Top SMD Priorities for RTMD Investment (Approved March 4, 2026)

1	Entry Systems Modeling (PSD)
2	Aerocapture Technology Demonstration (PSD)
3	Quantum Pathways Institute (ESD), Quantum Sensing Component Technology (APD, BPS, ESD)
4	Survive and Operate through the Lunar Night (ESSIO, BPS, PSD, APD, ESD)
5	Radioisotope Power Systems with Dynamic Power Conversion (PSD)
6	Research-Worthy Freezer Technology for Lunar PSR Sample Conditioning/Return (ESSIO, PSD)
7	Low-TRL Moon/Mars-Relevant Detector Technology (APD, PSD, ESD)
8	Automated In-Space Laboratory Equipment for Science (BPS)
9	Autonomous Navigation Demonstration (PSD, HPD, ESD, APD, ESSIO)
10	Inter-Satellite Networking and Interconnected Science Data Acquisition Methods (ESD, HPD, APD)
11	Rapid Long-Distance Lunar Rover Traversing (ESSIO)
12	Micro-Thrusters for Precision Attitude Control (HPD, APD)
13	ESPA-Class Propulsion (PSD, HPD)
14	Scalable Solar Sails (HPD)
15	High-Performance Spacecraft Computing Single Board Computer and Peripherals (PSD, HPD, APD)
16	Technology to Build Space-Based Large Structures (PSD, APD, ESD)
17	Ultra-Stable Structures (ESD, APD, ESSIO)
18	Low-Vibration Cryogenic Cooling for Single Photon Detectors (APD)
19	Micrometeoroid-Robust Deployable Membranes and Baffles (APD, ESD)

APD – Astrophysics Division
BPS – Biological and Physical Sciences
ESD – Earth Science Division
ESSIO – Exploration Science Strategy and Integration Office
HPD – Heliophysics Division
PSD – Planetary Science Division

Descriptions of Top SMD Priorities for RTMD Investment (Summer 2026)

1. Entry Systems Modeling	
Science objective	Atmospheric entry capability is mission-enabling for numerous planetary science destinations, including current and future missions to Mars, Venus, Uranus, and Titan. Sustaining and advancing this unique NASA capability is essential to enabling future high-priority Planetary Science missions identified in the Decadal Survey.
Needed Capability	Crosscutting models and simulation tools for end-to-end entry system analysis that improve performance, reduce mission risk, and enable new system capabilities for Solar System exploration. This capability spans technical areas including Thermal Protection Materials, Aerothermodynamics, Entry and Descent Vehicle Dynamics, and Advanced Numerical Methods, and incorporates the development of benchmark datasets and flight Entry, Descent, and Landing (EDL) instrumentation. Together, these capabilities establish the foundation for design, optimization, and risk assessment of future entry systems.
Gap	Entry Systems Modeling (ESM) directly addresses several mission-critical shortfalls in the ability to land science payloads on planetary surfaces, including the need to develop and validate performance models for entry systems and to advance low-cost, high-performance entry system technologies. There is a need for sustained improvements in fidelity, validation, and integration across EDL modeling, materials, aerothermodynamics, and vehicle-dynamics capability areas to support both near-term and long-term planetary science missions.
Technical details	Coordination and integration across multi-physics disciplines combined with targeted validation activities lead to improved model fidelity. These improvements will directly enhance predictive accuracy, reduce design margins, and provide mission-enabling insight for upcoming planetary missions.

2. Aerocapture Technology Demonstration	
Science objective	The Decadal Survey identifies the Uranus Orbiter and Probe (UOP) as the highest-priority flagship mission for 2023–2032. Aerocapture enables feasible mission design by reducing fuel, shortening transit times, and providing resiliency against launch-year slips beyond 2035. UOP will deliver an in situ atmospheric probe and conduct a multi-year orbital tour that will transform our knowledge of ice giants in general and the Uranian system in particular. Uranus is one of the most intriguing bodies in the solar system. Its low internal energy, active atmospheric dynamics, and complex magnetic field all present major puzzles. A primordial giant impact may have produced the planet's extreme axial tilt and possibly its rings and satellites, although this is uncertain. Uranus's large ice-rock moons displayed surprising evidence of geological activity in limited Voyager 2 flyby data and are potential ocean worlds. UOP science objectives address Uranus' (1) origin, interior, and atmosphere; (2) magnetosphere; and (3) satellites and rings. UOP will provide ground truth relevant to the most abundant, similarly sized class of exoplanets. Aerocapture enables UOP flagship class missions which may not launch until the mid-2030's due to budgetary and developmental challenges but can still reach the planet by the late 2040's during the scientifically important equinox.
Needed Capability	It is notoriously difficult to maintain the front-loaded funding profiles needed to develop flagship missions quickly. Given trajectory realities, if the launch date of the proposed Uranus Orbiter and Probe mission slips beyond 2035, it will be hard-to-impossible to reach the target using conventional propulsion methods. Aerocapture allows a substantial reduction in fuel, shorter transit time, and resiliency to launch date, and can do this in the packaging of proven, heritage-laden Mars missions, such as Mars Science Laboratory and Mars 2020. Although the emphasis for PSD is on the use of aerocapture for outer planets, this technology can also enable lower cost missions to Mars and Venus, especially the Mars Telecommunication Network in low Mars orbit, which gives a technology demonstration even more value. A flight-validated aerocapture system, lift-modulated or drag-modulated, that demonstrates guidance, navigation, and control (GN&C), model correlation, and system-level performance on Earth is needed. Demonstration does not need to replicate outer-planet heating environments and does not need to replicate the specific outer-planet change in velocity (ΔV) for orbit insertion.
Gap	A risk-reducing flight demonstration is needed to enable aerocapture for UOP and other flagships. Modeling fidelity, dynamics validation, and

