated absorption, induced fluorescence, or scattering (spontaneous and coherent) techniques. The lack of light sources and/or detectors with suitable spectral and
temporal characteristics or the challenges of implementation in impulse facilities have limited opportunities for such measurements. Techniques that enable measurement of these states would greatly expand opportunities for radiation transport model validation, particularly for conditions in which self-absorption would influence emission spectroscopy measurements.

For the HFFAF, shadowgraph and schlieren photography are used to provide time-resolved imagery for aerodynamic force and moment analyses of scaled flight vehicles in free flight. A high-speed shutter (40 ns duration) and a spark-gap light source enable images to be captured without motion blur. The shuttering system relies on Kerr cells filled with benzonitrile and a 35 kV pulse shaping and switching network. Advances are sought for the eventual replacement of the 32 heritage light source/shutter systems with components that offer equal or greater performance as well as improved safety and reliability.

Relevance / Science Traceability

Several potential future missions, outlined in decadal surveys, crewed exploration mission studies, and other supporting analyses, have ED/EDL architectures: Mars sample return, high speed crewed return, high mass Mars landers, Venus and gas/ice giant probes. Entry vehicles to these destinations will encounter radiative heating to varying degrees. Radiative heating of a vehicle’s back shell has been recognized as a significant concern, so ensuring a full range of diagnostic techniques for expanding flows has become a high priority for the EDL (Entry, Descent, and Landing) community.

Characterizing the aerodynamic stability of emerging deployable drag devices for entry vehicles is also of high importance for future high-mass lander missions. The HFFAF will be a key ground test facility for acquiring crucial free-flight aerodynamic data for study and simulation validation.

NASA planetary exploration programs supporting ED/EDL missions are the intended beneficiaries of this subtopic. Technology development projects supporting these programs are potential beneficiaries of new instrumentation for the EAST and HFFAF.

Z8.02 Communications and Navigation for Distributed Small Spacecraft Beyond LEO

Lead Center: ARC

Participating Center(s): ARC, GSFC, JPL, LaRC

Technology Area: TA15 Aeronautics

Scope Title

Distributed Spacecraft Mission Communications

Scope Description

Develop enabling technologies for beyond Low Earth Orbit (LEO) communications, relative and/or absolute position knowledge, and control of small spacecraft. Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct NASA Lunar and deep-space distributed spacecraft science missions. Innovations in communications and navigation technologies for distributed small spacecraft are essential to fulfill the envisioned science missions within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture, it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include data relay from lunar surface to surface, data relay to earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple smallsats may be necessary because of limited Size, Weight and Power (SWaP), but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the Martian domain are also solicited.

References
Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype hardware and/or software.

Desired Deliverables Description

Phase I - Identify and explore options for the Distributed Spacecraft Mission (DSM) configuration control, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling and networking solutions. Also identify, evaluate and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path towards a hardware/software infusion into practice. Bench-level or lab-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small spacecraft communications payloads through Phase II efforts and beyond.

State of the Art and Critical Gaps

Communications among spacecraft in the DSM configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (10s to 100s km apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- DSM configuration control – distributed operations of the DSM configuration and of individual small spacecraft alternatives need to provide: science data time and location stamping; temporary data storage;
distributed network control and data planes; networking protocols; and any other considerations associated
with control of the configuration. Control needs to allow a swarm to fly with the precision approaching that
of one large instrument, and/or produce relative position data that allows for compensation of
measurements over time.

- Uplinks (Earth-to-space) and Downlinks (space-to-Earth) – alternatives for coordinated command and
control of the DSM configuration and individual small spacecraft from Earth as well as return of science and
 telemetry data to Earth.
- Integrated communications payload– hardware and software designs for the common and unique
capabilities of each small spacecraft in the DSM configuration.
- Small Spacecraft Antennas – development of antennas optimized for either inter-satellite or uplink/downlink
 communications are sought across a broad range of technologies including but not limited to deployable
 parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning
 subsystems, and others suitable for use in high data rate transmission among small spacecraft over large
distances. Operations compatible with NASA’s space communications infrastructure [9] and Government
 exclusive or Government/non-Government shared frequency spectrum allocations is required. [6, 7, 8].
- Compatibility and interoperability with lunar communications and navigation architecture plans [1, 2, and 3].
 Application of the emerging lunar standards includes frequency allocations per link functionality,
 modulations, coding, and networking protocol standards.

Relevance / Science Traceability

Several missions are being planned to conduct investigations/observations in the cis-lunar region and beyond. All
of these missions will benefit from improved communications and navigation capabilities. For example, follow-on
missions to the current Mars Cube One mission.

Scope Title

Distributed Spacecraft Mission Position Knowledge and Control

Scope Description

The navigation portion of this subtopic solicits methods for determining and maintaining spacecraft position within a
configuration of small spacecraft. In addition, timing distribution solutions for the smallsats may be important.
Distributed Spacecraft Mission (DSM) navigation solutions may be addressed via hardware or software solutions,
or a combination.

References

[1] International Communication System Interoperability Standard (ICSIS), found at
https://www.internationaldeepspacestandards.com [41]


https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf [43]


[6] National Telecommunications and Information Administration - United States Frequency Allocation Chart:

[7] National Telecommunications and Information Administration - Tables of Frequency Allocations:
https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html [46]
Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype hardware and/or software.

Desired Deliverables Description

Phase I - Identify and explore options for the DSM configuration control, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling and networking solutions. Also identify, evaluate and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path towards a hardware/software infusion into practice. Bench-level or lab-environment level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small spacecraft communications payloads through Phase II efforts and beyond.

State of the Art and Critical Gaps

Science measurements of DSMs are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft are involved. Global navigation satellite services like the U.S. global positioning satellites (GPS) provide very limited services beyond GEO (Geocentric) distances and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs.

- Optical navigation - Solutions are sought for visual based systems that leverage advances in optical sensors (i.e., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. In particular, low SWaP absolute attitude determination using star trackers, etc. to achieve sub-arcsecond accuracy. JPL’s ASTERIA 6U CubeSat demonstrated pointing stability of 0.5 arcseconds (0.1 m°) RMS over 20 minutes using guide stars *might* represent the state-of-the-art. Opportunities for innovation include methods that do not require the execution of satellite maneuvers are/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various mission operations concepts are of interest.
- Long-term, high accuracy attitude determination; in particular, low SWaP absolute attitude determination using star trackers, etc. to achieve sub-arcsecond accuracy.
- Other novel navigation methods - Stellar navigation aids, such as navigation via quasars, X-rays and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters, and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small satellite platforms and do not assume particular orbit eccentricities.
NOTE: Small spacecraft propulsion technologies are not included in this subtopic.

