NASA SBIR 2022 Phase I Solicitation

Human Exploration and Operations

H3.08 Challenges in Carbon Dioxide Removal and Reduction: Carbon Particulate and Thermal Management

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, JSC, KSC

Scope Title:
Advancements in Carbon Dioxide Reduction

Scope Description:

Air Revitalization Systems (ARS) are necessary for human survival during space exploration missions. Technologies to efficiently remove carbon dioxide (CO\textsubscript{2}) from the cabin atmosphere and to reduce the captured CO\textsubscript{2} to recover oxygen are two systems that face technical challenges. Using adsorption beds to remove CO\textsubscript{2} is a proven technology, but optimization is needed. Please see the second scope "Advanced Heaters for Solid Sorption Systems" for more information. In the area of CO\textsubscript{2} reduction, several technologies produce solid carbon either intentionally or unintentionally. A current challenge to the development of these technologies is carbon management. Technologies and methods that will efficiently separate, remove, and store the carbon are sought. Technical solutions will allow for efficient operation of the carbon reduction process, prevent contamination of downstream hardware receiving effluent gases and avoid contamination of cabin atmosphere during carbon handling and disposal.

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors, almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long-duration missions. Techniques and methods leading to compact, regenerable devices or components for removing, managing, and disposing of residual particulate matter within Environmental Control and Life Support Systems (ECLSS) process equipment are sought.

NASA has invested in many CO\textsubscript{2} reduction technologies over the years to increase the percentage of oxygen recovery from CO\textsubscript{2} in human spacecraft for long-duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, methane pyrolysis, and microfluidic carbon dioxide electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty.

Examples where additional component technology development is needed include (this is a partial list):

- Separation of particulate carbon from process gas streams.
- Safe collection, removal, and disposal of solid carbon, including cases when continuously operating reactors are active.
- Subsystems to recharge reactors with new catalyst and to efficiently reuse or recycle consumable catalysts.
Technology solutions to mitigate solid carbon clogging of frits and filters in recycle gas streams.

Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator function should be capable of operating for hours at high particle loading rates. If necessary, periodic operations and methods could be employed to restore capacity/functionality back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of CO₂ reduction hardware with particular attention to solid carbon management.

**Expected TRL or TRL Range at completion of the Project:**

2 to 5

**Primary Technology Taxonomy:**

Level 1: TX 06 Human Health, Life Support, and Habitation Systems

Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Hardware
- Prototype

**Desired Deliverables Description:**

Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust as well as carbon exposure to downstream hardware.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. The system should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

**State of the Art and Critical Gaps:**

Advanced oxygen recovery systems are necessary for long-duration missions as resupply of consumables will not be available. The state-of-the-art Sabatier system, which has flown on the International Space Station (ISS) as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic CO₂. This is because there is insufficient hydrogen to react all available CO₂. The Sabatier reacts hydrogen with CO₂ to produce methane and water. The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars missions target >75% oxygen recovery from CO₂, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from CO₂.
toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with CO₂. Other technologies under investigation process CO₂, recovering a higher percentage of oxygen than the Sabatier. All these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight ECLSS.

Several of these alternative systems produce solid carbon either intentionally or unintentionally and solutions for safely filtering, removing, and storing solid carbon are critical to the maturation of these systems.

Relevance / Science Traceability:

These technologies would be essential and enabling to long-duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, lunar surface, and Mars, including surface and transit missions. This technology could be proven on the ISS as a flight demonstration.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in the area of atmosphere revitalization, and specifically, in the areas of CO₂ reduction and oxygen recovery, functional areas of ECLSS.

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.

References:

7. NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 “For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 ?m to 10 ?m ( respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 ?m to 100 ?m to <3 mg/m3.” https://www.nasa.gov/sites/default/files/atoms/files/nasa-std-3001-vol-2a.pdf [1]

Scope Title:

Advanced Heaters for Sorbent Systems

Scope Description:

Spacecraft carbon dioxide (CO₂), water, and trace contaminant (organics) removal systems must be regenerable and reliable and minimize resupply and equivalent system mass (ESM). In most sorbent systems, heat is used to regenerate the beds by expelling contaminants for disposal or to downstream processes for resource recovery. In future deep space exploration missions, such as those to the Moon and to Mars, sorption systems must drastically reduce power to minimize the dependence on scarce resources. The state-of-the-art (SOA) spacecraft sorption systems utilize commercial off-the-shelf (COTS) resistive heaters coupled with conductive fins. These Joule heating methods lead to inefficiencies such as high thermal contact resistance, high temperature differential within the...
sorption beds, high component mass and volumes, and long ramp-up times. The SOA cooling options utilize blowers, cooling channels or cold plates in conjunction with spacecraft liquid cooling loops. Since the spacecraft cooling systems are limited in capacity, efficient cooling methods are needed. Although it is recognized that the conductivity of the sorbent material is the limiting factor to the heating of sorption beds, it is also important to design integrated thermal management systems that transfer the heat quickly, uniformly, and efficiently throughout the bed. Some suggested, but not inclusive, areas of heater improvements are listed here:

- Decreasing the contact resistance between the heaters and the sorbent media.
- Increasing temperature uniformity within the sorbent beds.
- Improving tolerance to corrosion.
- Optimizing for various configurations of sorbent media, including granules, beads, porous solids, additively manufactured, and liquid sorbents.

Some thermal management components can function both as heaters and coolers. This will lead to reduced system mass and volume of heaters, fin stock, cooling channels, various supporting hardware, and sorption materials. Proposed concepts may include different heater types as well as heater configurations. Heater configurations could include those that are bound or embedded into the sorbent media.

This subtopic solicits advanced thermal management systems that offer a significant improvement over the SOA. The heaters, coolers, configurations, and all attached hardware must meet the following operational requirements:

- Continuous operation at temperatures as high as 200 °C or above.
- Minimize both heating and cooling rates compared to the SOA heaters capability.
- Heaters and cooling options must be able to operate in temperature swing sorption systems continuously 24 hours a day. Some example cycle times are those used in the current spacecraft system: the Carbon Dioxide Removal Assembly used a 144-minute cycle time; The 4BCO2 beds operate on 80-minute cycle times.
- Compatible with either liquid or solid sorbent systems.
- Capable of operating in microgravity and reduced gravity environment.
- Must be compatible with sorbent regeneration or thermally sorbent systems.
- Must be able to operate continuously for 3 years.
- Offer an improvement in heat conservation, efficiency, power consumption, reliability, resupply, and ESM over the spacecraft SOA systems.
- Heaters and cooling options must utilize the available power and cooling options expected in exploration spacecraft such as avionic air, the low-temperature loops, and the medium-temperature loops.
- Meet the space station safety requirement.

**Expected TRL or TRL Range at completion of the Project:**

2 to 4

**Primary Technology Taxonomy:**
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description:

Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Phase I analysis should include a trade study between the advanced heaters and the SOA and operation in the spacecraft environments.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data, and analysis. Prototypes must be for sorption beds sized for 4 crew members. Robustness must be demonstrated with extended operation and with periods of intermittent dormancy. Systems should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:

Current and future human exploration missions require regenerable systems that minimize mass, power, volume, and resupply and are highly reliable. Most SOA sorption systems in the Atmosphere Revitalization System (ARS) use COTS heaters that are inefficient, leading to high power requirements. Thermal management in systems such as the Carbon Dioxide Removal Assembly and the Sabatier could be improved by using advanced heating systems. Unfortunately, innovative heaters such as heat pipes and vapor chambers have been used elsewhere in space hardware but have yet to be developed for use in Environmental Control and Life Support Systems (ECLSS).

In addition, a significant amount of the spacecraft power is allocated to a variety of ECLSS. Alternative thermal management approaches that have multiple functions such as heating, cooling, thermal energy storage, and the thermal energy transfer over long distances will drastically reduce the loading on available resources for both in-transit and planetary base missions. These advanced heaters can be used for other NASA mission architectures as well, such as the extravehicular activity (EVA) and the Trash Compaction Processing System.

Relevance / Science Traceability:

This subtopic is relevant to Human Exploration and Operations Mission Directorate (HEOMD), especially ECLSS, by improving thermal management systems to minimize loading on facility resources such as power, heater, and cooling systems. In addition, efficient heaters minimize mass, power, and volume. The following ECLSS systems could benefit from improvements in thermal management technology: the ARSs, the Water Management Systems, and Solid Waste Management Systems including trash compaction. Other technical areas that may have interest are small satellites and EVA.

References:

**H3.09 Human Accommodations**

Lead Center: JSC

Participating Center(s): JPL

**Scope Title**

Human Accommodations for Exploration Missions

**Scope Description**

Humans have been living and working in low Earth orbit (LEO) for several decades; however, human accommodations such as galley and hygiene facilities are still fairly limited. As mission length and distance increase, these comforts of home will become even more important, and their resource footprint will need to be reduced. Missions to the Moon and Mars will introduce partial gravity where optimal design of human accommodations may be different than in LEO. Additionally, emerging commercial activities in LEO and the lunar vicinity will create a larger demand for human accommodations in space.

Innovative technologies that improve human accommodations over the state of the art are sought in the areas of galley, personal hygiene, laundry, and volumetrically efficient use of space for tasks.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 06 Human Health, Life Support, and Habitation Systems

**Level 2**

TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware

**Desired Deliverables Description**

Phase I deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and designs leading to Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solutions should clearly describe resource requirements such as hardware mass, volume, and power, as well as water use and crew time to operate.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated...
through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data, and analysis. Prototypes should be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA.

State of the Art and Critical Gaps

State of the art for most human accommodations is defined by International Space Station (ISS) hardware. For sleep and privacy, crew quarters consist of permanent rack-size compartments that accommodate sleeping bag, privacy, personal wall space, ventilation with limited temperature control, lighting, and personal entertainment. The ISS galley consists of a table, food warmer, and potable water dispenser, which can rehydrate food and drinks with hot or ambient temperature water. A small refrigerator has also been added for food and drink storage. Personal hygiene is accomplished with disposable wipes, wetted towels, no-rinse shampoo, Earth-like oral and hair care and normal clothing that is discarded when it gets too dirty. Housekeeping relies mainly on disposable disinfectant wipes and a vacuum cleaner. On ISS, there is no cooking, sink (handwash), shower, dishwasher, washing machine, or dryer.

Critical gaps include:

- Rapid food heating for 4 crewmembers at the same time so that crews can dine together. Ideally, heating of 16 food packages could be accomplished in 30 to 45 minutes with less than 500 W of electricity. Food must be heated in accordance with NASA Standard 3001 and the Human Integration Design Handbook, and all equipment must meet touch temperature limits.