<table>
<tr><td></td><td>system-integration behaviors (e.g., control algorithms, mechanisms, jettison dynamics) must be demonstrated.</td></tr>
<tr><td>Technical details</td><td>An Earth-based demonstration of the GN&C system of either drag-modulated or lift-modulated aerocapture would be beneficial. SMD has no expectation that the heating loads of outer planet atmospheres need to be demonstrated.

Recommendations from the Aerocapture Demonstration Relevance Assessment Team (ADRAT) team include:
Improve the integrated system TRL for aerocapture methods of Lift Modulation Direct Force Modulation or Drag Modulation
Provide data for model correlation, thereby improving model fidelity and providing more confidence in the extrapolations and scaling needed for an outer planet aerocapture
TRL advancement and model correlations would provide substantial benefit to destinations with a well-understood atmosphere and approach velocities similar to the demonstration velocity (e.g., Mars, Venus).
Demonstrate many elements of an integrated system, for instance drag tab control algorithms and mechanisms, heating rate modeling, center-of-gravity (cg) change control algorithms and mechanisms, skirt stow/deploy, jettison, packaging, mechanisms, and jettison timing control algorithms (i.e., Numerical Predictor Corrector algorithms)
For drag modulation, a demonstration could validate dynamics modeling of the separation event.
Data for CFD and TPS model correlation would improve scaling approaches and improve confidence in extrapolation to uncertain environments.
Scaling from a SmallSat to the larger interplanetary spacecraft is an important consideration. Limited studies have been done through scaled ground testing in air, but a flight demonstration would provide improved data.
Address concerns about laminar-to-turbulent flow regimes. Onboard instrumentation techniques (e.g., thermocouples and heating rates) can determine the transitions between laminar and turbulent flow regimes.
Please refer to https://smd-cms.nasa.gov/wp-content/uploads/2023/07/adrat-final-report.pdf for more details.</td></tr>
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3. Quantum Pathways Institute and Quantum Sensing Component Technology	
Science objective	In astrophysics, improving sensitivity, angular resolution, single-photon counting, and timing enables the observation of exceedingly faint, distant, and previously unresolved sources. Quantum sensing technologies offer measurement capabilities that surpass classical detectors. Furthermore, future advances in quantum information science and computing could unlock entirely new observational methodologies, allowing researchers to extract significantly more insight from every detected photon or particle. Examples include quantum computational sensing for significantly reduced noise and spatial resolutions that surpass the Rayleigh criterion, and entangled networks of telescopes for space-based very long baseline interferometry. Quantum sensing, quantum networking, and quantum computing have the potential to revolutionize space-based Earth science. Most notably, these technologies can significantly enhance the spatial and temporal resolution of remote sensing measurements, which is critical for understanding Earth's climate variability. By integrating quantum detectors into novel remote sensing platforms, SMD can leverage advanced quantum sensing components to meet its evolving Earth observation objectives. This integration promises unprecedented precision in established fields such as tracking groundwater and aquifers through advanced geodesy while driving new mission concepts capable of spatio-temporal super-resolution and dynamic broadband sensing. Similarly, these technologies can significantly enhance the sensitivity and resolution of in-situ measurements, which is critical for understanding fundamental physical phenomena and biological adaptations in space environments. The integration of quantum instruments into orbital laboratories and deep-space platforms promises unprecedented precision in established fields—such as cold atom physics and microgravity materials science—while driving new mission concepts capable of mapping nanoscale biological processes and testing the fundamental laws of physics. Quantum-entangled networks of ultra-high precision clocks could provide insights into the nature of dark matter. STMD funded the Quantum Pathways Institute to address some of these needs for Earth Science. SMD requests that this support continues and is extended to a follow-on quantum research institute consistent with the expected reauthorization of the National Quantum Initiative.
Needed Capability	• Innovative quantum sensing technologies to dramatically improve astrophysical measurements using the quantum properties of light such as entanglement. Specific areas of interest include quantum

	sensors leveraging local quantum computing for super-resolution imaging, and multi-spacecraft architectures linked through entangled quantum networks. • Efficient, noiseless, ultrasensitive photon detectors capable of measuring the energy of photons can drastically increase the scientific capability of NASA's future observatories. Developing such detectors across the full X-ray, UV/O/IR, mid-IR, far-IR, and submillimeter domains, with some or ultimately all of the following properties desired: high quantum efficiency, near-zero dark noise/dark count rate, near-zero read noise, scalability to large-format arrays, wide spectral coverage, energy resolving, ultra-stable in time, high count rate/saturation, and immunity to space radiation. Superconducting detectors such as KIDs, TES, QCDs, and SNSPDs are examples. Similarly, multiplexed readout of these large format, low noise detectors requires low noise readout electronics, potentially superconducting, with ideally negligible added noise. • For the Habitable Worlds Observatory (HWO) and Other Observatories: Photon counting/energy resolving detectors in the near infrared and visible spectral range. • Achieve substantial performance improvements over the current state of the art for measurements prioritized by the Earth Science Decadal Survey, especially those driving climate science research. • Components for networks of atom interferometers and ultra-precise atomic clocks are needed to enable high-sensitivity searches for dark matter signatures.
Gap	• Space-rated Quantum 2.0 sensors and in-space quantum networks • While early pathfinders (such as the Cold Atom Lab) have demonstrated the potential of quantum physics in space, a critical gap remains in ruggedizing and miniaturizing complex, lab-based quantum sensors. We currently lack low-SWaP (Size, Weight, and Power), flight-qualified quantum instruments capable of sustained operation in microgravity and high-radiation environments. • Quantum sensing components must be able to be robustly and reliably deployed in Earth orbit and in deep space to significantly improve the precision and resolution of critical science measurements.
Technical details	Most quantum sensors operate at cryogenic temperatures, and so there is an imputed reliance on cryocooling technologies.

