NASA's Lunar Surface Innovation Initiative: Ensuring A Cohesive, Executable Strategy for Technology Development

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In 2019, NASA's Space Technology Mission Directorate (STMD) established the Lunar Surface Innovation Initiative (LSII) which has evolved into a key agency asset aimed at spurring technology development and providing risk reduction for lunar surface system and infrastructure development. In the five years since its inception, LSII's work has serviced the needs of technology stakeholders from U.S. industry, academia, government agencies, non-profit institutions, and has expanded to include participation from international organizations. Continued domestic and foreign engagement has gained rapid momentum through LSII's Lunar Surface Innovation Consortium (LSIC), an innovative approach that encourages public-private partnerships and collaboration across sectors to support NASA's existing technology investments and prepare for increasingly complex lunar surface technology demonstrations.

I. Introduction

A key tenet of the Lunar Surface Innovation Initiative (LSII) is to bring together a broad range of stakeholders to accelerate technology capabilities for a sustainable Lunar Infrastructure (LI) to support continuous human presence on the Moon while enabling new opportunities to prepare for future crewed and robotic missions to Mars. LSII's activities have the potential to foster the creation of new industries, products, and services that will fuel a lunar economy and yield lasting benefits for decades. LSII coordinates activities implemented through a combination of in-house activities, competitive programs, and public-private partnerships to help transform technologies needed for lunar surface infrastructure and exploration. A crucial component of LSII is the consortium facilitator and systems integration task with The Johns Hopkins University Applied Physics Laboratory (JHU-APL). Through a contract with the University Affiliated Research Center (UARC), JHU-APL was tasked to establish the Lunar Surface Innovation Consortium (LSIC) and manage consortium operations. The LSIC is a nationwide alliance of stakeholders that includes universities, non-profit research institutions, commercial companies, NASA centers and

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program offices, and other government agencies with a vested interest in establishing a sustained presence on the surface of the Moon.

II. Lunar Surface Innovation Consortium

The Lunar Surface Innovation Consortium (LSIC) was established to harness the creativity, energy, and resources of the nation to help NASA keep the United States at the forefront of lunar exploration. To accomplish this, LSIC serves as a forum for NASA to communicate technological requirements, needs, and opportunities and for the broader community to share existing capabilities and identify critical gaps in need of government investment. Furthermore, LSIC provides a forum through which NASA can gather external feedback and understand external perspectives. Members share a common interest in helping NASA invest wisely in critical technologies while stimulating the lunar economy. By working side-by-side with commercial companies, academia, and international partners, NASA can leverage a greater knowledge base and harness expertise to inform technical advancements that will feed technological and economic growth. To that end, the consortium assists NASA to:

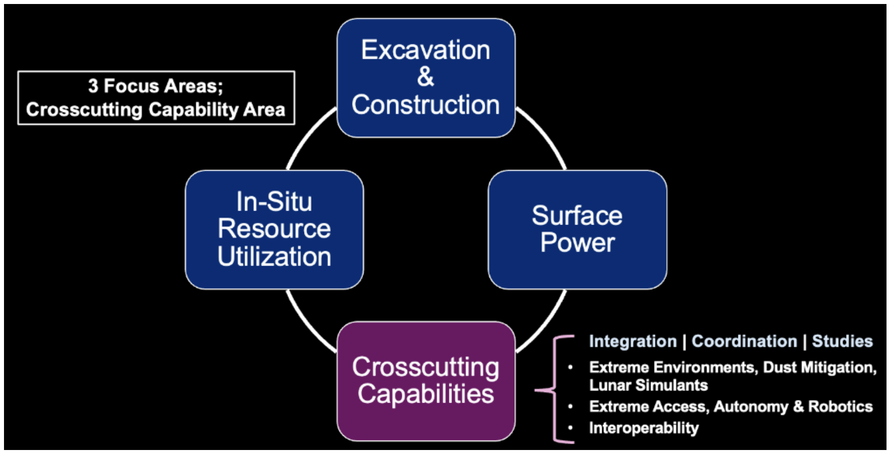
- Identify lunar surface technology needs and assess the readiness of relative systems and components.
- Make recommendations for a strategy for developing and deploying the technologies required for successful lunar surface exploration.
- Provide a central resource for gathering information, analytical integration, and sharing results between NASA, other government agencies, U.S. industry, academia, and international stakeholders.

The consortium is facilitated by the JHU-APL on behalf of NASA’s Space Technology Mission Directorate (STMD). A unique outcome from the execution of this work has been the collaborations between emerging private enterprises in space and traditional space ventures. Relevant developments from other terrestrial industries, such as mining and construction management, have bridged the gap between government-funded space exploration and near future commercial developments, showing promise that stakeholders are actively searching for pathways to sustained commercial development on the lunar surface.

A. LSIC Rebalanced Structure

When the Lunar Surface Innovation Consortium (LSIC) was created in 2020, NASA was still defining the goals and priorities for its lunar surface sustainability plans. Since then, the White House Office of Science and Technology Policy released the U.S. Space Priorities Framework and the National Cislunar Science and Technology Strategy to address how the U.S. will support responsible, peaceful, and sustainable exploration and use of Cislunar space, including the Moon. In response, NASA developed a Moon to Mars Architecture Definition Documentation, describing the elements needed for long-term, human-led scientific discovery in deep space. Furthering this effort, NASA's Space Technology Mission Directorate (STMD) developed a strategic framework to organize the agency's technology investments. Through the Envisioned Futures Priorities, STMD describes the technical priorities that need investment to expand NASA's technology development impact. Over time, LSIC has evolved into a large, engaged community and developed more connections with outside stakeholders. Adjustments were needed to facilitate growth and align with the newly defined goals and priorities. LSIC changed from six focus groups to three infrastructure-based capability (surface power, in-situ resource utilization (ISRU), excavation and construction) focus groups that align with the Moon to Mars objectives and one Crosscutting Capabilities Group. The new Crosscutting Capability Group combined the previous extreme environments, dust mitigation, and extreme access focus groups, adding lunar simulants and interoperability. This change allowed for more targeted integration across the lunar infrastructure foundational technologies, coordination, and studies of these critical crosscutting areas with relevant stakeholders. The new LSIC structure enables systems discussions across the inter-dependent areas, ensuring more robust cross-collaboration while better encompassing interoperability technology discussions and facilitating discussion of specific use cases (Fig. 1).