Relevance / Science Traceability

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of Distributed Spacecraft Missions (DSM) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cis-lunar region and beyond. All of these missions will benefit from improved communications and navigation capabilities.

Z8.06 DragSails for Spacecraft Deorbit

Lead Center: ARC

Participating Center(s): ARC

Technology Area: TA15 Aeronautics

Scope Description

DragSails are a generic family of drag devices that can:

- Provide coarse, non-propulsive de-orbit capability which can aid in the disposal of end-of-life spacecraft through burnup upon reentry.
- Provide an accurate means of de-orbiting by modulating the ballistic coefficient to guide the system to a desired point at the Von Karman altitude for precision reentry targeting.

Small, lightweight, deployable membranes have been tested and deployed in Earth for both solar sail and drag sail applications. NASA’s 10 square meter NanoSail-D2 solar sail and The University of Surrey’s InflateSail drag sail are two examples. These systems demonstrated the technical viability of developing a deployable drag device to accelerate the deorbit of satellites to comply with end-of-life regulations and to mitigate the growth of orbital debris. Given the underlining technology similarities between solar sail and drag sail systems there are opportunities for adaptation or cross-use of some system elements. Further, there is also opportunity for cross-use into other fields such as PowerSails, thin-film surface power generation, and thin-film thermal control systems.

In terms of controlled, targeted de-orbit, the NASA Exo-Brake development effort has yielded promising though nascent results with the development of controllable tension structures. Tension structures don't have the 'beam buckling' issue associated with the more common drag sails at the higher dynamic pressures at atmospheric entry interface. This approach, while not as applicable to larger disposal efforts, can allow for more targeted reentry with potential additional uses in inexpensive Entry, Descent, and Landing (EDL) test-beds or sample return concepts.

Developing systems to actively provide a de-orbit disposal, or targeted de-orbit/re-entry capability, is the next logical step toward such systems becoming widely available for spacecraft manufacturers, NASA and other government agencies as an alternative to conventional propulsion systems. Specific technology development areas of interest include:

- Restorable concepts which can deploy, operate, then re-stow multiple times. This may include new boom and materials concepts, but must include a restorable/redeployable deployment architecture capable of meeting the de-orbit requirements below.
- Phase I proof of concept and preliminary design efforts that will lead to, or can be integrated into, environmental qualification and/or flight demonstration prototypes in a Phase II effort are of interest.
- Desired system-level capabilities include the de-orbit of CubeSats (3U to 12U or larger) and small spacecraft in the 50kg - 200kg mass range (frontal areas on the order of 2000 to 2700 cubic cm) from altitudes between approximately 700km and 2,000km in 25 years or less. Spacecraft flying below 700km
will generally meet the 25-year-or-less requirement without augmentation.

References


Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, and Hardware

Desired Deliverables Description

Ideal Phase II deliverable would be DragSail subsystems tested in a relevant environment

State of the Art and Critical Gaps

State of the Art is currently being defined by the solar sail propulsion community whose interest is deploying similar large-area, lightweight sails to reflect photons and derive thrust. Technologies which support solar sail development are inherently similar to those that would be required to develop and implement DragSails. Thin-film membranes capable of being stored in a folded state for several years or decades, lightweight deployable and potentially retractable booms, and combinations thereof that can survive in Earth orbit environment (UV, atomic oxygen, ionizing radiation, etc.) that can deploy, augment a spacecraft's aerodynamic drag, and restow are of interest. Flight control systems for DragSails have yet to be demonstrated or tested and will be essential for DragSail systems that provide deorbit independently of other, proven, deorbit systems.

Relevance / Science Traceability

Any spacecraft in Earth orbit must demonstrate how it will be either de-orbited or moved to an orbit that poses no risk to other spacecraft within a set period after its useful life. Therefore, any spacecraft launched by government, universities or industry are potential customers for a DragSail deorbit system. Further, the concepts developed as a part of the DragSail are applicable to large area solar sails, power sails, thin-film surface power, and the like.

Z8.08 Technologies to Enable Cost & Schedule Reductions for Ultra-Stable Normal Incidence Mirrors for CubeSats

Lead Center: ARC

Participating Center(s): GSFC, JPL

Technology Area: TA15 Aeronautics

Scope Description

Relatively inexpensive small spacecraft offer several advantages over larger, more expensive spacecraft: small spacecraft can perform inspection and repair of larger spacecraft; several can be deployed for more frequent revisit rates over Earth’s surface or planetary objects; and multiple craft can achieve affordable mission reliability through redundancy. To date, the utility of small spacecraft in missions involving remote sensing (in any spectral band) has been constrained by their low budget and compact size: optical sensitivity is limited in proportion to the diameter of a telescope's aperture and magnification is limited by the effective focal length. The cost to produce one-of-a-kind optical assemblies is disproportionate and the production times too long to incorporate into the tight budgets and
The objective of this subtopic is to receive proposals that articulate a demonstrable ability to manufacture, test and control ultra-low-cost optical systems that can meet the reference mission performance requirements (including infrastructure issues) within a time frame and budget compatible with a small spacecraft development cycle. For the purposes of this subtopic, small spacecraft are defined as CubeSats of 12U volume. Proposals are sought that will specify telescope figures of merit for a potential small spacecraft mission (e.g. Earth resource management, maritime traffic monitoring, observations for agricultural industry, lunar exploration precursors, manned spacecraft inspection, NEO asteroid detection, or other reference mission to be specified by proposer) and will include discussion of current state-of-the-art for telescope optical parameters (sensitivity, resolution and magnification within a spectral band), production cost and schedule significantly improved by the proposed telescope design. Detector electronics are not specifically sought for this subtopic.

References

None

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Prototype telescope appropriate for inclusion in a 12U CubeSat with up to 8U available for optics. A CubeSat class precision optical system would include an aperture of up to approximately 0.2m diameter. For Phase I, deliverables should include a design reference mission relevant to the telescope design, with key performance parameters identified. Identification of key relevant subcomponents of a telescope system require a prototype demonstration for fabrication, test or control technology required for a successful Phase II delivery of a prototype. Ideally Phase I includes a reviewed preliminary design and manufacturing plan which demonstrates production feasibility, appropriate material behavior, process controls, optical performance, and mounting/deploying issues especially with considerations to small spacecraft should be resolved and demonstrated. While final manufacturing and assembly will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with proposed performance measures, survival of the launch environment and performance in the space environment (Earth orbiting or deep space).

In Phase II the project could complete environmental qualification testing of the telescope including measuring optical figure before and after vibration testing, acoustic testing, and thermal cycling. It would also demonstrate that the telescope maintains optical figure in a reference thermal environment including thermal gradients.

