Decadal Science: Artemis Crewed/Robotic Missions

Presentation to the Committee on Astrobiology and Planetary Sciences (CAPS) and the Committee on Biological and Physical Sciences in Space (CBPSS)

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NASA Science Mission Directorate

Exploration Science Strategy Integration Office (ESSIO)

NASA Headquarters

Exploration Science Strategy and Integration Office

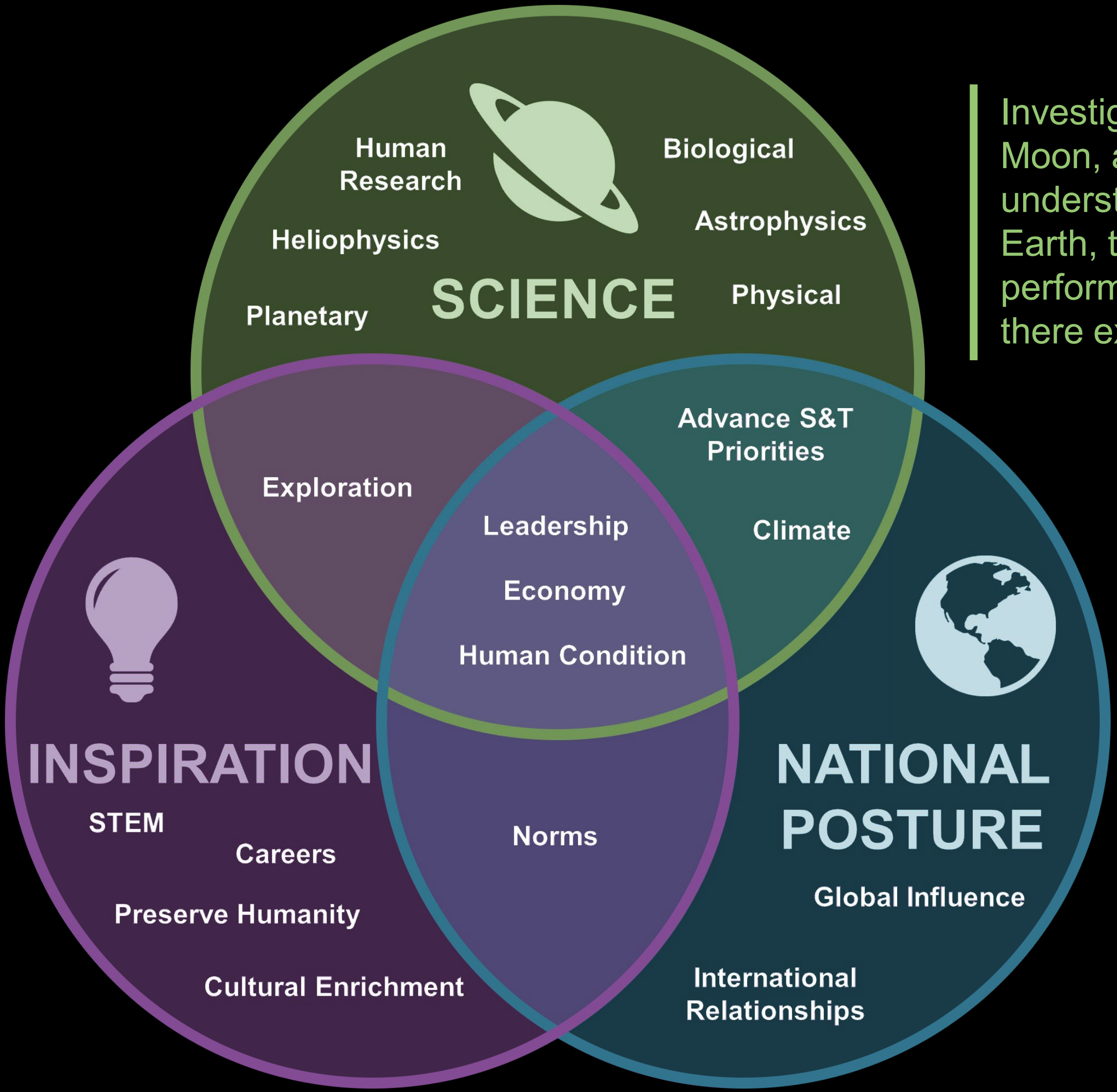
- Lunar Discovery and Exploration Program
- Moon to Mars (M2M) Science Objective and Architecture
- SMD Lunar Integration across all Divisions
- Integrated Lunar Science Strategy
- ESDMD/SOMD/STMD Engagement and Integration
- Science on Human Missions (Mars Missions with MEP)
- Science with Human Exploration Control Board (SHECB)
- External Community Engagement (AGs, WGs)
- ESDMD Control Boards
- Federated Board
- CLPS Manifest Selection Board (CMSB)
- Intergovernmental and International Partnerships

Lunar Discovery & Exploration Program (LDEP) Elements

- **Commercial Lunar Payload Services (CLPS)**
  - Two awards per year; two landings per year
  - Enabling community-driven science
- **Science Instrument Development for robotic missions**
  - Instruments deployed by CLPS (NPLP, LSITP)
  - Instrument Suites deployed by CLPS (PRISM)
  - Maturation of instrument concepts (DALI)
- **VIPER**
  - Project Closeout
  - VIPER Partnership
- **Lunar Reconnaissance Orbiter (LRO) mission operations**
- **ShadowCam/KPLO (from ESDMD)**

- **Lunar Trailblazer**
  - Project; IM-2 rideshare launch
- **Lunar International Mission Collaborations**
- **Science Instrument Development for Artemis Human Missions**
  - Includes HLS deployed, LTV deployed, Astronaut hand-held instruments
- **Lunar Science Research**
  - Competed Artemis Geology Teams, Internal Artemis Science Team, Curation, Data Infrastructure/Tools, Increased Lunar R&A, Apollo Next Generation Sample Analysis (ANGSA), NASEM Studies, SDTs
- **Mission Concept Studies for Endurance-A, LRO successor, LGN, etc.**
- **Future Missions/Projects (e.g., Endurance-A)**

Why Go



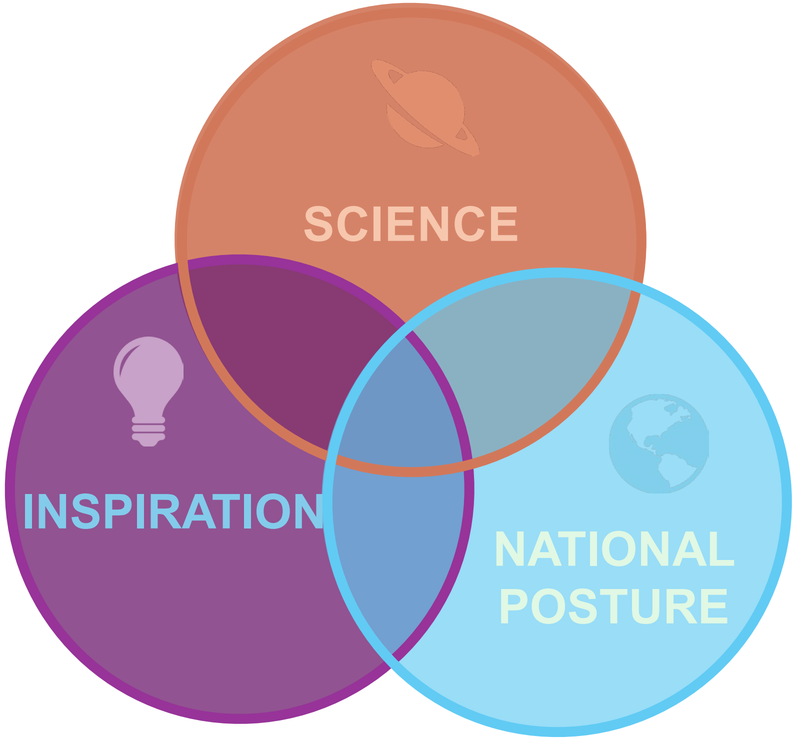
Investigations in deep space, on the Moon, and on Mars will enhance our understanding of the solar system, the Earth, the human body, and how to perform new operations while we are out there exploring.

Accepting audacious challenges and succeeding through perseverance and tenacity in the face of adversity motivates current and future generations to dare mighty things.

What we choose to do, how we do those things, and who we do them with greatly impacts our place in the world today, our quality of life, and our possibilities for the future.

Agency Priorities at the Moon

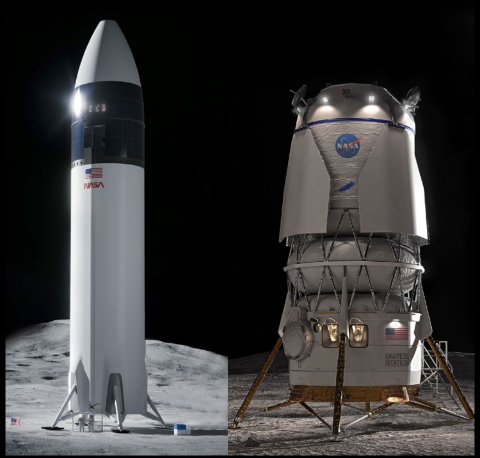
- **Why NASA explores – Three Pillars of Exploration:**
  - Science
  - National Posture
  - Inspiration
- **Safe transport and return of astronaut crew**
- **Human landings at Lunar South Pole (Space Policy Directive-1)**
- **Promote a lunar economy to produce rapid, frequent, and affordable access to the lunar surface and cislunar space**
- **Prepare for human and scientific exploration of Mars and beyond**



Artemis: A Foundation for Deep Space Exploration


Space Launch System


Orion Spacecraft


Human Landing System


Surface Operations


Gateway


Exploration Ground Systems


Space Communications and Navigation


Surface Mobility


Spacesuits


Surface Infrastructure

FY 2025 President's Budget Request Moon to Mars Manifest

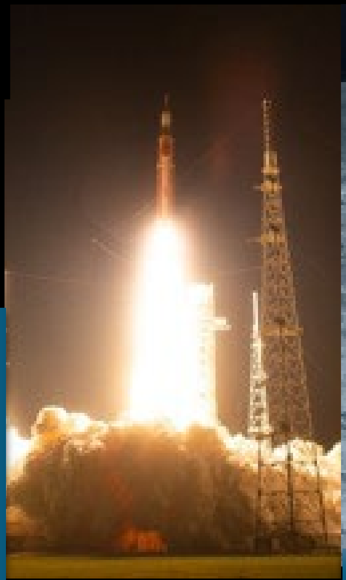
FY	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Exploration Systems Development Mission Directorate			**Artemis II** (Sep. 2025) Crewed Flight SLS Block 1/ Orion/ML1	**Artemis III** (Sep. 2026) Crewed Flight SLS Block 1/ Orion/ML1 HLS Crewed Lunar Demo xEVA Surface Suits *HLS Uncrewed Lunar Demo* *Gateway PPE/HALO Launch*	*Gateway PPE/HALO Arrival in NRHO*	**Artemis IV** (Sep. 2028) Crewed Flight SLS Block 1B/ Orion/ML2 I-Hab to Gateway Gateway Logistics Services Sustaining HLS Crewed Lunar Demo xEVA Surface Suits *Sustaining HLS Uncrewed Lunar Demo*		**Artemis V** (Mar. 2030) Crewed Flight SLS Block 1B/ Orion/ML2 ESPRIT to Gateway Sustaining HLS Crewed Lunar Demo xEVA Surface Suits LTV	**Artemis VI** (Mar. 2031) Crewed Flight SLS Block 1B/ Orion/ML2 Airlock to Gateway Gateway Logistics Services Gateway External Robotics System TBD Sustaining HLS Services xEVA Surface Suits	**Artemis VII** (Mar. 2032) Crewed Flight SLS Block 1B/ Orion/ML2 Gateway Operations TBD Sustaining HLS Services xEVA Surface Suits Pressurized Rover
Space Operations Mission Directorate	DSN Upgrades (DLEU) Completed DSS-36 [Canberra]	Completed DSS-24 [Goldstone]	DSS-34 [Canberra] DSS-56 [Madrid]		Lunar Communications Relay and Navigation Services (LCRNS)–Increment Increment Alpha	Lunar Exploration Ground Sites 1-3 DSS-54 [Madrid] Increment Bravo	Increment Charlie	Ongoing Science, Human Research Program, and Technology Development in LEO (ISS transition to CLD)		
Science Mission Directorate CLPS Flights Outlined	LRO Mars 2020:	ESCAPADE Attempted TO 2-AB Completed TO 2-IM TO 19D	TO 20A: VIPER HERMES ready for integration ESA Lunar Pathfinder delivered for launch AVATAR (Artemis II) TO PRIME-1 Lunar Trailblazer TO CP-11	Artemis III Surface Science Instruments MMX (MEGANE/ P-Sampler) TO CS-3&4 TO CP-12	LRO continued ops TO CS-06 TO CP-21 TO CP-22	Artemis IV Surface Science Instruments TO CS-6 TO CP-31	Rosalind Franklin Mission (RFM) Launch, Landing TO CP-41 TO CP-42 TO CP-51 TO CP-52 TO CP-61 TO CP-62	Artemis V Surface Science Instruments Artemis LTV Science Instruments	Artemis VI Surface Science Instruments	Artemis VII Surface Science Instruments
Space Technology Mission Directorate	MOXIE; MEDA DSOC	CFM SpaceX TP Flight Demo	Surface Robotic Scouts (CADRE) TO PRIME-1: Drill; Nokia LTE/4G Comm; IM Deployable Hopper CFM ULA TP Flight Demo PPE SEP qual. environ. complete CFM Eta Space TP Flight Demo	CFM Lockheed Martin TP Flight Demo NEP Concept Design	DRACO Demonstration	TO LIFT-1: Lunar Surface Power Demo (i.e., RFC, VSAT, Wireless Charging); Lunar Surface Scaled Construction Demo 1; ISRU Pilot Excavator; ISRU Subscale Demo	SEP qual. complete			Fission Surface Power demo delivered for launch TO LIFT-2: Lunar Surface Scaled Construction Demo 2; Autonomous Robotics Demo; Deployable Hopper 2; ISRU Subscale Demo 2

