Technology for Lunar Discovery and Exploration

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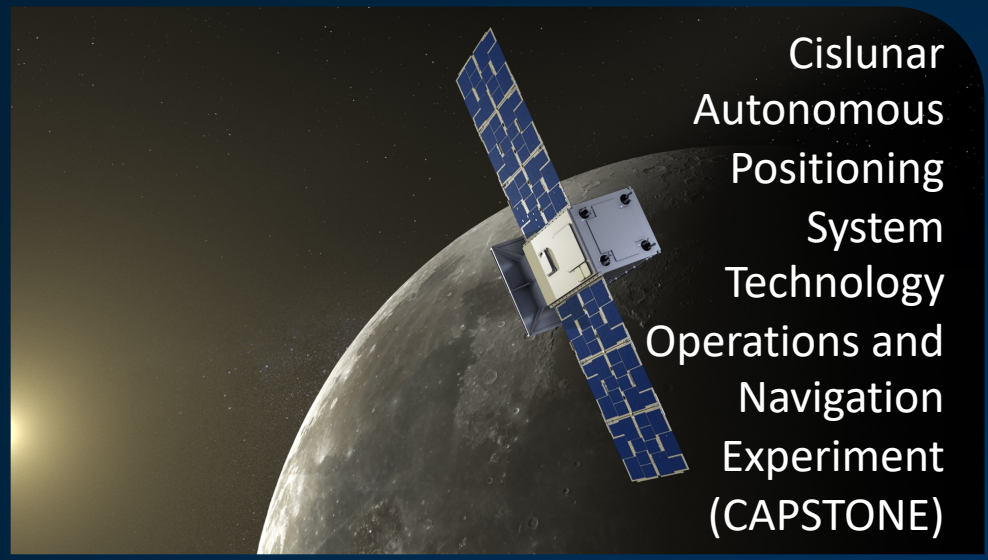
January 11, 2023