A successful mission oriented Phase II would yield a credible plan to deliver (in phase III) flight hardware within the allocated budget for a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis). Cost and schedule goals and optical performance goals are listed under State of the Art and Critical Gaps.

State of the Art and Critical Gaps

Technical Challenges: To accomplish NASA CubeSat-class missions, a low-cost telescope with ultra-stable, normal incidence mirrors with low mass-to-collecting area ratios, should be delivered on short schedules. After performance, the most important metric for an advanced optical system is affordability. Long telescope fabrication times add significant program cost. Current normal incidence space telescopes in the 0.2- 0.5m aperture class have lead times of 12-18 months and cost $1 million to $5 million. This research effort seeks a schedule compression and cost reduction for precision optical components by 10 times, to 4-6 months and $100K-$500K for a 0.2 m aperture class telescope.
Specific metrics are defined for each wavelength application region:

For UV/Optical:

- Wavefront Figure < 5 nm RMS.
- Wavefront Stability < 1 nm / 10 min
- First Mode Frequency >500 Hz.
- Actuator Resolution < 1 nm RMS.

For EUV:

- Slope < 0.1 micro-radian.

Also needed is ability to fully characterize surface errors and predict optical performance.

Relevance / Science Traceability

A new class of low-cost, optically stable, wide spectral range telescopes designed specifically for small spacecraft have application in a variety of exploration, commercial and science missions. Existing missions can be accomplished in novel and more affordable ways with small spacecraft, and new missions will be enabled by high-performance telescopes in small spacecraft. A few examples include: Earth resource management, maritime traffic monitoring, observations for agricultural industry from Low Earth Orbit; lunar exploration precursors and manned spacecraft inspection in cislunar space; and near Earth object detection or exoplanet transit detection in deep space.

Z8.09 Small Launcher Lunar Transfer Stage Development

Lead Center: ARC

Participating Center(s): AFRC, GRC

Technology Area: TA15 Aeronautics

Scope Description

NASA desires to explore the lunar environment using small spacecraft. The lunar environment in this case includes: the lunar surface with specific interest in the south pole, low lunar and frozen lunar orbits, as well as cislunar space including Earth-moon LaGrange points and the lunar Near Rectilinear Halo Orbit (NRHOs) intended for Gateway. To allow CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, to exploit these locations, NASA is interested in the development of a low cost cis-lunar transfer stage to guide and propel small spacecraft on Trans Lunar Injection (TLI) trajectories that will enable the spacecraft to enter the above referenced lunar locations or orbits, either with on board propulsion capability or via the transfer stage itself.

Transfer stage architectures and designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching in the next year. Proposals should identify one or more relevant small launch vehicles and shall describe how their designs fit within the constraints of those vehicles. Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication in order to complete the lunar mission. Any and all propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy smallsat payloads once on a TLI trajectory or upon arrival in lunar orbit.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium or heavy lift launch vehicles (e.g. Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.
Design reference mission:

- Launch on a small launch vehicle (ground or air launch)
- Payload (deployable spacecraft) mass: at least 25 kg
- Provide sufficient delta V and guidance to enter into TLI after separation from small launch vehicle. An example mission is the CAPSTONE / NRHO Pathfinder 12U (25 kg) CubeSat that requires a Trans Lunar Injection orbit with a C3 of -0.6 km²/s².
- (Optional) provide sufficient delta V and guidance to place a 25 to 50 kg spacecraft directly into lunar NHRO orbit
- Deploy spacecraft from transfer stage
- Safe and dispose of transfer stage

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https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010585.pdf [53]

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Expected TRL or TRL range at completion of the project

Proposed technologies should mature to TRL 4 to 6 by the end of Phase II effort.

Desired Deliverables of Phase II

Prototype Hardware and Software

Experimental data

Mission design and analysis data

Desired Deliverables Description

A Phase I effort should include a Preliminary Design Review (PDR) level design for a flight-like system and a near-Completion Design Review (CDR) level design for the prototype system. The feasibility of key elements in the system design should be evident through fabrication or testing demonstrations. The phase 1 report should include a mapping of key performance parameters (mass, power, cost, etc.) from the prototype to the flight design, along with potential opportunities for technology demonstration and commercialization. It is highly desired that the Phase II deliverable include demonstration test data for the prototype system along with detailed metrics (mass, power, cost, etc.) which are traceable to a flight design for the reference mission. Efforts leading to Phase II delivery of integrated prototype systems that could either be ground tested or flight-testing as part of a post-Phase II effort are of particular interest.

State of the Art and Critical Gaps

Many cubesat/small sat propulsion units are designed for low delta-V maneuvers such as orbit maintenance, station keeping, or reaction control. Larger delta-V systems are employed for larger satellites and science/exploration missions, but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bi-propellant storables with electric systems also viable for very small systems. Aerojet Rocketdyne and Moog are prominent suppliers of SOA thrusters including commonly used variants of the R-4D engine. Rocket Labs has recently introduced an upgraded version of their kick-stage using a monopropellant system to support LEO operations for small sat payloads. While many of the right component technologies are reasonably mature, no integrated system capability has been developed and implemented specifically as a low cost
solution for trans-lunar or cis-lunar mission designs.

Relevance / Science Traceability

This subtopic extends the capabilities of the Flight Opportunities Program and Launch Services Program by seeding potential providers to establish lunar/cis-lunar transfer capabilities.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight test beds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors.

Z8.10 Wireless Communication for Avionics and Sensors for Space Applications

Lead Center: ARC

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

Technology Area: TA15 Aeronautics

Subtopic Description

This subtopic solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for small spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the Size, Weight, and Power (SWaP) consumption and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems and software across multiple spacecraft and missions while reducing production and operating costs.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems including software incorporating functions compatible with common spacecraft components. This means being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other non-related components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through the use of innovative methods such as the use of flexible materials and additive manufacturing. The use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats including ESPA-class), but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include: cislunar, lunar orbiting, lunar landed, exploration precursor; Low Earth Orbit (LEO) “swarms” for Earth science and heliophysics; disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:
1. Improve the reliability and applicability of wireless avionics for small spacecraft with significant improvements in subsystem size, mass, volume, particularly if the technology can simplify the spacecraft fabrication, test and integration process.

2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small satellite missions.

3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address Developmental and Flight Instrumentation use.

4. Use additive manufacturing techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.

5. Use additive manufacturing of wireless components such as antennas, sensors and processing elements into materials and structures that enable in-situ structural health management, contributing to the development of smart structures and materials.

6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the moon, Mars or other celestial bodies.