Icons are representative only, and may not reflect final configurations, not to scale | Icons represent the fiscal year in which an event occurs | Based on FY 2025 President's budget request

Increasing Capabilities = Increasing Science

MISSION (FY25 PBR)

2022
ARTEMIS I
Uncrewed flight test



2026
ARTEMIS II
Crewed Flight Test

2027
ARTEMIS III
First human surface landing

2028
ARTEMIS IV
Gateway assembly, crewed sustaining lander expedition

2030
ARTEMIS V
Crewed mobile surface exploration, Gateway expansion

2031
ARTEMIS VII
First pressurized rover

ARTEMIS VII AND BEYOND
Longer missions = preparation for human Mars missions

Access to more of the Moon = new scientific discoveries

ARCHITECTURE

- Continued addition of new elements
- Pressurized rover
- Human landing system (Blue Origin); Lunar terrain vehicle
- Gateway space station
- Human landing system (SpaceX/Starship); spacesuits; EVA tools
- Fly up to four astronauts to cislunar space and return safely
- Space Launch System rocket; Orion crew spacecraft; CLPS landers

SCIENCE

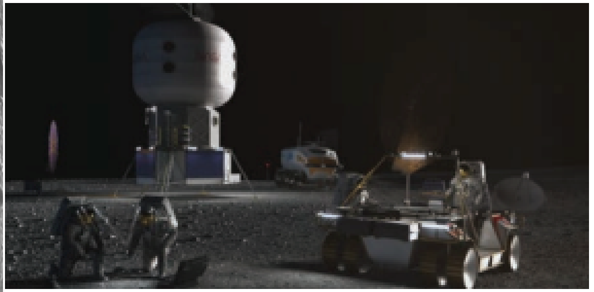
- Crew conducting science observations and demonstrating technology in orbit
- Lunar surface field geology; unconditioned sample collection and return; crew-deployed instruments and experiments; intravehicular studies
- Crew-tended and autonomous experiments on Gateway
- Cold-conditioned sample return (Orion freezer); increased area for field work (several km); increased sample return mass; crew-handheld instruments
- Substantially increased area and time for field work (10s to 100s of km); crew access to PSRs
- Cryogenic sample collection and return; deep drilling capability

ARCHITECTURE SEGMENTS

HUMAN LUNAR RETURN

Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (e.g., science) on and around the Moon.

Orion, SLS, EGS, Gateway, HLS, Deep Space Logistics, xEVAS, CPNT



FOUNDATIONAL EXPLORATION

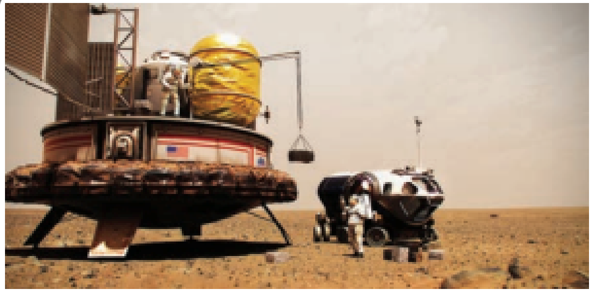
Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

LTV, PR, MPH, Large Cargo

SUSTAINED LUNAR EVOLUTION

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

Surface Power, ISRU, Expanded Mobility/Habitation



HUMANS TO MARS

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

Transportation, EDL, Ascent, Science Ops, Return needs

M2M Objectives – 26 Science Objectives

Lunar/Planetary Science (LPS)

Goal: Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, a

LPS-1^{LM}:	Uncover the record of formed and differentia Moon and Mars, and recorded on the Moon
LPS-2^{LM}:	Advance understandi structures, characteri exospheres, and inve
LPS-3^{LM}:	Reveal inner solar sy abundance, composit
LPS-4^{M}:	Advance understandi habitable environmen habitable conditions h solar system beyond

Human and Biological Science (HBS)

Goal: Advance understanding of how biology responds to the environments of the Moon, Mars, and deep space to advance fundamental knowledge, to support safe, productive human space missions, and to reduce risks for future exploration.

HBS-1^{LM}:	Understand the space on biolo and plants.
HBS-2^{LM}:	Evaluate and v with mission du
HBS-3^{LM}:	Characterize a human health,

Science-Enabling (SE)

Goal: Develop integrated human and robotic me questions to be addressed around and on the Mo

SE-1^{LM}:	Provide in-depth, mission-specific transformational science on the su
SE-2^{LM}:	Enable Earth-based scientists to advanced techniques and tools.
SE-3^{LM}:	Develop the capability to retrieve on the Moon and volatile-bearing facilities on Earth.
SE-4^{LM}:	Return representative samples fr sample mass commensurate with
SE-5^{LM}:	Use robotic techniques to survey in advance of and concurrent wit surface and maximize science retu
SE-6^{LM}:	Enable long-term, planet-wide rese and surface locations at the Moon
SE-7^{LM}:	Preserve and protect representat regions and the radio quiet far sid science investigations.

Heliophysics Science (HS)

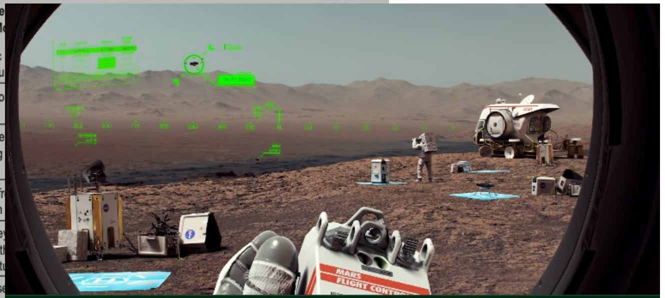
Goal: Address high-priority heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space.

HS-1^{LM}:	Improve understanding of space weather phenomena to enable enhanced observation and prediction of the dynamic environment from space to the surface at the Moon and Mars.
HS-2^{LM}:	Determine the history of the Sun and solar system as recorded in the lunar and Martian regolith.
HS-3^{LM}:	Investigate and characterize fundamental plasma processes, including dust-plasma interactions, using the cislunar, near-Mars, and surface environments as laboratories.
HS-4^{LM}:	Improve understanding of magnetotail and pristine solar wind dynamics in the vicinity of the Moon and around Mars.

Physics and Physical Science (PPS)

Goal: Address high-priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment.

PPS-1^{L}:	Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side.
PPS-2^{LM}:	Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.



Applied Science (AS)

Goal: Conduct science on the Moon, in cislunar space, and around and on Mars using integrated human and robotic methods and advanced techniques, to inform design and development of exploration systems and enable safe operations.

AS-1^{LM}:	Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.
AS-2^{LM}:	Coordinate on-going and future science measurements from orbital and surface platforms to optimize human-led science campaigns on the Moon and Mars.
AS-3^{LM}:	Characterize accessible lunar and Martian resources, gather scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.
AS-4^{LM}:	Conduct applied scientific investigations essential for the development of bioregenerative-based, ecological life support systems.
AS-5^{LM}:	Define crop plant species, including methods for their productive growth, capable of providing sustainable and nutritious food sources for lunar, Deep Space transit, and Mars habitation.
AS-6^{LM}:	Advance understanding of how physical systems and fundamental physical phenomena are affected by partial gravity, microgravity, and general environment of the Moon, Mars, and deep space transit.

1:1 Trace of Lunar Themes from Planetary Decadal to M2M Objectives (M2M LPS Objectives in BLUE)

BOX 22.2 Science Themes for Lunar Exploration [Planetary Decadal]

Science Theme 1: Uncover the lunar record of solar system origin and early history. The Moon's composition, structure, and ancient surface preserve a record of early events: from the giant impact that produced the Earth−Moon system to ongoing bombardment as life on Earth emerged and evolved.

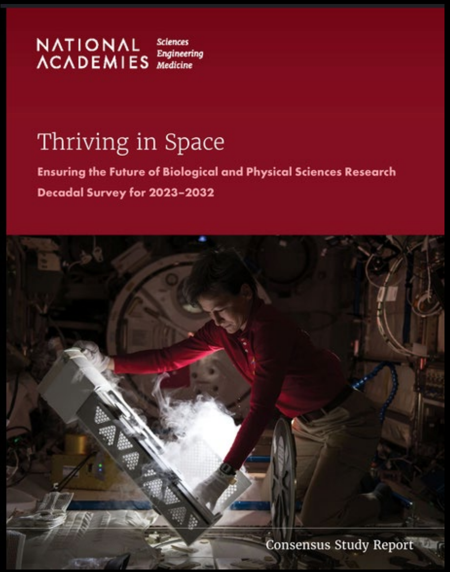
[LPS-1: Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.]

Science Theme 2: Understand the geologic processes that shaped the early Earth that are best preserved on the Moon. The Moon retains a record of processes that set the evolutionary paths of rocky worlds, including volcanism, magnetism, tectonism, and impacts.

[LPS-2: Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.]

Science Theme 3: Reveal inner solar system volatile origin and delivery processes. The Moon hosts water and other volatiles in its interior, across its surface, and in ice deposits at its poles, providing a record that may help constrain the origins of Earth's oceans and the building blocks for life, as well as ongoing volatile delivery processes.

[LPS-3: Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.]

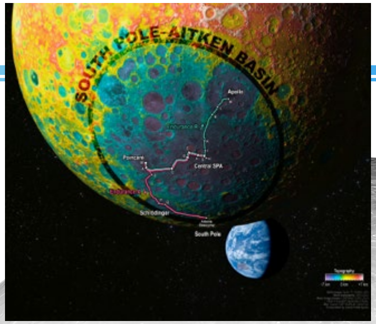


- The 2023 BPS Decadal Survey's commentaries, recommendations, themes, and key scientific questions (KSQs) for biological and physical sciences present a continuum of scientific research that spans the Earth, Low Earth Orbit, the Moon, and Mars
  - Data and findings from each research location contribute to and enable critical scientific advancements, research and development, and innovating technology and applications for each subsequent exploration destination

- BPS Division Moon-based science and its association with lunar research and development and technology/application innovations are embedded in the Decadal Survey's themes, recommendations, and KSQs

- These NASA Moon to Mars Strategy and Objectives and associated Architecture Definition Document all trace to the 2023-2032 BPS Decadal Survey findings, commentaries, themes, recommendations, and KSQs
  - Human and Biological Sciences (HBS)-1^{LM} and -3^{LM}
  - Physics and Physical Sciences (PPS)-1^{L} and -2^{LM}