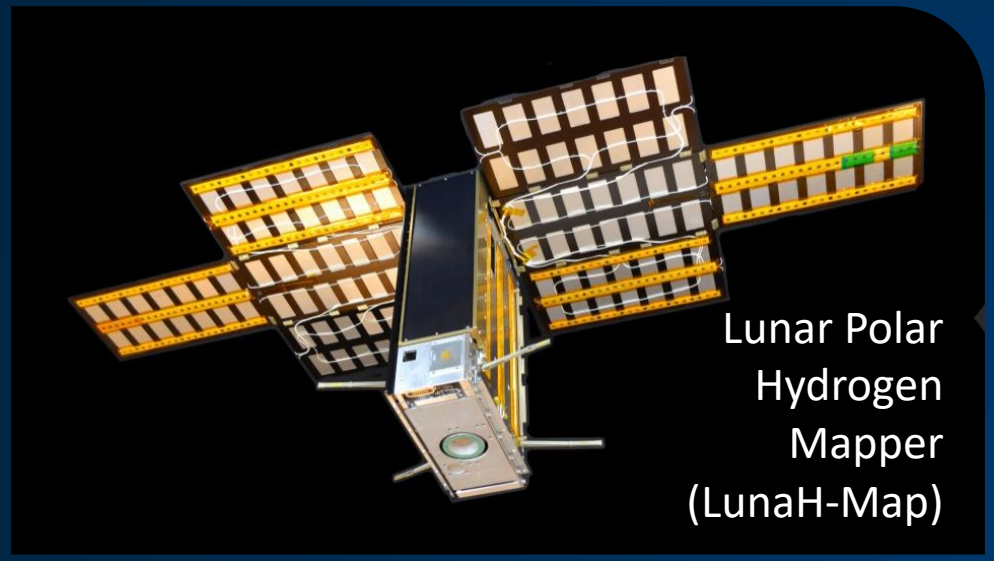
2022:
Year of the **Moon**

Dec 5, 2022:
Orion Return Powered Flyby

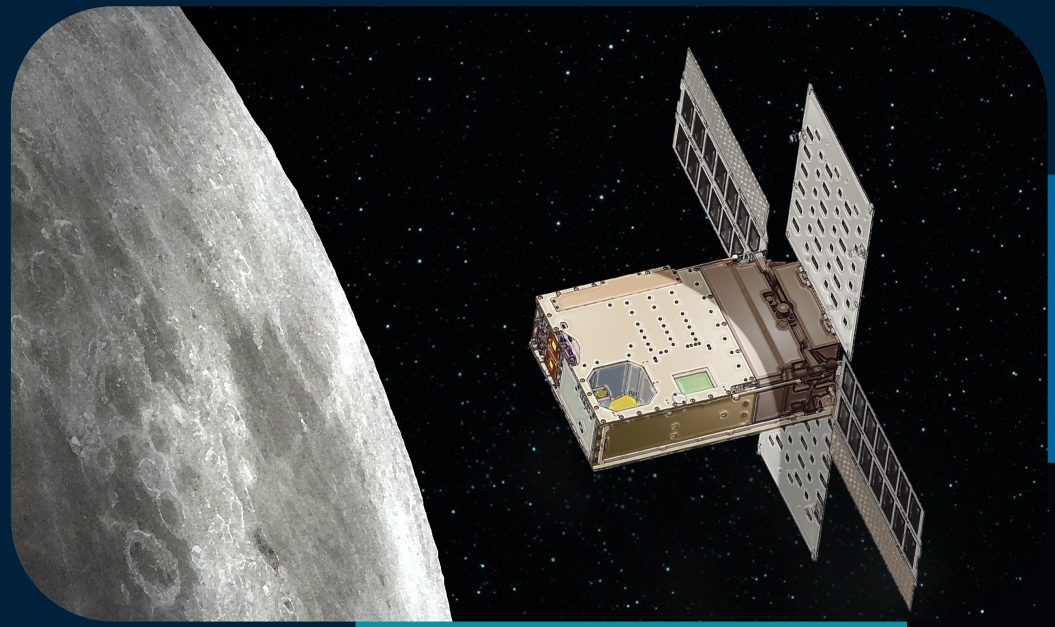
Dec 11, 2022:
Orion Splashdown

2022: Year of the Moon





2022: Year of the Moon



Lunar
Flashlight

ispace
Hakuto-R M1

4

CLPS Deliveries
2023-2026

Delivery Site:
Gruithuisen Domes
Provider TBD
CP-21 | 2026

Delivery Site:
Sinus Viscositatis
Provider: Astrobotic
TO2-AB | Q1 2023

Delivery Site:
Lunar Far Side &
Orbit Insertion
Provider TBD
CS-3 | 2025

Delivery Site:
Reiner Gamma
Provider: IM
CP-11 | 2024

Delivery Site: South Pole Region
Provider: Intuitive Machines (IM)
TO2-IM | Q1 2023

Delivery Site:
Mare Crisium
Provider: Firefly
TO19D | 2024

Delivery Site:
Shackleton Connecting
Ridge **Provider:** IM
TO PRIME-1 | Q3 2023

Delivery Site:
Nobile Crater
Provider : Astrobotic
VIPER | Nov 2024

Delivery Site:
Schrödinger Basin
Provider: Draper
CP-12 | 2025

Delivery Site:
South Pole Region
Provider TBD
CP-22 | 2026

Delivery Site:
Haworth Crater
Provider: Masten
TO19C | Nov 2023

Updated 1/3/2023

FY23 PBR Moon to Mars Planning Manifest

CY	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
ESDMD-Led ● Commercial Launch	**Artemis I** Uncrewed Flight Test SLS Block 1 10 CubeSats • 4 ESDMD • 2 SMD • 1 STMD • 3 International Lunar Communications Network Upgrades (SOMD)		**Artemis II** Crewed Flight Test SpaceX Uncrewed Lunar Demo PPE/HALO Launch	**Artemis III** xEVA Surface Suits ready for integration SpaceX Crewed Lunar Demo Science Payloads HERMES – SMD ERSA – ESA IDA – ESA/JAXA Lunar Relay (SOMD)		**Artemis IV** I-Hab delivered to Gateway SLS Block 1B Mobile Launcher 2	**Artemis V** ESPRIT delivered to Gateway Deep Space Logistics TBD Human Lander Lunar Terrain Vehicle ready for surface operations	**Artemis VI** Airlock delivered to Gateway Deep Space Logistics TBD Human Lander	**Artemis VII** Deep Space Logistics TBD Human Lander Pressurized Rover via Cargo Lander	**Artemis VIII** Deep Space Logistics TBD Human Lander Surface Logistics Surface Habitat
SMD-Led CLPS uses commercial launches. CLPS include multiple payloads from multiple directorates	LRO 2-IM 2-AB	VIPER PRIME-1 19C 20A	Lunar Trailblazer HERMES Ready for Integration 19D CP-11	Artemis Surface Science Instruments ESA Lunar Pathfinder delivered for launch CP-12 CS-3 CP-21	CP-22 CP-31 CP-32	MSR *Earth-Return Orbiter* (ESA) CT-1 CP-41 CP-42	Artemis Surface Science Instruments LTV Instruments MSR Lander: *Sample Fetch Rover* MSR Lander: *Mars Ascent Vehicle* CP-51 CP-52 LTV	Pressurized Rover Instruments CP-62 CT-2	MSR *Mars Ascent Vehicle launch*	
STMD-Led All Commercial Launches	CAPSTONE Preliminary Nuclear Thermal Propulsion reactor design LOFTID	• Polar Resources Ice Mining Experiment (PRIME-1) • IM Deployable Hopper • Nokia 4G/LTE Lunar Comm CFM TP Demos	SEP Qual Preliminary Nuclear Electric Propulsion vehicle design	• SPLICE-1 • PSI Mini-Suite	• ISRU Subscale Demo • ISRU Pilot Excavator (IPE) • Vertical Solar Array Technology (VSAT) • Regenerative Fuel Cell Power • Wireless Charging for Lunar Surface • Lunar Surface Scaled Construction Demo 1 Tech	Fission Surface Power delivered for launch • Lunar Auger Dryer ISRU (LADI)	ISRU Pilot Plant delivered for launch	