- Food refrigeration for long-term storage on the way to and from Mars. Stored food volumes of 2 to 8 m$^3$, with average packaged food density of 388 kg/m$^3$, may be required at temperature ranges of -25 to 5 °C. Concepts must be volumetrically efficient, mass efficient, and highly reliable since loss of food quality can result in loss of crew performance. Secondary mass penalty for cold stowage should be below 0.2 kg per 1 kg of food. The refrigeration and insulation systems should be efficient enough to run (at steady state) on less than 0.15 W/kg of food frozen at -22 °C in a 23 °C ambient.

- Personal hygiene with less consumables is needed. Currently 0.11 kg/person/day of wet wipes are supplied and the goal is to reduce this below 0.05 kg/person/day.

- Water efficient handwash for use in microgravity environment. Soap, water, and crew interface aspects must all be considered.

- Clothes washer/dryer combination for use on the Moon (1/6g) or Mars (1/3g) that can clean up to 4.5 kg of cotton, polyester, and wool clothing at a time in less than 7 hours using <50 kg machine mass, <0.3 m$^3$ external machine volume and <300 W electrical power (Note: 101.3 kPa habitat pressure may be assumed for prototype development).

- Devices and systems for volumetrically efficient use of habitable volume in spacecraft. This may include random access stowage concepts where equipment and stowage could be packed together densely and slide open for random access when needed. Such a concept could optimize volumes according to real-time crew needs, while maximizing volume for stowage and equipment. Flexible work surfaces will also be considered. For example, systems that allow the crew to maximize "wall" and "ceiling" as work surfaces in a microgravity environment but allow reconfiguration if the habitat transitions into a gravity environment (i.e., walls and ceilings are less useful, but fold-out table tops or overhead features may deploy on demand). Logistics-2-Living concepts are also of interest, such as secondary stowage structure repurposing for the real-time creation of partitions, furniture, glove-boxes, etc.

Out of Scope:

Proposals are not solicited for toilets nor hardware considered life support systems, including air revitalization, water processing, or waste processing. Lunar dust mitigation technologies are covered elsewhere, but innovative interior surface cleaning including dust removal may be submitted to this subtopic. Crew quarters, exercise devices, and electronic devices for entertainment are not in scope here.

Relevance / Science Traceability
The Logistics Reduction (LR) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected initial customer. The LR Project will consider sponsoring Phase III Small Business Innovation Research (SBIR) activities and assist with technology infusion into NASA Moon-to-Mars missions.

References

- "Dual Use of Packaging on the Moon: Logistics-2-Living", AIAA-2010-6049
- "Lessons Learned for the International Space Station Potable Water Dispenser", ICES-2018-114
- "Will Astronauts Wash Clothes on the Way to Mars?", ICES-2015-53

H4.06 Low-Power Multi-Gas Sensor for Spacesuits

Lead Center: JSC

Scope Title

Spacesuit Gas Sensors

Scope Description

As the design for the new Exploration Extravehicular Mobility Unit (xEMU) is developed, technology gaps have been identified for the gas sensors employed in the portable life support system (PLSS). These gaps need to be fulfilled to meet the new exploration requirements.

To ensure the safe operation of the spacesuit there is a need to measure the following major constituents in the gas stream across a total pressure range of 3.5 to 23.5 psia and temperature range of 35 to 125 °F: \( O_2 = 20 \text{ to } 100\% \); \( CO_2 = 0 \text{ to } 30 \text{ torr over } 3.5 \text{ to } 23.5 \text{ psia} \); \( H_2O = 5 \text{ to } 90\% \text{ relative humidity (RH)} \). During ground testing these measurements can be made by ancillary equipment, however, the current design of the PLSS only includes nondispersive infrared (NDIR) sensors for \( CO_2 \). For reference, the outer mold line for these sensors is approximately 2.3 x 2.2 x 6.1 inches.

Since these sensors are continuously powered during an extravehicular activity (EVA) their power consumption is a direct driver of spacesuit battery capacity and in consequence spacesuit mass. It is, therefore, desirable to have a sensor power consumption below 2.5 W. The current \( CO_2 \) sensors consume 2 W during operation.

The intended use case for these sensors in the PLSS is to provide general situational awareness of the major constituents, in contrast to highly accurate measurements. The required accuracy of the sensors is therefore 1% or better for \( O_2 \) concentration and RH and 0.3 torr for \( CO_2 \) partial pressure.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1
TX 06 Human Health, Life Support, and Habitation Systems

Level 2

TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II

- Prototype

Desired Deliverables Description

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the xEMU. Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xEMU or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps

As the design for the new xEMU is developed, there are obvious gaps in technologies that need to be fulfilled to meet the new exploration requirements. The currently employed gas sensors are functionally limited, draw significant power, and require new, innovative ideas. This solicitation is an attempt to seek new technologies for low-power multi-gas sensors. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, the additional information provided by such sensors will be indispensable for the situational awareness of astronauts in space, as well as flight controllers on the ground.

Relevance / ScienceTraceability

It is relevant to the new xEMU, International Space Station (ISS), as well as commercial space companies. As the xEMU is being designed, built, integrated, and tested at Johnson Space Center, solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References


H4.07 Low Volume, Power and Mass CO2 and Humidity Control for xEMU

Lead Center: JSC

Scope Title: Spacesuit CO2 and Humidity Control for xEMU (SBIR)

Scope Description:

This solicitation is seeking to identify sorbent candidates that will compete with or outperform the current baseline sorbent technology used within the Exploration Extravehicular Mobility Unit (xEMU) for carbon dioxide (CO2) and humidity control. It is desired that sorbent candidates meet or exceed the characteristics and goals listed below.

Key goals for sorbent characteristics and performance:
• 600- to 1,000-µm-sized beads.
• Vacuum desorb technology (desorb at a pressure of 140 Pa).
• CO₂ loading uptake (noncyclic) 25 °C, 8 mmHg CO₂, 10 °C dewpoint, 6.0 g CO₂/100 g sorbent.
• H₂O loading uptake (noncyclic) 25 °C, 15 °C dewpoint, 7.0 g H₂O/100 g sorbent.
• Uptake (cyclic) 25 °C, 8 mmHg CO₂, 10 °C dewpoint, 2.0 g CO₂/100 g sorbent at 2 to 3 minute half-cycle timing (e.g., adsorb for 2 minutes/desorb for 2 minutes).

In order to ensure the safe operation of the xEMU, CO₂ and humidity levels need to be controlled to levels in accordance with requirements established by the NASA medical community. The technology currently baselined for the xEMU is the Rapid Cycle Amine (RCA) technology and information on the RCA is also available in the reference section below. New technology alternatives to the RCA are desired in order to have a robust suit program that is able to fall back on alternate technologies if the need arises.

For the majority of an extravehicular activity (EVA), the CO₂ partial pressure required at the breathing gas inlet to the helmet of the spacesuit needs to be maintained at or below 2.2 mmHg when the astronaut is generating 2.44 g/min of CO₂. The flow rate of the oxygen ventilation loop that circulates the breathing gas from the suit, through the CO₂ and humidity removal unit and back to the helmet of the suit is maintained at 6 ft³/min.

The driving humidity requirement is to maintain the relative humidity of the breathing gas flowing into the helmet between 5 and 45% with the water vapor production level of 0.2 lb/hr and 6 ft³/min ventilation flow rate through the suit. The CO₂ and humidity control unit should also be able to handle situations where the generation rates are higher during shorter periods as described in the detailed requirements listed in the references section.

The goals for the mass of alternate technology units to be less than 14 lb, the volume to be less than 0.4 ft³, and the power consumption to be less than 1.4 W on average.

This subtopic is relevant to the xEMU, International Space Station (ISS), Gateway, and human landing system (HLS), as well as other endeavors currently in development by commercial space companies. The goal is to have proposed solutions to be designed, built, integrated and tested at Johnson Space Center and integrated into the xEMU. These solutions have the potential for a direct infusion path as the xEMU is matured to meet the design and performance goals.

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

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

• Prototype

Desired Deliverables Description:

Phase I products: By the end of Phase I, it would be beneficial to have candidate sorbent(s) identified that meet the goals listed for this solicitation. Testing of sorbent candidate is required at this Phase.

Phase II products: By the end of Phase II, testing of sorbent in the xEMU equivalent application and conditions is desired. Vendors may collaborate with research institutes if desired.

State of the Art and Critical Gaps:

The current state-of-the-art utilized on the ISS EMU is a metal oxide technology that requires astronauts to remove the unit from the PLSS, regenerate it in an oven, and reinstall it into the PLSS prior to the subsequent EVA.

The baseline xEMU technology provides regenerative CO₂ and humidity removal via a pressure swing adsorption system with a high-capacity sorbent that desorbs upon exposure to vacuum and requires little to no maintenance by the astronaut. This technology is well developed, but unparalleled. Ultimately, this solicitation is an attempt to
lead to an alternate CO₂ and humidity removal system with regenerable capabilities requiring minimal astronaut maintenance to provide options for the new xEMU should unforeseen issues arise with the current technology. Additionally, xEMU has goals of reducing power draw, volume envelope, and mass while maintaining the current CO₂ and humidity removal capacity at the conditions described previously.

Relevance / Science Traceability:

It is relevant to the new xEMU, ISS, as well as commercial space companies. As the xEMU is being designed, built, integrated, and tested at Johnson Space Center, solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References:

1. ICES-2016-073 Design and Development Comparison of RCA 1.0, 2.0, and 3.0 (Design and Development Comparison of Rapid Cycle Amine 1.0, 2.0, and 0 (tdl.org) [5])
2. ICES-2019-400 RCA Testing History (Rapid Cycle Amine Testing History (tdl.org) [6])

H5.01 Lunar Surface 50 kW-Class Solar Array Structures

Lead Center: MSFC

Participating Center(s): GRC

Scope Title

Lunar Surface 50-kW-Class Solar Array Structures

Scope Description

NASA intends to land near the lunar South Pole (at S latitudes ranging from 85° to 90°) by 2024 in Phase 1 of the Artemis Program, and then to establish a sustainable long-term presence by 2028 in Phase 2. At exactly the lunar South Pole (90° S), the Sun elevation angle varies between -1.5° and 1.5° during the year. At 85° S latitude, the elevation angle variation increases to between -6.5° and 6.5°. These persistently shallow sun grazing angles result in the interior of many polar craters never receiving sunlight while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the 354-hr nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

Under a recently announced “Game Changing” project in NASA’s Space Technology Mission Directorate (STMD) named Vertical Solar Array Technology (VSAT), several firms are developing relocatable 10-kW vertical solar arrays for initial modular power generation at the lunar South Pole [Refs. 3-4]. These adaptable 10-kW arrays can be retracted and moved as needed to support evolving requirements for initial South Pole human occupation. Their relatively small size (35 m² of deployed area) allows them to be used individually or in combination to power loads up to a few tens of kilowatts. However, because the Sun is always near the horizon at lunar polar sites, using numerous small interconnected arrays for electrical power loads >>10 kW can result in excessive shadowing of one array onto another as well as considerable positioning, leveling, and deployment challenges when locating them at optimally illuminated locations.
This subtopic seeks structural and mechanical innovations for relocatable 50-kW-class (40- to 60-kW) lightweight solar arrays near the lunar South Pole for powering second-generation lunar base infrastructure including habitats and laboratories, rechargeable rovers, and in situ resource utilization (ISRU) mining and processing machines, and that can deploy and retract at least 5 times. Increasing the unit solar array size from first-generation 10 kW to second-generation ~50 kW is a logical course of action as power needs increase for new higher-power capabilities such as ISRU or the Foundation Surface Habitat, which can require >>10 kW of power. This increase in size by 5 times while maximizing specific power (>75 W/kg) needs structures and mechanisms innovations and development effort to ensure compact packaging, safe transportation in space and on the lunar surface, reliable deployment, stable operation while sun tracking, and retraction and relocation as needed. Small Business Innovation Research (SBIR) contracts provide important near-term investment to flesh out specific technical requirements and new technical challenges for these larger 50-kW-class solar arrays based on VSAT results for smaller 10-kW arrays and on assumed Design, Development, Test, and Evaluation (DDT&E) schedules.