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<tr><th colspan="2">4. Survive and Operate through the Lunar Night</th></tr>
<tr><td>Science objective</td><td>The Planetary Science Decadal describes top level lunar science goals. They fall into two classes: those requiring a few lunar days of operations, and those that require years.
• Shorter duration missions include studying dust transport and plasma environment changes throughout the day/night cycles.
• Longer duration missions include the Lunar Geophysical Network (LGN) to continuously monitor the Moon's interior and geophysical properties over several years and the Endurance-A Mission Concept Study Report lists representative measurements and instruments needed for lunar science. Endurance: Lunar South Pole–Aitken Basin Traverse and Sample Return Rover (nasa.gov)

To fulfill its scientific mandates, BPS requires experimental durations that extend beyond a single lunar daytime cycle, necessitating critical lunar night survival capabilities.

The far side of the moon is shielded from RF emissions from Earth. Astrophysics telescopes built or deployed there offer an opportunity to study the dark ages of the universe in the RF spectrum.

Earth-pointing telescopes can provide full-disk coverage of the Earth to observe global phenomena, complementing higher resolution, narrower field-of-view observations from orbiting spacecraft.</td></tr>
<tr><td>Needed Capability</td><td>Survive-the-night capability is needed to ensure multiple, subsequent daytime science data collection at multiple points on the lunar surface spanning the globe.

Operating during the lunar night is the goal, with the following three classes of interest. We expect that a combination of power, thermal, electronics, and materials technologies will be needed.

Small: 50 – 100 W for 1 to 4 lunar day/night cycles to power small instruments on the lunar surface at globally distributed sites. The Lunar Geophysical Network needs this level of power for 8 years at at least 4 sites.

Medium: 100 – 500 W at multiple, distributed locations for months of day/night cycles would also be valuable to operate more science instruments simultaneously, with actuated sample handling. This will also</td></tr>
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	serve CLPS-sized structures for automated biology and physical science experiments. Large: nominally 1 kW for continuous 10 year operations of telescopes, including a far-side RF telescope and a near-side Earth observing telescope. Note that MMRTG (Multi-Mission Radioisotope Thermoelectric Generator) solutions are already available; technology is needed to either increase the efficiency of those supplies, use alternate isotopes, or provide non-nuclear approaches. Power systems based on non-plutonium radioisotopes are being developed by the commercial sector. Investments are needed to help this sector develop products suitable for use on the lunar surface.
Gap	A critical technology gap exists in the ability to survive and operate continuously during the extreme cold of the lunar night without incurring prohibitive mass penalties. While early point-solutions are being developed for specific payloads (e.g., FSS, LEMS, and LUSEE-Night), there is a lack of mature, scalable, and commercially viable technologies across power generation, thermal management, and cold-operable mechanisms to support a broad suite of future, long-duration lunar science instruments. The goal is to have commercial solutions to enable a broad suite of science instruments.
Technical details	SMD wants components and subsystems that can enable lunar night operations (power, thermal management, cold-operable components, etc.) so they can be pieced together to provide application-specific solutions. Solutions should be component-level technologies that commercial providers can integrate into PRISM and CLPS architectures (power, thermal management, cold operable components, etc.). • Planetary science instruments can be housed on a lander, a rover, or on an individually deployed payload. • BPSD payloads require sufficient power, communications, data collection/storage, and thermal management to maintain science operations of biological and physical science payloads through the lunar night. Payloads will be externally mounted to CLPS landers. Technologies are needed to support continuous operations landing site agnostic.