Imagery is meant to represent the calendar year in which the launch occurs.
Does not include impact from FY22 appropriations.

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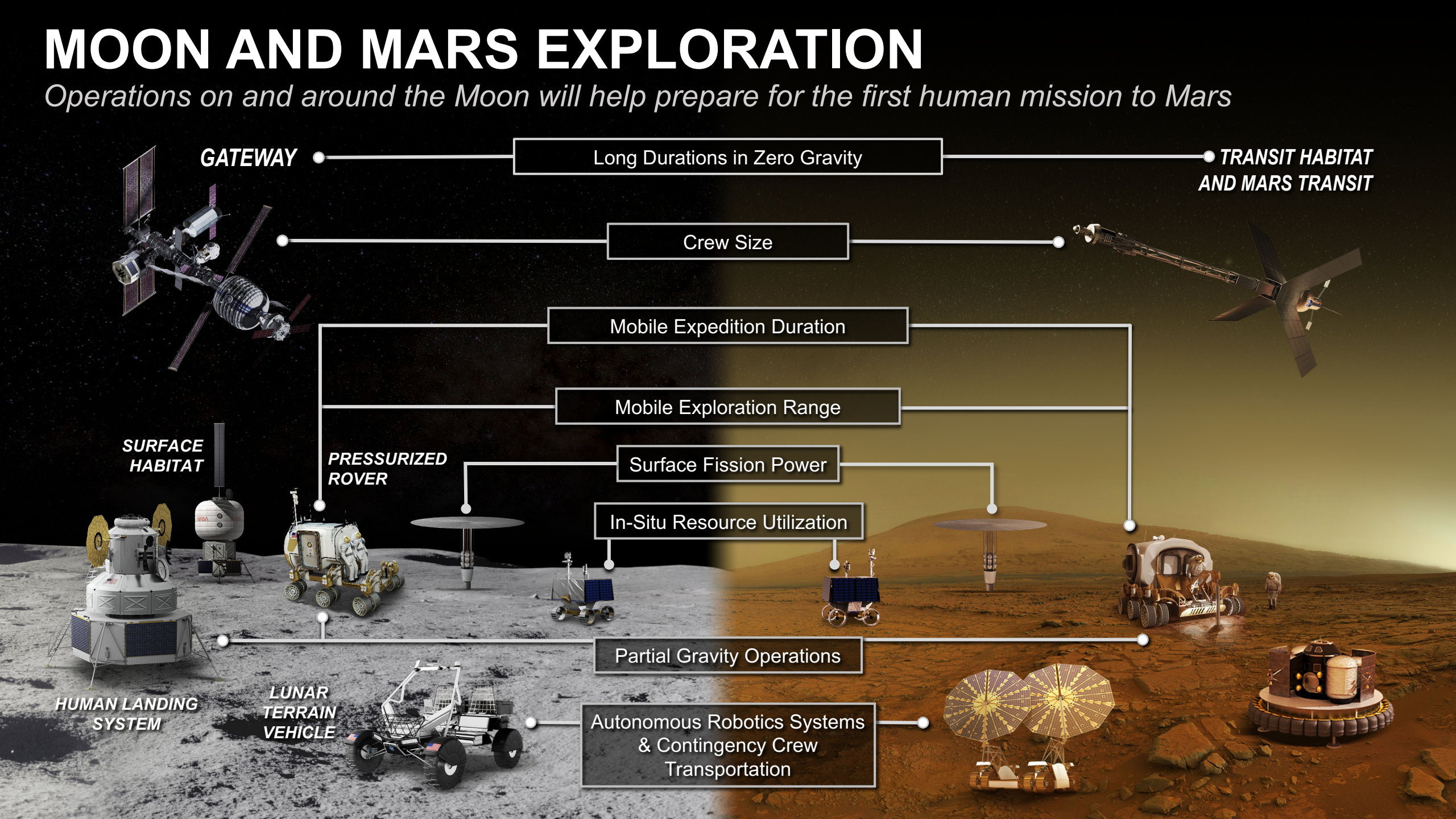
MOON AND MARS EXPLORATION