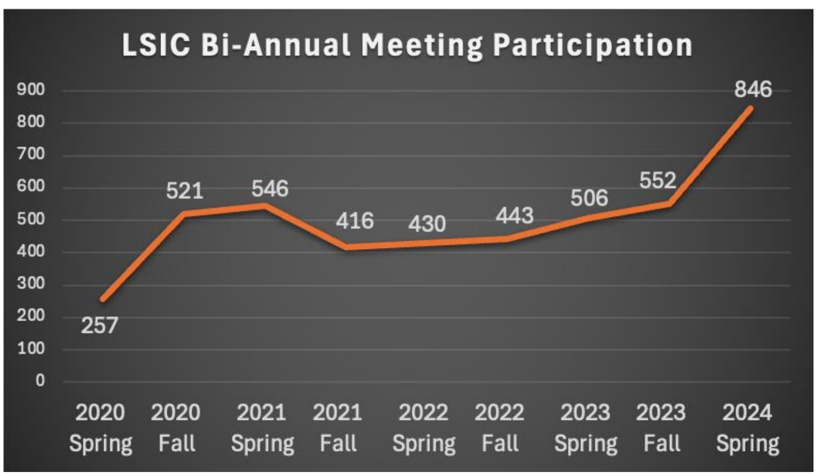
Fig.1 LSIC Organization



B. Demographics

Through LSIC, LSII has engaged over 900 organizations with more than 3,000 participants from 50 U.S. states, including the District of Columbia (D.C.), Guam, and Puerto Rico. While most participation continues to be from U.S. entities, the number of individuals who self-identify as foreign nationals participating in LSIC activities has steadily risen to 554. These participants represent seventy-two countries, with many from international industries followed by academic institutions, government agencies, and nonprofits. Over 4,500 people have attended the nine semi-annual meetings, and 2600 have participated in fourteen thematic workshops on topics driven by community interests (Fig. 2).

Fig 2. Bi-Annual Meeting Participation Growth



C. Bi-Annual Meetings

In the Fall and Spring, LSIC hosts multi-day meetings to unite the community for NASA and community updates, thematic plenaries, networking sessions, technology showcases, panels, and more. Fall Meetings typically occur at an academic member institution, aiming to spotlight the related work conducted there, while Spring Meetings are held at the Johns Hopkins University Applied Physics Laboratory (JHU-APL) in Laurel, MD. The meetings also foster student engagement by offering free and reduced student registration, which is made possible by industry sponsorship, and through professional development opportunities such as private luncheons with NASA senior executive leaders. Past Fall meeting hosts have included Arizona State University (Tempe, AZ. 2020), Bowie State University (Bowie, MD. 2021), the University of Texas at El Paso (El Paso, TX. 2022), and Community College of Allegheny County in partnership with Astrobotic, and Moonshot Museum (Pittsburgh, PA. 2023).

1. 2024 LSIC Spring Meeting

The 2024 Lunar Surface Innovation Consortium (LSIC) Spring Meeting was held April 23-25, 2024, at the Johns Hopkins Applied Physics Laboratory in Laurel, MD. The meeting showcased technologies relevant to the LSIC community. It included updates on NASA's Moon to Mars Architecture, LSII/LSIC updates, Lunar Surface Technology Research (LuSTR) 2021 updates, a Commercial Lunar Payload Services (CLPS) initiative 2024 manifest panel, a partnership panel that included the international perspective, a technology showcase panel, updates related to the 10-Year Lunar Architecture Capability (LunA-10) Study led by the Defense Advanced Research Projects Agency (DARPA) , and a technology "show and tell" – a networking event allowing teams from across the community to display technology exhibits. A key takeaway from the meeting was that the community identified a need for alignment on expected behaviors of international Moon-related activities (i.e., data/resource sharing, lessons learned, and best practices), a need to address Intellectual Property (IP) challenges and lack of interoperability/standards.

D. Workshops

One method LSII takes to identify technological hurdles is leveraging LSIC workshops as a mechanism to create a focused forum where idea generation and information gathering can be done. LSIC facilitators actively engage with community feedback and discussion to design the theme, content, and format that addresses NASA's and the participant's most pressing technological challenges pertinent to increasing the readiness of relative systems and components. These workshops aim to extract insights, feedback, and key findings which are then distilled into Workshop Outcome Reports. These reports provide recommendations to LSII, guiding future initiatives for both the consortium and NASA to act upon. Between September 2020 and November 2023, over 2,900 individuals participated in fourteen thematic workshops (Table 1). The following sections offer detailed summaries and key findings of the most recent five workshops:

Table 1. LSIC Workshops to Date

Date	Workshop
17 Sept 2020	ISRU Supply and Demand
04 Feb 2021	Dust Mitigation
02-04 Mar 2021	Lunar Mapping for Precision Landing
22-23 July 2021	Power Beaming
20 Aug 2021	Excavation and Construction
23 Feb 2022	Regolith to Rebar
28 July 2022	Low-Temperature, Sub-kW Power and Energy Storage
05 Aug 2022	Designing for Extremes
26 April 2023	Space Technology Competitive Opportunities
12-13 July 2023	Lunar Proving Grounds Definition
26-27 Aug 2023	Power Systems Reliability
21-24 Aug 2023	Autonomy
11 Oct 2023	Transition to Commercial Lunar Operations
07 Nov 2023	Path to Sustainable Technology

1. Space Technology Competitive Opportunities Workshop

As part of the 2023 LSIC Spring Meeting, a one-day workshop was held, to equip participants with resources and knowledge on NASA's Space Technology Mission Directorate (STMD) solicited proposal opportunities. A total of 271 individuals from over 160 institutions registered, with 142 unique attendees. The workshop was conducted in three sessions consisting of STMD program representatives discussing recurring funding opportunities, explaining various funding mechanisms such as grants (e.g., LuSTR, NASA Space Technology Graduate Research Opportunities (NSTGRO), NASA Innovative Advanced Concepts (NIAC), NASA Innovation Corps (I-corps)), contracts (e.g., Small Business Innovation Research / Small Business Technology Transfer (SBIR/STTR), Civilian Commercialization Readiness Pilot Program (CCRPP)), funded and unfunded space act agreements (e.g., Announcement of Collaboration Opportunity (ACO), Tipping Points), and unique one-time contracts (e.g., Vertical

Solar Array, Fission Surface Power). Former STMD proposal awardees shared insights. NASA Science Mission Directorate (SMD) representatives also presented the 2023 NASA SMD Entrepreneurs Challenge. This challenge, which in part has a lunar focus, is aimed at commercializing and developing lunar payloads through an entrepreneurial and venture lens to advance NASA science exploration goals. Key findings showed:

- LSIC community members are interested in how LSIC might have a future role in driving more collaborations between industry and academia (e.g., an event at which LSIC industry & academia members can exchange ideas and collaboration opportunities at one of the bi-annual meetings or focus group meetings).
- There is continued interest in international eligibility and participation related to STMD funding opportunities.
- Workshop interest included individuals from industry and non-industry organizations, with the former making up over half of the registrants.
- Grant Opportunities (e.g., LuSTR, NSTGRO, NIAC) garnered the most interest among workshop registrants as the first choice of funding opportunity to learn more about during breakout sessions.
- Workshop participation was evenly split among in-person and virtual attendees, with just under half of workshop attendees having worked with, already applied, or with a plan to apply to work with Space Tech.

2. Lunar Proving Grounds Definition Workshop

A recurring theme emerged across all six LSIC focus groups: technology developers face challenges accessing systems testing for lunar surface applications. Consequently, the Lunar Proving Ground (LPG) workshop was initiated to investigate the technical and programmatic requisites for system-of-systems level testing through the concept of a “lunar proving ground.” Over two days, participants focused on defining the notional technical characteristics and capabilities, as well as implementation approaches, of facilities dedicated to testing systems in complex operational lunar environments. The workshop began with briefings from the Chief Architect of NASA’s Space Technology Mission Directorate, providing context on the Moon to Mars Architecture and objectives, and highlighting areas where NASA anticipates onramps for industry technology contributions. In total, 480 individuals registered for the hybrid (in-person and virtual) event, with 300 actively participating. Key findings showed:

- A LPG should focus on integration, validation, lifecycle testing, and humans-in-the-loop.
- A LPG is critical for the technologies needed to enable sustained presence and operational validation.
- A LPG should include interoperable infrastructure representative of the operational space.
- Deconflicted and coordinated facilities can serve many of the component-level testing before an LPG is needed, while reducing administrative burden and building efficiencies.
- Digital engineering tools can meet a subset of LPG elements, but the appropriate technologies and environments must be detailed.
- A LPG should have a pathway for international access to facilities, which should be considered during planning.