5. Radioisotope Power Systems with Dynamic Power Conversion	
Science objective	SMD wants an integrated approach to all nuclear space-power technologies needed, including Nuclear Thermal Propulsion (NTP), Nuclear Electric Propulsion (NEP), fission surface power, and radioisotope power systems (RPS). Note that there are substantial synergies between power conversion, thermal and control systems needed for both fission surface power and RPS systems. A key objective is enabling efficient, commercial high-efficiency power-conversion systems that reduce reliance on Pu-238 and broaden isotope options. The use of alternate isotopes will decrease demand for Pu-238 needed for outer planet missions. The development of efficient power conversion technologies benefits the usage of all isotopes and can stretch the Pu-238 supply across more science missions with applicability to future long-duration future lunar and Mars rovers powered by Stirling-based RPS. These will be required to traverse long distances over uneven, highly variable terrain, subjecting all onboard systems to continuous shock, vibration, and structural loading. While Stirling converters offer higher efficiency and reduced isotope mass compared with thermoelectric systems, their moving components introduce unique mechanical sensitivities that have not yet been evaluated for rough-terrain rover environments. To ensure reliability over multi-year missions, NASA must develop a deeper understanding of how Stirling RPS units respond to vibration, cyclic fatigue, and integration loads within a mobile rover architecture. Addressing these unknowns is critical before Stirling-based systems can be confidently infused into planetary surface missions.
Needed Capability	The most needed technology development efforts are: • Testing requirements and demonstration campaigns across multiple isotopes • High-efficiency dynamic power-conversion demonstrations applicable to lunar night survival and surface missions • Complete initial testing of vibration survivability, fatigue, and mechanical integration for Stirling RPS on a rover traversing rough lunar or Mars terrain • Community-building mechanisms (e.g., LSIC engagement, potential JETSON-like cross-agency partnerships)
Gap	The use of alternate isotopes (e.g. Am-241) will decrease demand for Pu-238 needed for outer planet missions. The development of efficient power conversion technologies benefits the usage of all isotopes and can stretch the Pu-238 supply across more science missions.

Technical details	Dynamic radioisotope power systems require maturation across thermal, mechanical, and electrical domains to support future lunar, Mars, and deep-space missions. Key needs include establishing standardized test requirements for multiple isotopes, validating long-duration converter performance, and ensuring stable operation across extreme thermal environments. Mechanical robustness must also be assessed, including vibration survivability, cyclic fatigue, and structural integration for mobile platforms such as lunar or Mars rovers. Thermal-mechanical interfaces—particularly radiator performance, waste-heat utilization, and stable converter operating temperatures—must be validated under realistic environmental conditions. Coordinated development across NASA, DOE, and commercial partners is essential to ensure manufacturable, modular systems that can integrate with evolving commercial lander and rover architectures.

6. Research-Worthy Freezer Technology for Lunar PSR Sample Conditioning/Return	
Science objective	The return of pristine, volatile-rich samples from lunar permanently shadowed regions (PSRs) to study, among other things, the early solar system's impact history, solar wind activity, and water delivery. Cryogenic sample return from other deep space bodies such as comets is also of interest to study solar system formation.
Needed Capability	Maintaining the integrity of volatile samples from PSRs is critical throughout the steps needed to return them to Earth, including robotic sample insertion, autonomous location and tracking, continuous storage monitoring, and extreme low-SWaP constraints over multi-year transits. Each of these functions are needed as described by the end-to-end sampling concepts of operations being developed by SMD's sampling and curation task (SAC26). The emphasis of this request is for sample storage in a container that can be returned on either crewed or uncrewed lunar return missions. Sample return technology for comets and other deep space locations is secondary to the need for lunar sample return and will utilize these developments as applicable.
Gap	Cryogenic containment and temperature maintenance systems for volatile-rich samples from lunar PSRs.
Technical details	Cryogenic freezer below -85C (with a further performance increase to -150C) that is vacuum environment compatible for a minimum of 0.5kg sample size plus appropriate containment system mass.

7. Low-TRL Moon/Mars-Relevant Detector Technology	
Science objective	A broad range of sensors and instruments are needed to understand planetary surfaces, interiors, atmospheres, and environments and to study the Earth and universe from the lunar surface. These include but are not limited to microscopic stereo imagers, seismometers, hyperspectral imagers, radiometers, dosimeters, Gamma-ray and X-ray detectors, energetic particle analyzers, particle detectors, and spectrometers spanning UV to far IR.
Needed Capability	Advancements in detector technology (detector arrays, read-out systems, power supplies, materials, etc.) are needed to enable low-SWaP instruments with: • A range of photon detection spanning from low-energy radar (GHz, ~10^{-7} eV) to high-energy measurements (10^4 eV) critical for elemental composition analysis, with single-photon sensitivity from the UV through microwave and high-contrast imaging from UV to NIR. • For large-format arrays, advancements are needed in the coupling between detection materials and pixel readout circuitry. • Across all instrument classes, development must drive toward improved energy resolution, minimal dead time, enhanced solar-blind UV detection, and reduced jitter. • Radiation tolerance for harsh planetary environments • Decreased performance gap between uncooled and cooled systems by drastically reducing dark current.
Gap	Ultra-low noise and high-sensitivity detectors. High quantum efficiency detectors to reduce power consumption. 50 kV power supplies to miniaturize detectors.
Technical details	Detector performance metrics for Astrophysics can be found at: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html.

8. Automated In-Space Laboratory Equipment for Science	
Science objective	• Increase throughput of science and ability to monitor environment and sample health during physical and biological experiments • Enable biology science payload deployment in deep space, lunar, and/or Martian environments to understand how these environments affect human performance
Needed Capability	• Automated capabilities to perform physical and biological science experiments in LEO and on the surfaces of the Moon and Mars with minimal crew time. • The absence of automated capabilities severely limits NASA's ability to understand how deep space exploration affects human performance. Automated lab capabilities are needed for biological and physical science experiments to fully leverage CLPS and other uncrewed deep space missions. Specific capability needs should focus on maintaining optimum lab environment (including external environmental detectors and sensors), media exchange, analysis techniques (such as microscopy, omics, etc.) and data capture, storage and transmission.
Gap	• Most biological experiments involve some level of crew interaction during sample preparation, experiment initiation, sample collection, and sometimes preservation. • While some hardware allows remote operations from Earth, true automated end-to-end experiment operations are limited to specific hardware. The gap is additional hardware for fully automated science operations on the lunar surface, Mars, and on commercial LEO platforms.
Technical details	Integration of sensors and control technology to enable automated lab capabilities. Development in fluid, pH, temperature, atmospheric pressure, and gas composition sensors will enable automated lab capabilities needed when conducting science in deep space, LEO, and on the lunar surface.