These 50-kW-class solar arrays are listed in NASA’s HEOMD-405 Integrated Exploration Capabilities Gap List as tier 1 (highest impact) development gap #03-04 for which at least 1 potential solution has been identified, but additional work is required to ensure feasibility of the new and/or novel performance or function in a specific operational application [Ref. 5]. The largest similar lightweight solar array under development is the 30-kW “ROSA” wing for NASA’s Lunar Gateway, but it is considerably smaller than desired for second-generation lunar surface arrays, and it is not designed to retract or to survive the unique lunar gravity, insolation, and dust and terrain environments. Exploration Capabilities Gap #03-04 is described as “Medium-power solar array technology for human-rated missions with specific power (>75 W/kg) and operation in mission specific environment.”

Retraction will allow valuable solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m above the surface to reduce shadowing from local terrain are required [Ref. 6]. The ability to be relocated is assumed to be through use of a separate surface-mobility system (i.e., not necessarily part of the solar array system), but design of array structures and mechanisms should accommodate loads likely to be encountered during transport along the lunar surface. Suitable innovations, variations, or combinations of existing 10-kW array components to these much larger 40- to 60-kW arrays including those being developed under the VSAT project are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 140 m$^2$ (40 kW) initially; up to 210 m$^2$ (60 kW) eventually per unit, assuming state-of-the-art space solar cells.
- Single-axis Sun tracking about the vertical axis.
- Up to 10-m height extension boom to reduce shadowing from local terrain.
- Deployable, stable base for supporting tall vertical array on unprepared lunar surface.
- Base must accommodate a local 15° terrain slope with adjustable leveling to <0.5° of vertical.
- Retractable for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Lunar dust, radiation, and temperature resistant components.
- Specific mass: >75 W/kg and specific packing volume: >20 kW/m$^3$, including all mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Lifetime: >10 years.

Suggested areas of innovation include:

- Novel packaging, deployment, retraction, and modularity concepts.
- Novel lightweight, compact components including booms, ribs, solar cell blankets, and mechanisms.
- Novel actuators for telescoping solar arrays such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Methodology for stabilizing large vertical arrays such as compactly packageable support bases, using regolith as ballast mass, or novel guy wire and surface anchor systems.
- Optimized use of advanced lightweight materials, including composite materials with ultra-high modulus (>280 GPa) combined with low coefficient of thermal expansion (<0.1 m/m/°C).
- Integration of novel structural health monitoring technologies.
- Validated modeling, analysis, and simulation techniques.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts; e.g., thinned rigid panel or 3D-printed solar arrays, nonrotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays. Solar array concepts should be compatible with state-of-the-art solar cell technologies with documented environmental degradation properties. Design, build, and test of scaled flight hardware or functioning lab models to validate proposed innovations is of high interest.

**Expected TRL or TRL Range at completion of the Project**

4 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

**Level 2**

TX 12.2 Structures

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their TRL. TRLs at the end of Phase II of 4 or higher are desired.

**State of the Art and Critical Gaps**

This subtopic addresses capability gap #03-04 in the 2021 HEOMD-405 Integrated Exploration Capabilities Gap List titled “50 kW class solar power generation systems.” Gap #03-04 is one of just three tier 1 (highest impact) capability gaps in the 03) Aerospace Power and Energy Storage category, and is considered to be a development gap for which at least one potential solution has been identified but additional work is required to ensure feasibility of the new and/or novel performance or function in a specific operational application.
Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for lunar surface power. Furthermore, there is usually no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 50-kW-class (40- to 60-kW) solar array for surface electrical power near the lunar South Pole for diverse needs including ISRU, lunar bases, dedicated power landers, and rovers.

Relevance / Science Traceability

Robust, lightweight, redployable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the Moon. New this year, the subtopic extends the focus area from human landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10 to 20 kW of power for first-generation capabilities and 40 to 60 kW for second-generation capabilities.

References

that are exposed to extreme heating environments. The hot structure technologies proposed for development must be for reusable, nonmetallic, oxidation-resistant, fiber-reinforced composite structures. Hot structure is an enabling technology for reusability, thus facilitating the development of advanced propulsion systems requiring multiple engine firings and vehicles requiring aerocapture/aerobraking followed by entry, descent, and landing. The development of hot structure technology for (a) combustion-device liquid rocket engine propulsion systems and (b) aerodynamic structures for aeroshells, control surfaces, wing leading edges, and heatshields is of great interest.

Desired hot structure systems encompass multifunctional structures that can reduce or eliminate the need for active cooling, and in the case of aerodynamic structures, separate thermal protection system (TPS) materials. The potential advantages of using hot structure systems in place of actively cooled structures or a TPS with underlying cool structure include reduced mass, increased mission performance (such as reusability and greater thermal efficiency), improved aerodynamics for aeroshell components, improved structural efficiency, and increased ability for nondestructive inspections. These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during liquid rocket engine firings and/or atmospheric entry. Examples of prior flight-proven hot structures include: (a) the composite nozzle extensions for the Centaur RL10 family of upper-stage rocket engines, and (b) the wing leading edges and control surfaces for the Space Shuttle Orbiter, Hyper-X (X-43A), and/or X-37B.

This subtopic seeks to develop innovative, low-cost, damage-tolerant, reusable, lightweight fiber-reinforced composite hot structure technology adhering to the following:

- At a minimum, the subject hot structures must be capable of operating at temperatures of at least 1,510 °C (2,750 °F)—higher temperatures are of even greater interest, such as up to 2,204+ °C (4,000+ °F).
- Constructed from composite fiber-reinforced materials, such as carbon-carbon (C-C) and ceramic matrix composite (CMC) materials.
- Potential applications of interest for hot structure technology include: (a) propulsion system components (hot gas valves, combustion chambers, nozzles, and nozzle extensions) and (b) primary load-carrying aeroshell structures, control surfaces, leading edges, and heatshields.

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability, and material system properties, as well as the need to reduce cost and manufacturing time requirements. Technology focus areas for submitted proposals should address one or more of the following:

- Repeatable materials properties: Improvements in manufacturing processes and/or material designs to achieve repeatable uniform material properties, while minimizing data scatter, that are representative of actual vehicle components; specifically, material property data obtained from flat-panel test coupons should correlate directly to the properties of prototype and flight test articles.
- Improved toughness/durability: Material/structural architectures and multifunctional systems providing significant toughness and/or durability improvements over typical 2D interlaminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include incorporating through-the-thickness stitching, braiding, or 3D woven preforms. Advancements in oxidation resistance that enhance durability are also of interest, and may include: matrix inhibition, oxidation resistant matrices, functionally graded material systems, and exterior environmental coatings. The goals here are to eliminate/reduce discontinuities in material properties and to provide robust material systems.
- Reduced cost and/or delivery time: Manufacturing process methods that enable a significant reduction in the cost and time required to fabricate materials and components. There is a great need to reduce cost and processing time for hot structure materials and components—current state-of-the-art materials are typically expensive and have fabrication times often in the range of 6 to 12 months (or longer), which can limit or exclude the use of such materials. Approaches enabling reduced costs and manufacturing times should not lead, however, to significant reductions in material properties. Advanced manufacturing methods may include but are not limited to the following: (a) rapid densification cycles, (b) high char-yield resins, (c) additive manufacturing (AM), and (d) automated weaving, braiding, layup, etc.

Expected TRL or TRL Range at completion of the Project
Primary Technology Taxonomy

Level 1

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2

TX 12.1 Materials

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description

Research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware or prototype demonstrations. Phase I feasibility studies should also address cost and the risks associated with the hot structure technology.

In addition to delivery of a Phase I final report, a representative sample(s) of the material and/or technology addressed by the Phase I project should be provided at the conclusion of the Phase I contract. Examples of representative Phase I sample deliverables include:

- Coupons appropriate for thermal and/or mechanical material property tests.
- Arc-jet test specimens.
- Subelement or subcomponent structures.

Plans for potential follow-on Phase II contracts should include the delivery of manufacturing demonstration units to NASA or a commercial space industry partner during Phase II. Testing of such demonstration articles should be a part of the anticipated Phase II effort. Depending upon the primary application addressed by the Phase II contract, such test articles may include subscale nozzle-extensions, arc-jet specimens, or other representative hot structure components. Opportunities and plans should also be identified and summarized for potential commercialization with at least one aerospace company. Vehicle integration issues (attachment, joining, etc.) should be addressed.

State of the Art and Critical Gaps

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1,093 to 1,593 °C (2,000 to 2,900 °F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before potential reuse. Critical gaps or technology needs include:

- Increasing operating temperatures to 1,649 to 2,204+ °C (3,000 to 4,000+ °F).
- Increasing resistance to environmental attack (primarily through oxidation).
- Increasing manufacturing technology capabilities to improve reliability, repeatability, and quality control.
- Increasing durability/toughness and interlaminar mechanical properties (for 2D reinforcement) or introducing 3D architectures.
- Decreasing manufacturing cost.
- Decreasing overall manufacturing time requirements.

Relevance / Science Traceability
Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance, and the durability to withstand long-duration space exploration missions. The ability to allow for delivery and/or return of larger payloads (and crewed vehicles) to various space destinations, such as the lunar South Pole and Mars, is also of great interest.