3. Power System Reliability

The topic of lunar grid reliability emerged as a significant concern during discussions and events involving the Surface Power LSIC Focus Group participants. In response, LSIC organized a two-day virtual workshop to convene stakeholders from NASA, academia, and commercial space and terrestrial power industries to examine the system design challenges of a power grid on the lunar surface. The discussion centered around understanding the unique challenges inherent in decentralized versus monolithic systems design, and trades between the two. The main objective of this workshop was to develop useful metrics for characterizing and quantifying reliability at both the system and component level, with careful consideration of the appropriate level of redundancy needed to carry out safe crewed and robotic missions, and the systems needed to maximize interoperability. A presumption was that optimizing interoperability would simplify the early stages of technology development and streamline the eventual maintenance and repair of a fully operational lunar grid. Included in the agenda were three panel discussions, four NASA plenary talks, and sixteen technical presentations. Key findings showed:

- By planning for reliability, maintainability, and scalability now, developers can prevent designing into a corner and learning in-situ.
- Reliable power distribution has many open technology and knowledge gaps, which will benefit dramatically from technology-forward missions to the lunar surface.

- There is a need to incentivize the sharing of information, such as through data buys, engineering data of opportunity, etc. Power Management and Distribution (PMAD) is an area of concern.
- Load profiles are not well-considered and will significantly impact on technology development. The disconnect between power providers (generation) and the user base (loads) must be bridged.
- Standards need to be developed in consensus, commensurate with the state of knowledge and technology. No existing entity is coordinating this sufficiently across government, industry, and international partners.

4. Autonomy Workshop

The Extreme Access LSIC Focus Group conducted a virtual, two-day workshop to explore the role of autonomy in future robotic and human-led surface missions and identify technology gaps and use cases from operational scenarios. In total, 302 people registered for the workshop, with approximately 233 unique participants. The workshop's content included a deep dive into state-of-the-art technologies solving autonomous system needs in surface exploration. The technologies presented addressed Situational and Self Awareness, Reasoning and Acting, and Collaborative Systems capabilities. Each session consisted of a 40-minute panel, three 10-minute presentations, and a networking discussion where participants joined breakout groups to discuss their experiences and thoughts on the session utilizing Miro, a digital collaboration platform. Key findings showed:

- To enable sustained lunar presence, autonomous systems will be necessary. The specifics of these systems and the level of autonomy needed will be scenario dependent.
- Autonomous systems need to be accounted for during mission design, not built in afterward.
- Data needs for computer vision algorithms and training of machine learning networks are considerably high and are not supported by current space-grade technology.
- Lower barriers to entry for new players in autonomous space systems are needed. This may include greater funding opportunities, digital engineering tools, and specific use cases and requirements to define autonomy needs at appropriate levels.
- An open-source sandbox for autonomous system development and data- and model-sharing is needed to support interoperability and the continued progression in innovation of these technologies.

5. Path to Sustainable Technology Workshop

The Extreme Environments and Dust Mitigation LSIC focus groups convened the community to discuss the qualification pathway for resilient technologies anticipating long operational life on the lunar surface. A total of 304 individuals registered for the one-day workshop, with 159 unique participants in attendance. The workshop had three sessions:

- 'Existing Standards and Facilities,' featured five presentations detailing NASA and industry testing standards and design guidance. LSIC also provided overviews of supplemental information created for the LSIC community including a facilities database and the Essential Compilation of Lunar Information in Preparation of Sustained Exploration (ECLIPSE) resource guide (now known as Lunar Engineering 101).
- Centered on panels with NASA subject matter experts and industry and academia representatives to understand stakeholder needs. Each panel allotted 15 minutes for remarks and half an hour for audience Q&A.
- Facilitated in-depth discussions through breakout groups and a Town Hall, where participants engaged in hour-long conversations on testing, knowledge, and hardware relevant to deploying long-lived technologies. The workshop concluded with a collective reflection on the day's insights and closing remarks.

Key findings showed:

- Industry and academic partners need clear standards for what will be accepted for flight programs and interoperability with other systems.
- All stakeholders, regardless of affiliation, are highly concerned about the lack of relevant environmental knowledge for the Lunar South Pole region.
- Industry and academic partners continue to be highly interested in teaming with other institutions.
- Workshop attendees requested more communication from NASA on various topics, including funding, flight opportunities, and acceptance standards for path-to-flight opportunities.
- Industry attendees repeatedly emphasized that economic viability is a major component of their ability to execute long-term lunar plans.

- There was high interest in all resources presented during the workshop, both extant and forthcoming.

III. LSII Capability Areas

A. Sustainable Surface Power

Critical advancements in power generation and energy storage will provide the capability for continuous power throughout extreme lunar day and night operations. Solar array technology under development can generate energy in extreme environments, including low-light intensity and low temperature. NASA is investing in technologies such as the Vertical Solar Array Technology (VSAT) project, which will develop lightweight solar arrays capable of autonomous 10-meter vertical deployment on uneven terrain through three contracts with industry. This technology will enable near continuous capture of sunlight by the solar arrays at the South Pole region. In addition, NASA is developing and demonstrating a primary fuel cell system to support operations with long discharge times, including applications on rovers, powering of habitats and in-situ resource utilization systems, and general energy storage.

1. Vertical Solar Array (VSAT)

The VSAT project focused on developing solar array technologies necessary for a sustained presence on the lunar surface. Existing solar array structures and deployment systems are designed for zero-g or horizontal deployment. VSAT sought vertical deployment of arrays on extension masts of up to 20 meters to capture near continuous sunlight at the lunar south pole. VSAT solicited concepts for an autonomous system capable of vertical array development on an extended mast. The deployment mechanism needed to be designed for reliable, autonomous retraction and mobility to allow for the relocation of the array. In addition, the designs needed to remain stable on steep terrain, be resistant to abrasive lunar dust, and minimize both mass and packaged volume to aid in the system's delivery to the lunar surface.

NASA initially selected five vendors to complete initial vertical solar array designs and conduct analysis. In August of 2022, three companies were selected to further advance work on their deployable solar array systems: Astrobotic Technology of Pittsburgh, Pennsylvania; Honeybee Robotics of Brooklyn, New York; and Lockheed Martin of Littleton, Colorado. These companies are furthering their designs by building prototypes and performing environmental testing. These prototypes will provide promising solutions for reliable power sources required for a long-term presence on the Moon.

Fig. 3 Artist conception of Vertical Solar Arrays. Credit: NASA

B. Excavation and Construction

NASA is developing and demonstrating technologies that enable affordable, autonomous manufacturing and construction using lunar surface materials. Critical to NASA's ISRU subscale demonstration plant is the ability to excavate regolith under lunar environmental conditions, which include lunar dust, extreme temperatures, and minimal gravity. The Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project will utilize lunar in-situ materials for the on-demand construction of large-scale infrastructure elements such as habitats, berms, landing pads, and blast shields [3]. These structures could protect astronauts, science instruments, and other assets while on the lunar surface to enable sustained surface exploration.