Operations on and around the Moon will help prepare for the first human mission to Mars



Commercial Lunar Payload Services (CLPS)

- CLPS is an innovative, service-based, competitive acquisition approach that enables rapid, affordable, and frequent access to the Lunar surface via a growing market of American commercial providers
- Service task orders are Firm Fixed Price (FFP) for the full scope of delivery: from payload hand-over to delivery (and often operation) on the lunar surface
  - All payload requirements must be captured in the originating Request for Task Plan (RFTP)
- NASA wants to be one of many customers for CLPS services
- CLPS deliveries are CLPS Provider missions (not NASA missions)
- CLPS launches are commercial launches provided via the CLPS provider and approved/licensed by the U.S. Gov't FAA (Federal Aviation Administration) and other agencies (not NASA)

CLPS Contract and Portfolio

- Competition open to U.S. commercial providers of space transportation services, consistent with National Space Transportation Policy and Commercial Space Act
- Structured for NASA as one of many customers of commercial service
- On ramps to the CLPS contracts will be used to provide additional capabilities as made available
- 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.

CP-12 2025
Draper
SERIES-2 Lander

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.*

TO2 2022
Astrobotic
Peregrine

TO2/20C 2022
Intuitive Machines
NOVA-C

TO19C 2023
Masten
XL-1

TO PRIME-1 2022
Intuitive Machines
NOVA-C

TO20A 2023
Astrobotic
Griffin

TO19D 2023
Firefly Aerospace
Blue Ghost

CP-11 2024
Intuitive Machines
NOVA-C

Payload Accommodations

- Providers are required to “accommodate” the needs of NASA payloads, including:
  - Utilities: power, data, commanding, etc.
  - Mounting: fields of view, alignments, co-locations, etc.
  - Environments: thermal, vibe, emi/emc, etc.
  - Operations: conops, mission phases, etc.
- CLPS Task Orders are generally awarded competitively; payloads should therefore not be designed for a specific CLPS provider
- Firm Fixed Price (FFP) Task Orders necessitate stable definition of interfaces and requirements PRIOR to release of the Request for Task Plan (RFTP)
  - If it is not defined in the RFTP then it is defined de facto by the CLPS provider, or else is a “new” requirement at a cost
  - If requirements cannot be finalized, RFTP should specify achievable envelope for both sides to work toward
  - “Requirements” in an FFP procurement environment are what you are going to get, so RFPT requirements should align with what is needed for mission success

Future Definition of CLPS

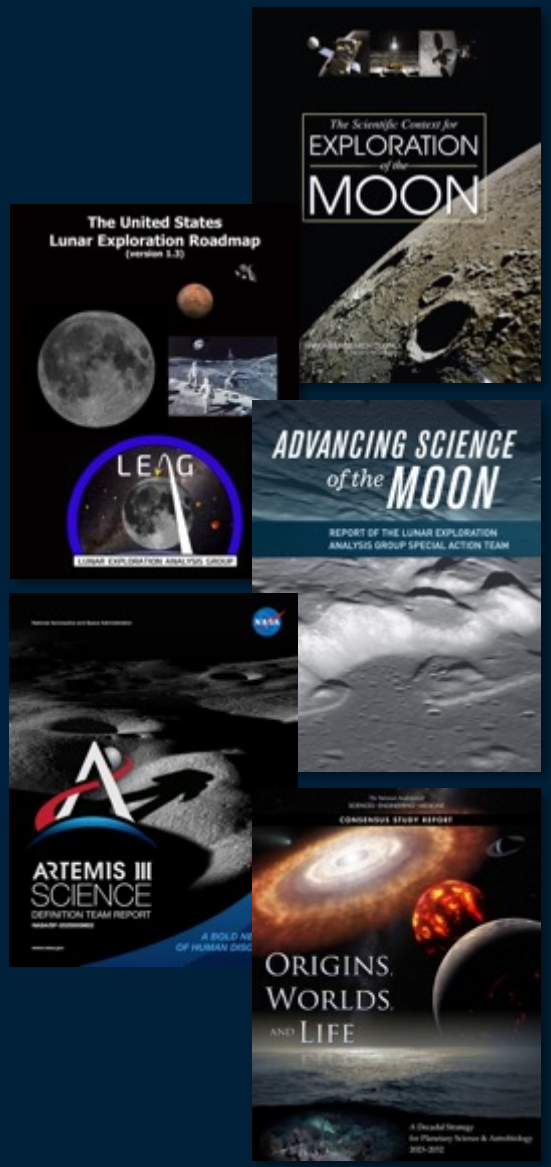
- Continue building the commercial market; CLPS service options are expected to expand as market and company capabilities evolve
- Estimating periodic on-ramp opportunities into the CLPS Vendor Pool going forward depending upon need and service availability
- Maintain flexibility of the CLPS IDIQ to 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
  - EMI Quiet Operation
  - Increased Delivery Mass
  - Surviving/operation throughout the lunar night
  - Articulation / Regolith Manipulation
  - PSR/Cold Operations
  - Sample Return