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NASA Trade Study: https://pdfs.semanticscholar.org/b7d6/e6d92ec78b6bee4cfd5a7f613b90b4508b8.pdf?_ga=2.244696965.1321060048.1563032260-1133117962.1563032260 [64]

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Expected TRL or TRL range at completion of the project

TRL 1 to 2 concepts for science instruments and sensory systems for vehicles and observatories

TRL 3 to 6 for embedded sensor systems and modular avionics technology development and prototype demonstration

Desired Deliverables of Phase II

Prototype Hardware and Software, Demonstrations

Desired Deliverables Description

Possible deliverables include bench-top hardware systems that demonstrate reliable wireless inter-connectivity of two or more modules with a host flight CPU, or payload/DFI processor, inside a Cubesat or Small Satellite form-factor bus. This system need not be flight-ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Lunar Gateway, and other Artemis projects.

Specific Deliverables Include:
• Methods of improving reliability of wireless avionics technology
• Redundancy methods to broaden mission applicability
• Improvements in tolerance to extreme environments including radiation
• Novel avionics architecture definition and demonstration
• Software support for redundant modular avionics
• Plug and Play methods for handling dynamic changes to avionics configuration
• Fault detection and recovery for wireless avionics
• Improvements in spacecraft production
• Improvements in spacecraft Integration and Test
• Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
• Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near to mid-range time frames

State of the Art and Critical Gaps

Development of small satellites missions benefits from a growing number of users worldwide, resulting in a large pool of COTS components available for specific missions, depending on the type and class of mission. A variety of C&DH (Command and Data Handling) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the on-board computer, memory, electrical power system and the ability to support a variety of input & output for the CubeSat class of small spacecraft. Wireless networks have been incorporated as crew support networks aboard ISS, freeing the astronauts from cables. Wireless sensor networks have been flown as demonstrations aboard CubeSats. Dynamic self-configuring wireless networks have been evaluated in the lab. The AIAA has defined the Space Plug-and-Play (SPA) standard and flight demonstrations are planned.

The maturation of additive manufacturing and 3D printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multi-functional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management for future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent such as parachutes and inflatable structures

Relevance / Science Traceability

NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred to any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

Z10.01 Cryogenic Fluid Management

Lead Center: MSFC

Participating Center(s): JSC, MSFC

Technology Area: TA15 Aeronautics

Scope Description

This subtopic seeks technologies related to cryogenic propellant (e.g. hydrogen, oxygen, methane) storage and transfer to support NASA’s space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include, but are not limited to upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in-situ
resource utilization. Anticipated outcome of Phase 1 proposals are expected to deliver proof of the proposed concept with some sort of basic testing or physical demonstration. Proposals shall include plans for a prototype and demonstration in a defined relevant environment (with relevant fluids) at the conclusion of Phase II.

Desired technology concepts are listed below in order of priority:

- Develop cryogenic mass flow meters applicable to liquid oxygen and methane, having a volumetric flow measurement capacity of 1 - 20 L/min (fluid line size of approximately ½ inch), of rugged design that is able to withstand launch-load vibrations (e.g., 20g rms), with remote powered electronics (not attached to the flowmeter), able to function accurately in microgravity and vacuum environment, and having measurement error less than +/- 0.5% of the mass flow rate reading. Ability to measure bi-directional flow, compatibility with liquid hydrogen, and ability to measure mass flow rate during two-phase flows is also desired. Designs that can tolerate gas flow without damage to the flowmeter are also desired. Goal is Proof of concept end of Phase 1. Working prototype flow meter end of Phase 2.

- Broad area cooling methods for cryogenic composite propellant tanks (reduced and/or zero boil-off applications or liquefaction): Design and integration concepts must exhibit low mass, high-heat transfer between cooling fluid and propellant in tank, high heat exchanger efficiency (>90%), and operate in reduced gravity environments (10-6 g worse case). Proposers should consider structural and pressure vessel implications of the proposed concept. Target applications include liquid oxygen liquefaction system (16 g/s neon gas, 85K < T < 90K, pressure drop < 0.25 psia, 2.6m diameter, 3m tall tank) and reduced and/or zero boil off liquid hydrogen nuclear thermal propulsion system (3.5 g/s helium gas, 20K < T < 24K, 7m diameter, 8m tall tank).

- Cryogenic liquid/vapor phase separators capable of delivering single-phase liquid flow at least up to 10 gallons per minute, void fractions up to 30%, with an emphasis on minimizing pressure drop across the separator. Devices should be able to maintain performance (phase separation at highest flow rate) after multiple (> 15) thermal cycles (room temperature to 77K and back). Phase separator should tolerate transient (transfer line and separator are chilling down). Phase 1 concept should yield a proof of concept using liquid cryogens. Phase 2 should focus on minimizing phase separator pressure drop, overall integration of phase separator into transfer system (i.e. where to route the vapor), and development a unit to test in liquid hydrogen.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: [https://www.nasa.gov/content/commercial-lunar-payload-services](https://www.nasa.gov/content/commercial-lunar-payload-services) [1]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References


Expected TRL or TRL range at completion of the project 2 to 4

Desired Deliverables of Phase II

Hardware, Software
Desired Deliverables Description

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

Z10.03 Nuclear Thermal Propulsion

Lead Center: MSFC

Participating Center(s): GRC, SSC

Technology Area: TA15 Aeronautics

Scope Title
Reactor and Fuel System

Scope Description

The focus is on highly stable materials for nuclear fuels and non-fuel reactor components (i.e., moderator tie tubes, etc.) that can heat hydrogen to temperatures greater than 2600K without undergoing significant dimensional deformation, cracking, or hydrogen reactions. Current technology hurdles related to ceramic metal fuels center around refractory metal processing and manufacturing (i.e., welding of refractories, refractory metal coatings, etc.). The development of refractory alloys with enhanced/targeted material properties are of key interest (i.e., tungsten or molybdenum with increased ductility, or dispersion strengthen Mo/W alloys). Current technology hurdles with carbide fuels include embedding carbide kernels with coatings in a carbide matrix with potential for total fission product containment and high fuel burn-up. Manufacturing and testing of the insulator and reflector materials are also critical to the success of a Nuclear Thermal Propulsion (NTP) reactor.

Technologies being sought include:

- Low Enriched Uranium reactor fuel element designs with high temperature (> 2600K), high power density (>5 MW/L) to optimize hydrogen propellant heating.
- New advanced manufacturing processes to quickly manufacture the fuel with uniform channel coatings.
and/or claddings that reduce fission product gas release and reactor particulates into the engines exhaust stream.