1. Moon-to-Mars-Planetary Autonomous Construction Technology (MMPACT)

The MMPACT project goal is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface using in-situ manufactured materials from regolith. MMPACT offers solutions to autonomous lunar excavation, construction, and outfitting capabilities (Fig. 4) by addressing technology gaps in the production of manufacturing and construction feedstock, and scalable processes for extraction and purification of regolith.

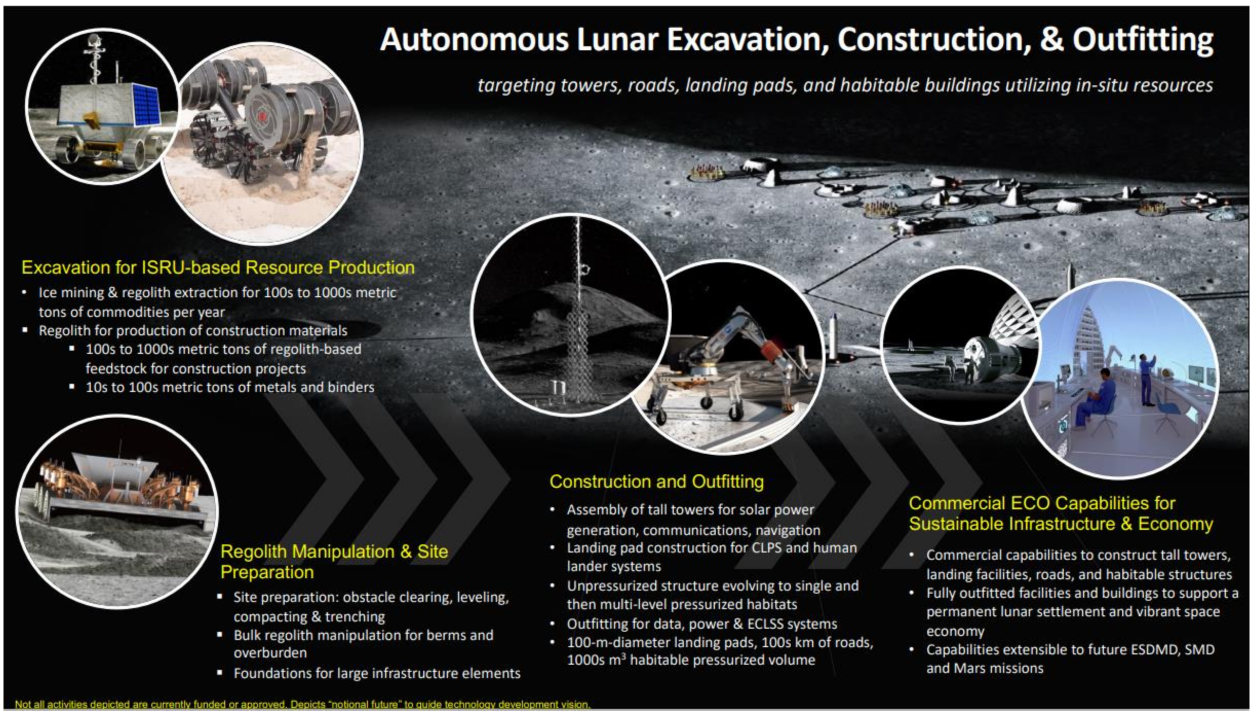


Fig. 4 Autonomous Lunar Excavation, Construction and Outfitting Capabilities Description. Credit: NASA

C. In-Situ Resource Utilization (ISRU) Technologies

In In-Situ Resource Utilization (ISRU), LSII is developing and demonstrating technologies to use the Moon's natural resources. Following the development and maturation of ISRU technologies at the component, subsystem, and scaled system levels, this effort will demonstrate the ability to produce propellants, other mission consumables, products, and infrastructure from regolith and atmospheric resources at various destinations. The Polar Resources Ice Mining Experiment-1 (PRIME-1) will be the first ISRU demonstration on the Moon. The project includes a flight-ready instrumentation package that will robotically sample and analyze for ice from below the lunar surface. PRIME-1 is a critical instrument suite that will be integrated on the Intuitive Machines commercial Nova-C lunar lander to assess volatiles and determine water content at the lunar South Pole. PRIME-1 will demonstrate technology in the lunar environment and help provide the knowledge necessary to find critical resources to produce propellant, water, and oxygen for lunar missions.

1. Polar Resources Ice Mining Experiment-1 (PRIME-1)

The goal of the PRIME-1 project, managed at NASA's Kennedy Space Center, is to develop a flight ready system that can assess the composition of regolith for water content and other volatiles at a near polar lunar landing location. The technology consists of a mass spectrometer for observing lunar operations, Mass Spectrometer Observing Lunar Operations (MSoLo), and the Regolith and Ice Drill for Exploring New Terrain (TRIDENT). NASA selected Intuitive Machines to fly PRIME-1 to the Shackleton Connecting Ridge on the Intuitive Machines (IM-2) Mission. TRIDENT will be lowered from the Nova-C lander and drill into the Moon's surface, harvest and bring ice to the lunar surface, and use a MSoLo to measure how much is lost to sublimation as it turns from solid into vapor in the vacuum. The data from the PRIME-1 mission will help scientists understand how a future NASA mission called the Volatiles Investigating Polar Exploration Rover (VIPER) can search for water at the Moon's pole and how much water may be available for use as NASA plans to establish a sustainable human presence on the Moon.