Science Activities Planned for Artemis



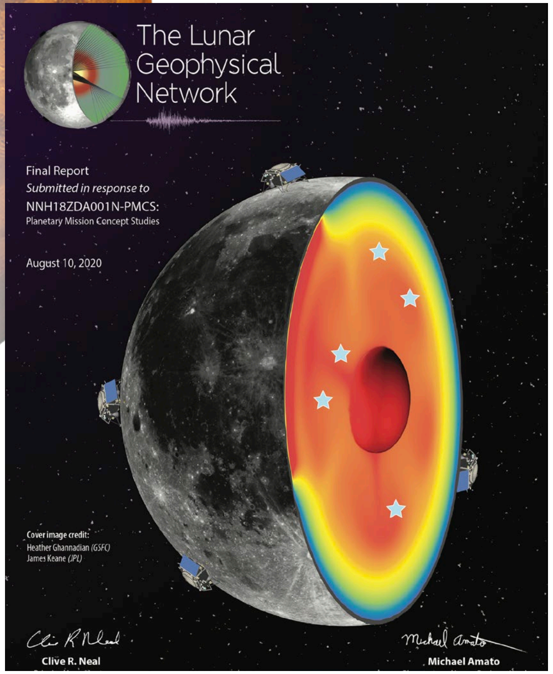
South Pole-Aitken Basin Sample Return

VIPER Partnership

LRO/Orbital Science

Science Team and Science Evaluation Room

LTV and Pressurized Rover Instruments

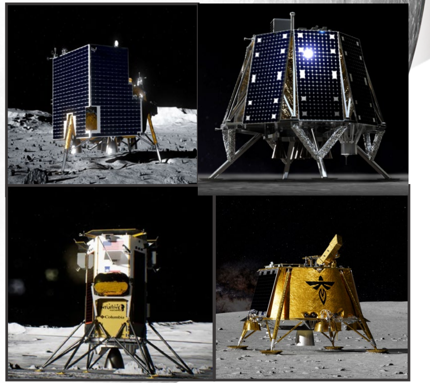


Lunar Geophysical Network (Currently being studied)

Artemis Deployed Instruments

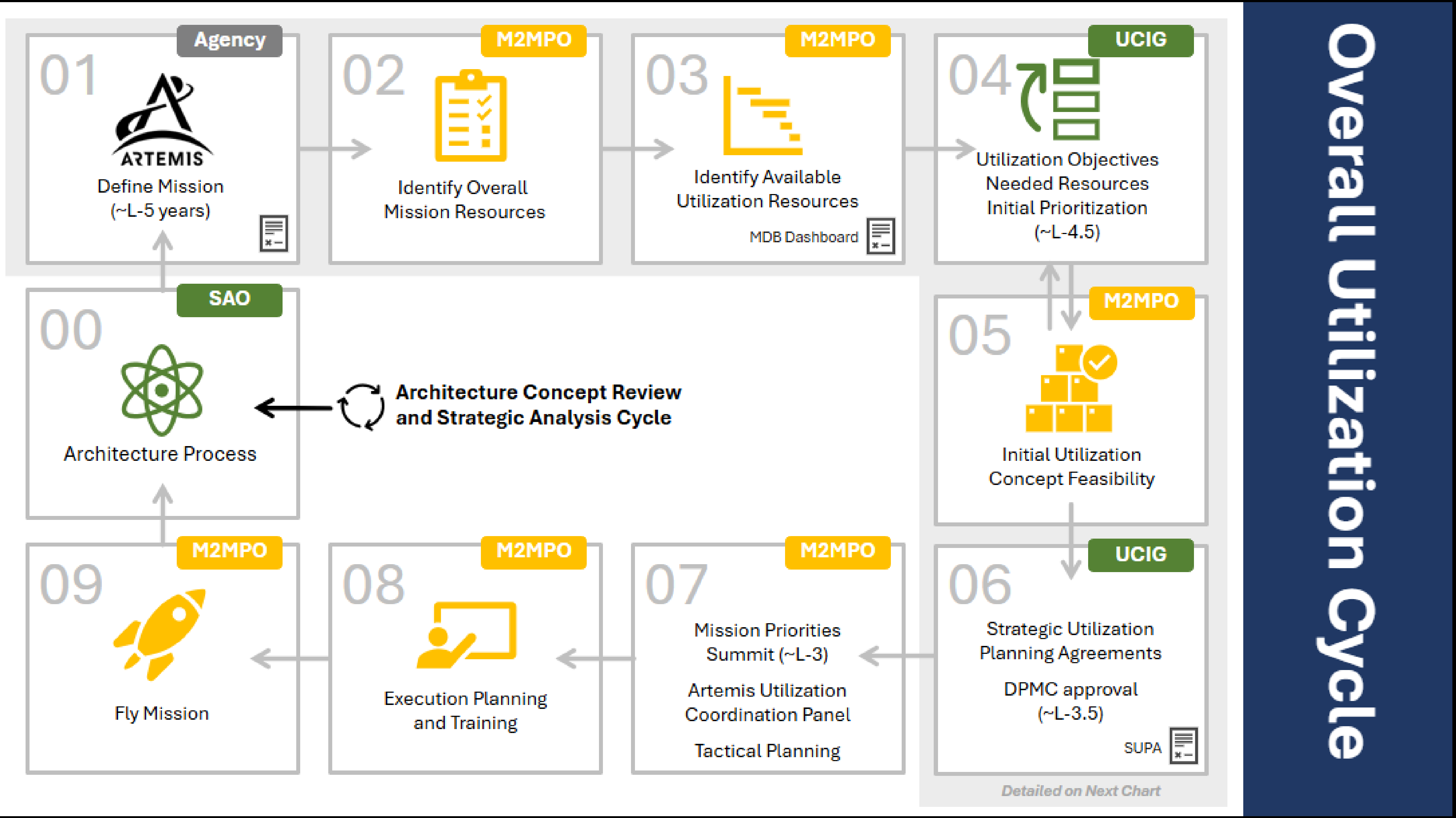
Handheld tools/instruments

Sample Return and Curation



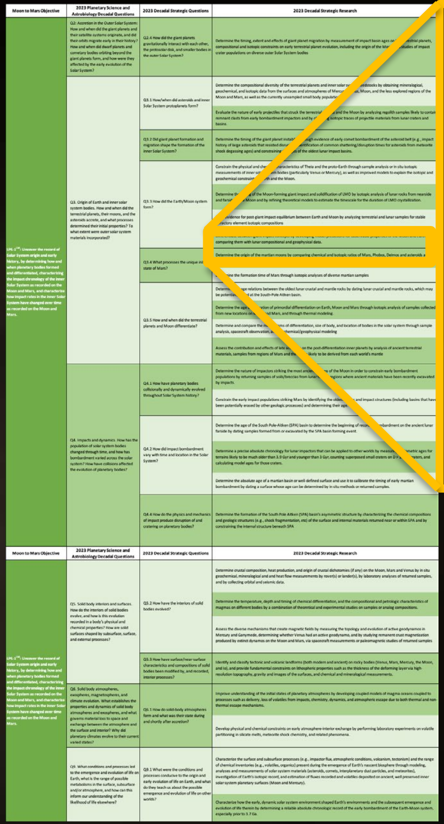
CLPS-Hosted Payloads

How Science Fits within Artemis Mission Planning



Progress towards M2M Objectives

- Progress towards addressing Science Objectives should be measured differently than currently represented by existing metrics for elements, vehicles, and systems
  - Science objectives are never fully satisfied and instead evolve and generate new questions the more we uncover
- Incremental progress towards addressing an objective(s) is made through execution of our mission-specific science campaigns utilizing both robotic and human elements.
- Significant progress towards an objective requires post-mission research and analyses, which may not be known for years



Appendix C from M2M Strategy and Objectives Development Document

Strategic Research: Determine the timing of the Moon-forming giant impact and solidification of Lunar Magma Ocean (LMO) by isotopic analysis of lunar rocks from nearside and farside of the Moon and by refining theoretical models to estimate the timescale for the duration of LMO crystallization.

Science decomposition will lead to additional needs, e.g., local/global access to diverse locations/geological units, sample return, in situ analyses, deployment of diverse instruments, access to subsurface, etc. Additionally, R&A programs need time to parse and analyze the data… we may not know how much progress we've made towards an objective for years.

- What metrics need to be established in order to track progress against an ever-evolving end goal?

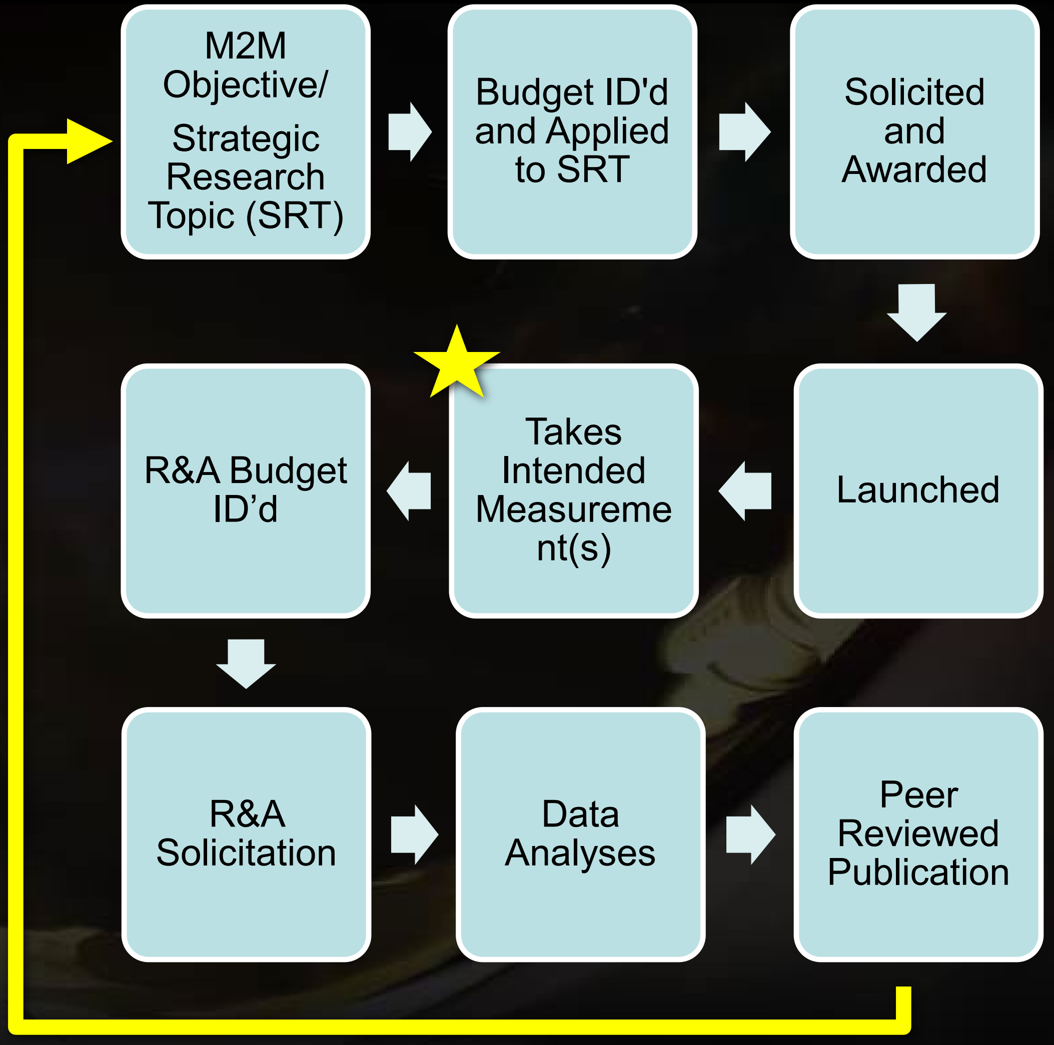
SMD Proposed Metrics and Values

- Given that each investigation makes incremental progress towards addressing M2M objectives, values will be captured through a series of waypoints, each a required gate to get from one stage to another.