9. Autonomous Navigation Demonstration – (for cruise phase of missions)	
Science objective	"Autonomous onboard navigation" is broadly defined as the ability for a spacecraft to determine its orbit and plan a path to achieve navigation goals while operating independently of external control and without the use of external informational aids, potentially even during anomalous conditions. Autonomous navigation offers significant promise to make immediate impacts in mission operations across SMD. Within SMD, the primary beneficiaries would be the Planetary Science Division and the Exploration Science Strategy Integration Office. Missions by the Astrophysics, Heliophysics, and Earth Science Divisions that fly outside of GPS range would also benefit. No spacecraft to date has demonstrated autonomous navigation across multiple mission phases. A demonstration mission offers opportunity to reduce risk and help enable broader adoption. Autonomy can reduce operations costs by minimizing the need for deep space network contacts for orbit determination, command uplinks, and data handling & prioritization.
Needed Capability	SMD missions already autonomously land, rendezvous, and target deep space destinations by imaging the target and using terrain relative navigation. What is needed is the ability to autonomously execute the cruise phase of deep space missions when the target is not in sight and to demonstrate autonomous navigation across mission phases. Capabilities specifically needed include: • Self-directed operations, including internal decision-making in response to unforeseen circumstances • Autonomous orbit determination, navigation, and spacecraft health assessment • Highly efficient onboard data triage, compression, and storage for infrequent downlink opportunities
Gap	• Lack of a risk-reducing, flight-proven demonstration that validates autonomous navigation operations • Insufficient demonstration of self-directed onboard decision systems, especially for missions with weeks-to-months communication latency or complete blackout
Technical details	Refer to the SMD Autonomous Navigation Demonstration Relevance Assessment report for details about what is needed from a technology demonstration to reduce risks for SMD missions.

10. Inter-Satellite Networking and Interconnected Science Data Acquisition Methods	
Science objective	Across SMD, science is increasingly being conducted with fleets of spacecraft to acquire data from different vantage points and at different times. The ability to operate these spacecraft as a coordinated fleet will enable responsive science, where one spacecraft can react to what another has seen. In Astrophysics, this enables time-domain and multi-messenger (TDAMM) astronomy by coordinating observations of neutrinos, photons, and gravitational waves to study the universe through time-variable phenomena such as supernovae, fast radio bursts, and gamma-ray bursts. Dynamically observed environmental conditions and transient phenomena allow for a better understanding of the interconnected Earth system, including monitoring mass change; quantifying changes to lakes, sea level, and underground water storage; and tracking ice sheets and glaciers. Coordinated space-based and sub-orbital Heliophysics measurements help to understand the Sun's influence on the Earth and the broader solar system. These observations are critical for monitoring the dynamic space weather environment, tracking solar wind interactions with Earth's magnetosphere, assessing ionospheric variability, and understanding how solar-terrestrial interactions drive changes in Earth's upper atmosphere and impact critical technological infrastructure.
Needed Capability	• Coordinated measurements across multiple spacecraft to observe transient phenomena in real time or near-real time (e.g., solar flares, coronal mass ejections, magnetic reconnection, supernovae, gamma-ray bursts, methane plumes, wildfires) to enable continuous monitoring with high spatial and temporal resolution • Autonomous detection of sporadic or episodic events and dynamic cueing of onboard sensors (or tip-and-cue secondary spacecraft) optimize burst-mode data collection as the event evolves. On-board data acquisition and processing techniques to merge multi-instrument data streams into real-time or near-real-time actionable information
Gap	• Autonomous communication between multiple space-based spacecraft and between spacecraft and ground-based observatories • Autonomous spacecraft pointing control

	• Low-SWaP autonomous on-board data processing (for instruments and spacecraft) • Data scrubbing within the observation context to tip and cue other spacecraft via inter-satellite communication • Reliable, trusted artificial intelligence/machine learning (AI/ML) methods, tailored to specific mission contexts and automated event detection • Insufficient low-SWaP, automated onboard computing to process high-cadence data in real time • Lack of onboard data triage capabilities to intelligently cue secondary spacecraft via inter-satellite links during transient events • Maximized downlink capacity; specifically, bridging the gap between high-bandwidth optical communications and the current lack of compatible optical ground stations
Technical details	TDAMM astronomy often requires fast (within seconds or minutes, sometimes hours) response from other observatories to allow them to make follow-up observations of prompt emission from a target.