What Needs **"Survive the Night"** on the Moon?

- Science Instruments and suites delivered by robotic landers
- Science Instruments deployed by astronauts from Artemis Human Lander Systems (HLS)
- Systems to extract frozen volatiles from Permanently Shadowed Regions (PSRs)
- Pre-positioned containers of scientific instruments for later use by astronauts

High Priority Science to be Accomplished at the Moon



NATIONAL RESEARCH COUNCIL (NRC) | 2007
The Scientific Context for Exploration of the Moon (SCEM)
https://nap.nationalacademies.org/read/11954/chapter/1

- **Scope: All lunar science**
- Length: 121 pages
- 8 concepts, 35 goals

LUNAR EXPLORATION ANALYSIS GROUP (LEAG) | 2016
The United States Lunar Exploration Roadmap
https://www.lpi.usra.edu/leag/roadmap/US-LER_version_1_point_3.pdf

- **Scope: All lunar science**
- Length: 143 pages
- 3 themes, 9 goals, 74 objectives, 288 investigations

LUNAR EXPLORATION ANALYSIS GROUP (LEAG) | 2017
Advancing Science of the Moon
https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

- **Scope: All lunar science**
- Length: 69 pages
- 11 key concepts (3 more than SCEM), 35 goals

NASA SCIENCE MISSION DIRECTORATE (SMD) | 2020
Artemis III Science Definition Team Report
https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf

- **Scope: Artemis III**
- Length: 188 pages
- 54 goals, 7 overarching objectives, 183 investigations (30 prioritized)
- 126 white papers

NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE (NASEM) | 2022
Origins, Worlds, and Life (OWL): A Decadal Strategy for Planetary Science and Astrobiology 2023–2032
https://nap.nationalacademies.org/read/26522/chapter/1

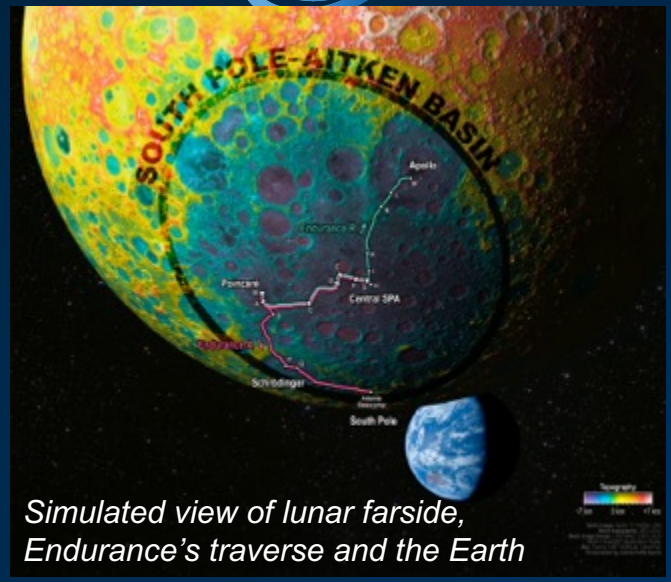
- **Scope: All planetary science**
- Length: 782 pages
- 3 themes, 12 priority science questions, 69 main questions, 259 sub-questions, 364 strategic research items
- 527 white papers

Info from James Tuttle Keane (JPL/Caltech — james.t.keane@jpl.nasa.gov)