- Generation of a heatmap against all M2M Science Objectives and Strategic Research topics
  - SMD will bin/track instruments/investments against each individual M2M science objective and the Strategic Research topics

- Decadal Surveys reset the bar every 5-10 years based on how well we've addressed each objective
  - Need to revise objectives based on new decadal priorities that have been released in the past two years (HS, HBS, PPS)
    - To stay current and relevant to all science disciplines, updates to M2M Objectives need to occur regularly

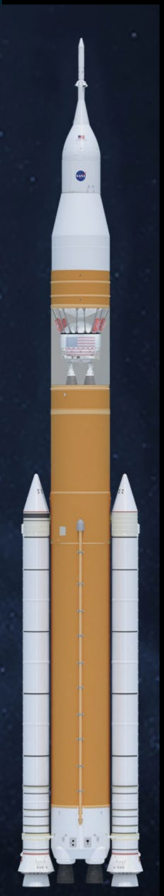
The Science Decomposition process will be enacted as a SAC25 task and will result in an annual mapping of assets/investments to the decomposition to show progress towards M2M Science Objectives



Science Strategy and Decadals

★ Assessment of how well an investigation was accomplished in a given mission

Science on the Moon: Human and Robotic



Artemis Human Missions <M2M Obj. Focus>

- Artemis II <LPS-1, HBS-1>: Photographic observations of varied lunar geologic terrain; impact flashes; conops/data archiving pathfinding; space biology
- Artemis III <LPS-2, 3, HS-2, HBS-1>: seismology; space biology; electrostatics
- Artemis IV <LPS-1, 2, HS-1>: A4 Science Campaign TBD; A4 deployed instruments; environmental characterization
- Artemis V <LPS-1,2,3>:; A5 Science Campaign TBD; A5 deployed instruments; LTV ops; cold-conditioned sampling
- LTV <LPS-1, 2, 3>: Enables crew-enhanced science campaign; uncrewed mode utilizes science instrumentation to take measurements during traverses; robotic arm allows for subsurface sampling and instrument deployment; Instruments solicitation out in 2024
- Handheld Instruments <LPS-1, 2, 3>: characterization of geologic samples/units

Artemis Orbital Missions:

- LRO <LPS-1, 2, 3> – supporting landing site analyses; volatile content; thermal environment
- Lunar Trailblazer <LPS-2, 3>– Lunar surface mineralogy, volatile content and temperature maps
- HERMES <HS1, 4> – Gateway Instrument suite; space weather; magnetotail and solar wind dynamics

Artemis CLPS Missions <M2M Obj. Focus>:

- PRIME-1 (IM, 2024) <LPS-3>: South Pole volatiles; rocket drone to PSR; wifi comm tech demo; collaboration with STMD
- 19D (FF, 2024) <LPS-2>: Geophysics of Crisium Basin; tech demos
- CP-11 (IM, 2025) <LPS-2, HS-1>: magnetic anomalies/swirls; solar wind/dust/plasma
- CS-3 (FF, 2025) <PP-1>: Cosmology observations from lunar far side; collaboration with Dept. of Energy
- CP-12 (Draper, 2026) <LPS-2, PP-1>: Seismology; heat flow; magnetotellurics; electromagnetics
- CP-22 (TBD, 2027) <LPS-2, 3, HBS-1>: Space biology; mineralogy; volatiles
- CP-21 (TBD, 2028) <LPS-1, 2>: Volcanics; plume-surface interactions
- CP-32 (TBD, 2029) <LPS-1, 2>: Geochronology; volcanics
- CS-6 (TBD, 2029) <LPS-2, 3>: Composition and temperature of regolith; polar volatiles

Current Science Activities Advancing M2M Objectives

M2M Objective	Activity (Enabling Exploration Element)
LPS-1: Solar system origin and early history	DIMPLE (CP-32, CLPS); Artemis IV Geochronology Science Campaign & Sample Return (Artemis IV); Handheld Instruments (Artemis IV+); Endurance Rover (CLPS); Sample Return (MSR)
LPS-2: Planetary Interiors and Processes	LEMS (Artemis III); Lunar-VISE (CP-22, CLPS); Lunar Vertex (CP-11, CLPS), FSS and LITMS (CP-12, CLPS); DIMPLE (CP-32, CLPS); CSA LEAP Rover/LAFORGE (CLPS)*; Lunar Geophysical Network (CLPS); NGLR/LMS/LISTER (19D, CLPS); APXS/ChemCam/CheMin/REMS (Curiosity); Sample Return (MSR); Supercam/PIXL/MEDA/RIMFAX (Perseverance)
LPS-3: Volatiles	PROSPECT* (CP-22, CLPS, ESA); Neutron spectrometer copies on ~4 missions (MoonRanger/CLPS, LuPEX/JAXA*, PM-1, VIPER); TBD LTV instruments (LTV); Pyrometer data from IM hopper in PSRs (CLPS/STMD); Freezers/Cold curation of samples (Artemis V+); PRIME-1 drill and mass spec (CLPS/STMD); LDA* (Artemis III); DAN (Curiosity); Sample Return (MSR); SHERLOC/RIMFAX (Perseverance)
LPS-4: Life in the Universe	Mars Sample Return (MSR); SAM Suite (Curiosity); SHERLOC/PIXL (Perseverance); NIAC Study for Life Detection Instrumentation; SAG for in-situ life detection rover; MOMA* (Rosalind-Franklin/ESA)
HS-1: Space Weather	LETS instrument on 3 missions (CLPS, Beresheet*); Lunar Vertex (CP-11, CLPS); HERMES (Gateway); ERSA* (Gateway, ESA); IDA* (Gateway, JAXA); RAD (Curiosity);
HS-2: Solar History	Requires sample return from Artemis missions; Mars Sample Return (MSR)
HS-3: Plasma/Dust	Lunar Vertex (CP-11, CLPS)
HS-4: Magnetotail and Solar Wind Dynamics	Lunar Vertex (CP-11, CLPS); HERMES (Gateway); ERSA* (Gateway, ESA); IDA* (Gateway, JAXA); EscaPADE
HBS-1: Effects of space on Biological Systems	LEIA (CP-22, CLPS); LEAF (Artemis III); AVATAR (Artemis II+); Immune Biomarkers** (Artemis II); ARCHeR** (Artemis II+); Lunar Landing & Egress** (Artemis III); Lunar Landing/Ascent Dynamics** (Artemis III+); Physiological & Psychological Assessments** (Artemis III+); Mars Sample Return (MSR)
HBS-2: Earth-Independent Crew Health & Perf.	ARCHeR** (Artemis II+); Pharm** (Artemis IV+); Physiological & Psychological Assessments** (Artemis III+)
HBS-3: Human Systems Integration with Architecture	Immune Biomarkers** (Artemis II); ARCHeR** (Artemis II+); Lunar Landing & Egress** (Artemis III); Lunar Landing/Ascent Dynamics** (Artemis III+); Physiological & Psychological Assessments** (Artemis III+)
PPS-1: Astrophysics and Fundamental Physics	LuSEE Night (CS-3, CLPS, NASA/DoE)
PPS-2: Physical Systems	RAC/RADPC (19D, CLPS). Flammability of Materials at the Moon (FM2) (Starship Uncrewed Demo)

* International Partnership; ** SOMD/HRP led project

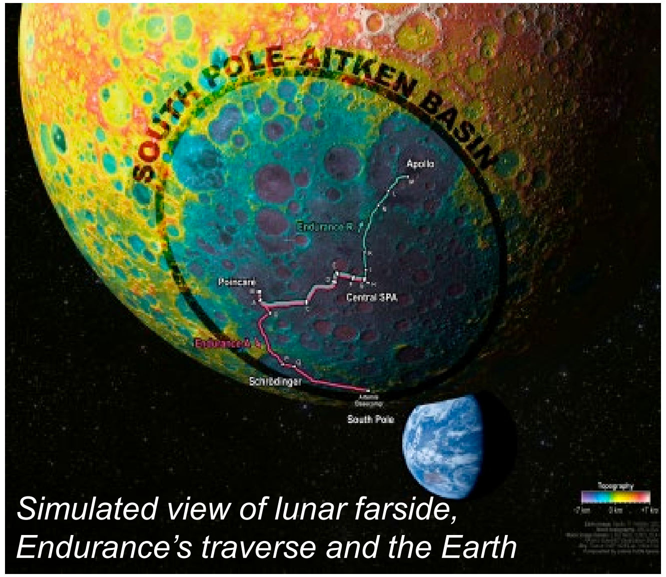
Current Science Activities Advancing M2M Objectives

M2M Objective	Activity (Enabling Exploration Element)
LPS-1: Solar system origin and early history	DIMPLE (CP-32, CLPS); Artemis IV Geochronology Science Campaign & Sample Return (Artemis IV); Handheld Instruments (Artemis IV+); Endurance Rover (CLPS); Sample Return (MSR)
LPS-2: Planetary Interiors and Processes	LEMS (Artemis III); Lunar-VISE (CP-22, CLPS); Lunar Vertex (CP-11, CLPS), FSS and LITMS (CP-12, CLPS); DIMPLE (CP-32, CLPS); CSA LEAP Rover/LAFORGE (CLPS)*; Lunar Geophysical Network (CLPS); NGLR/LMS/LISTER (19D, CLPS); APXS/ChemCam/CheMin/REMS (Curiosity); Sample Return (MSR); Supercam/PIXL/MEDA/RIMFAX (Perseverance)
LPS-3: Volatiles	PROSPECT* (CP-22, CLPS, ESA); Neutron spectrometer copies on ~4 missions (MoonRanger/CLPS, LuPEX/JAXA*, ~~PM-1,~~ VIPER); TBD LTV instruments (LTV); ~~Pyrometer data from IM hopper in PSRs (CLPS/STMD);~~ Freezers/Cold curation of samples (Artemis V+); ~~PRIME-1 drill and mass spec (CLPS/STMD);~~ LDA* (Artemis III); DAN (Curiosity); Sample Return (MSR); SHERLOC/RIMFAX (Perseverance)
LPS-4: Life in the Universe	Mars Sample Return (MSR); SAM Suite (Curiosity); SHERLOC/PIXL (Perseverance); NIAC Study for Life Detection Instrumentation; SAG for in-situ life detection rover; MOMA* (Rosalind-Franklin/ESA)
HS-1: Space Weather	LETS instrument on 3 missions (CLPS, Beresheet*); Lunar Vertex (CP-11, CLPS); HERMES (Gateway); ERSA* (Gateway, ESA); IDA* (Gateway, JAXA); RAD (Curiosity);
HS-2: Solar History	Requires sample return from Artemis missions; Mars Sample Return (MSR)
HS-3: Plasma/Dust	Lunar Vertex (CP-11, CLPS)
HS-4: Magnetotail and Solar Wind Dynamics	Lunar Vertex (CP-11, CLPS); HERMES (Gateway); ERSA* (Gateway, ESA); IDA* (Gateway, JAXA); EscaPADE
HBS-1: Effects of space on Biological Systems	LEIA (CP-22, CLPS); LEAF (Artemis III); AVATAR (Artemis II+); Immune Biomarkers** (Artemis II); ARCHeR** (Artemis II+); Lunar Landing & Egress** (Artemis III); Lunar Landing/Ascent Dynamics** (Artemis III+); Physiological & Psychological Assessments** (Artemis III+); Mars Sample Return (MSR)
HBS-2: Earth-Independent Crew Health & Perf.	ARCHeR** (Artemis II+); Pharm** (Artemis IV+); Physiological & Psychological Assessments** (Artemis III+)
HBS-3: Human Systems Integration with Architecture	Immune Biomarkers** (Artemis II); ARCHeR** (Artemis II+); Lunar Landing & Egress** (Artemis III); Lunar Landing/Ascent Dynamics** (Artemis III+); Physiological & Psychological Assessments** (Artemis III+)
PPS-1: Astrophysics and Fundamental Physics	LuSEE Night (CS-3, CLPS, NASA/DoE)
PPS-2: Physical Systems	RAC/RADPC (19D, CLPS); Flammability of Materials at the Moon (FM2) (Starship Uncrewed Demo)

* International Partnership; ** SOMD/HRP led project

Progress towards South Pole-Aitken Sample Return Campaign

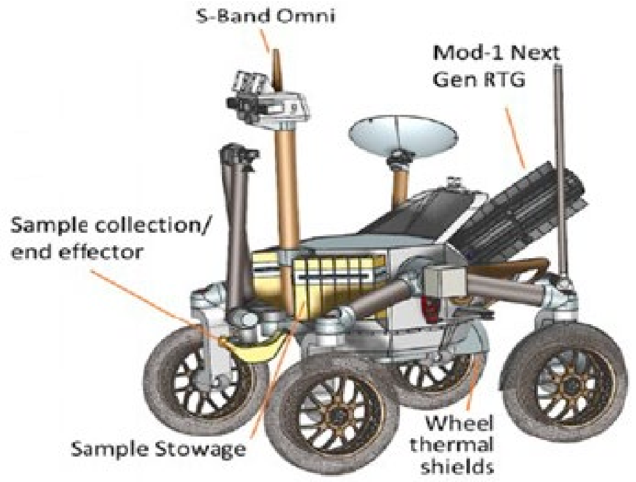
- **Top lunar priority of the Planetary Decadal Survey: "Endurance A"**
  - long-duration rover
  - traverses ~2000km
  - Brings ~100kg of samples, taken at strategic sites throughout the South Pole-Aitken basin, to South Pole for HLS to Earth



Simulated view of lunar farside, Endurance's traverse and the Earth

> ***Recommendation*: Endurance-A should be implemented as a *strategic medium-class mission* as the *highest priority* of the Lunar Discovery and Exploration Program. Endurance-A would utilize CLPS to deliver the rover to the Moon, a long-range traverse to collect a substantial mass of high-value samples, and astronauts to return them to Earth.** – *Origins, Worlds, and Life (Planetary Decadal), 22-17*

- **Activity on SPA Sample Return**
  - Established the South Pole-Aitken Basin Sample Return and eXploration (SPARX) Science Definition Team (SDT)
  - Contracts with JPL to conduct multiple studies
    - Rover translation speed
    - Autonomous roving capabilities
    - Integration and field testing
    - Mobility/robotic arm
    - Actuators
    - LIDAR & GNC.