- High temperature fuels that build on experience from AGR (Advanced Gas Reactor) TRISO (Tristructural-isotropic) design and testing. Potentially enable NTP with Isp> 900 seconds.

Fuels focused on Ceramic-metallic (cermet) designs:

- Fabrication technique for full length W/UN or W/UO2 fuel elements with greater than 60% volume ceramic loading

Fuels focused on carbide designs:

- Compatibility with high temperature hydrogen.
- High thermal conductivity and other properties (e.g., ductility) needed for high power density operation (~5MW/l).
- Kernel diameters, including coatings for fission product containment, which allow the fuel element to be fabricated with adequate strength for high temperature and high-power density operation.

Insulator design (one application is for tie tubes and the other is for interface with the pressure vessel) which has very low thermal conductivity and neutron absorption, withstands high temperatures, compatible with hot hydrogen and radiation environment, and light weight.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype hardware is desired.

Desired Deliverables Description

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

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

Phase II Deliverables - A full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 4-5). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for NTP application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology.

State of the Art and Critical Gaps

The SOA (State-Of-the-Art) is reactor fuel developed for the Rover/NERVA program in the 1960's and early 1970's. The fuel was carbon based and had what is known as "mid-ban" corrosion, which effected the fuel endurance. Switching over to cermet (metal and ceramics) or advance carbide fuels shows promise, but has fabrication challenges.

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

Focus is on a range of modern technologies associated with NTP using solid core nuclear fission reactors and
technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf
with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the
spacecraft's primary propulsion system. The NTP can have multiple start-ups (>4) with cumulative run time >100
minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of
engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current
regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test
requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Relevance / Science Traceability

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

Future mission applications:

- Human Missions to Mars
- Science Missions to Outer Planets
- Planetary Defense

Some technologies may have applications for fission surface power systems.

Scope Title
Ground Test Technologies

Scope Description

Included in this area of technology development needs are identification and application of robust materials,
advanced instruments and monitoring systems capable of operating in extreme temperature, pressure and
radiation environments. Specific areas of interest include:

- Devices for measurement of radiation, pressure, temperature and strain in a high temperature and radiation
  environment.
- Non-intrusive diagnostic technology to monitor engine exhaust for fuel element erosion/failure and release
  of radioactive particulates.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype hardware is desired

Desired Deliverables Description

Desired deliverables for this technology would include research to determine the technical feasibility during Phase I
and show a path toward a Phase II hardware demonstration. Determine a prototype instrument arrangement which
can be strategically positioned to monitor NTP operation as good as possible. To monitor fuel degradation in the
exhaust stream, the optimum position of the sensors must account for anomalies near an operating reactor core
and have the ability to withstand the radiation and heat environment. Testing the technology in a simulated (as
close as possible) NTP environment as part of phase II is preferred. Delivery of a prototype test unit at the
completion of phase II allows for follow-up testing by NASA.
Phase I Deliverables - Feasibility analysis and/or small-scale experiments proving the proposed technology to develop a given product (TRL 2-3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables - A full report of component and/or breadboard validation of sensor measurements, including populated verification matrix from Phase I (TRL 4-5). Also delivered is a prototype of the proposed technology for NASA to do further testing if phase II results show promise for NTP application. Opportunities and plans must also be identified and summarized for potential commercialization of the proposed technology.

State of the Art and Critical Gaps

The SOA NTP ground testing involved open air testing in the 1960's and early 1970's. The current regulations require an exhaust treatment system to avoid release of significant quantities of fission products into the air. Validating various exhaust treatment concepts requires a subscale simulation of NTP hot hydrogen, the cooling system, filtering, and special instrumentation to monitor what is coming out in the hydrogen exhaust, which could lead to shutdown.

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

Focus is on a range of modern technologies associated with NTP using solid core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~25,000 lbf with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple start-ups (~4) with cumulative run time >100 minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test requirements can have multiple start-ups (~8) with the longest single burn time ~50 minutes.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) is supporting NTP project. Future mission applications:

- Human Missions to Mars
- Science Missions to Outer Planets
- Planetary Defense

Z10.04 Manufacturing processes enabling lower-cost, in-space electric propulsion thrusters

Lead Center: MSFC

Technology Area: TA15 Aeronautics

Electric propulsion for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. During recent flight thruster development projects, NASA has identified manufacturing issues that have resulted in significant costs to achieve performance repeatability and hardware reliability. Without addressing the process and materials issues, both the production of existing thrusters and the development of new thrusters will continue to face the prospect of high costs that limit the commercial viability of these technologies.
NASA thus seeks proposals that address improved fabrication processes or materials to reduce the total life cycle cost of electric propulsion thrusters. For example, a proposed component or assembly manufacturing process that improves fabrication reliability could permit reductions in the scope of acceptance testing and thus lower the overall cost of the technology.

Critical NASA needs have been identified in the scope areas detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state-of-the-art (SOA) and quantitatively (not just qualitatively) describe improvements over relevant SOA processes and materials that substantiate NASA investment. Prospective proposers in fields outside of electric propulsion are highly encouraged to apply if they have experiences with manufacturing processes that may be suitable for this solicitation.

Scope Title
Material joining in hollow cathodes

Scope Description
SOA hollow cathodes in thrusters are complex assemblies with metal-to-ceramic (e.g., alumina, magnesium oxide, etc.) and metal-to-metal joints where dissimilar materials may have large thermal expansion mismatches. In such cathodes, operating temperatures can range from 1000 - 1700 °C (necessitating the use of refractory metals such as molybdenum, rhenium, tantalum, tungsten, etc.), and material joints must be able to survive in excess of 10,000 thermal on-off cycles without failure. Existing material joining processes used to construct Hall-effect and ion thruster cathodes have demonstrated inconsistencies in joint strength and the presence of impurities that may degrade cathode performance during vacuum operations. Efforts to mitigate these issues have to date contributed to the high cost for the integrated cathode assembly and thruster; thus, making them less attractive for commercial usage, particularly for small satellite propulsion applications. Proposed material joining processes to this area must be compatible with critical high-temperature materials; be performed readily, reliably, and with some economy; demonstrate structural integrity at typical cathode operating conditions; and avoid contaminant release that could degrade the performance of common cathode emitter materials such as barium oxide (BaO) and lanthanum hexaboride (LaB6).