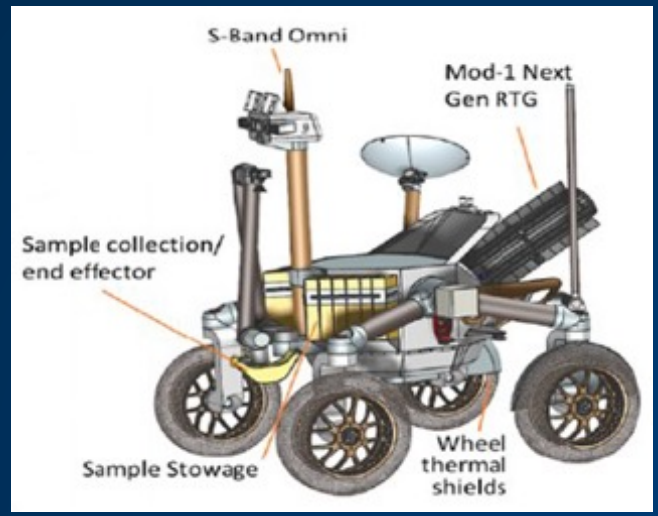
Planetary Science Decadal Survey
Endurance A:
South Pole-Aitken Sampling Campaign

- One of the top lunar priorities of the Planetary Decadal is Endurance A, a long-duration rover capable of traversing ~2000km and returning ~100kg of samples taken at strategic sites throughout the South Pole-Aitken basin to investigate several lunar science objectives:
  - Solar System Chronology: Anchors the earliest impact history of the Solar System, tests the giant planet instability, impact cataclysm, and late heavy
  - hypothesis, characterizes the thermochemical evolution of terrestrial planets, and explores the geologic diversity

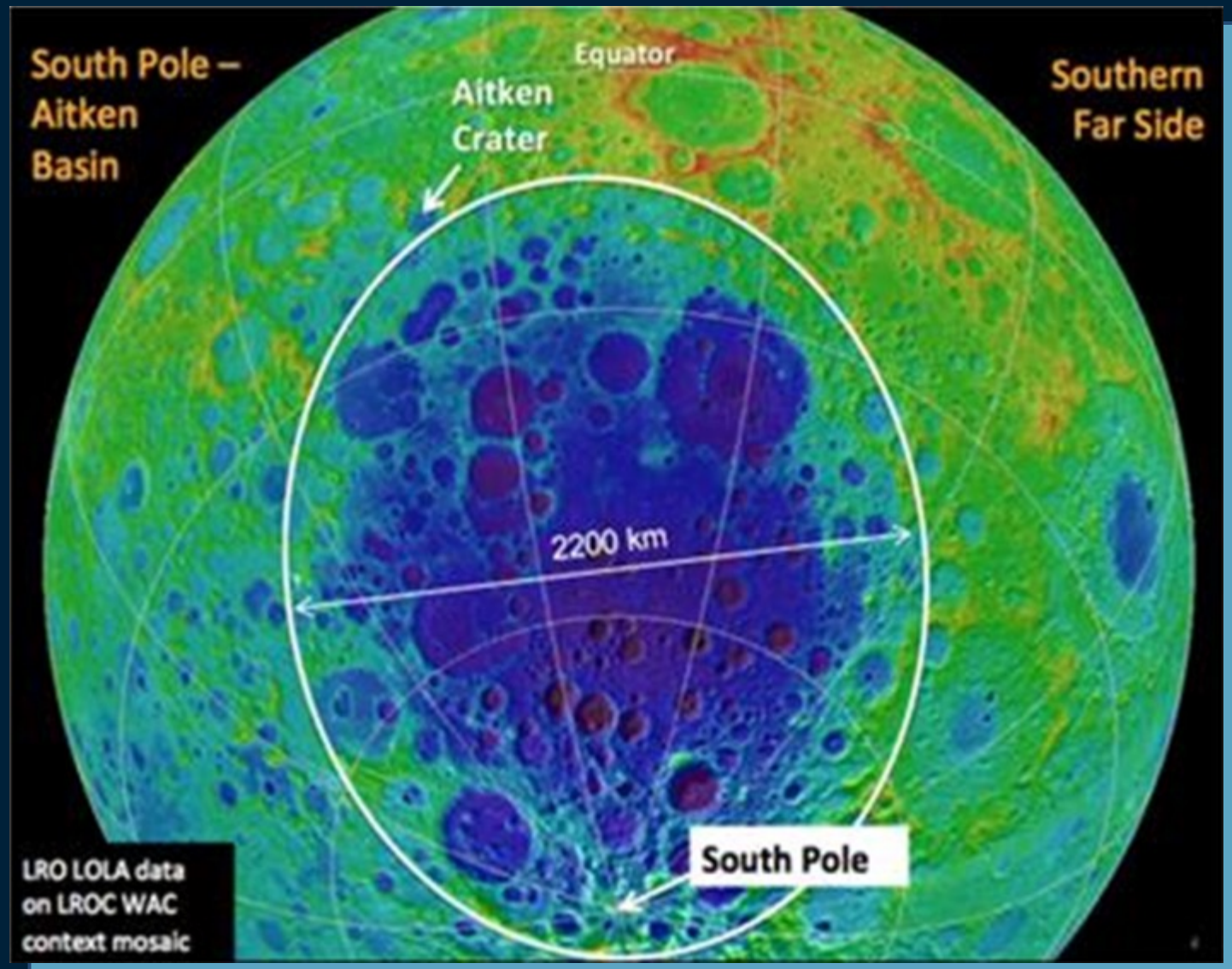
***Recommendation*: Endurance-A should be implemented as a strategic medium-class mission as the highest priority of the Lunar Discovery and Exploration Program. Endurance-A would utilize CLPS to deliver the rover to the Moon, a long-range traverse to collect a substantial mass of high-value samples,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