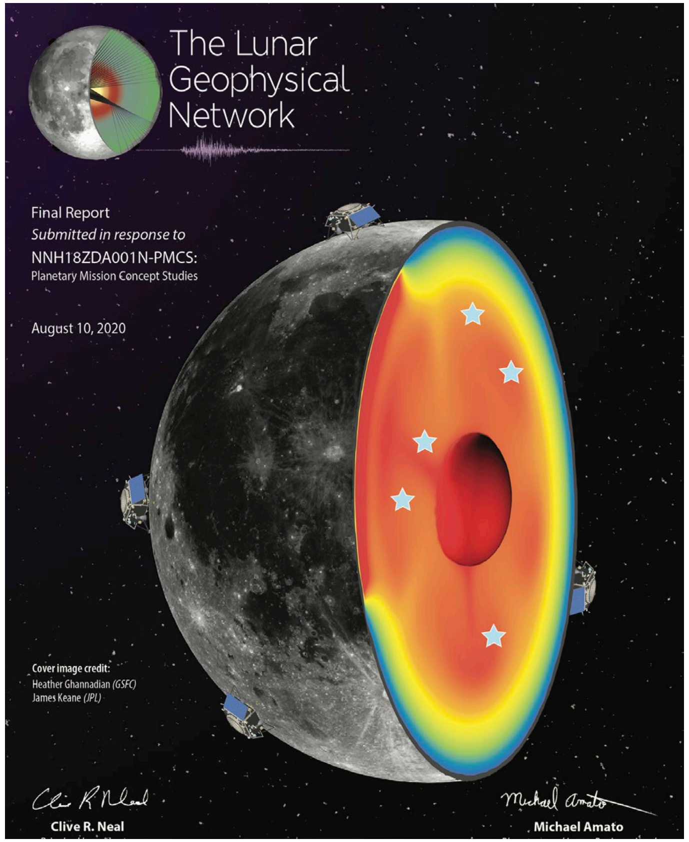


The full Endurance Report is available at https://tinyurl.com/2p88fx4f

Progress towards Lunar Geophysical Network

- **High lunar priority of the Planetary Decadal Survey**
  - A global network of geophysical instruments operating concurrently on the lunar surface for > 6 years
  - At least 4 nodes required with more optimal
  - Measurements taken: seismic, heat flow, laser ranging, magnetic field/electromagnetic sounding

***Recommendation*: The Lunar Geophysical Network should be listed among the candidate mission themes for New Frontiers 5, 6, and 7 … to determine the internal structure, constrain composition, mineralogy, discover the origins of lunar seismic activity, provide insights into current dynamics of lunar interior, and constrain distribution of heat producing elements and thermal evolution of the Moon –** *Origins, Worlds, and Life (Planetary Decadal), 22-33*



- **Progress towards achieving LGN science**
  - Successful demonstrations of Lunar Magnetotelluric System (LMS) and Next Generation Laser Retroreflector (NGLR) on Firefly Blue Ghost Mission 1 on the lunar surface.
  - FSS and LITMS on upcoming CLPS delivery CP-12 and and LEMS on Artemis III crewed mission.
  - Conducting a NASA internal study to look at technical and science challenges of accomplishing the mission with the CLPS approach and identify likely solutions and major issues or trades.

"Finding 2: The science proposed by the Lunar Geophysical Network (LGN) addresses multiple decadal survey priority science questions. There are currently no programmatic avenues, including the NASA Lunar Discovery and Exploration Program (LDEP) and the Commercial Lunar Payload Services, that could accomplish LGN other than the New Frontiers (NF) program. Therefore, the inclusion of LGN as a theme in the next NF announcement of opportunity is warranted." - *Proposed Science Themes for NASA's 5th New Frontiers Mission – NASEM (2025)*

CLPS Indefinite Delivery Indefinite Quantity (IDIQ) Contract and Portfolio

- 14 domestic companies eligible to compete for Lunar surface delivery task orders
- 8 awarded lunar surface deliveries actively in work with initial deliveries as soon as Q1 2023
- NASA expects to continue cadence of ~2 flights per year
- CLPS contractors are encouraged to sell lunar delivery services outside of the CLPS IDIQ to non-NASA and non-USG customers

Initial CLPS companies (Nov 2018):

- Astrobotic
- Deep Space Systems
- Draper
- Firefly Aerospace
- Intuitive Machines
- Lockheed Martin Space
- Masten Space Systems
- Moon Express
- Orbit Beyond

First On-Ramp (Nov 2019):

- Blue Origin
- Ceres Robotics
- Sierra Nevada Corporation
- SpaceX
- Tyvak Nano-Satellite Systems, Inc.