The Advanced Exploration Systems (AES) Program (https://www.nasa.gov/directorates/heo/aes/index.html) would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial space programs, such as the Commercial Resupply Services (CRS) Program, the Commercial Crew Program (CCP), the Commercial Lunar Payload Services (CLPS) Program, and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology for propulsion upgrades or block changes in the future include the Artemis Space Launch System (SLS), Orion, and Human Landing System (HLS). Hot structure technology is also highly relevant to the NASA Aeronautics Research Mission Directorate’s (ARMD's) Hypersonic Technology (HT) Project (https://www.nasa.gov/aeroresearch/programs/aavp/ht). Other relevant efforts include the work done by NASA and the Defense Advanced Research Projects Agency (DARPA) in developing nuclear thermal propulsion (NTP) systems, both for reactor materials and nozzle extensions.

Potential NASA users of this technology exist for a variety of propulsion systems and other applications requiring the use of similar materials, including the following:

- Upper-stage engine systems, such as those for the Artemis SLS.
- In-space propulsion systems, including nuclear thermal propulsion systems.
- Lunar/Mars lander descent/ascent propulsion systems.
- Propulsion systems for the commercial space industry, which is partnering with and supporting NASA efforts.
- Atmospheric entry vehicle aeroshells, such as those for use at Earth, Mars, or other planets and their moons.
- Related applications include the structures required for hypersonic flight vehicles.

Finally, the U.S. Air Force is interested in such technology for its National Security Space Launch (NSSL), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Army, the U.S. Navy, the U.S. Space Force, the Missile Defense Agency (MDA), and DARPA. The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high-temperature composites technology.

References

Liquid Rocket Propulsion Systems:


Hypersonic Flight Vehicle Structures:

H5.05 Inflatable Softgoods for Next Generation Habitation Systems

Lead Center: MSFC

Participating Center(s): JSC, LaRC

Scope Title

Inflatable Softgoods for Next Generation Habitation Systems: Testing and Structural Health Monitoring

Scope Description

A key enabling technology for future crewed habitation systems is the development of inflatable softgoods materials and structures. In the past, habitat structures have typically consisted of metal alloys, but larger habitable volumes with lower structural mass will be required for long-duration, exploration-class missions. This subtopic seeks activities to mature inflatable softgoods through integration of sensing capabilities for structural health monitoring (SHM) and development of accelerated testing techniques.

Activities that may be undertaken under a Phase I effort include:

Development of approaches for accelerated materials creep testing, specifically for high-strength materials in inflatable softgoods such as webbings and cords. In implementing these materials in habitation structures, one long-term risk is failure of the structural material due to creep (deformation under sustained loading). Real-time creep testing at the component and subscale levels can take years and new test methods need to be developed to help certify softgoods for flight in their intended use environment. Approaches may include novel test methods to reduce the duration of the test (while still generating meaningful data relative to long term use of a material system in its environment) and/or a combination of test methods and modeling approaches to accelerate generation and capture of relevant lifetime material data. Development of new approaches will help to increase testing throughput and mitigate potentially catastrophic risks in failure of inflatable materials.

Scope of work includes:

- Develop a methodology and test approach that can be validated to produce accurate predicted lifetime creep strain data and time-to-failure (TTF) for high-strength softgoods over a range of percent creep loads (50-90% nominally) within a year. (Within 1 to 3 months would be preferable).
  - "High strength" refers to webbings and cordage of strength nominally in the range 5,000 to 20,000 lbs/in.
- Produce master creep curves for each percent load and failure points.

The second focus area is integrated SHM. Integrated sensing capabilities in inflatable softgoods material systems are needed to monitor the structural performance of the material in situ, measure load/strain on softgoods components, detect damage, and predict further degradation/potential failures. The ability to acquire, process, and make use of this data in real time is an important risk mitigation for potential structural failure modes. The current...
state of the art in this field are instrumentation systems such as high-resolution strain gauges, fiber optics, accelerometers, and acoustic sensors using flexible electronics. However, there is a technology gap in developing a proven system that can integrate into a softgoods material system and continually monitor performance through its life. For this activity, integration of a system as a proof of concept and preliminary testing on an integrated inflatable softgoods structure are expected as part of the Phase I.

Scope of work includes:

- Develop robust/repeatable integration approach with high-strength softgoods during manufacture or afterwards, that minimizes impact on the performance of the softgoods.
- Develop sensor(s) that are robust to packaging/deployment/handling of the softgoods they are integrated into.
- Repeatable performance and high-accuracy strain measurement (creep strain is typically 0.1 ~ 0.5%) once deployed and over the lifespan of the inflatable module.
- Sensor(s) are inherently able to (or have a defined path to) survive the extreme environment of space.

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy

Level 1

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2

TX 12.2 Structures

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I: Depending on the activity the proposer chooses to focus on, a Phase I effort would result in:

1. Development of accelerated creep test methods for inflatable softgoods at the component level and a laboratory proof of concept.
2. Approach to SHM for inflatable softgoods, a laboratory proof of concept of efficacy of approach, and/or preliminary design, which integrates the SHM approach into test articles.

Phase II: Depending on the activity the proposer chooses to focus on, a Phase II effort would result in:

1. Implementation of accelerated testing methods for evaluation of material creep and comparison with traditional (real-time) testing approaches at the component level.
2. Integration of SHM approach into inflatable softgoods components or subscale inflatable softgoods prototype and preliminary testing under load.

State of the Art and Critical Gaps
Development of approaches for accelerated materials creep testing. Current state of the art for testing uses straps for real-time creep testing at the component level and subscale (or full-scale) inflatable softgoods test articles for (a) burst and (b) creep-to-burst testing. These tests are needed to understand the behavior of the inflatable softgoods over the mission lifetime and predict failure due to creep, which represents a catastrophic risk. Real-time testing takes months to years to collect data (depending on load level) and predictions require extrapolation from a limited number of data points. Accelerated testing techniques would enable higher fidelity characterization of the performance of the inflatable softgoods system over the entire mission scenario prior to flight and reduce risk.

Integrated SHM. Approaches for SHM in inflatable softgoods are needed to track the performance of the material system in real-time and identify when the structure has incurred damage or is at risk of failure. SHM typically uses strain gauges, digital image correlation, or accelerometers. SHM for inflatable softgoods requires novel approaches, as the material system is multilayer and fundamentally different from many other habitat structures. New techniques, such as flexile electronics, wireless systems, and fiber optics, are also generally unproven in a flight scenario for SHM.

**Relevance / Science Traceability**

Technology for inflatable softgoods has historically been developed under Human Exploration Operations Mission Directorate (HEOMD) and Advanced Exploration Systems (AES). Current work on inflatable softgoods is under NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) A: Habitation Systems Broad Agency Announcement opportunity, which has been ongoing since 2016 and focuses on design of next-generation habitat systems for cislunar space, the lunar surface, and Mars transit scenarios. The work under this subtopic will strongly complement ongoing work under the NextSTEP habitat project and increase the potential for the infusion of inflatable softgoods into future habitation concepts by reducing risk associated with understanding and predicting material behavior.

**References**

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

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

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

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

Expected TRL or TRL Range at completion of the Project

4 to 6

Primary Technology Taxonomy

Level 1

TX 10 Autonomous Systems

Level 2

TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Software

Desired Deliverables Description

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

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

State of the Art and Critical Gaps

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

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

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

Relevance / Science Traceability

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

References

Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com [21]
Future deep space human missions will place crews at long distances from Earth causing significant communication lag due to the light distance along with occasional complete loss of communication with Earth. In deep space, crews will be required to manage, plan, and execute the mission more autonomously than currently required on the International Space Station (ISS) due to time delays and communication blackouts. NASA must migrate current operations functionality from Mission Control to the spacecraft to be performed by the crew and autonomous agents supervised by the crew so that the crew is not overburdened.

Novel capabilities for crews and ground staff will be required to manage spacecraft operations, including spacecraft and systems health, crew health, maintenance, consumable management, payload management, and activities such as food production and recycling. Autonomous agents with cognitive architectures could interface directly with the crew and with the onboard systems, reducing the cognitive loads on the crew, as well as perform many of the tasks that would otherwise require scheduling crew time. Cognitive agents can provide assistance, operate systems, provide training, perform inspections, and provide crew consulting, among other tasks. In addition, cognitive agents are necessary in many circumstances to respond to off-nominal events that may overload the crew, particularly when the event limits crew activity such as high-radiation events or loss of atmospheric pressure events requiring crew safety or sequestration.

Today, typical computer agents can easily perform super-human memory recall and computation feats, but at the same time are severely cognitively impaired in that they fail to recognize the values, implications, severity, reasonableness, and likelihood of the assertions they hold, and how inferences can be applied. The consequence is that computer agents often fail to recognize what is obvious and important to humans, appear to be easily deceived, and fail to recognize and learn from mistakes. Thus, crew interfaces to such typical computer agents for the current state of the art can be burdensome.

Due to the complexity of such systems and the need for them to be continually updated, the architecture must be modular, such that modules can dynamically be added, removed, and enhanced. Such a cognitive architecture is consistent with that proposed by Prof. Marvin Minsky in "The Society of Mind", 1988. The cognitive architecture is required to be capable of supporting multiple processes executing on multiple processors to be able to meet the expected computational loads as well as be robust to processor failure.

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

An effective cognitive architecture would be capable of integrating a wide variety of artificial intelligence modules or managers depending on mission requirements. The following (nonexhaustive) list of managers provides capabilities useful for a wide variety of spacecraft cognitive agents:

**State estimation manager:** This manager’s capabilities include extracting information from sensors, including images, for use by other managers and by crew. State estimation includes separating signal from noise in sensor data, extracting and compressing useful information, along with fault management and prognostics. The state estimation manager must categorize information on both vehicle-wide and subsystem-by-subsystem bases, including crew health and performance, security, and scientific objectives.
Skill/behavior manager: This manager orchestrates execution of individual tasks on short timescales. This involves incorporating specialized knowledge needed for different tasks, e.g., orbit/trajectory planning, robotics operations, spacecraft subsystem control. The skill/behavior manager includes a "smart executive" that robustly executes high-level plans produced by the planner/scheduler manager, on schedule, by coordinated commanding of multiple subsystems.

Planner/scheduler manager: This manager creates and updates plans and schedules that accomplish goals. This functionality involves maintaining lists of goals, priorities for achieving those goals, and spacecraft and mission-wide constraints.

Knowledge manager: This manager ensures that the system's declarative knowledge is consistent and updated, including the incorporation of learned knowledge. Learning and modeling techniques capture system and operational knowledge from different types of knowledge sources; these must be incorporated into existing knowledge bases.

Human-machine interactions manager - Natural Language Processing (NLP), Extended Reality (XR): This manager enables multimodal interface/communications with the crew about the current and future state of the systems. This manager must communicate information from all other managers.

Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA software, with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable for providing crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true, necessitating this NASA investment.