References:

Scope Title
High-temperature electromagnets

Scope Description
Thermal management of integrated electric propulsion systems is often challenging, especially for compact micro-propulsion devices or high-power-density systems. For thrusters with electromagnetic coils, such as Hall-effect thrusters or plasma thrusters utilizing magnetic nozzles, these magnetic circuits may experience operational temperatures in excess of 500 °C due to coil self-heating and close proximity to plasma-wetted surfaces; such magnetic circuits, may also need to survive in excess of 10,000 thermal on-off cycles without failure. High wire packing density is frequently desirable to achieve high magnetomotive forces (i.e., high ampere-turns). This is facilitated by small wire diameters with thin insulation, with the drawback of being more susceptible to heating and insulation failure. Existing processes for manufacturing and potting magnetic wire have exhibited instances of insulation and potting degradation during thruster operations that can lead to early thruster failure; however, the associated extensive acceptance testing required to ensure high reliability contributes to the current high cost of thrusters. Proposed solutions to this scope area must be compatible with high ampere-turn, multi-layer
electromagnets; be fray-resistant; and avoid performance degradation at the operational conditions indicated above. Any formation of volatile materials under operational conditions, particularly if binders or potting materials are used (e.g., for electrical insulation between wire layers or for thermal management), must be limited so as to preserve the insulating materials' dielectric strength and to remain compliant with general NASA material outgassing guidelines (i.e., < 1% total mass loss and < 0.1% collected volatile condensable material).

References:


Scope Title

Robust ceramics for Hall-effect thruster discharge channels

Scope Description

State-of-the-art Hall-effect thrusters make use of hot-pressed, hexagonal boron nitride (BN) or derivative ceramics, for the machined discharge channel in which plasma is generated and accelerated. The discharge channel (typically with outer diameters between 2 and 14 inches depending on the thruster's power level) must maintain electrical isolation between the thruster electrodes while being subjected to an energetic plasma environment, large thermal gradients and transients, and back-sputtered material from other thruster components or the vacuum test facility. To date, these materials have exhibited substantial lot-to-lot variability in key material properties (including mechanical strength, moisture sensitivity, and thermal conductivity and emissivity) that have resulted in discharge channel damage during vibration, shock, and thermal testing of the assembled thruster. Such material property inconsistencies have thus necessitated costly thruster design features to improve survivability margins against mechanical and thermal shock. Proposed processes to improve the lot-to-lot consistency should focus on the BN family of materials or similar ceramics compatible (i.e., exhibiting low ion-bombardment sputtering yields) with a Hall-effect thruster's discharge plasma.

References


ASTM E1933-14, "Standard Practice for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers".

Desired Deliverables

Phase I: In addition to a final report with supporting analysis, awardees shall deliver NASA material samples from the effort that can be utilized for independent verification of claimed improvements over SOA technologies.

Phase II: In addition to a final report with supporting analysis, awardees shall demonstrate functionality of components derived from the effort when integrated with operating thruster hardware. Partnering with electric propulsion developers may be required.

Expected TRL or TRL range at completion of the project: 2 to 6

Relevance / Science Traceability
Both NASA’s Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. Planetary spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; furthermore, mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys [66]). For HEOMD, higher-power electric propulsion is a key element (e.g., the Power and Propulsion Element of the Lunar Gateway) in supporting sustained human exploration of cis-lunar space.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in electric propulsion systems related to such missions. The innovations would enable lower-cost electric propulsion systems for small spacecraft, Discovery-class missions, and low-power NEP (nuclear electric propulsion) missions while improving the reliability and robustness of higher-power electric propulsion systems to support human missions. The roadmap for such in-space propulsion technologies is covered under the 2015 NASA Technology Roadmap TA-2 (In-Space Propulsion Technologies).

Z12.01 Extraction of Oxygen from Lunar Regolith

Lead Center: JSC

Participating Center(s): GRC, JPL, KSC, MSFC

Technology Area: TA15 Aeronautics

Scope Title
Solar Concentrator Technologies for Oxygen Extraction and In-Situ Construction

Scope Description
Solar concentrators have been used to successfully demonstrate multiple In-Situ Resource Utilization (ISRU) technologies including hydrogen and carbothermal reduction, sintering of surfaces pads, and production of blocks for construction. Terrestrial state of the art solar concentrators are heavy, not designed for easy packaging/shipping and assembly/installation, and can be maintained and cleaned on a periodic basis to maintain performance. For ISRU space applications, NASA is interested in solar concentrators that are able to be packaged into small volumes, are light weight, easily deployed and set up, can autonomously track the sun, and can perform self-cleaning operations to remove accumulated dust. Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface: up to 110°C (230°F) during sunlit periods and survive temperatures down to -170°C (-274°F) during periods of darkness. Systems must also be able to operate for at least one year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that regolith mining operations will be tens of meters away from the solar concentrators, but that regolith processing systems and solar concentrators will be co-located on a single lander. Phase 1 efforts can be demonstrated at any scale, Phase 2 efforts must be scalable up to 11.1 kW of delivered solar energy assuming an incoming solar flux of ~1350 W/m² while also considering volumetric constraints for launch and landing. Each of the following specific areas of technology interest may be developed as a standalone technology, but proposals that address multiple areas are encouraged.

Lightweight Mirrors/Lenses: Proposals must clearly state the estimated W/kg for the proposed technology. Phase 2 deliverables must be deployed and supported in Earth 1-g (without wind loads) but should include design recommendations for mass reductions for lunar gravity (1/6-g) deployment. Proposals should address the following attributes: high reflectivity, low coefficient of thermal expansion, strength, mass, reliability and cost.

(See Z13.01 - Active and Passive Dust Mitigation Surfacesto propose dust repellent mirror/lens related technologies. This will help to solve issues where dust particles cling to the surface of a mirror or lens and degrade the performance of a solar concentrator.)
Efficient transmission of energy for oxygen/metal extraction: While the solar concentrator will need to move to track the sun, reactors requiring direct thermal energy for oxygen extraction will be in a fixed position and orientation. Concentrated sunlight must be able to be directed to a single or multiple spots to effectively heat or melt the regolith. Proposals must define the expected transition losses from collection to delivery and should capture any assumptions made regarding the distance from collection to delivery.

Sintering end effector: Solar concentrators have been used to demonstrate the fabrication of 3D printed components using regolith as the only feedstock. However, an end effector designed to melt regolith at 1600°C will not be optimized for selective sintering. Proposals responding to this specific technology area must produce a focal point temperature between 1000°C to 1100°C for the purpose of sintering lunar regolith.

References


Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

TRL4 hardware that can be deployed during a field demonstration

State of the Art and Critical Gaps

The 2011 paper Thermal Energy for Lunar in Situ Resource Utilization: Technical Challenges and Technology Opportunities summarized the work performed in this area and recommends future efforts focus on lightweight mirrors (possibly using composite materials) and dust mitigation techniques.