Awarded Deliveries

TO2AB 2024
Astrobotic
Peregrine

TO2IM/20C 2024
Intuitive Machines
NOVA-C

TO19D 2025
Firefly Aerospace
Blue Ghost

PRIME-1 2025
Intuitive Machines
NOVA-C

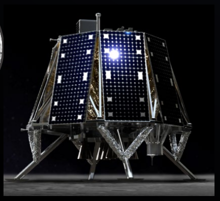
CT-3 2025
Blue Origin
Blue Moon Mark 1

CP-11 2025
Intuitive Machines
NOVA-C

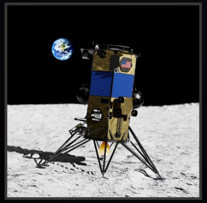
TO20A 2025
Astrobotic
Griffin

TOCS3/CS4 2026
Firefly Aerospace
Blue Ghost

CP-12 2026
Draper
APEX 1.0



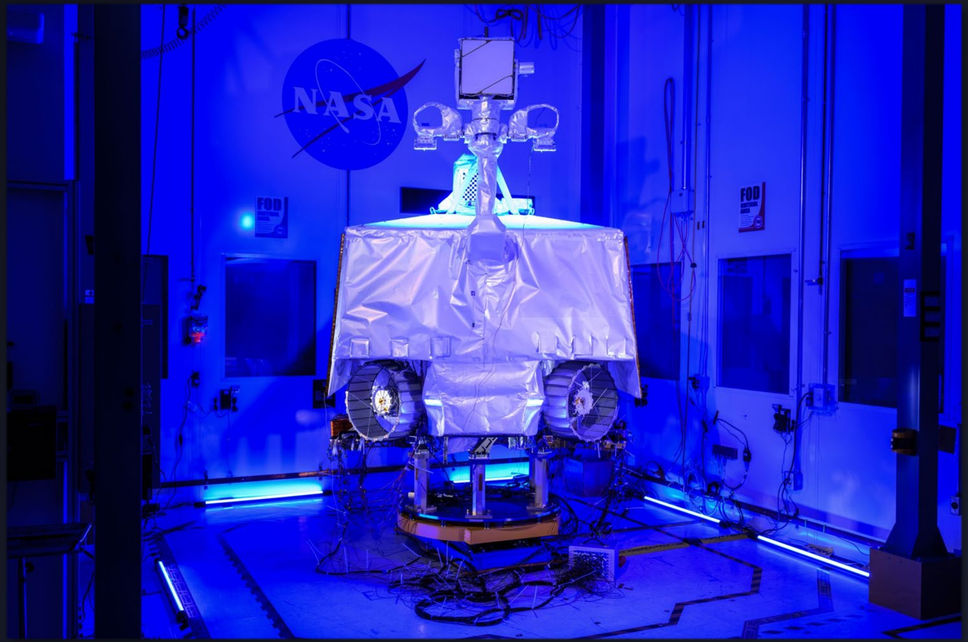
TO CP-22 2027
Intuitive Machines
NOVA-C



CP-21 2028
Firefly
Blue Ghost 3

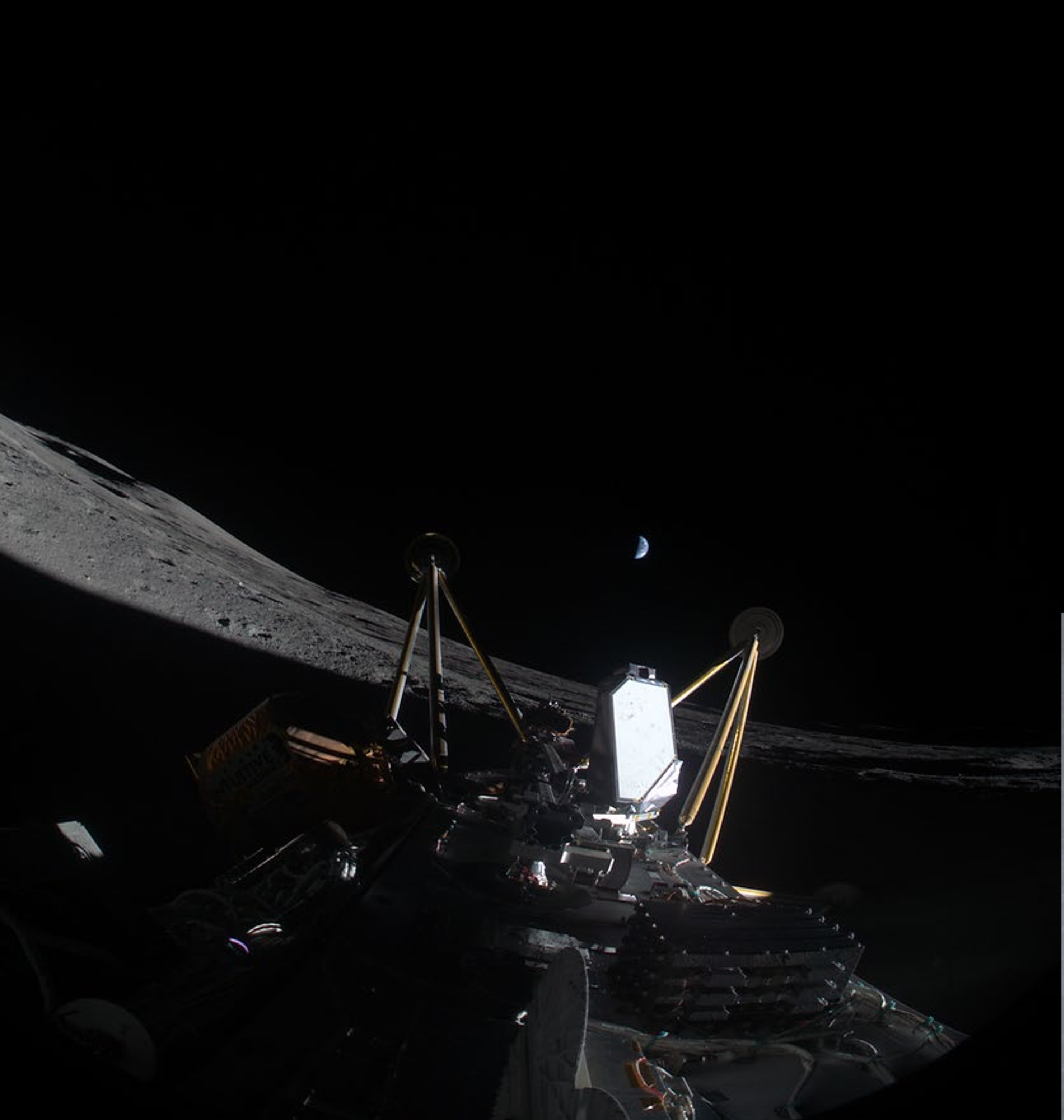
VIPER

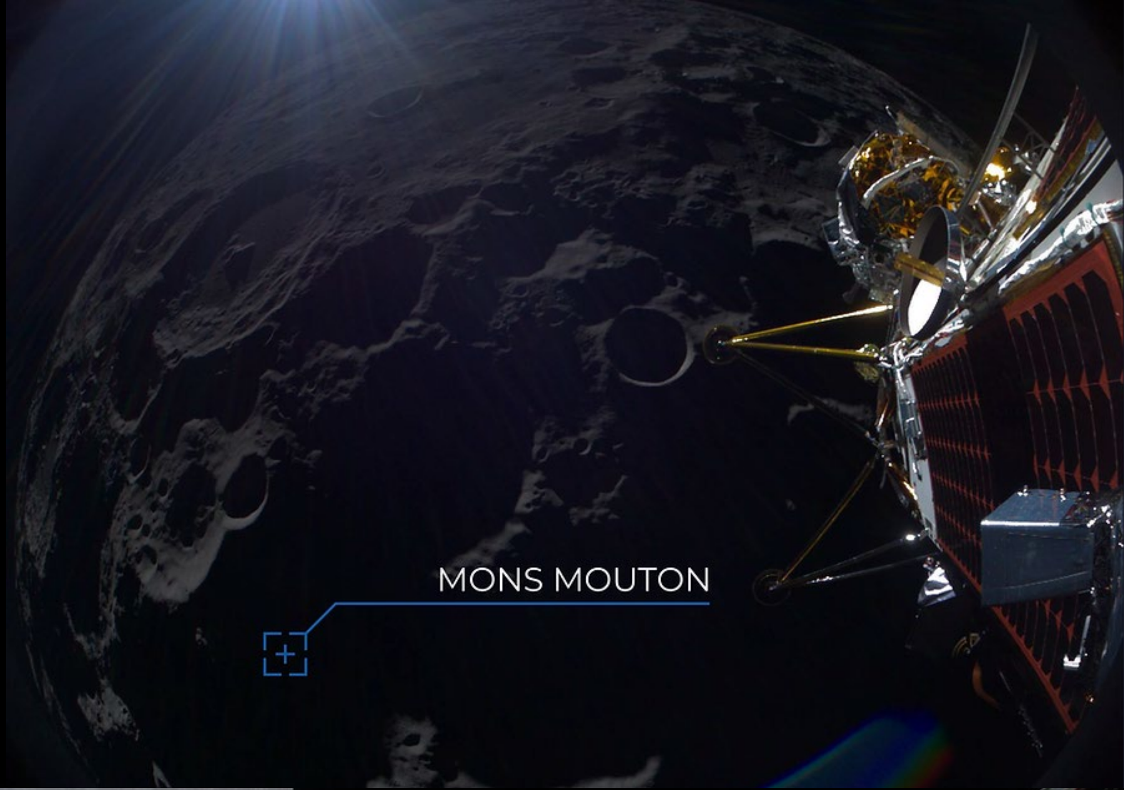
- Following project cancellation, SMD is exploring partnership opportunities to land VIPER on the Moon and accomplish mission science objectives
- Announcement for Partnership Proposals (AFPP) released February 3, 2025
  - Step-1 proposals received March 3, 2025; evaluations underway
  - Seek to complete evaluations Summer 2025



IM-2 Update

- Launched February 26;
- Touchdown March 6
- Images and onboard IMU indicated that the Athena Lander had landed on its side
- Contingency ops allowed for exercising the TRIDENT drill and MSolo mass spectrometer
- Other NASA-supported payloads (Micro Nova Hopper and Nokia 3GPP demonstration) were unable to complete objectives
- End of Mission called at 12:15 am March 7

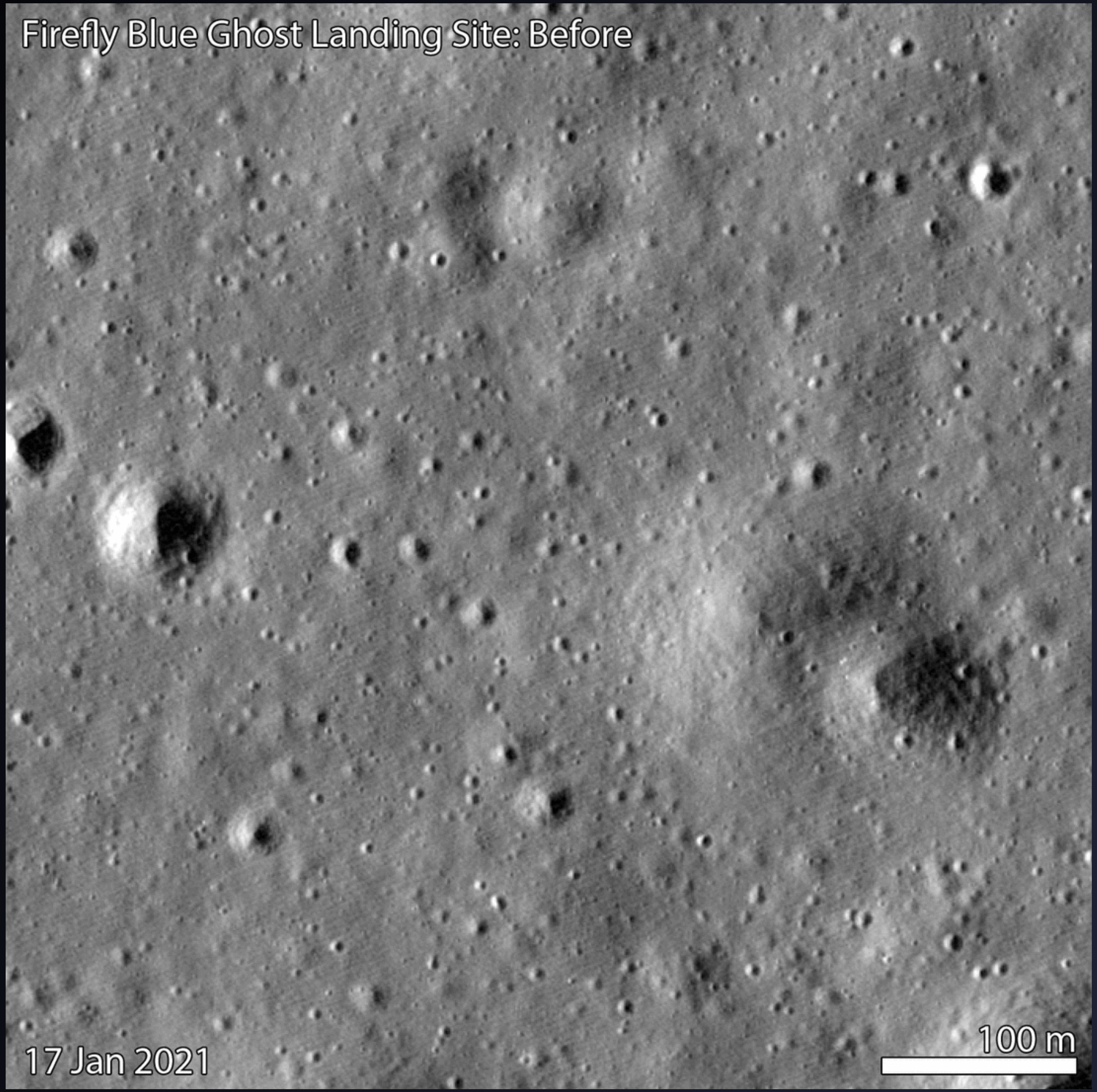




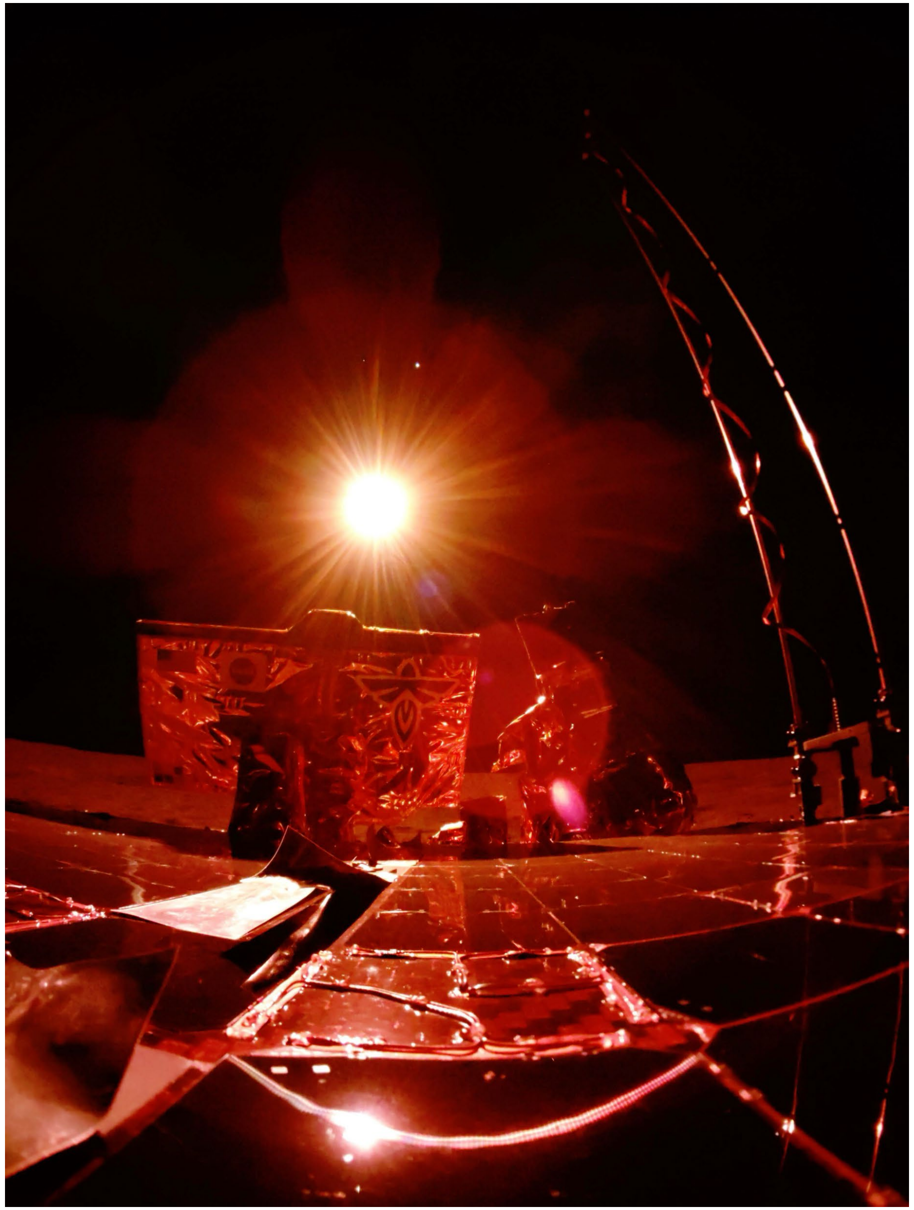
All images credited to Intuitive Machines


Firefly BGM-1 Update

Blue Ghost Mission 1



Credit: LROC

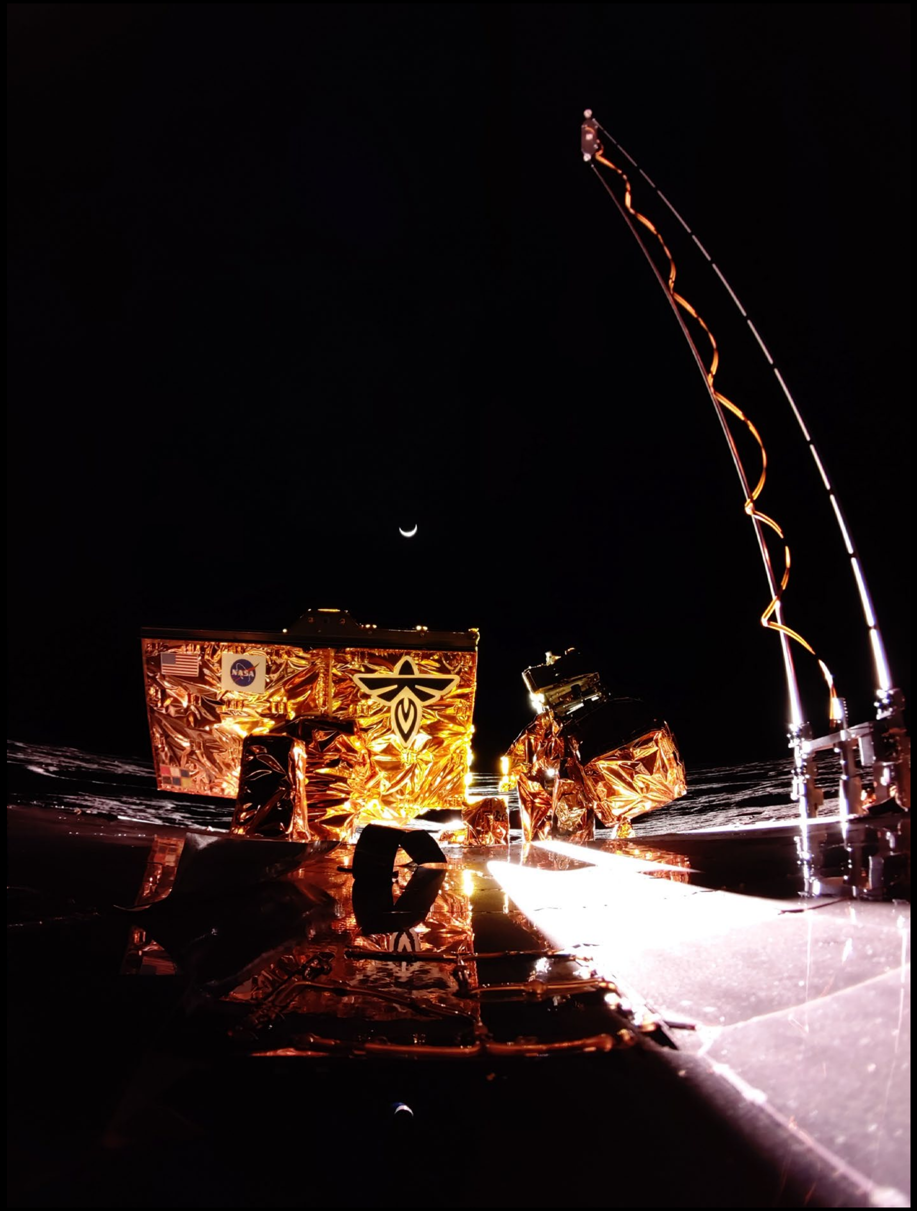


BGM-1 Final Illuminated Image

EOM: March 16, 2025. 6:15 CDT

Operations continued several hours into lunar night operations/survival

- LMS and LEXI data through LN+30 mins, ~4:14 CDT (21:14 UTC),
- LuGRE data through EOM – 1 hr, until ~5:00 CDT (22:00 UTC)
- SCALPSS as long as there is light, so LN+20 mins, ~4:04 CDT (21:04 UTC)
- LISTER and RadPC as long as possible
- All goals were achieved.