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

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 10 Autonomous Systems

Level 2

TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description

For Phase I, a preliminary cognitive architecture, preliminary feasibility study, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. A preliminary demonstration prototype of the proposed cognitive architecture is highly encouraged.
For Phase II, the Phase I proposed detailed feasibility study plan is executed, generating a comprehensive cognitive architecture, a comprehensive feasibility study report including design artifacts such as Systems Modeling Language/Unified Modeling Language (SysML/UML) diagrams, a demonstration of an extended prototype of an agent that instantiates the architecture interacting with a spacecraft simulator and humans executing a plausible Human Exploration and Operations Mission Directorate (HEOMD) design reference mission beyond cislunar orbit (e.g., Human Exploration of Mars Design Reference Mission: [22]), associated source code, and a detailed plan to develop a comprehensive cognitive architecture feasibility study suitable for proposing to organizations interested in funding this flight capability. Open-sourcing prototype agent and simulation software on [23] is encouraged. A Phase II prototype suitable for a compelling flight experiment on the ISS is encouraged.

State of the Art and Critical Gaps

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

The majority of Apollo missions required the timely guidance of mission control for success, typically within seconds of an off-nominal situation. Outside of cislunar space, the time delays will become untenable for Earth to manage time-critical decisions as was done for Apollo. The emerging field of cognitive computing is a vast improvement on previous information retrieval and integration technology and is likely capable of providing this essential capability. This subtopic is directly relevant to the HEOMD Advanced Exploration Systems (AES) domain: Foundational Systems - Autonomous Systems and Operations.

Relevance / Science Traceability

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

References

IBM (Watson), Apple (Siri®), Microsoft (Cortana), Amazon (Alexa), Google (Dialogflow) are just a few of the companies developing intelligent autonomous agents. However, as they generally are proprietary, they do not meet the need of this subtopic. Importantly, these types of systems only contain limited knowledge about specific tasks such as making reservations or ordering takeout from a restaurant, but do not have the depth of knowledge to represent and reason about the spacecraft systems and operations.

A survey of cognitive architectures can be found at: [24]

Conferences that include cognitive architecture papers include International Joint Conferences on Artificial Intelligence (IJCAI), Association for the Advancement of Artificial Intelligence (AAAI), Advanced Computer Systems (ACS), Autonomous Agents and Multiagent Systems (AMAAAS), as well as the ongoing Cognitive Architectures (CogArch) series of workshops.

Human Exploration of Mars Design Reference Mission: [25]

H8.01 Low-Earth Orbit Platform and Microgravity Utilization for Terrestrial Applications

Lead Center: JSC

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

Scope Title

Use of the International Space Station (ISS) to Foster Commercialization of Low Earth Orbit (LEO) Space

Scope Description

Background: The White House letter to the appointee for the Office of Space Technology Policy included a number of significant challenges from the President that are intended to ensure the United States is "the world leader in the technologies and industries of the future that will be critical to our economic prosperity and national security." These challenges can be addressed through continued NASA investment in new and promising commercial In-Space Production Applications (InSPA) that utilize the ISS National Lab (ISS NL). NASA has been investing in such commercial technologies for many years, including through use of Small Business Innovation Research (SBIR) topic H8, and is seeing great possibilities for the commercial in-space production of materials that can be made in microgravity to levels of performance and quality that exceed those made on Earth. These technologies not only help to maintain and strengthen U.S. leadership in this area, but they support development of a strong U.S.-led commercial space economy in LEO.

Scope: This subtopic seeks proposals that advance NASA's objective of leveraging the unique capabilities (microgravity, exposure to space) of the ISS to maintain and strengthen the U.S. leadership in the area of commercial in-space production of materials, technologies, and industries of the future that will be critical to our economic prosperity amid increasing global competition. Proposals should describe how the commercial technologies benefit from the space environment to produce a level of quality and performance superior to that which is possible on Earth, while also supporting NASA's objective to catalyze emerging markets leading to a broad non-NASA demand for use of U.S.-based LEO commercial destinations in the future. Of specific interest are proposals that could lead to valuable terrestrial applications and foster a scalable and sustainable demand for commercial markets in LEO. Use of the ISS will facilitate validation of these applications and enable development of a commercial product at reduced cost in order to attract significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: thin-layer deposition, crystal production, tissue engineering and regenerative medicine, and advanced materials production. Phase I proposals for this subtopic should include increased emphasis (beyond the suggested page limit) on the anticipated business case as defined in Part 7 (The Market Opportunity) of this SBIR Solicitation. This subtopic is not intended for use by applications seeking a TRL 9 flight demonstration for a system or technology not aligned with in-space production goals.

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

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description:

For Phase I, as a minimum, development and test of a bench-top prototype and a written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware demonstration in orbit. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.

Desired deliverables at the end of Phase II would be a preliminary design and concept of operations, development and test of an engineering development unit in a relevant environment (ground or space), and a report containing detailed science requirements, results of testing, and an updated business case analysis and/or application plan. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable.

State of the Art and Critical Gaps:

The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy, while being aligned with the national goal to ensure the United States remains a world leader of in-space manufacturing and production of advanced materials.

Relevance / Science Traceability:

This subtopic is in direct support of NASA’s recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development and strengthen U.S. leadership in in-space manufacturing and production.

References:

2. Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer [28]
3. Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org [29] and In-Space Production Applications (issnationallab.org) [30]. Both links are external.
4. President's Letter to Dr. Eric Lander (OSTP Nominee): A Letter to Dr. Eric S. Lander, the President's Science Advisor and nominee as Director of the Office of Science and Technology Policy | The White House [31]

H9.01 Long-Range Optical Telecommunications

Lead Center: JPL

Participating Center(s): GRC, GSFC

Scope Title

Free-Space Optical Communications Technologies

Scope Description
Summary: This free-space long-range optical communications subtopic seeks innovative technologies for advancing free-space optical communications (FSOC) by pushing future data volume returns to and from space missions in multiple domains with return data rates >100 Gb/s (cislunar, i.e., Earth or lunar orbit to ground), >10 Gb/s (Earth-Sun L1 and L2), >1 Gb/s from 1 astronomical unit (AU) (deep space), and >1 Gb/s (planetary lander to orbiter and/or inter-spacecraft). Ground-to-space forward data rates >25 Mb/s to farthest Mars ranges are targeted. Optical metrology services include high-precision ranging, while Doppler and astrometric measurements derived from the optical communications signal are sought as well.

Innovative technologies offering low size, weight, and power (SWaP) with improved efficiency, reliability, robustness, are sought for novel state-of-the-art (SOA) spaceflight laser communication systems with supporting ground technologies.

Multifunctional photon-counting sensitivity, near infrared (NIR), spaceflight-worthy detectors/detector arrays for supporting acquisition and tracking, uplink communication receiving, and laser ranging for potential navigation and science are of particular interest. High wall-plug efficiency flight-qualified lasers with high peak-to-average power are sought. Ground-based technologies that support operations of large-aperture daytime light collectors are needed to transition deep space optical communications (DSOC) to operational status. High-power, NIR, intensity-modulated lasers with fast rise times and low timing jitter (sub-nanosecond) are needed to support high forward data rates and laser ranging.

Priorities: This sub-topic is broadly divided between Flight and Ground technologies for free-space optical communications. Innovation priorities are listed in order below.

For flight technologies,
1. Lowering size weight and power (SWaP)
2. Solutions for pointing narrow laser beams from space platforms
3. Technology choices that ease space qualification for radiation, random vibrations and thermal-vacuum
4. Photonics solutions for combining with, or replacing, discrete optics

For ground technologies,
1. Innovations leading to large aperture diameters for collecting faint optical signals through atmospheric turbulence while operating under daytime conditions
2. Kilowatt class ground laser transmitter with narrow pulses and high repetition rates

Proposals are sought in the following specific areas:

FLIGHT LASER TRANSCEIVERS:
Low-mass, high-Effective Isotropic Radiated Power (EIRP) laser transceivers for links over planetary distances with:

- 30 to 50 cm clear aperture diameter telescopes for laser communications.
- Targeted mass of opto-mechanical assembly per aperture area, less than 200 kg/m².
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and spaceflight thermal environments by the optics and structure, at least -20 to 70 °C operational range.
- Design to mitigate stray light while pointing transceivers 3° from the edge of Sun.
- Survive direct Sun pointing for extended duration (few hours to days).

Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon-assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, light-weighted thermally stable structural properties are sought.
• Acquisition, tracking, and pointing architectures that can operate with dim laser beacons (irradiance of few picowatts per square meter at entrance of flight aperture) from Mars farthest ranges.
• Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%).
• Receiver field-of-view (FOV) of at least 1 mrad angular radius for beacon-assisted acquisition, tracking, and pointing.
• As a goal additional focal plane with wider FOV (>10 mrad) to support onboard astrometry is desired.
• Beaconless pointing subsystems for space-to-ground operations beyond 3 AU.
• Assume integrated spacecraft micro-vibration angular disturbance of 150 µrad (<0.1 to ~500 Hz).

Low-complexity small-footprint agile laser transceivers for bidirectional optical links (>1 to 10 Gb/s at a nominal link range of 1,000 to 20,000 km) for planetary lander/rover-to-orbiter and/or space-to-space crosslinks.

• Disruptive low-SWaP technologies that can operate reliably in space over extended mission duration.
• Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high-frequency base disturbance by at least 50 dB.
• Desire integrated launch locks and latching mechanism.
• Should afford limited ± 5 to ±12 mrad actuated field-of-regard for the optical line of sight of the transceiver.

HIGH WALL-PLUG EFFICIENCY FLIGHT LASER TRANSMITTERS:

High-Gb/s laser transmitters:

• 1,550 nm wavelength.
• Lasers, electronics, and optical components ruggedized for extended space operations.
• High rate 10 to 100 Gb/s for cislunar.
• 1 Gb/s for deep space.
• Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the emerging Consultative Committee for Space Data Systems (CCSDS) optical communications standards.

High peak-to-average power laser transmitters for regular or augmented M-ary pulse position modulation (PPM) with M = 4, 8, 16, 32, 64, 128, 256 operating at NIR wavelengths, preferably 1,550 nm, with average powers from 5 to 50 W.

• Subnanosecond pulse.
• Low-pulse jitter.
• Long lifetime and reliability operating in space environment (>5 years and as long as 20 years).
• High modulation and polarization extinction ratio with 1 to 10 GHz linewidth.

Space-qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power >20 W per channel; peak-to-average power ratios >200; >10 GHz channel modulation capability.

• >20% wall-plug efficiency, direct current (DC)-to-optical, including support electronics) with description of approach for stated efficiency of space-qualifiable lasers. Multiwatt Erbium Doped Fiber Amplifier (EDFA), or alternatives, with high-gain bandwidth (>30 nm, 0.5 dB flatness) concepts will be considered.
• Radiation tolerance greater than 50 krad is required (including resilience to photodarkening).