11. Rapid Long-Distance Lunar Rover Traversing	
Science objective	To support the ambitious Moon Base objectives, ESSIO emphasizes the critical need for rapid long-distance lunar rover traversing. Fulfilling these science objectives requires advanced technologies that enable autonomous, long-distance lunar traverses at nominal speeds of 1 km/hr. This priority directly aligns with recommendations from SMD's Planetary Exploration Science Technology Office, which calls for integrated surface navigation systems capable of continuous day and night driving. Specifically, future lunar rovers require robust local hazard detection, dynamic path planning, and precise global localization to navigate complex, crater-ridden, and high-rock-density terrain. These capabilities are essential for enabling flagship-class concepts such as the proposed Endurance-A mission, which requires a rover to autonomously traverse approximately 2,000 km across the lunar surface over a few years, representing a 100-fold increase in distance compared with prior planetary rovers.
Needed Capability	Development of integrated surface navigation architectures that enable rapid (nominal 1 km/hr), autonomous, long-range lunar traversing. This requires advanced local hazard detection, dynamic path planning, and precise global localization capable of functioning in both illuminated and unilluminated (lunar night/shadowed) environments to navigate complex, crater-ridden, and rocky terrain.
Gap	• Current planetary rovers rely heavily on slow, ground-in-the-loop commanding and lack the onboard autonomy required for rapid, continuous traversing. A critical technology gap exists in flight-proven, integrated surface navigation systems capable of executing long-range (e.g., 2,000 km) autonomous drives across hazardous lunar terrain without continuous human oversight. • Rad-hard high-performance computing, power, and autonomous surface navigation to achieve long distance traversing
Technical details	Please refer to the https://science.nasa.gov/wp-content/uploads/2023/11/endurance-spa-traverse-and-sample-return.pdf for more details. Reference: "Endurance – Lunar South Pole Aitken Bain Traverse and Sample Return Rover," J.T. Keane, S.M. Tikoo, J. Elliott concept study submitted to the 2022 Planetary Science Decadal Survey.

12. Micro-Thrusters for Precision Attitude Control

Science objective	Future astrophysics observatories such as the Habitable Worlds Observatory (HWO) will require extreme stability to point at faint, distant objects such as exoplanets. These observatories are expected to be large to accommodate large collection optics and complex instrument suites, and will require extreme pointing stability and fine positioning control. Micro-thrusters (µN to mN thrust range) are essential to enable continuous momentum management while enabling milli-arcsecond-level pointing stability. To measure magnetic fields, charged particles, and other elements of the solar wind, heliophysics missions often use spinning spacecraft to scan point measurement sensors across a wider field of view and average out directional sensor errors. HPD is increasingly reliant on constellations of small, lower cost spacecraft. Spin-stabilization can reduce mass, complexity and cost of small satellites, and solar sails are another lower cost platform. Micro-thrusters provide atmospheric drag makeup, solar pressure compensation, and fine control for spinning spacecraft, spacecraft constellations, and solar sails.
Needed Capability	Risk reduction for micro-propulsion systems funded by HWO, targeting 5 – 10 mN thrust capacity with ultra-low mechanical disturbance and low optical contamination with reliable operation for years. High specific impulse (>1000s) to meet low mass requirements. Micro-thrusters for heliophysics enable highly precise orbital maneuvers, formation flying, and solar sails with reliable operation for 10 years. Requires validated models of operation and demonstrated long-duration operations in ground test facilities
Gap	Achieving ~5 mN of thrust with ultra-low mechanical disturbance presents a significant scale-up challenge for current electrospray technology. Furthermore, a critical gap exists in demonstrating the extended thruster lifetime and high total impulse (>0.5 MN-s) required to reliably support 10 years of continuous mission operations.
Technical details	n/a

13. ESPA-Class Propulsion	
Science objective	SMD's Earth Science, Heliophysics, and Astrophysics Divisions have achieved high quality science results using small spacecraft in Earth orbit, generating needed science measurements for a fraction of the cost of larger missions. To realize this cost benefit, the Planetary Science Division requires small spacecraft that can reach destinations beyond cislunar space. The type of science that would be enabled by small spacecraft at planetary bodies include simultaneous, multipoint measurements of phenomena across magnetospheric boundaries to understand energy transport, and simultaneous measurements on opposite sides of a planet to study global weather. HPD requires advanced propulsion solutions capable of inserting and sustaining spacecraft in Very Low Earth Orbit (VLEO) for extended durations (weeks to months). Unlike highly elliptical orbits that only briefly transit below 400 km at perigee, these propulsion systems must enable a continuous, sustained presence in VLEO. This continuous access is critical for conducting prolonged in-situ and remote sensing observations to advance upper-atmospheric and ionospheric science.
Needed Capability	• Reliable transportation for small spacecraft to destinations beyond cislunar space. Electric propulsion systems are enabling because their high efficiency reduces propellant volume. ESPA-class spacecraft are preferred over CubeSats because there is no need to constrain the volume for rides that are easily available on ESPA ring adapters, and it is more difficult to design a capable science mission using an unnecessarily small spacecraft format. • Propulsion systems that enable VLEO operations.
Gap	High delta-V electric propulsion systems for ESPA-class spacecraft
Technical details	• Nominally 7 km/s reliable operation, less than nominally 1 kW input power • Supporting the commercialization of such a system is required to keep the costs of these missions low