CLPS Firefly BGM-1: Mission Success Criteria

Payload	Criteria	Minimum Criteria	Full Criteria	Augmented/Night Ops
LuGRE	Receive and downlink GNSS measurements and demonstrate navigation.	Reception: Receive and downlink at least one type of GNSS measurement from any of the GPS L1 C/A, GPS L5, Galileo E1, or Galileo E5a signals, at the Moon. [L101] Navigation: Demonstrate GNSS-based navigation in transit beyond 30 RE from Earth or on the lunar surface using payload-collected data. [L102] Supporting criteria: Perform at least 1 high-rate sample collection operation.	Reception: Receive and downlink GNSS measurements from the GPS L1 C/A and L5 signals, and from the Galileo E1 and E5a signals, at the Moon. [L101] Navigation: Demonstrate real-time GNSS-based navigation in transit beyond 30 Earth radii (RE) from Earth and on the lunar surface. [L102] Supporting criteria: Perform both planned high-rate sample collection operations.	Perform full set of transit operations and collect data up to the full duration of the surface mission. Night Ops: Continue measurements into nightfall to capture data as GNSS constellations set behind the limb of the Moon.
LMS	Electric and Magnetic Field Time Series	Collect data for a minimum of 96 hours. Measure 3 components of the magnetic field and 1 component of electric field.	Collect data to the end of the daytime mission Measure 3 components of magnetic field and 2 components of electric field	Night Ops: Continue measurements past nightfall as long as possible to assess abrupt change in environment
SCALPSS	SFL Image sets (1 frame each/4 SFL cameras) + timestamp LFL Image sets (1 frame each/2 LFL cameras) + timestamp	1 full resolution (HDR) SFL image set taken after the lander is at rest on the surface and all dust has settled (@ TD+10s) PLUS 1 full resolution LFL image set taken from altitude (~8m) prior to the onset of PSI	LFL descent image sets @ 10 fps from 50m to 5m in altitude PLUS SFL descent image sets @ 8 fps from 30m altitude to TD+10s (~25 sec), plus surface full resolution (HDR) SFL image sets every 10 sec from TD+10s for 10min, then every 1m for 10min, then every 10m for 1h and then hourly to TD+4h	1 full resolution (HDR) SFL image set each hour during day ops; 1 HDR image set each minute beginning around sunset - 10m
EDS	Images of the EDS at various levels of dusting	Image with dust on the EDS and image after EDS operation	Image with dust on the EDS, video during EDS operation, and image after Footpad EDS operation	(Extended A) Video during re-dusting and video during EDS operation. (Extended B) Video during concurrent re-dusting and EDS operation.
LISTER	Demonstrate pneumatic drilling and measurement of temperature and thermal conductivity. FF to provide images from the drilling operation.	LISTER performs nominal deployment and commissioning. If mechanism can contact lunar surface, then one thermal-conductivity measurement will be performed.	Penetrate the regolith (LISTER) at 2 depths >1 m with spacing >0.3 m, performing passive and active thermal measurements.	Zombie Ops!! Periodically measure the bottomhole and mechanism temperatures until the end of the mission.

CLPS Firefly BGM-1: Mission Success Criteria

Payload	Criteria	Minimum Criteria	Full Criteria	Augmented/Night Ops
RAC	Digital photographs of RAC payload materials samples	One set of digital photographs of all 30 RAC payload materials samples. Each sampe photographed from above and below.	Digital photographs of all 30 RAC payload materials samples taken once-per-day during 7 days of the surface mission duration. Each sample photographed from above and below	
RadPC	Operate during transit and on the lunar surface and receive time geo/stamped data	Successfully operate the RadPC payload for 4 hours during transit and successfully receive 3.7 Mbytes of time/geo-stamped data back. Successfully operate the RadPC payload for 4 hours on the lunar surface and successfully receive 3.7 Mbytes of time/geo-stamped data back.	Successfully operate the RadPC payload for 750 hours during transit and successfully receive 691 Mbytes of time/geo-stamped data back. Successfully operate the RadPC payload for 230 hours on the lunar surface and successfully receive 211 Mbytes of time/geo-stamped data back.	RadPC Lunar Night Operations
LPV	Deliver regolith to sample container. Take images before and after delivery. Capture beam breaker data. FF to provide images of the surface before and after sampling.	Deliver 1 g regolith to sample container and verify delivery using beam breaker and camera. FF to provide images of the surface before and after sampling.	Deliver 10 g regolith to sample container and verify delivery using beam breaker. Take images before and after delivery. Perform sieving operation and take images before and after. FF to provide images of the surface before and after sampling.	Deliver multiple samples to sample container while verifying with a beam breaker and/or via image, and perform sieving operations.
LEXI	Monitoring the position of Earth's subsolar magnetopause as a function of time through pointed X-ray imaging	Pointed measurements of Earth's magnetosheath and dayside magnetopause to monitor subsolar magnetopause position to within 0.3 RE.	Collect imaging data for a minimum of 156 hours while pointed at Earth's magnetosheath and dayside magnetopause. Image with absolute knowledge and control more accurate than 0.3deg to measure the position of the subsolar magnetopause with 5 minute cadence	Observe flank magnetosheath LEXI Lunar night operations
NGLR	Lunar Laser Ranging Range Measures by LLROs	Deployment with an unobstructed view to Earth for ranging by LLROs	Known landing site location/orientation Receive A Laser Return form One LLRO	Receive more than one Laser Returns from more than one LLRO

Green – Mission success criteria accomplished

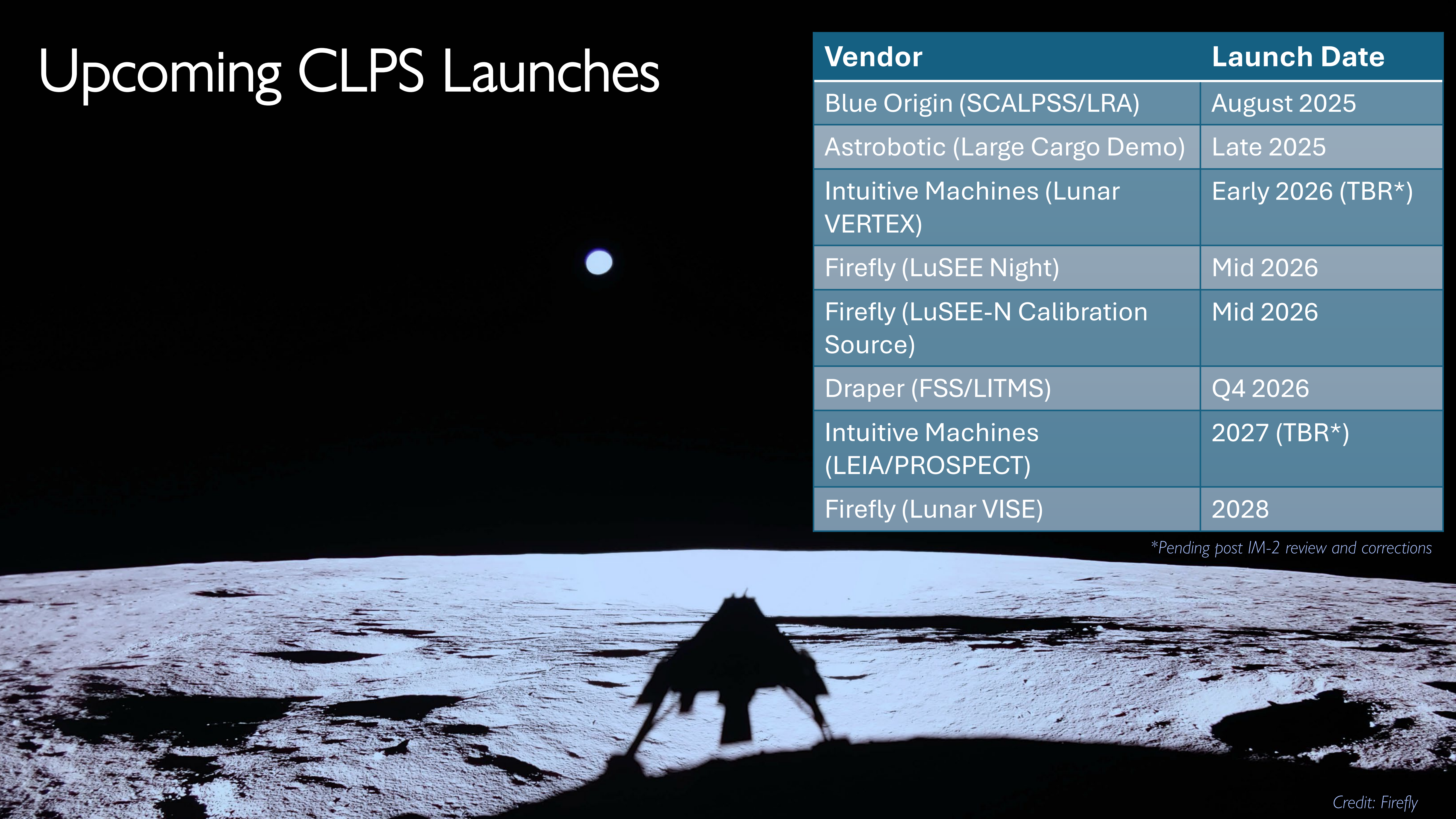
* - Operational for ~186 hours

** - Data collected. Science team determining fidelity of data.

Upcoming CLPS Launches

Vendor	Launch Date
Blue Origin (SCALPSS/LRA)	August 2025
Astrobotic (Large Cargo Demo)	Late 2025
Intuitive Machines (Lunar VERTEX)	Early 2026 (TBR*)
Firefly (LuSEE Night)	Mid 2026
Firefly (LuSEE-N Calibration Source)	Mid 2026
Draper (FSS/LITMS)	Q4 2026
Intuitive Machines (LEIA/PROSPECT)	2027 (TBR*)
Firefly (Lunar VISE)	2028

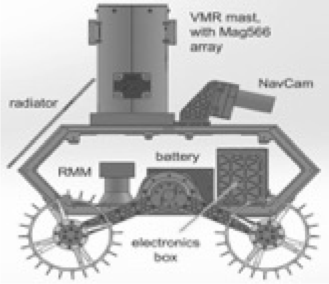
**Pending post IM-2 review and corrections*

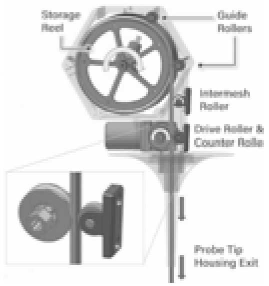


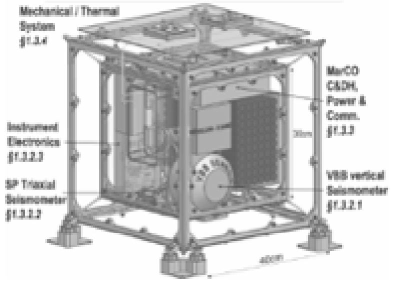
Credit: Firefly

Future Direction of CLPS

- **Continue building the commercial market; CLPS service options are expected to expand as market and company capabilities evolve**
- **Estimating periodic on-ramp opportunities into the CLPS Vendor Pool going forward depending upon need and service availability**
- **Maintain flexibility of the CLPS IDIQ to award Task Orders for upcoming capabilities, data buys**
- **SMD manifests will continue to be competitively-selected payloads**
- **Expect to continue cadence of ~2 flights per year**
- **Support of other mission directorates and international partners through delivery of priority science/technology investigations to the lunar surface**