RECEIVERS/SENSORS:

Space-qualifiable high-speed receivers and low-light-level sensitive acquisition, tracking, pointing, detectors, and detector arrays.

• NIR wavelengths: 1,064 and/or 1,550 nm.
Sensitive to low irradiance incident at flight transceiver aperture (~ femtowatts per square meter to picowatts per square meter) detection.
Low subnanosecond timing jitter and fast rise time.
Novel hybridization of optics and electronic readout schemes with built-in preprocessing capability.
Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high-precision range and range-rate measurements.
Tolerant to space radiation effects, total dose >50 krad, displacement damage and single event effects.

NOVEL TECHNOLOGIES AND ACCESSORIES:

Narrow Bandpass Optical Filters.

- Space-qualifiable, subnanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~40 dB).
- NIR wavelengths from 1,064 to 1,550 nm region, with high transmission through Earth’s atmosphere.
- Reliable tuning over limited range.
- Thermally stable with well characterized temperature dependence of passband.

Novel Photonics Integrated Circuit (PIC) devices targeting space applications with the objective of reducing SWaP of modulators without sacrificing performance. Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.

Concepts for offering redundancy to laser transmitters in space.

- Optical fiber routing of high average powers (tens of watts) and high peak powers (1 to 10 kW).
- Redundancy in actuators and optical components.
- Reliable optical switching.
- Innovative applications of machine learning to ease flight operations of deep space optical communications transceivers, for example, to achieve improved pointing performance from space.

GROUND ASSETS FOR OPTICAL COMMUNICATIONS:

Low cost large aperture receivers for faint optical communication signals from deep space subsystem technologies:

- Demonstrate innovative subsystem technologies for >10 m diameter deep space ground collector.
- Capable of operating to within 3° of solar limb.
- Better than 10 µrad spot size (excluding atmospheric seeing contribution).
- Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than $35K per square meter.
- Low-cost techniques for segment alignment and control, including daytime operations.
- Partial adaptive correction techniques for reducing the FOV required to collect signal photons under daytime atmospheric “seeing” conditions.
- Adaptive optics for uplink laser transmission in order to be able to transmit low-beam divergence lasers with near diffraction limited performance.
- Innovative adaptive techniques not requiring a wave-front sensor and deformable mirror of particular interest.
- Mirror cleanliness monitor and control systems.
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics.
- Large core diameter multimode fibers with low temporal dispersion for coupling large optics to detectors remote (30 to 100 m) from the large optics.

1,550 nm sensitive photon counting detector arrays compatible with large-aperture ground collectors with a means of coupling light from large-aperture diameters to reasonably sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion.
• Integrated time tagging readout electronics for >5 gigaphotons/sec incident rate.
• Time resolution <50 psec, 1-sigma.
• Highest possible single-photon detection efficiency, at least 50% at highest incident photon-flux rates.
• Total detector active area >0.3 to 1 mm².
• Integrated dark rate < 3 megacounts/sec.

Optical filters.

• Subnanometer noise equivalent bandwidths.
• Tunable in a limited range in the 1,550 nm spectral region.
• Transmission losses <0.5 dB.
• Clear aperture >25 mm, and acceptance angle >40 mrad or similar etendue.
• Out-of-band rejection of >50 dB at 0.7 to 1.8 µm

Multikilowatt laser transmitters for use as ground beacon and uplink laser transmitters.

• Near infrared wavelengths in 1.0 or 1.55 μm spectral region.
• Narrow linewidths <0.3 nm.
• Capable of modulating with nanosecond and subnanosecond rise times.
• Low timing jitter and stable operation.
• High speed real-time signal processing of serially concatenated pulse position modulation operating at a few bits per photon with user interface outputs.
• 15 to 60 MHz repetition rates.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1
TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Level 2
TX 05.1 Optical Communications

Desired Deliverables of Phase I and Phase II

• Prototype
• Hardware
• Software

Desired Deliverables Description

For all technologies, lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly
prove technical feasibility (proof of concept) during Phase I, ideally with hardware deliverables that can be tested and/or compelling simulations, to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

State of the Art and Critical Gaps

The SOA for FSOC can be subdivided into near-Earth (extending to cislunar and translunar distances) and planetary ranges with the Lagrange points falling in between.

Near-Earth FSOC technology has matured through a number of completed and upcoming technology demonstrations from space. Transition from technology demonstration to an operational service demands low-SWaP, novel high-speed (10 to 100 Gbps) space-qualified laser transmitters and receivers. Transmitters and receivers servicing near-Earth applications can possibly be repurposed for deep space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5,000 to 100,000 km or intersatellite links. Innovative light-weight space-qualified modems for handling multiple optical-modulation schemes. Emerging photonics technologies that can benefit space FSOC applications are sought.

Deep space FSOC is motivated by NASA's initiative to send humans to Mars. Critical gaps following a successful technology demonstration will be lightweighted 30 to 50 cm optical transceivers with a wide operational temperature range -20 to 50 °C over which wave-front error and focus is stable; high peak-to-average power space-qualified lasers with average powers of 20 to 50 W; and single photon-sensitive radiation-hardened flight detectors with high detection efficiency, fast rise times, and low timing jitter. The detector size should be able to cover 1 mrad FOV with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from Earth or use celestial beacon sources. For DSOC, ground laser transmitters with high-average power (kilowatt class) but narrow linewidths (<0.25 nm) and high-variable repetition rates are required. Innovative optical coatings for large-aperture mirrors that are compatible with near-Sun pointing applications for efficiently collecting the signal and lowering background and stray light. Reliability through space-qualified materials and component selection and implementation of redundancy are highly sought after to enable sending humans to planetary destinations, as well as enable higher resolution science instruments. Deriving auxiliary optimetrics from the FSOC signals to support laser ranging and time transfer will also be critical for providing services to future human missions to Mars. High-rate uplink from the ground to Mars with high-modulation-rate high-power lasers are also currently lacking.

Relevance / Science Traceability

A number of FSOC-related NASA projects are ongoing with launch expected in the 2021 to 2024 time frame. The Laser Communication Relay Demonstration (LCRD) is an Earth-to-geostationary satellite relay demonstration to launch in 2021. The Illuma-T Project will follow to extend the relay demonstration to include a low Earth orbit (LEO) node on the International Space Station (ISS). In 2023, the Optical to Orion (O2O), Artemis II, demonstration will transmit data from the Orion crewed capsule as it performs a translunar trajectory and return to Earth.

In 2022, the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to astronomical unit (AU) distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstrations Missions (TDM) program and Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.

Of the 6 technologies recently identified by NASA for sending humans to Mars, laser communications was identified

(https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars [32])

References
H9.03 Flight Dynamics and Navigation Technologies

Lead Center: JPL

Participating Center(s): JPL, JSC, MSFC

Scope Title

Advanced Techniques for Trajectory Design and Optimization

Scope Description

NASA seeks innovative advancements in trajectory design and optimization for Earth orbit, cislunar, and interplanetary missions, including:

- Low-thrust spiral trajectories.
- Low-thrust trajectories in a multibody dynamical environment.
- Small-body (moons, asteroids, and comets) exploration.
- Distributed space systems (swarms, constellations, or formations).
- Advanced interactive visualization for spacecraft trajectory design and optimization.

NASA is seeking innovative techniques for optimization of trajectories that account for:

- System uncertainties (i.e., navigation errors, maneuver execution errors, missed maneuvers, etc.).
- Spacecraft and operational constraints (power, communications, thermal, etc.).
- Trajectory constraints imposed by navigational and/or science observation requirements.

Furthermore, innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoon/multibody tours; low thrust, multispiral Earth orbits), improved visualization techniques including (but not limited to) 3D graphics, virtual/augmented reality, detailed terrain models, or manipulation of trajectory parameters in a 3D scene are sought.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT); Collocation Stand Alone Library and Toolkit (CSALT); Copernicus; Evolutionary Mission Trajectory Generator (EMTG); Mission Analysis Low-Thrust Optimization (MALTO); Mission Analysis, Operations, and Navigation (MONTE); and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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Expected TRL or TRL Range at completion of the Project
Primary Technology Taxonomy

Level 1

TX 15 Flight Vehicle Systems

Level 2

TX 15.2 Flight Mechanics

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps

Algorithms and software for optimizing trajectories while considering system uncertainties, spacecraft and operational constraints, and trajectory impacts on making navigational or science observations, do not currently exist. In addition, designing trajectories for complex missions, such as low-thrust cislunar or multibody tour missions that rely heavily on hands-on work by very experienced people. That works reasonably well for designing a single reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

Relevance / Science Traceability

Relevant missions include:

- Artemis - Lunar Gateway.
- Europa Clipper.
- Lucy.
- Psyche.
- Dragonfly.
- Roman Space Telescope.
- SmallSat and CubeSat class missions, such as Lunar IceCube.

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to explore trade spaces more fully and more quickly respond to changes in the mission.

References

Scope Title
Autonomous Onboard Spacecraft Navigation, Guidance, and Control

Scope Description

NASA missions require precision landing, rendezvous, formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous, onboard spacecraft navigation and maneuver planning technologies for applications in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning, including:

- Onboard relative and proximity navigation (relative position, velocity and attitude, or pose), which support cooperative and collaborative space operations such as On-orbit Servicing, Assembly, and Manufacturing (OSAM).
- Advanced filtering techniques that address rendezvous and proximity operations as a multisensor, multitarget tracking problem; handle nonGaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, and terrain relative navigation.
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations in low and variable lighting conditions, including artificial intelligence/machine learning (AI/ML) algorithms.
- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission resequencing, onboard targeting/retargeting, onboard computation of large divert maneuvers, primitive body/lunar proximity operations, and pinpoint landing, including robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).
- Software that provides insight into autonomous guidance, navigation, and control system status and its decision-making for ground controllers and crew.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS), Navigator NavCube, core Flight System (cFS), or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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Expected TRL or TRL Range at completion of the Project

2 to 6

Primary Technology Taxonomy
Level 1

TX 17 Guidance, Navigation, and Control (GN&C)

Level 2

TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps

Currently navigation, guidance, and control functions rely heavily on the ground for tracking data, data processing, and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round-trip communication time delays make it necessary to reduce reliance on Earth for navigation solutions and maneuver planning. For example, spacecraft that arrive at a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids, and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently does not have the navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

Relevance / Science Traceability

Relevant missions and projects include:

- OSAM.
- LunaNet.
- Autonomous Navigation, Guidance, and Control (autoNGC).