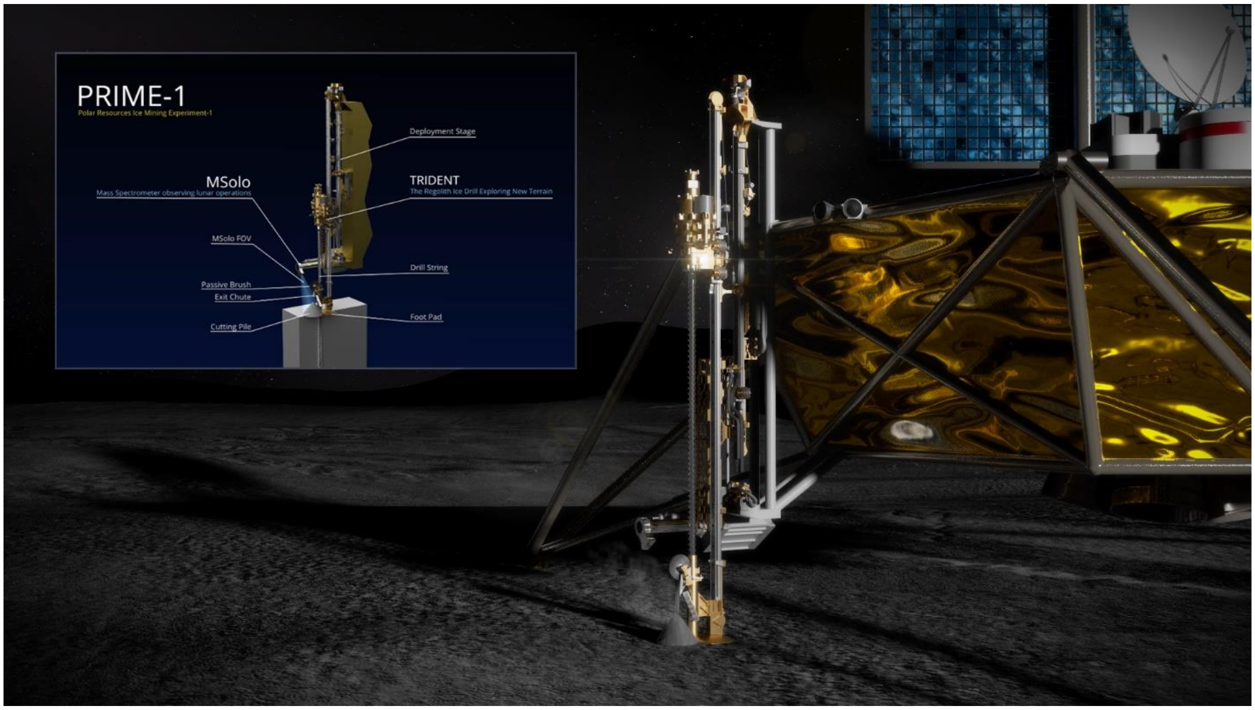


Figure 5. Artist conception of PRIME-1 operating on the lunar surface. Credit: NASA

D. Dust Mitigation

Mitigation strategies that diminish lunar dust hazards to astronauts and systems and components ranging from habitats, cameras, solar panels, and space suits are critical to the safety of future surface missions. As part of risk reduction to astronauts and architectural elements, NASA has identified an integrated, end-to-end dust mitigation strategy. This strategy is a three-pronged approach that includes: considerations in operational and architecture planning, passive technologies, and active technologies [4]. Examples of LSII investments in active technologies and technologies that contribute to filling knowledge gaps for operational and architecture considerations are the Electrodynamic Dust Shield (EDS) and Stereo Camera for Plume Surface Interaction 1.1 (SCALPSS 1.1), respectively.

1. Electrodynamic Dust Shield (EDS)

The Electrodynamic Dust Shield (EDS) is an active dust mitigation technology demonstration that uses electrostatic fields (Fig. 6) to move dust from surfaces and prevent accumulation on surfaces [2]. Without moving parts, EDS will lift, transport, and remove particles from a small camera located under the lander's deck and on a white aluminum panel on the lander's footpad [2]. This demonstration will prove the feasibility of self-cleaning glass and thermal radiators with the potential for other surface applications, including spacesuit fabrics, solar panels, etc. An EDS flight demonstration is scheduled on the Firefly CLPS 19D mission in late 2024.

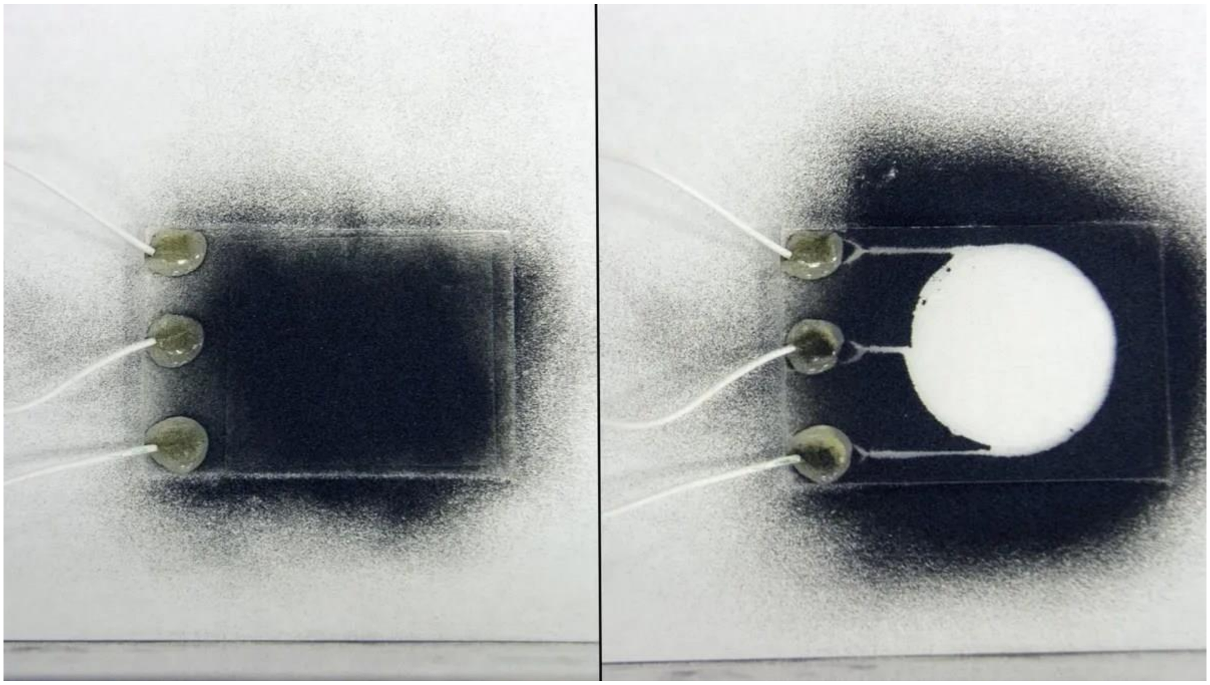


Fig. 6 Electrodynamic Dust Shield during an experiment in the Electrostatics and Surface Physics Laboratory at NASA's Kennedy Space Center in Florida. Credit: NASA

2. Stereo Camera for Lunar Plume Surface Studies 1.1 (SCALPSS 1.1)

The SCALPSS 1.1 is a technology demonstration that will collect topographical data through stereo photogrammetry prior to, during, and after interaction between the lander's descent engines plumes and the lunar surface. Plume surface interaction data collected will be used to understand the rate of change of the surface morphology [2] and inform predictive modeling. The 1.1 version is an enhanced version of the original SCALPSS payload and features two additional cameras designed to capture higher-altitude data. SCALPSS was deployed as part of the Intuitive Machines TO-1 mission that successfully landed in early 2024 at Malapert A crater 300 km from the Moon's south pole.[6]. The SCALPSS 1.1. demonstration is scheduled on the Firefly CLPS 19D mission in late 2024.