14. Scalable Solar Sails	
Science objective	Solar sails have tremendous potential for Heliophysics missions but are not yet feasible because of a low level of technical readiness. Future progress in solar and space physics hinges on (among other things) access to unique locations in space. Heliophysics can benefit from observations of the Sun, Earth, and heliosphere from orbits requiring continuous propulsive activity to maintain or reach in a timely fashion. Vantage points above Earth's poles, at sub-L1 locations, and at high ecliptic latitudes have unique properties that enable important observations. Heliophysics mission concepts (that would use a solar sail) include a solar polar imager, a stationary Earth polar observatory, upstream solar wind monitoring at a sub-L1 location, an L5 mission, Solar Sentinels, and Interstellar Probe. The current Decadal Survey strongly urges that [a solar sail demonstration mission] be pursued to demonstrate a 25 g m–2, ~40-m solar sail (40x40 = 1600 sqm) to achieve Ac = 0.12 mm/s2 and 13mN thrust.
Needed Capability	Low-cost transportation to deliver magnetometers, imagers, and other field instruments to locations including a solar polar orbit, S-E L5, S-E L1, and interstellar space
Gap	Flight data to reduce risks for composite solar sail booms so they can be proposed to future Heliophysics science mission solicitations.
Technical details	n/a

15. High-Performance Spacecraft Computing Single Board Computer and Peripherals

Science objective	NASA's science missions rely on the RAD-750 microprocessor, which is flight-qualified for deep space radiation environments. This computational power is insufficient for the types of onboard autonomy and interconnected science operations described elsewhere in this document (see items #9 Autonomous Navigation Demonstration and #10 Inter-Satellite Networking and Interconnected Science Data Acquisition Methods)
Needed Capability	A high-performance radiation-hardened computer is needed to enable advances in onboard autonomy for both spacecraft control and data processing. AI/ML for science autonomy can help in: • Real-time hazard avoidance and GN&C • High-rate instrument data reduction • Flexible power-scaling and low-power modes
Gap	• Legacy radiation-hardened processors cannot meet future autonomy needs. • Current baseline (e.g., RAD-750) is decades old and lacks the computational performance required for emerging onboard autonomy, science data processing, and next-generation mission profiles. • Lack of a flight-proven, high-performance radiation-hardened computing system • HPSC exists as a developing architecture, but the technology remains at lower TRL and has not yet demonstrated long-duration reliability, resilience, and safety in operational space environments. • Need for computing capable of running modern autonomy, AI/ML, and real-time science algorithms on board • Insufficient energy-flexible computing architectures • Future missions require processors that can dynamically scale power usage, shut down unused computation blocks, and support multi-phase mission profiles with changing energy envelopes. Enterprise documents show that existing processors cannot support: • Onboard ML for science autonomy • Rapid instrument data reduction • Complex navigation or hazard-avoidance algorithms

	All of these are highlighted as necessary in PSD and MINDSET deliverables.
Technical details	• A multi-core radiation-hardened flight processor featuring dual quad-core ARM A53 clusters (15–100 GOPS), real-time A53/R52 subsystem, and M4 supervisory core • Includes 4 MB L3 cache and high-rate interfaces (6×SRIO at 40 Gb/s, TTE, PCIe, SpaceWire) • Architecture supports scalable power (<10W), long-duration reliability, and fault-tolerant lock-step execution • Radiation-tolerant high-performance GPUs and FPGAs for data intensive tasks • Provides robust support for onboard autonomy, AI/ML and high-throughput scientific data processing; supported by a full QEMU emulator

16. Technology to Build Space-Based Large Structures	
Science objective	The Moon offers a unique vantage point for studying the Earth, offering continuous views of the full Earth disk. This enables a global perspective on 3D cloud and storm structures, ocean dynamics and coastal monitoring, and global views of aerosols, trace gases, vegetation, the cryosphere, and disasters to complement data from Earth-orbiting remote-sensing satellites. A telescope mounted on the lunar surface could provide that view. The far side of the moon is shielded from RF emissions from Earth. Telescopes built there offer an opportunity to study the dark ages of the universe in the RF spectrum. Deep drilling rigs for Mars per the NASEM study, enabling access to subsurface geological records that constrain the planet's thermal, chemical, and hydrological evolution. Large space-based structures, including deployable towers, booms, and surface-assembled platforms, are required to support future deep drilling systems and associated science payloads. These structures would provide stable mounting, vibration isolation, and load-bearing capability necessary for penetrating deep into the Martian crust, while also supporting ancillary science instruments (e.g., seismology, subsurface sounding, geophysical packages). Advancing this capability enables investigation of subsurface habitability potential, long-term geologic processes, volatile distribution, and possible biosignature preservation environments. The supporting infrastructure is also aligned with Decadal priorities calling for increased access to deep planetary sub-surfaces for high-value science return.
Needed Capability	• Structures to support Earth-observing RF telescopes on the lunar surface and deep surface drills on Mars. • A scalable, autonomous in-space assembly capability that enables construction, deployment, and maintenance of large structures (10s–100s of meters), using lightweight modular components, robotics, and precision metrology suitable for deep-space environments
Gap	An integrated system for autonomous assembly of large structures in microgravity and partial-gravity environments. Current robotics, material joining, structural metrology, and in-situ inspection technologies are insufficient for maintaining alignment, load-bearing performance, or structural stability during construction of large observatory elements, towers, booms, or platforms.