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time replanning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

References

Conjunction Assessment Risk Analysis (CARA)

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 cm, and the number of objects in orbit is steadily increasing, which causes an increasing threat to spacecraft in the near-Earth environment. The NASA CARA team is responsible for protecting NASA assets by submitting owner/operator trajectory information on the protected spacecraft, including predicted maneuvers, to the 18th Space Control Squadron (SPCS) at Vandenberg Space Force Base in California. The trajectories are screened against the catalog of space objects, and information about predicted close approaches between NASA satellites and other space objects is sent back to CARA. CARA then determines the risk posed by those events and works with the spacecraft owner/operator to develop an appropriate mitigation strategy. The ability to perform risk assessment more accurately and rapidly will improve space safety for all near-Earth operations and cislunar (Earth + 2 million kilometers) operations.

Because CARA does not produce ephemeris data for the NASA-protected assets or the catalogued objects, the orbit determination aspect of the problem is not of interest in this call. Additionally, CARA does not control the screening process and is therefore not looking for solutions in that area. Only the conjunction assessment (CA) risk assessment aspect is within the scope of this call.

This subtopic seeks innovative technologies to improve the risk assessment process, including the following specific areas (see Reference 1 for the 2020 NASA Technology Taxonomy (TX) areas TX05.6.4, TX10.1.4, TX10.1.5, and TX10.1.6):

1. The Probability of Collision (Pc) is the standard metric for assessing collision likelihood. Its use has substantial advantages over the previous practice of using stand-off distances. The Pc considers the uncertainties in the predicted state estimates at the time of closest approach (TCA) so it provides a probabilistic statement of risk. A number of concerns with the use of the Pc, however, have been identified, including “diluted” probability (see Reference 2) and “false confidence” (see Reference 3). While it is believed that use of the Pc is a responsible approach, there is always interest in alternative risk assessment techniques and parameters that may confer certain advantages. Special consideration will be directed to approaches that explicitly avoid extreme conservatism but instead enable the CARA mission statement of taking “prudent measures, at reasonable cost, to improve safety of flight, without imposing an undue burden on mission operations” and the balancing required to improve safety while allowing largely unencumbered space mission operations.

2. It is appropriate to take explicit cognizance of all the uncertainties in the inputs to the Pc calculation in order to emerge with a range or Probability Density Function (PDF) of possible collision probabilities, or some other parameter that takes account of these uncertainties in some way. Approaches to characterizing the uncertainties in the hard-body radius and object covariances are logical (see Reference 4), although NASA is open to entirely different constructs and approaches while keeping in mind that CARA cannot control the orbit determination process and cannot change the state estimation/propagation and uncertainty representation paradigm.

3. The number of conjunction events is expected to continually increase with the increase of resident space objects from large constellations, the ability to track smaller objects, the increasing numbers of CubeSat/SmallSats, and the proliferation of space debris. New or improved techniques are sought to increase the speed of risk analysis of conjunction events that also retain the ability to screen the planned trajectory via the 18 SPCS process. A semiautomatic approach for risk analysis could involve preliminary analysis on the severity levels of a given conjunction as a form of triage. Given the information available in
Conjunction Data Message (CDM) and the historical information of a given space object, new or improved
techniques or algorithms using for predicting event severity in either a singular event or an ensemble risk
assessment for contiguous close approaches for several events including those using artificial intelligence
(AI) or machine learning (ML) are sought.

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subtopic as an available technology, use of the available NASA IP is strictly voluntary. Whether or not a firm uses
available NASA IP within their proposal effort will not in any way be a factor in the selection for award.

See section 1.6 for additional details on TAV requirements.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

**Level 2**

TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Software

**Desired Deliverables Description**

Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA
testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature
algorithms and software components complete and preliminary integration and testing in a quasi-operational
environment.

**State of the Art and Critical Gaps**

CARA has identified the following challenges to which we are actively looking for solutions: efficient ways to
perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk
assessment, middle-duration risk assessment (longer duration than possible for discrete events but shorter than
decades-long analyses that use gas dynamics assumptions), improved CA event risk evolution prediction,
ML/AI applied to CA risk assessment parameters and/or event evolution. The decision space for collision
avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for CA.

**Relevance / Science Traceability**

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth, cislunar,
and lunar environments. The ability to perform CARA more accurately will improve space safety for all near-Earth
operations, improve operational support by providing more accurate and longer-term predictions, and reduce
propellant usage for collision avoidance maneuvers.
References

1. 2020 NASA Technology Taxonomy: 2020_nasa_technology_taxonomy_lowres.pdf [54]
6. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/ [56]
13. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c1.pdf [62]

H9.07 Cognitive Communication

Lead Center: JPL

Participating Center(s): GSFC, JPL

Scope Title

Lunar Cognitive Capabilities

Scope Description

NASA’s Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks, and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by onboard data processing and modern space networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden. Examples of these cognitive capabilities include:
Link technologies—reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference.

Network technologies—robust intersatellite links, data storage/forwarding, multinode routing in unpredictable environments.

System technologies—optimal scheduling techniques for satellite and surface relays in distributed and real-time environments.

NASA’s Artemis program is committed to landing American astronauts on the Moon in collaboration with our commercial partners. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling. Examples of research and/or technology development include:

- Onboard processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft.
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics.
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment.
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems.
- Flexible communication platforms with novel signal processing technology to support cognitive approaches.
- Other innovative, related areas of interest to the field of cognitive communications.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, and surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low size, weight, and power (SWaP) suitable for small satellite (e.g., 50 kg) or CubeSat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of onboard resources, such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

**Expected TRL or TRL Range at completion of the Project**

4 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

**Level 2**

TX 05.5 Revolutionary Communications Technologies

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits, and show a path towards a Phase II implementation. Phase I deliverables include a feasibility assessment and concept of
operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3 to 4), and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting the Cognitive Communication Project’s Cognitive Ground Testbed and/or demonstration operations on a small satellite or CubeSat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools, as necessary, for NASA to modify and use the cognitive software capability or hardware component(s) and evaluate them in the Cognitive Ground Testbed for greater infusion potential. Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Algorithms must be implemented in software and should be ready to be run on the testbed’s Software Defined Radios and/or appropriate general-purpose processor.

Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software-defined radio platforms shall be compliant with the latest NASA standard for software-defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009A, and NASA-HDBK-4009A. The deliverable shall be demonstrated in a relevant emulated environment and have a clear path to Phase III flight implementation on a SWaP-constrained platform.

State of the Art and Critical Gaps

To summarize NASA Technology Roadmap TA5: “As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks.... Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data.... Reconfigurable radio systems...could autonomously optimize the RF [radiofrequency] links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance.”

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc.
- Data routing between lunar relay satellites, as necessary, to conserve power, route data to Earth, and meet quality of service requirements.
- Efficient use of lunar communication spectrum while coexisting with future/current interference sources.
- On-demand communication resource scheduling.
- Multihop, delay tolerant routing.

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms.
- Integrated wide-band sensing and narrow-band communication on the same radio terminal.
- Intersatellite networking and routing, especially in unpredictable and unscheduled environments.
- On-demand scheduling technology for communication links.
- Cross-layer optimization approaches for optimum communication efficiency at a system level.

Relevance / Science Traceability

Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will
be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short- and long-term performance for improvements.

References

Several related reference papers and articles include:

- "Implementation of a Space Communications Cognitive Engine": https://ntrs.nasa.gov/search.jsp?R=20180002166 [66]
- "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications": https://ntrs.nasa.gov/search.jsp?R=20170009153 [69]
- "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits": https://ntrs.nasa.gov/search.jsp?R=2017009386 [70]
- "Architecture for Cognitive Networking within NASA's Future Space Communications Infrastructure": https://ntrs.nasa.gov/citations/2017006033 [71]

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: https://ieee-ccaa.com/ [21]

H10.01 Advanced Propulsion Systems Ground Test Technology

Lead Center: SSC

Participating Center(s): KSC

Scope Title

Advanced Propulsion Test Technology Development

Scope Description

Rocket propulsion development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and nonchemical propulsion, boost stage, in-space propulsion, and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were
designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system-level ground test systems that enhance chemical and advanced propulsion technology development and certification. The goal is to advance propulsion ground test technologies to enhance environment simulation; minimize test program time, cost, and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, current technology needs include advanced computational simulation capabilities for robust and rapid modeling of large-scale high-speed chemical reacting multiphase flows, and advanced instruments and monitoring systems capable of operating in those extreme temperature and harsh environments. For example, this might include applications such as launch or test stand rocket plume deflectors which involve shock-laden rocket exhaust plumes impinging and mixing with water sprays and pools.

This subtopic seeks innovative technologies in the following areas:

- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8,000 psi), high flow rate (>100 lbm/sec), and cryogenic environments.
- Robust and reliable component designs that are oxygen compatible and can operate efficiently in high-vibroacoustic environments.
- Computational tools which can robustly, accurately, and efficiently capture unsteady sharp gradients in rocket flows such as propagating shock and blast waves, free surfaces at liquid/gas interfaces, etc. Specifically, new nondissipative flux techniques to fully eliminate the carbuncle phenomena that occur in Roe/HLL-based schemes is of interest (numerical routines to solve governing fluid equations). In addition, more efficient and novel adaptive meshing techniques for unsteady, large-scale applications is desired.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand pounds per second, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; and fluid-structure interactions in internal flows.

**Expected TRL or TRL Range at completion of the Project**

4 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 13 Ground, Test, and Surface Systems

**Level 2**

TX 13.1 Infrastructure Optimization

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Software

**Desired Deliverables Description**
For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I as a final report and show a path toward Phase II hardware/software demonstration, with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

**State of the Art and Critical Gaps**

This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies, and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids, reduce logistics costs, reduce times required for ground processing and launch, reduce mission risk, and reduce hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DOD), and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next-generation testing requires the ability to produce very high-temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

**Relevance / Science Traceability**

This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at Stennis Space Center (SSC), and other propulsion system development centers.

**References**

- [https://www.nasa.gov/centers/stennis/home/index.html](https://www.nasa.gov/centers/stennis/home/index.html) [73]
- [https://technology.ssc.nasa.gov/](https://technology.ssc.nasa.gov/) [74]

**H10.02 Autonomous Operations Technologies for Ground and Launch Systems**

Lead Center: SSC

Participating Center(s): ARC, LaRC, SSC

**Scope Title**

Autonomous Operations Technologies for Ground and Launch Systems

**Scope Description**

For the scope of this solicitation, ground systems are considered to be the planetary or lunar surface-based infrastructure and processes used to assemble, validate, support, load, and maintain launch vehicles and payloads (including non-spacecraft payloads) in preparation for flight. Launch systems are considered to be the planetary or lunar surface-based infrastructure and processes used to transition launch vehicles to flight operation.

Autonomous operations technologies (AOT) are required to manage ground and launch systems activities where human intervention/interaction/presence needs to be minimized or eliminated, such as in hazardous
AOT performs functions such as system and component fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision making and control; and intelligent components and devices.