[6] 7c27f7_51f84ee63ea744a9b7312d17fefa9606.pdf (intuitivemachines.com)

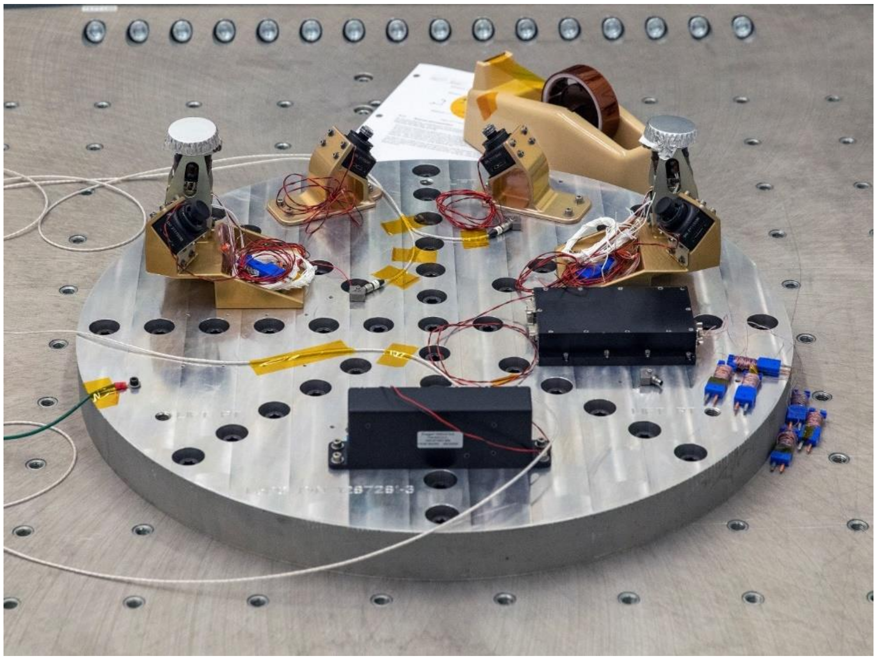


Fig. 7. SCALPSS undergoing environmental testing in lab. Credit: NASA

E. Extreme Environments

Extreme Environments technologies require advancing designs of systems to operate throughout the full range of environmental conditions. Conditions such as temperature vary significantly based on a variety of aspects, such as local topography, latitude, and solar illumination. Lunar rovers, manipulators, and other systems must be equipped to operate throughout the full range of lunar surface conditions including lunar noon (up to 150 ℃ at the equator), night (down to -180 ℃ at the equator), multiple day/night cycles, and in permanently shadowed regions (down to -250 ℃). Cross-cutting technologies built to withstand rapid temperature changes and permanently shadowed regions are essential for safe and successful crew and robotic operations. Example of a supporting technology: NASA's Bulk Metallic Glass Gear (BMGG) project, in which researchers are developing special gearboxes (mechanical units) that can operate despite low temperatures in extreme environments — from the Moon to Mars to icy worlds such as Jupiter's moon, Europa.

F. Extreme Access

Extreme Access technologies are being designed to assist humans and autonomous systems to effectively access, navigate and explore difficult-to-access or inaccessible surface and subsurface areas. To address this need, NASA is investing in projects such as the Cooperative Autonomous Distributed Robotic Exploration (CADRE) project and encouraging workforce development through student challenges meant to prepare the next generation of scientists and engineers to create autonomous systems.

1. Cooperative Autonomous Distributed Robotic Explorers (CADRE)

The CADRE (Cooperative Autonomous Distributed Robotic Exploration) project is a NASA STMD Game Changing Development program sponsored technology developed by the Jet Propulsion Laboratory (JPL). The JPL team is building the flight hardware and software for three rovers to autonomously cooperate on the lunar surface during the daytime. The rovers will simultaneously collect data and collaboratively report data from different locations. It will be a first of its kind demonstration of multi-agent autonomous rovers, featuring three fully autonomous, shoebox-sized rovers demonstrating a distributed measurement of the lunar surface and sub-surface with stereo cameras and a ground-penetrating radar, respectively. CADRE is scheduled to fly on the Intuitive Machines IM-3 Mission.

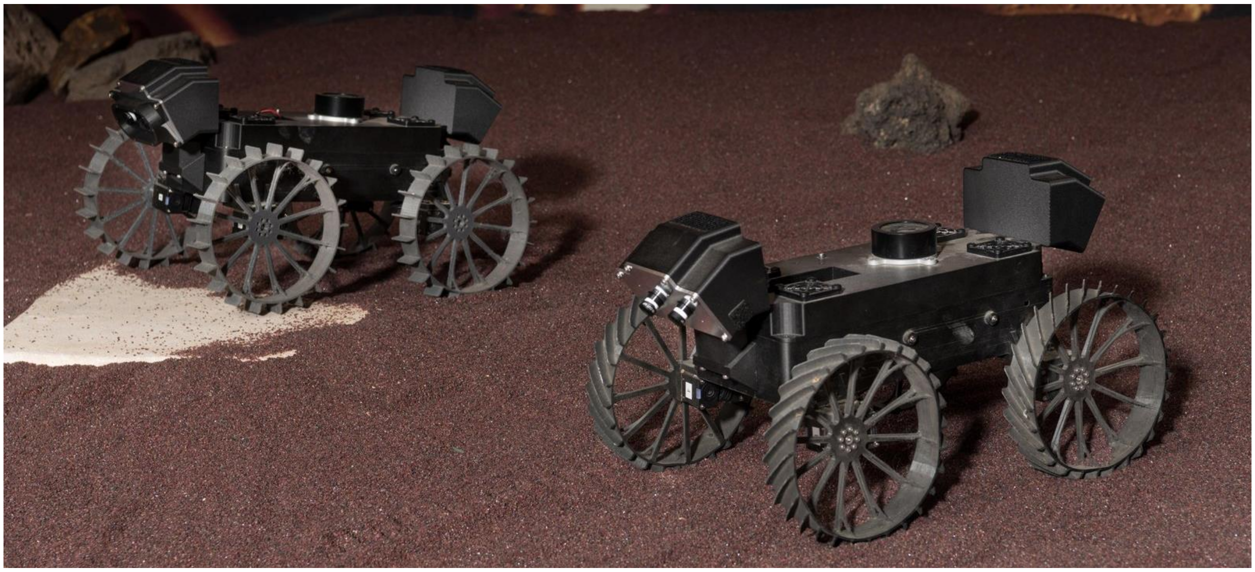


Fig 8. Prototypes of the CADRE rovers being tested at the agency's Jet Propulsion Laboratory in Southern California in August 2022. Credit: NASA

2. Lunar Autonomy Challenge

The Lunar Autonomy Challenge established through a strategic collaboration between NASA, JHU-APL, Caterpillar, and Embodied AI to foster innovative solutions to technology gaps while training the early-career workforce in developing programs for autonomous systems controls. The challenge leverages an open-source simulator developed for autonomous driving research named CARLA in which a digital twin of the NASA developed ISRU Pilot Excavator (IPEx) operates in the lunar surface environment. [Fig. 9). In this challenge, teams of university students will compete by developing algorithms to instruct the IPEx rover to map the lunar surface around the landers within a limited amount of time. Students will need to plan and balance sensor use against power, thermal, and data budgets. Future challenges will involve the development of algorithms to have the IPEx rover conduct excavation activities. The student challenge is currently undergoing formulation but is targeting a launch in Fall 2024.