- **Support of Artemis crewed activities through delivery of scientific equipment, supplies for longer duration missions, human-centric infrastructure (e.g., LTV, ISRU demos/equipment, etc.)**
- **New capabilities that would enhance science return, ops, and open new avenues for scientific investigations**
  - ➢ **Mobility**
  - ➢ **Orbital Drop-off**
  - ➢ **Comm Relay**
  - ➢ **Electro Magnetic Interference Quiet Operation**
  - ➢ **Increased Delivery Mass**
  - ➢ **Surviving/operation throughout the lunar night**
  - ➢ **Articulation**
  - ➢ **PSR/Cold Operations**
  - ➢ **Sample Return**

Current International Collaborations on Artemis & CLPS

IP Hardware/Instruments on Artemis

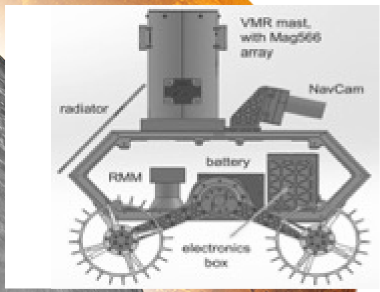
- Lunar Dielectric Analyzer (LDA), JAXA, Artemis III, A3DI
- Power/Communications Station for Deployed Instruments, ESA, Artemis IV+, NASA/ESA Utilization Technical Understanding

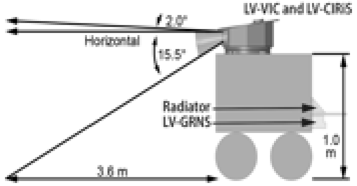
IP Contributions/Instruments on CLPS

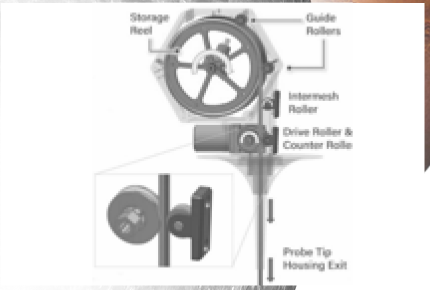
- PITMS, ESA, TO2-AB (Did not land)
- LuSEE-Light, CNES, CP-12 (Schrodinger Basin)
- MPAC Retroreflector, ESA, CP-11 (Reiner Gamma)
- LUSEM, KASI, CP-11 (Reiner Gamma)
- PROSPECT, ESA, CP-22 (South Pole)
- DIMPLE, CP-32 (Ina Irregular Mare Patch)
- Lunar Pathfinder Comm Relay, ESA/SSTL, CS-3 (Orbital drop-off)
- Lunar Rover Mission (LRM), CSA, CS-6 (South Pole)
- Laser Ablation Ionization Mass Spectrometer (LIMS), SSO, CS-6 (South Pole)
- LVRAD/LMAG/GrainCams, KASI, Not manifested yet

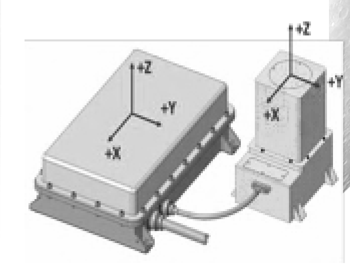
Current/Future US Science Hardware/Instruments on IP Platforms

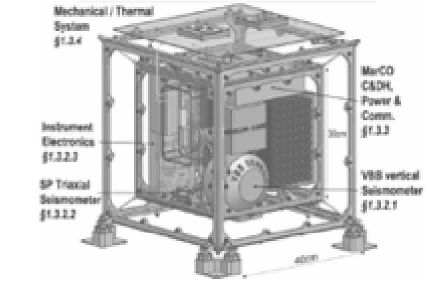
- Pressurized Rover (JAXA) Instruments
- Multi-Purpose Habitat (ASI) Instruments
- Argonaut Lander (ESA)
- LRAs on SLIM (JAXA) and Beresheet (ISA)
- Neutron Spectrometer System on LUPEX (JAXA)
- Shadowcam on KPLO (KARI)
- LETS on Beresheet (ISA)





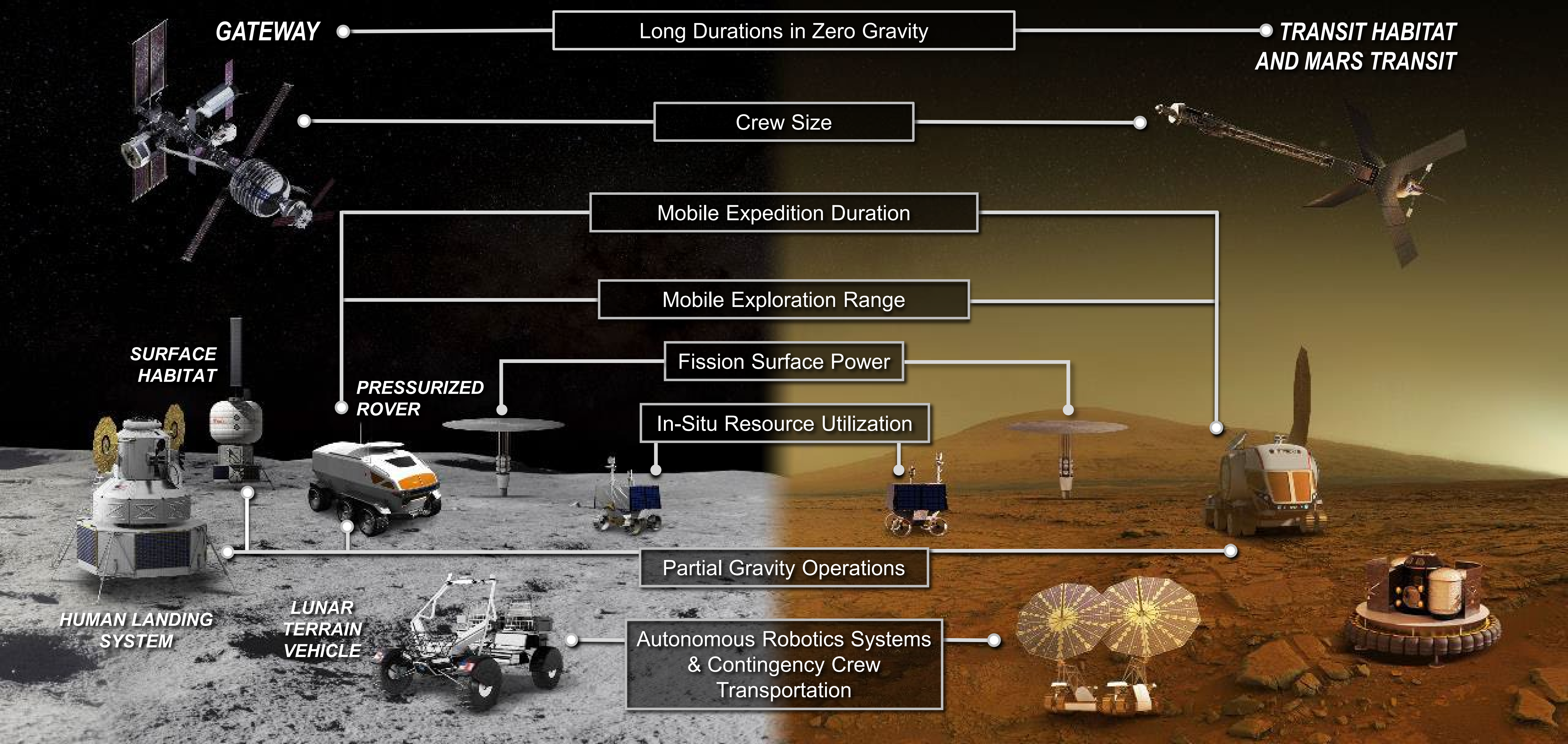






MOON AND MARS EXPLORATION

Scientific exploration and operations at the Moon will help prepare for the first human missions to Mars



Open and Upcoming Program Elements

- Artemis IV Deployed Instruments (received March 7)
- PRISM Stand-Alone Landing Site Agnostic (SALSA)
- PRISM-4
- Artemis III Participating Scientists
- Artemis Handheld Instruments

Other Engagement Opportunities

- Lunar Surface Science Workshops
  - Uncrewed Science with Pressurized Rover (April 9 to 10)
  - Outbriefs from NASA Headquarters and Artemis (May 7)
  - Artemis Orienteering / Geolocation (TBD)
- Mars Surface Science Workshops
- Community-led Studies (commissioned and ongoing)
  - South Pole-Aitken Basin Sample Return and eXploration (SPARX)
  - NASEM: Science with Humans on Mars; Non-Polar Lunar Science

Backup

Backup: SPARX TOR

- Define and prioritize science goals for a South Pole-Aitken Basin Sample Return and Exploration mission that is traceable to the science questions and objectives outlined in the OWL and other community documents such as, but not limited to, the Scientific Context for the Exploration of the Moon (SCEM) Report;
  - The committee shall consider and prioritize scientific objectives that are relevant to both sample return and in-situ measurements within SPA.
- Define a hierarchy of science objectives that are responsive to the prioritized goals above and identify the criteria that will enable these objectives to be met;
- Discuss the criteria used to prioritize the science goals and objectives;
- Determine example location(s) in SPA where the science goals can be met;
- Define the number and type of samples and in situ measurements that are needed to address the prioritized science objectives. The committee should specify key measurements, if any, that must be made in-situ or on the lunar surface as well as those that must be made in terrestrial labs in order to achieve the identified science objectives;
  - The committee shall also note the minimum expected number of kilograms of samples required to meet the baseline and threshold objectives.
- Define a set of strawman science instrument types that fully address the SDT-defined science objectives, as well as their required measurement capabilities;
  - At the proper time NASA will determine the final science payload suite for the mission.
- Develop a Science Traceability Matrix (STM) that flows from the top-level science goals through science objectives and derived measurements, culminating in functional requirements and capabilities for the strawman payload suite, mobility system (if applicable), and sample return system;
- Assess the role of astronauts in accomplishing these science goals and objectives, plausibly including triage of samples, in situ analyses, or other EVA activities.

- Determine what technology(ies) need to be matured before the project starts;
- Define and present implementation approaches to achieving the proposed science objectives, considering a variety of approaches that allow different levels of the hierarchy of science objectives to be met.
  - The committee should identify the key discriminators between the various implementation approaches and outline the rationale for why these approaches are best suited to meeting the science objectives.
- From the range of implementation approaches, the SDT shall develop one nominal mission concept that maximizes the overall science return and progress towards NASA's goals within the resources and risk posture constraints provided by NASA (see below).
  - For this mission concept, the SDT shall develop both a baseline and threshold mission.
  - For both the baseline and threshold mission, the SDT shall prioritize payload options and describe priorities for scaling the mission concept up or down (in cost and capability) and describe potential trades.

2. Factors to Consider

A few factors and constraints the SDT committee should consider are listed below. The SDT shall assume:

- A cost cap of $1.5B (FY25), not including the lunar delivery service, for Phases A–E (including margin and reserves). Costs should be broken down by mission phase.
  - Curation and Earth-based sample analysis will occur during Phase F and is not included in the Phase A-E cost cap and associated schedule. However, the SDT shall document what analyses need to be done on the sample(s) in order to satisfy the STM requirements. The SDT will not be asked to generate a cost/schedule estimate for Phase F.
- A competed instrument suite with a nominal cost limit of $75M (FY25; including margin and reserves) and a notional mass limit of 20 kg. Note this cost limit is for instruments only; other components such as sample acquisition and retrieval mechanisms are not included in this cost limit.
- A launch nominally in 2031.
- A nominal mission duration of 2-4 years, depending on the scope of the science objectives.
- A maximum roving speed of 1 kilometer per hour, if roving is included as part of any implementation approaches.
- That any proposed sample return utilizes returning samples either to Artemis astronauts at the south pole, or via commercial-derived robotic sample return capabilities. The SDT should state and justify all sample needs.
  - Artemis sample return capability shall not exceed 100 kg, inclusive of sample containers.
  - CLPS-derived robotic sample return capability shall not exceed 10 kg.

Additionally,

- The SDT may consider the use of Radioisotope Power Systems (RPS).
  The SDT will work iteratively with JPL mission pre-project which will provide additional constraints and information on payload size, mass, power, data rates, configuration, and cost.

Detailed landing site selection and traverse planning is outside the scope of this SDT, but the SDT should identify key sites of interest for achieving the science objectives.