The last solar concentrator system developed for ISRU had an overall efficiency of ~33%. The performance of the system is captured in the 2011 Paper Solar thermal system for lunar ISRU applications: development and field operation at Mauna Kea, HI

Relevance / Science Traceability

The last time NASA was focused on a lunar destination, solar concentrators were used for multiple ISRU applications.

Scope Title

Novel Oxygen Extraction Concepts

Scope Description

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from silicates using various techniques such as carbothermal reduction and molten regolith electrolysis. NASA is interested in developing novel oxygen extraction
systems that can be proven to handle large amounts of lunar regolith throughput, while minimizing consumables, mass and energy.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 1.85 kg O\textsubscript{2}/hr (10 metric tons of Oxygen in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 1.85 kg O\textsubscript{2}/hr.
- Demonstrations do not need to produce actual oxygen gas, but can end at a reaction product that has successfully removed oxygen atoms from the silicate mineral.
- Proposers need to define any Earth supplied reagents or hardware that might be consumed or need to be recycled and should estimate replenishment or loss rates expected.
- Proposals should state expected energy requirements (both electrical and thermal) as well as temperatures at which the proposed process will operate.
- Proposers should estimate Wh/kg O\textsubscript{2} for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address how concepts can be shutdown and restarted.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

References


Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

TRL 4-6 hardware that can demonstrate a scalable oxygen extraction process in a manner that accommodates the movement of material through the extraction zone.

State of the Art and Critical Gaps

The carbothermal reduction process was demonstrated at a relevant scale using an automated reactor in 2010. The approach was successful but used many moving parts and was never life tested for the types of durations that will be required on the lunar surface. Molten Regolith Electrolysis has been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Both processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

Relevance / Science Traceability

STMD (Space Technology Mission Directorate) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to know if it would offer a better return on energy investment than oxygen extracted from the regolith. A lunar water prospecting mission is required to properly assess the utilization potential of water on the lunar surface. Until water prospecting data becomes available, NASA recognizes the need to make progress on the technology needed to extract oxygen from dry lunar regolith.
Scope Title
Lunar Ice Mining

Scope Description
We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in Permanently Shadowed Regions (PSR), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. One challenge with extracting the water is that desorption and sublimation can occur at temperatures as low as 150 Kelvin. The inverse challenge exists with water collection. Unless the water vapor is under pressure, extremely cold temperatures will be necessary to capture it. NASA is seeking methods to acquire lunar water ice from permanently shadowed regions. Proposals must describe a method for extracting and/or collecting lunar water ice that exists at temperatures between 40 to 100 Kelvin and 10-9 torr vacuum.

- Phase 1 demonstrations can be at any scale, but eventually the technology must be able to demonstrate an average rate of 2.78 kg H₂O/hr (15 metric tons of water in 225 days).
- Phase 2 demonstrations can be subscale, but must define the number of subscale units necessary to achieve an average extraction rate of 2.78 kg H₂O/hr.
- Proposals should state expected energy requirements (both electrical and thermal).
- Proposers should assume a mobile platform is considered to be available, but should not be necessary for technology demonstration.
- Proposers should state their assumptions about water ice concentration.
- Proposals should describe a tolerance for a trace amount of organics or volatiles that may accumulate on collection surfaces.
- Proposers should estimate Wh/kg H₂O for concepts and/or provide a plan to determine that value as part of the effort.
- Proposers should address the ability of a concept to be able to operate for at least one year with a goal of 5 years without substantial maintenance.

Estimates for mass and volume of the final expected hardware should be specified.

References


Expected TRL or TRL range at completion of the project 4 to 6

Desired Deliverables of Phase II
Prototype, Analysis, Hardware

Desired Deliverables Description
TRL 4-5 hardware that can demonstrate scalable water ice extraction technology in a relevant environment

State of the Art and Critical Gaps
Scoops and bucket-wheel excavators have been demonstrated for the collection of unconsolidated material but may not be effective at excavating consolidated regolith-ice composites. The Planetary Volatiles Extractor (PVEx) developed by Honeybee Robotics is the state of the art for heated core drills, but life testing is required to determine the rate of wear due to repeated excavation. Multiple groups have investigated the use of thermal mining methods to separate water from regolith, but the depth of water removed is relatively shallow. Very little work has been performed on the ability to capture water in a lunar environment after it has been released from the surface.

Relevance / Science Traceability

The current NASA Administrator has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. STMD has identified the need for water extraction from permanently shadowed regions. Multiple mission directorates over the past several years have provided funding for a water prospecting mission so that we can gain the information required to establish an ice mining architecture.

Z13.01 Active and Passive Dust Mitigation Surfaces

Lead Center: KSC

Participating Center(s): JSC, LaRC

Technology Area: TA15 Aeronautics

Subtopic description

NASA seeks new technologies that can be used to remove dust from surfaces that may have accumulated as a result of interactions of systems or subsystems exposed to dusty surfaces either directly or indirectly as a result of missions to the moon, Mars and/or small bodies (like asteroids, comets, and Near-Earth Objects). Unique materials and technologies that reduce or mitigate lunar dust adhesion will be critical to support long duration missions and eventual sustained presence on the lunar surface. This call in particular seeks new technologies for the prevention and accumulation of dust on surfaces which could cause deleterious effects in lunar environments. Such technology could be implemented onto various surfaces such as solar panels, thermal radiators, space suit outer layers, helmets, visors, boots, displays, control panels, viewports, batteries are examples of solid flat transparent or non-transparent surfaces depending on the dust-loading requirements for each subsystem. More complex mechanisms such as hatches, hatch seals, hatch mechanisms, hinges, quick disconnects, etc. that require dust mitigation technologies are covered by subtopic "Dust Tolerant Mechanisms.

Scope Title

Active Dust Mitigation Surfaces

Scope Description

Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations or other means necessary to keep vital surfaces clean under space conditions. Self-cleaning surfaces are highly desired which require minimal effort by astronauts. Proposers are expected to show an in-depth understanding of the current state-of-the-art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- Brushing – a self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power or temperature activated such as shape memory alloys
- Electrostatic Removal – methods to use DC electric fields to remove dust from surfaces either internal to the surface (embedded) or external using a removed high voltage source
- Liquid removal – a jet of liquid is applied to the surface which traps particles and removes them from the
Vacuum – methods to remove particles from surfaces using suction of gases
Jets - high-velocity gas jet which blows dust particles from surfaces.
Spinning surfaces – surface rotates in a manner which does not allow collection of dust on it
Vibrational surfaces – vibrating surface bounces the particles off of a surface
Electrodynamic Removal – the surface contains embedded electrodes with varying high voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be combined with the SOA of passive dust mitigation technologies. For example passive dust mitigation strategies include:

- Electrostatic Discharge (ESD) coatings and films– statically dissipative coatings are less likely to accumulate charge and hence dust in dry environments
- Superhydrophobic coatings – materials with a very high contact angle can lower the adhesion of water-based contaminants not allowing the capillary forces to take hold.
- EVA and robotic compatible dust proof electrical, fluid, and gas connectors
- Dust proof bearings and mechanical spacesuit connectors
- Dust tolerant or resistant hatches
- Docking systems - including suit port docking systems and pressurized rover and habitat docking systems
- Lotus leaf coating – microscopic nanostructures used to limit the Van der Waals force of adhesion
- Peel away coating – removable coatings from surfaces

Strong proposals are those which identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above.