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



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



South Pole-Aitken (SPA) Basin:

Crucial Destination for Solar System Science

A unique location on the Moon and in the Solar System

- SPA is the largest, oldest, clearly recognizable lunar impact basin
- SPA impact completely resurfaced a large part of the Moon and reset ages over an enormous area
- SPA anchors the lunar impact chronology

The determination of SPA basin formation age and chronology is crucial science

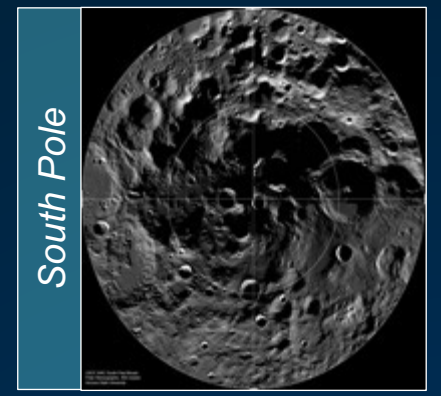
Payloads and Research Investigations on the Surface of the Moon (PRISM)

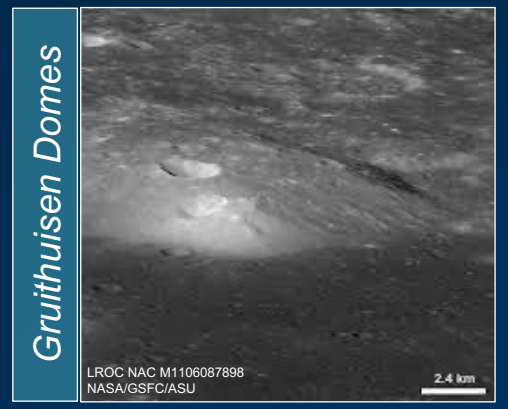
PRISM is SMD's primary way of selecting science payloads for delivery via CLPS.

- Annual ROSES call for PI-led suites of instruments (7120.8)
- Nominally ~$30M per delivery for payloads, including phases A-F, instrument development, engineering, ops, science, data archival
- Solicitation will identify site specific vs site agnostic instruments desired

PRISM 1

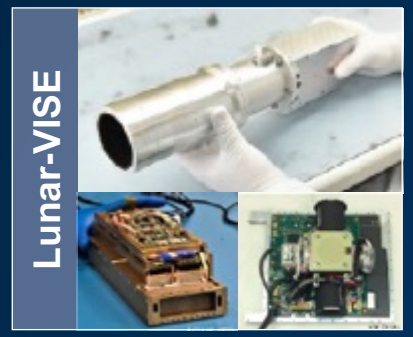
- Task Order CP-11: Lunar Vertex will land at Reiner Gamma, a lunar swirl feature on the near side, in 2024 with 2 partnered international payloads: ESA's MoonLIGHT Pointing Actuator (MPAc) and KASI's Lunar Space Environment Monitor (LUSEM)
  - Planetary decadal science: Understand how lunar surface has been modified by geological processes within a lunar magnetic anomaly and determine the origin of magnetized crust
- Task Order CP-12: Farside Seismic Suite (FSS) and Lunar Interior Temperature and Materials Suite (LITMS) will land at Schrödinger Basin, the first CLPS lunar farside delivery
  - Planetary decadal science: Characterize differentiation and evolution of the Moon's interior using geophysical techniques





Payloads and Research Investigations on the Surface of the Moon (PRISM)