	Key gaps include: • Materials and joining processes suitable for large-scale assembly in vacuum and extreme temperature ranges • Robotic manipulation systems capable of precise, high-fidelity assembly at meter to decameter scale • Metrology systems that maintain alignment and shape stability during construction • Autonomous planning and verification algorithms for structure growth and health monitoring
Technical details	For details about a Mars drilling rig, refer to https://www.nationalacademies.org/projects/DEPS-SSB-23-02. A sampling of lunar telescope studies: • Daniel F. Lester (2004). “Lunar-based astronomy: A review of the issues” Space Policy, Vol. 20, Issue 3, pp. 161–166 https://doi.org/10.1016/j.spacepol.2004.06.001 • Burns, J. O., Duric, N., Taylor, G. J., & Johnson, S. (1990), “LOUISA – A Lunar Optical-Ultraviolet-Infrared Synthesis Array”. Presented at Space 90: The Second International Conference. NASA Technical Reports Server (NTRS) • Burns, J. O., et al. (2026), The FarView Low Frequency Radio Array on the Moon’s Far Side: Science and Array Architecture, arXiv:2601.16170. • Guo, H., Wang, L., Liang, D., & Liu, Z. (2018), Earth observation from the Moon: theoretical basis and potential applications, International Journal of Digital Earth, 11(2), 165–179. DOI: 10.1080/17538947.2017.1356879 • Yang, J., et al. (2019), Observing the Earth from the Moon: Science and applications, Remote Sensing, 11(6), 708. DOI: 10.3390/rs11060708 • National Aeronautics and Space Administration (NASA) (2015), Deep Space Climate Observatory (DSCOVR): Earth observation from L1 perspective (relevant precursor for full-disk Earth observations from deep space).

17. Ultra-Stable Structures

Science objective	This capability is a critical enabler for SMD flagship objectives: • The Habitable Worlds Observatory (HWO) requires ultrastability to directly image and characterize faint, Earth-like exoplanets using high-contrast coronagraphy. Quantum Gravity Gradiometry (QGG) requires ultrastability to map subsurface density variations (e.g., underground water, mineral deposits, and geological structures) by measuring the spatial derivative of the gravitational field, rather than just its absolute strength.
Needed Capability	A comprehensive structural and active-control architecture capable of maintaining alignment and positioning to within tens of picometers. Specifically, this requires: • Picometer-level thermo-mechanical stability (10s of picometers) • Active wave-front control and continuous alignment sensing • Vibration isolation to decouple sensitive payloads from spacecraft bus disturbances • The ability to maintain high-precision relative positioning between distributed payloads (such as paired atom interferometers)
Gap	The lack of flight-proven structural, thermal, and isolation architectures capable of bridging the gap between current nanometer-level stability (JWST) to the picometer-level stability required for next-generation astrophysics and Earth science missions.
Technical details	This requires advanced, zero-CTE structural materials and active vibration decoupling. Whether maintaining the perfect alignment of optical mirrors to suppress starlight (10^{10} contrast for HWO) or holding two atom interferometers perfectly still relative to each other (for QGG), the underlying spacecraft structure must be completely isolated from thermal distortion and mechanical jitter.

18. Low-Vibration Cryogenic Cooling for Single Photon Detectors	
Science objective	Enable the observation of extremely faint cosmic sources by supporting superconducting, single-photon, and energy-resolving detectors for future flagship and Probe-class observatories (HWO, Far-IR, and X-ray missions).
Needed Capability	Continuous, space-rated cryocoolers capable of cooling large-format focal plane arrays to sub-Kelvin temperatures (50mK–4K) while transmitting near-zero mechanical vibration to the detectors and telescope structure
Gap	The lack of low-SWaP, flight-proven sub-Kelvin refrigeration systems that operate without generating the cold-end mechanical jitter that can adversely impact the detectors and the ultra-stable, high-contrast optical imaging.
Technical details	Detectors like SNSPDs, TES bolometers, and KIDs require extreme cryogenic temperatures to eliminate detector noise. Such sensitive focal plane arrays are susceptible to vibrations from the coolers themselves. Further, HWO requires picometer-level stability, so the mechanical pumps and compressors typical of standard cryocoolers cannot be used without massive improvements in vibration isolation or the development of zero-vibration cooling methods.

19. Micrometeoroid-Robust Deployable Membranes and Baffles	
Science objective	This capability is a critical enabler for SMD flagship objectives requiring massive, deployable apertures: • Great telescopes such as Habitable Worlds Observatory (HWO) will operate in orbit at Sun-Earth L2 for thermal stability, propulsion efficiency, and communications accessibility. Prior telescopes—including Cassegrain designs such as Kepler and glancing-incidence X-ray instruments—integrated protective baffles directly into the telescope structure, but these components were heavy. • Next-generation Earth-observing satellites require massive, lightweight radar antennas and radiometers that remain structurally resilient to Low Earth Orbit (LEO) space debris to ensure uninterrupted, high-resolution mapping (e.g., soil moisture, sea surface topography).
Needed Capability	Large-scale, deployable protective membranes and segmented structures capable of surviving high-velocity impacts. They must provide light-tight thermal shielding for 6-10m optical telescopes and maintain strict surface tension for 10-15m long-wavelength radar antennas.
Gap	The unavailability of ultra-lightweight, deployable materials that can simultaneously provide impact resilience (against L2 micrometeoroids and LEO orbital debris) without suffering cascading structural failure or degrading optical/RF performance.
Technical details	SMD requires structures exceeding standard launch fairing dimensions. Specifically, HWO requires materials that will not spall or introduce optical contamination into the telescope upon impact. In Earth science, large apertures require advanced tensioning architectures that prevent localized debris strikes from warping the 10–15m antenna geometry, which would ruin the radar signal.