AOT will be integrated into activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will enable surface O&M, which requires a high degree of autonomy and reliability for unattended operations during extended periods of time. AOT will complement in situ resource utilization (ISRU) operations by supporting ISRU ground systems infrastructure with O&M autonomy. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants used in launch vehicles and maneuvering systems. APM includes preplanned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting, and system reconfiguration.

AOT solutions may enable the autonomous command, monitoring, and control of entire integrated systems, such as a propellant loading system and all other associated support systems involved in the loading process. AOT will also support tasks such as systems setup, testing and checkout, troubleshooting, maintenance, upgrades, and repair. These additional tasks drive the need for autonomous element-to-element interface connection and separation, multielement inspection, and recovery of high-value cryogenic propellants and gases to avoid system losses.

AOT software may include prerequisite control logic (PCL) and reactive control logic (RCL), and may utilize machine learning or other forms of artificial intelligence to manage nominal system behavior and adapt to off-nominal conditions.

In addition to propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high-pressure gases for purging, pressurization, or conditioning. Propellant management systems may also include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and observe vehicle states during propellant management operations.

Specifically, this subtopic seeks the following:

- Development of technologies for automated/autonomous propellant (including cryogenic propellants) management and the servicing of commodities for launch vehicles and payloads.
- Development of high-fidelity physics-based cryogenic-thermal models and ground process simulations capable of real-time and faster than real-time performance.
  - Development of automated/autonomous algorithms for ground systems applications.
  - Machine learning environments (simulation and learning agent) for ground systems processes and applications.
  - Development of high-fidelity models and simulations for complex payload system processing, servicing, maintenance, etc.
  - Development of test and evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models, and simulations.
- Development of technologies for ground systems Health Determination and Fault Management.
  - Prediction, prognosis, and anomaly detection algorithms and applications.
  - Detection, isolation, and recovery of system and component faults and degradation.
  - Development of T&E, and V&V methods for Health Determination and Fault Management algorithms and applications.
- Development of technologies for automated/autonomous planning and scheduling (P&S).
  - Automated/autonomous assets management tools and applications.
  - Scheduling and prioritization algorithms and applications.
  - Human-machine information interactions and intent inferencing.
Development of technologies for automated/autonomous inspection, maintenance, and repair (IM&R).
  - Use of robotic caretakers for IM&R needs.
  - Self-diagnosis in systems and components to inform condition-based maintenance.
  - Software to aid robotic agents or systems to learn IM&R functionality.

Development of technologies for enhanced logistics and reliability.
  - Optimization and/or reduction of logistics needs (design for maintainability, commonality, and reusability).
  - Commonality of maintenance equipment, tools, and consumables.
  - Automated/autonomous asset management.
  - Automated/autonomous personnel location and condition determination.
  - Intelligent devices (sensors, actuators, and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.).

Standardization of architectures and interfaces for ground and launch systems.

Standardization of ground systems design (design for maintainability, commonality, and reusability).

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I, show a path toward Phase II demonstration and deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).

**Expected TRL or TRL Range at completion of the Project**

5 to 8

**Primary Technology Taxonomy**

**Level 1**

TX 04 Robotics Systems

**Level 2**

TX 04.6 Robotics Integration

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I deliverables: Research, identify, and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms to enable autonomy of ground systems. Demonstrate technical feasibility and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. It should identify improvements over the current state of the art and the feasibility of the approach in a multicustomer environment. Bench or lab-level demonstrations are desirable. Deliverables shall include a report documenting findings.

Phase II deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions using analog ground systems hardware and processes. Deliverables shall include a report detailing performance testing results, a plan for maturing and applying the technology to mission-worthy systems, and other relevant documentation. Delivery of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.
State of the Art and Critical Gaps

There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1. High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9).
2. Simulation component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9).
3. Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9).
4. Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9).
5. Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9).

Relevance / Science Traceability

In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration and Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation, and maintenance of ground systems and systems on the surfaces of other planets and moons. The directive from the President to accelerate the timeline for landing astronauts on the Moon, with the goal of a sustainable lunar presence after 2028, has made these technologies even more relevant to mission success. These technology development areas are identified in the 2020 NASA Technology Taxonomy, published by the Office of the Chief Technologist, under TX04 - Robotic Systems, TX10 - Autonomous Systems, and TX13 - Ground, Test, and Surface Systems.

This subtopic also produces technologies useful to the Space Technology Mission Directorate (STMD).

References

- NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html [76])
- NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/offices/oct/home/sstip.html [77])

H12.07 Protective Pharmaceutical Packaging

Lead Center: JSC

Participating Center(s): ARC, GRC

Scope Title

Protective Medication Packaging Technologies Supporting Exploration Spaceflight Operations

Scope Description

Successful long-duration space exploration missions will require robust crew support systems. These systems will rely on exponentially increasing crew autonomy, operate in low-to-no logistical resupply settings, and facilitate independent decision making within the context of challenging communication scenarios due to limited to no terrestrial-based support asset reach back. In addition, the long-duration spaceflight environment will require medically trained crew members who can assess, diagnose, and treat each other for a variety of illnesses and injuries. These medical events will require the preselection and long-term storage of various medications onboard human crewed spacecraft or predeployed in advance of human missions. Although currently there is no available method to sufficiently characterize or quantify the pharmaceutical stability, quality, or potency of repackaged
medications (stored and eventually utilized for human consumption during long-duration space flight missions), available data shows that the median risk of drug failure (based on U.S. Pharmacopeia (USP) acceptance thresholds) for a 2-year exploration mission is approximately 59%. This risk increases to about 82% for a 3-year mission. These factors expose the distinct possibility that the provision of safe and effective drug treatment of long-duration crew may be at significant risk due to the current operationally derived need to repack crew medications to reduce resource "costs" (i.e., mass, volume, and power) possibly adversely impacting crew wellness, performance, and long-term health.

While baseline instability has not been experimentally investigated, most of the pharmaceuticals tested in spaceflight studies to date have been removed (due to mass, volume, and power considerations) from manufacturer's containers and repackaged into either polypropylene container (Du et al. 2011) or lightweight, resealable plastic zipper storage bags. This type of repackaging remains the norm for supplying medications to the International Space Station (ISS). Unfortunately, such containers are not protective, therefore repackaged pharmaceuticals are exposed to ingress of atmospheric factors at concentrations in equilibrium with the ambient atmosphere (Putcha et al. 2016; Waterman et al. 2002). It is well established that such packaging is permeable to atmospheric factors such as moisture and oxygen and that prolonged exposure of susceptible medications is detrimental to shelf life (Roy et al. 2018; Waterman et al. 2002; Waterman et al. 2004).

Whereas exposure to spaceflight conditions (e.g., galactic cosmic radiation (GCR), microgravity, or zero-gravity, etc.) is only a minor factor contributing to the cumulative risk of drug failure, with the significant factor being the baseline risk (observed in paired terrestrial controls under similar environmental conditions), repackaging of pharmaceuticals likely reduces medication effectiveness significantly (and increasingly, as "out of package" exposures extend in long-duration spaceflight), diminishes therapeutic effectiveness, thus potentially compromising crew health and performance.

In the past, repackaging methods have not been a significant limitation for missions where flight duration was much shorter than drug expiry (e.g., Apollo, Space Transport System (STS)) or where low Earth orbit permits regular replacement of expiring drugs (i.e., ISS). However, long-duration exposure of pharmaceuticals to atmospheric factors during exploration space missions will increase the risk of analytical drug failure over time, increasing the risk of therapeutic failure and potential exposure to toxicologically active impurities. Therefore, proven repackaging countermeasures are required to assure adequate stability of susceptible medications for the entire duration of exploration space missions.

This subtopic solicits proposals that address the critical need for exploring novel protective packaging technologies. Candidate technologies will retain or replicate (a) "initial" pharmaceutical packaging standards (i.e., minimization or elimination of atmospheric conditions), (b) acceptable shelf life (active pharmaceutical ingredient (API) minimums that meet or exceed Food and Drug Administration standards with respect to planned long-duration spaceflight timelines), (c) reduce reliance or need for cold storage/refrigeration of pharmaceuticals while, (d) preserving, optimizing, or reducing resource "costs" in regards to operational mass, volume, and power constraints (e.g., reducing power and mass requirements for an "in-vehicle" cold storage system), and (e) provide the potential for development of cross-cutting storage/repackaging technologies that integrate across, streamline, or expand the capabilities of multiple vehicle human support systems.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 06 Human Health, Life Support, and Habitation Systems

**Level 2**

TX 06.3 Human Health and Performance

**Desired Deliverables of Phase I and Phase II**
Prototype
Hardware
Software

Desired Deliverables Description

Drug packaging that minimizes mass, volume, and material waste and protects contents from ingress of atmospheric factors, including moisture, oxygen, and carbon dioxide.

Drug packaging technologies that help preserve API integrity and efficacy across exploration spaceflight mission durations with minimal (or reduced) mass/volume/power resource cost(s).

Phase I Deliverable – Candidate packaging solutions.

Phase II Deliverable – Experimentally demonstrated effectiveness under long-term (2-year) and accelerated conditions.

State of the Art and Critical Gaps

The state of the art of medication/pharmaceuticals packing technologies for exploration missions is uncertain. Foil packaging is an industry standard for pharmaceutical products and ensures low moisture transmission. Aclar® films have similar low moisture transmission and can be layered with other materials to increase the barrier to gas permeation. Mylar ® films have been used as a high barrier packaging to protect foods and bulk pharmaceutical ingredients from the effects of oxygen, moisture, and light. Such materials—possibly combined with purging packaging headspace with inert gas (argon) or nitrogen—may be effective strategies to extend medication shelf life. Enclosing materials that scavenge oxygen, moisture (e.g., silica gels), and CO₂ may offer additional advantages.

Relevance / Science Traceability

This subtopic seeks technology development that benefits the Exploration Medical Capability Element (ExMC) of the NASA Human Research Program (HRP). Pharmaceutical repackaging technologies are needed to address the following assigned risks:

- Risk of ineffective or toxic medications during long-duration exploration spaceflight.
- Risk of adverse health outcomes and decrements in performance due to inflight medical conditions.

and supports the following identified HRP Gaps:

- Pharm-101: "... determine the optimal packaging/storage strategy for medications in space that balances the needs of mitigating toxicity, preserving effectiveness, and minimizing resource "costs" (mass, volume, power, etc.)."
- Pharm-401: "... perform further research to understand and characterize the active pharmaceutical ingredient and degradation profiles of medications for which we have low to moderate confidence in their safety and effectiveness for exploration missions."
- Pharm-601: "... characterize the extent to which spaceflight alters pharmacokinetics and pharmacodynamics."

References

• HRP Human Research Roadmap: Evidence Reports: https://humanresearchroadmap.nasa.gov/evidence/reports/Pharm.pdf?rnd=0.294621103114738 [81]