- PRISM-2
  - Lunar Vulkan Imaging and Spectroscopy Explorer (Lunar-VISE) will land at Gruithuisen Domes, to study geologic processes preserved on the Moon, by investigating rare lunar volcanism | PI: K. Donaldson Hanna
    - Planetary decadal science: How do the interiors of solid bodies evolve, and how is this evolution recorded in a body's physical and chemical properties? How are solid surfaces shaped by subsurface, surface, and external processes?
  - Lunar Explorer Instrument for space biology Applications (LEIA) will land near south pole to study the biological response of yeast to the environment and determine how partial gravity and deep space radiation influence biological processes | PI: A. Settles
- PRISM-3 solicitation text was released via ROSES-22 in Sept 2022. Step-2 proposals were due Dec 20, 2022. Selections in ~May 2023
  - Proposers must specify non-polar landing site (< 75d N/S)



Development and Advancement of Lunar Instrumentation (DALI) Program

Typical Solicitation Timeline:

- ROSES Solicitation Release – February
- Step 1 Proposals Submitted – April
- Step 2 Proposals Submitted – June
- Panel Reviews – October

Typical budget/award	~ $1.0M/year
Maximum award duration	Up to four years

Solicitation Overview:

- DALI supports the development of **spacecraft-based instruments** for use on **future lunar missions** including commercial ventures (i.e. CLPS).
  - The DALI program goal is to develop lunar science instruments to the point where they may be **proposed to future flight opportunity announcements** (i.e. PRISM) without additional technology development.
  - DALI generally supports TRL maturation from **TRL 4 to TRL 6**.
- DALI seeks to mature lunar science instruments that **support NASA's broader lunar exploration goals**.
  - Goals applicable to human exploration, in situ resource utilization, and lunar science.
  - All instrument types, including rover-based and orbital, are considered with specific interest in small, stationary lander instruments.

Upcoming Lunar Solicitations

2022 → Artemis III Geology Team → Artemis III Deployed Instruments → PRISM-3

The following are expected solicitations out of SMD's Lunar Discovery and Exploration Program (LDEP) within the calendar year*

Artemis III/V

- Artemis III Geology Team
- Deployed Instruments Call – Includes Surface deployed instruments, lander mounted instruments, and/or Astronaut-utilized instruments

PRISM-3

- For the next CLPS delivery to a) a south polar location and b) a TBD location

DALI

**A community announcement will be released ~3 months prior to all solicitations*

LTV mounted

Astronaut Utilized

Lander mounted

Astronaut Deployed

Lunar Discovery and Exploration Program

The Lunar Discovery and Exploration Program (LDEP):

- Develops lunar surface science instruments that address Decadal and other community document science priorities
  - NASA-internal payloads, Community-developed payloads, PRISM, DALI
- Uses commercial companies to deliver payloads to the Moon (CLPS)
- Develops mobility systems to expand and enhance science investigations on the lunar surface
- Leverages international partnerships for additional opportunities (e.g., instruments, rovers)
- Defines, integrates, and leads Artemis science efforts across SMD, other NASA mission directorates, and with other US and international agencies

> …Infusing decadal-level science goals into both the Lunar Discovery and Exploration Program in general, and into the Artemis program in particular, is viewed by the committee as an essential priority for the next decade.

- Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032


National Aeronautics and
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How the Lunar Science Themes Map to Key Science Questions
(As Defined in the Planetary Science Decadal Survey)

2023 Planetary Science and Astrobiology Decadal Lunar Themes	2023 Planetary Science and Astrobiology Decadal Main Questions
Lunar Science Theme 1: Solar System origin and early history	**Q3.** Origin of Earth and inner solar system bodies. How and when did the terrestrial planets, their moons, and the asteroids accrete, and what processes determined their initial properties? To what extent were outer solar system materials incorporated?
	Q10. Dynamic habitability. Where in the solar system do potentially habitable environments exist, what processes led to their formation, and how do planetary environments and habitable conditions co-evolve over time?
Lunar Science Theme 2: Geologic processes of early Earth preserved on the Moon	**Q4.** Impacts and dynamics. How has the population of solar system bodies changed through time, and how has bombardment varied across the solar system? How have collisions affected the evolution of planetary bodies?
	Q5. Solid body interiors and surfaces. How do the interiors of solid bodies evolve, and how is this evolution recorded in a body's physical and chemical properties? How are solid surfaces shaped by subsurface, surface, and external processes?
	Q6. Solid body atmospheres, exospheres, magnetospheres, and climate evolution. What establishes the properties and dynamics of solid body atmospheres and exospheres, and what governs material loss to space and exchange between the atmosphere and the surface and interior? Why did planetary climates evolve to their current varied states?
Lunar Science Theme 3: Volatile origin and delivery processes	**Q5.** Solid body interiors and surfaces. How do the interiors of solid bodies evolve, and how is this evolution recorded in a body's physical and chemical properties? How are solid surfaces shaped by subsurface, surface, and external processes?