Scope Title
Passive Dust Mitigation Surfaces

Scope Description
This call seeks unique research proposals focused on passive approaches, i.e., those that do not require external stimulus, that will minimize the potential impact Lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system). Novel materials may include high performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous, and rough or smooth with topography imparted by any number of approaches including but not limited to: lithography, embossing, roll-to-roll processing etc. Both the material and surface modification approach must be demonstrated to be scalable and exhibit a dramatic reduction (>90% relative to a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for micro-particles, specifically those described as Lunar dust simulant, with diameters < 50 micrometers.

References
Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Research, Analysis, Prototype, Hardware

Desired Deliverables Description

At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton or Teflon) in particulate adhesion for microparticles, specifically those described as Lunar dust simulant, with diameters < 50 micrometers. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, then further development of the technology shall be required, including a prototype delivered to NASA at the end of the two-year project with a goal of achieving TRL 6. A prototype of the new...
technology must be provided which shows the feasibility of the dust removal method. The technology must be demonstrated in a laboratory environment removing and/or keeping dust from adhering to a surface. The mass, power, volume and potential costs associated with the implementation of this technology must be addressed.

**State of the Art and Critical Gaps**

**Active Dust Mitigation Technologies**

All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield or EDS which lifts and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references above.

The EDS can be incorporated into a variety of configurations addressing many of NASA’s needs. However, there are several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- **Miniaturized high voltage 3-phase power supply** – The current SOA for the EDS power supply is approximately 10 cm X 5 cm X 3 cm. It is highly desired to have smaller power supplies both in size and power to drive the EDS waveform for a variety of applications.
- **High dielectric breakdown strength for both glues/epoxies as well as the coating material** – The efficiency of dust removal for the EDS is limited to amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2-D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- **Flexible transparent surfaces with high current capabilities** – The optically transparent version of the EDS uses Indium Tin Oxide as the main conductive medium for its electrode. Although the EDS is not a high current DC device, the displacement current (I dV/dt) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.
- **The EDS technology also works on fabrics. However high voltage flexible wires than can be used as threads are unavailable. The electrodes would need to be low profile and sufficient to withstand up to +10 kV DC before breakdown.** A unique feature of the EDS on fabrics is that it needs to be a multilayer system as most space fabrics are. One layer would have to support electrical grounding to protect the astronaut but intermediate layers would have withstand high voltage breakdown. The top layer would house the HV wire system comprised of the EDS requirements.
- **Electrical attachment** – most EDS systems have issues with the electrical connections between the HVPS and the electrodes. Any possibility of arcing and/or sparking as a result of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key issue for attaching HV wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of the materials such as: copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT) and graphene to name a few. Likewise these and other electrodes are usually resting on or embedded into a substrate such as glass, Polyimide (Kapton), clothing fibers, PET, PTFE, nylon, acrylic, Lucite and other surfaces.
- **Minimizing electromagnetic interference (EMI)** - Most EDS designs can generate electrical noise that would be disadvantageous for it to be incorporated into a system. Methods to reduce electrical noise and EMI would be highly sought.
- **Safety** - with all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- **Smart EDS technology** - as with all dust mitigation technologies, methods to included adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary, and if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:

- **Effective and scratch resistant brushing techniques.** Apollo astronauts used brushes that are largely
ineffective for large surface areas and tended to scratch sensitive equipment, such as astronaut visors.

- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

### Passive Dust Mitigation Technologies

Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants. These relatively soft materials though would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications. Triboelectrification, however, of an insulating material would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the Lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment.

### Relevance / Science Traceability

Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface's energy, chemistry, mechanical properties and the particle's surface is a fascinating but not well understood science. This call will not only extend exploration missions on the lunar surface, they will enable exploration missions that would not have be possible. For example every mechanical seal was compromised on the Apollo missions in the course three days due to the exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expound our survival on dusty surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, then the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.
interaction of the lunar soil with multiple mechanical, electrical and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that will protect from or tolerate dust intrusion in the following areas:

- Rotary joints (steering, suspension, hinges, bearings, etc.)
- Linear joints (latches, shafts, restraint systems, landing gear, etc.)
- Static joints (quick disconnects, covers, airlocks, sample tools, etc.)

Successful solutions will enable operation in a lunar environment for 10 to 100 months with limited or no maintenance.

References

Dust mitigation gap assessment report - The International Space Exploration Coordination Group (ISECG) -

Expected TRL or TRL range at completion of the project: 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables - Research, identify and evaluate candidate technologies or concepts for dust tolerant mechanisms. Simulations or lab-level demonstrations are desirable. Deliverables must include a report to documenting findings.

Phase II Deliverables - Emphasis should be placed on developing, prototyping and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results and other associated documentation. Deliverable of a functional prototype is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps

Previous solutions used in the Apollo program did not address the current need of long term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Rotary joints
  - Seals: Rotary joints are very common for actuation in dusty environments because of the widespread availability of rotary seals. Most of these seals however use elastomers that would off-gas and become brittle in a lunar environment. Solutions are needed that employ materials or non-traditional techniques that can operate in the lunar environment for an extended period of time.
Bearings: Regolith getting past the protective seals of rotary joints bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.

- Linear joints
  - Seals: Linear joints are less common in dusty environments because of the challenge of sealing the sliding joints. Similar to rotary seals, linear joint seals are often made from elastomers and would need to be modified to operate in a lunar environment. Solutions are needed that employ materials or non-traditional techniques that can operate in the lunar environment for an extended period of time (months to years).
  - Bearings: Regolith getting past the protective seals of linear joints bearings is a common failure point. Bearings designs that are highly dust tolerant may be needed to reduce the risk of failures due to dust intrusion.

- Static joints
  - Operations on the lunar surface will include assembly, construction, and Extra-Vehicular Activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination (e.g. power connection/termination related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically-enabled high voltage connectors and/or near-field wireless power transfer in the 1-10kW range).

Relevance / Science Traceability

Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological, physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.