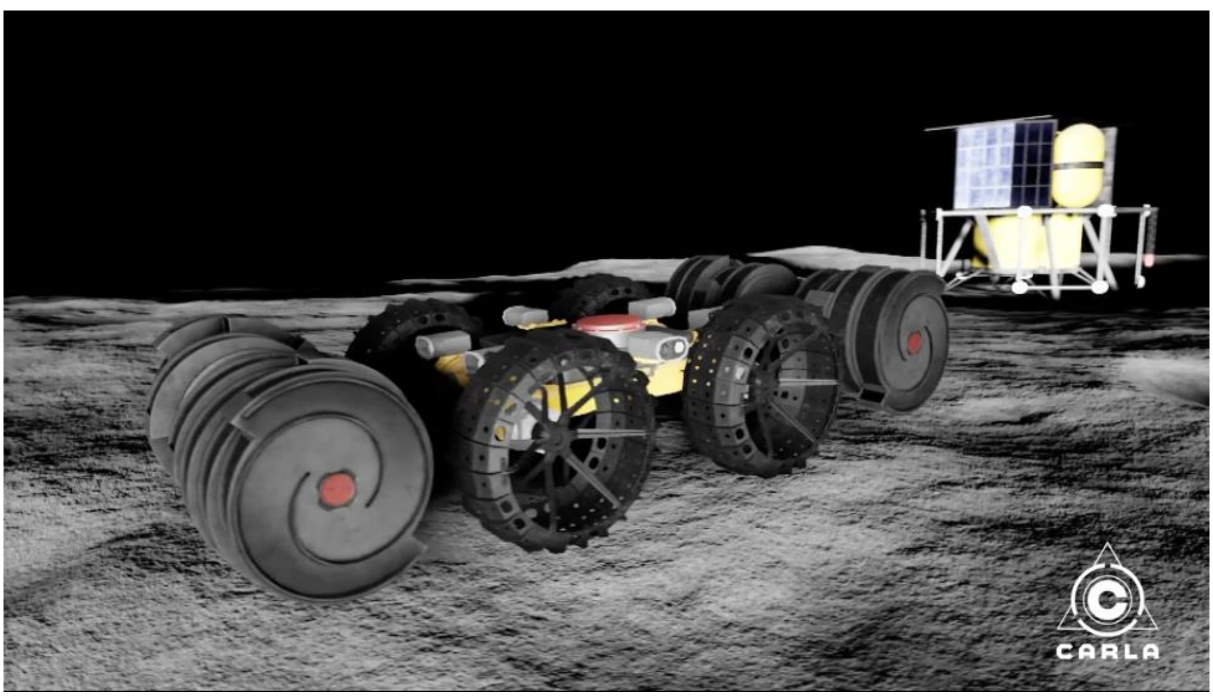


Fig. 9 The digital twin of the IPEx Rover in the simulated environment created by CARLA. Credit: Embodied AI

IV. Lunar Surface Technology Demonstrations

Within the pipeline of LSII investments, the most promising technologies will mature their technology readiness level through ground or flight technology demonstrations. Early lunar surface demonstrations are required to increase the technology readiness for seven of the nine Moon to Mars Infrastructure objectives (Fig. 11). One way NASA accomplishes this is by leveraging the CLPS Project, a mechanism through which lunar surface flight opportunities are acquired from commercial providers. LSII currently has six near-term technology demonstrations manifested on Intuitive Machines and Firefly Aerospace commercial missions (Fig. 10).

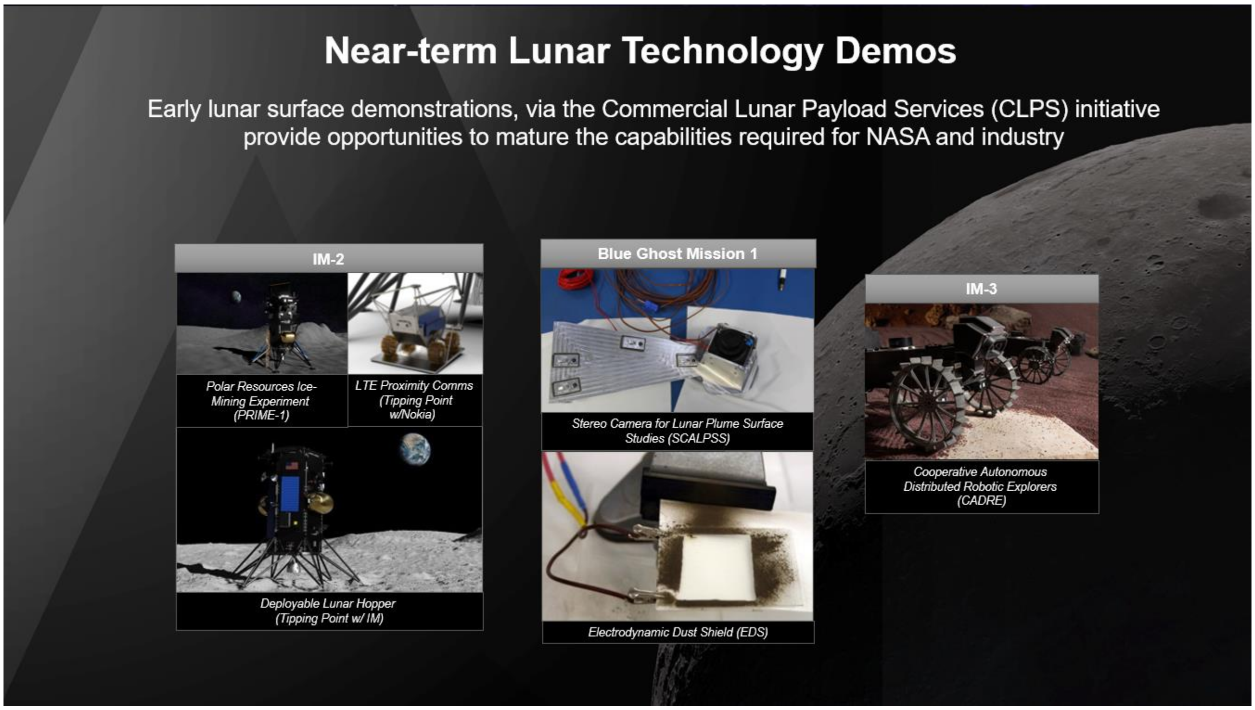


Fig 10. Early lunar technology demonstrations developed under the Commercial Lunar Payload Services (CLPS) initiative. Credit: NASA

A. Lunar Infrastructure Foundational Technologies-1 (LIFT-1) Demonstration

Among the lunar infrastructure objectives identified within the Moon to Mars Infrastructure objectives is demonstrating industrial-scale ISRU capabilities (LI-7). LI-7 represents a critical component establishing an interoperable, global lunar utilization infrastructure and the ability to support continuous human presence. To reduce the risk of implementing commercial ISRU operations, initial lunar demonstrations will need to both obtain critical data on lunar regolith and the environment, as well as demonstrate scalable, critical technology performance and operations in the actual lunar environment.

STMD’s LSII has strategically positioned opportunities for lunar surface technology demonstrations throughout the coming decade to achieve this ambitious goal. With a target date of no earlier than 2028, Lunar Infrastructure Foundational Technologies (LIFT-1) is intended to be the first in a series of planned cooperative, technology-forward flight demonstrations. While the primary objective of LIFT-1 is to advance lunar ISRU system capabilities, other associated objectives are promoted, including landing on the lunar surface and establishing lunar presence, regolith operations, and scalable power generation in the south pole region. NASA intends for the LIFT-1 demonstration to leverage collaboration with industry, academia, and other government agencies to increase the technology readiness of many of the agency’s Moon-to-Mars Infrastructure Objectives. Upon successful completion, LIFT-1 will validate a viable method for extracting oxygen from lunar regolith, laying the groundwork for future production, capture, and storage endeavors.

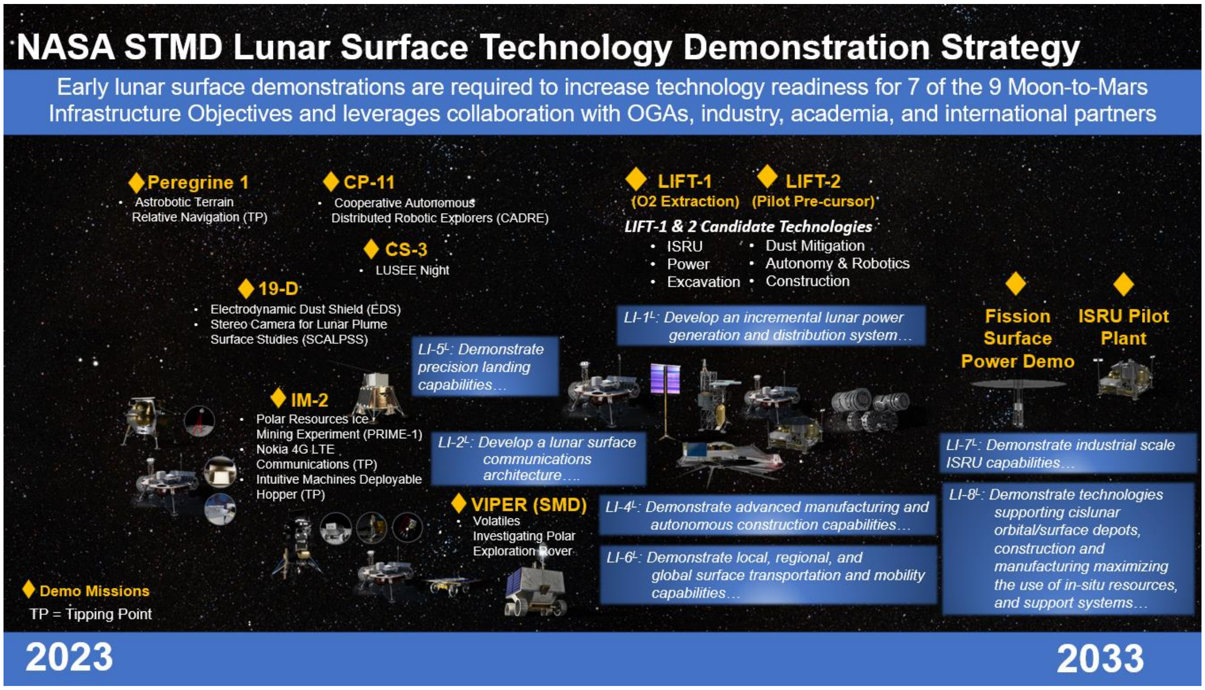


Fig 11. STMD Lunar Surface Technology Demonstration Strategy Credit: NASA

1. LIFT-1 Request for Information (RFI)

STMD released the LIFT-1 RFI in November 2023 to collect community feedback on potential concepts for an industry-led LIFT-1 surface demonstration. The RFI collected responses on acquisition and partnering approaches, the state of the art for required technologies, risks, and cost/schedule feasibility. The RFI also requested information from the community on associated infrastructure objectives, data buy opportunities, preferred integration approaches, and the relationship of the demonstration to the longer-term objectives of establishing an economy for in situ lunar resources. The community demonstrated a high level of interest in the demonstration by providing a healthy response. There were 79 submissions from 73 unique organizations representing 21 states and eight foreign countries. The majority of responses were from industry that varied across both small and large companies, but there were also responses from academia, other government agencies, several NASA centers and Federally Funded Research and Development Centers. The information gathered from the RFI responses will inform a solicitation for executing the surface demonstration. NASA intends for the solicitation to minimize prescriptive requirements on how to accomplish the relevant objectives, which will provide the flexibility for companies to form industry teams and/or contribute investments based on their business models or commercial plans. Future activities in 2024, including a follow-on acquisition strategy, are currently delayed pending budget appropriations, but LIFT-1 remains a priority for STMD.

B. Data Buy Survey

Starting in 2022, the LSIC surveyed the community's interest and opinions on "Data Buys" as a mechanism for acquiring new data that advances our ability to develop a sustained lunar presence on the lunar surface. The survey collected comments on two types of data: acquired as a by-product of landing on the Moon and new data sets, that would likely require a specific instrument to be flown either in orbit or to the lunar surface. Concurrently, LSII conducted the same survey internal to NASA across the directorates. The survey results provided insight into the most valuable types of data technology developers and scientists prioritize to support their efforts and are influencing discussions with the CLPS Project Office regarding data buys. The highest interest was for data related to illumination, elevation, dust and imagery. The next level of interest was for thermal, radiation, landing effects, and navigation data. An overwhelming two-thirds of respondents are looking for data in the south pole region of the lunar surface.

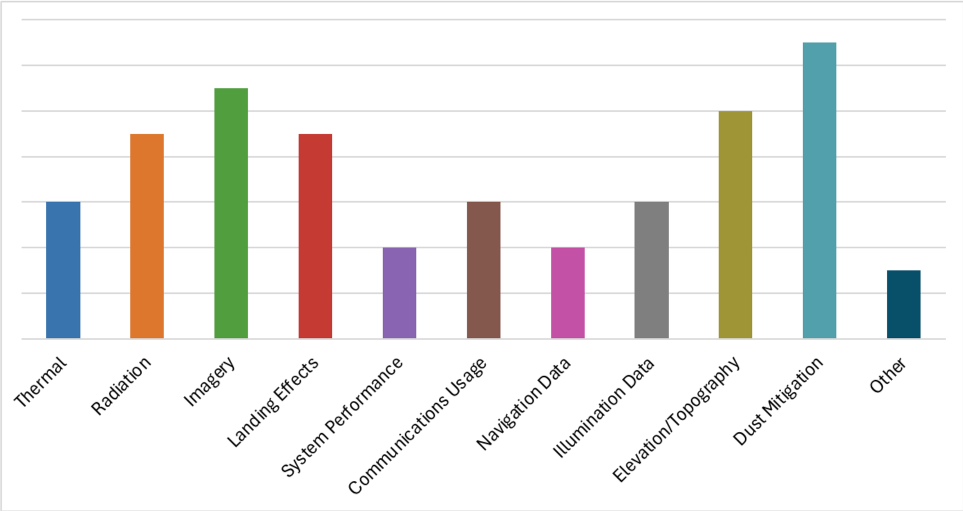


Fig 12. Data Buy Survey Relative Importance by Product Data

C. Access to Space Opportunities Portal

From the feedback received from LSIC meetings, Lunar Exploration Analysis Group (LEAG) meetings, and a CLPS Survive the Night Workshop, LSIC identified a need from the community for a centralized location to track missions, launch vehicles, payloads, and services intended for the lunar surface. The goal of Access to Space is to create a clearinghouse that focuses on vendors' residual available services and technology developers' needs in order to cultivate the lunar ecosystem by connecting providers and customers. Host types range from landers to surface mobility systems to cislunar orbital or suborbital opportunities. Payloads range from physical payloads to data only payloads or data buys. The site is populated by the providers and developers with the intent to provide reasonably up-to-date knowledge of platform residual resources and/or needs, timing deadlines, and a credible designated point of contact (POC). Through the Access to Space website, providers and developers communicate directly with each other regarding potential opportunities, while LSIC provides basic moderation to ensure content posted is reviewed and verifiable.

References

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