Keck Institute for Space Studies: Astronomical Optical Interferometry from the Lunar Surface

Short Course Lecture #2: Lunar Opportunities: Artemis, International

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Short Course Outline

- Why the Moon?
- Programmatic Considerations for Lunar Interferometer Project(s)
- Overview of U.S. & International Lunar Plans
- Q&A

Why the Moon?

- Primary attraction of the lunar surface for *initial, modest-baseline* optical interferometer(s) is to provide a **stable platform in vacuum**
  - Build on terrestrial optical interferometry experience and techniques
  - See discussions & references in "Unique Science from the Moon in the Artemis Era", Valinia, A., et al., NASA NESC Report, November 2022, https://ntrs.nasa.gov/api/citations/20220017053/downloads/20220017053.pdf;

- Challenges include Mass to the Surface, Power, Communications, Thermal Environment, One-sixth Gravity, Mobility, Lunar Dust, etc.
  - These will be considered in turn during the course of this workshop…
    - Key: Leverage capabilities & infrastructure being developed by other programs

Why the Moon?

- *Is dust a showstopper for (UV-optical) telescopes on the Moon?*

The available evidence says, “**No, it is not**”

- The risks and dust mitigation protocols will depend on the facility architecture (e.g., aperture, wavelength) and scientific applications
  - Relevant examples:
    - Far-Ultraviolet Camera/Spectrograph on Apollo 16
    - Chinese Lunar Ultraviolet Telescope (LUT) on Chang’E-3

Far-Ultraviolet Camera/Spectrograph on Apollo 16


Credit: U.S. Naval Research Laboratory

George R. Carruthers, "Apollo 16 Far-Ultraviolet Camera/Spectrograph: Instrument and Operations," Appl. Opt. **12**, 2501-2508 (1973)
https://opg.optica.org/ao/abstract.cfm?URI=ao-12-10-2501

Abstract

A far-ultraviolet camera/spectrograph experiment was designed and constructed for studies of the terrestrial upper atmosphere and geo
from the lunar surface. The experimen
21–23 April 1972. Discussed are the de
events and operations during the Apol
suggested improvements for future ex
utility of the electronographic techniq
lunar surface as a base for astronomic

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Science
Volume 177, Issue 4051
Sep 1972

Apollo 16 Far-Ultraviolet Ca
Earth Observations

Abstract. *A far-ultraviolet camera ... the lunar surface during the Apollo ... images and spectra of the terrestria ... length range below 1600 angstroms. ... tive intensities of emissions due to ... nitrogen, and other species—some o*

THE ASTROPHYSICAL JOURNAL, **205**:397–404, 1976 April 15

FAR-ULTRAVIOLET BRIGHTNESS OF NEBULAE IN CYGNUS

GEORGE R. CARRUTHERS AND THORNTON PAGE
E. O. Hulburt Center for Space Research, Naval Research Laboratory
Received 1975 June 30; revised 1975 September 8

ABSTRACT

A far-ultraviolet electrographic Schmidt camera was operated on the lunar surface during the *Apollo 16* mission 1972 April 21–23. Among the results obtained were imagery, in the 1050–1600 and 1250–1600 Å wavelength ranges, of a 20° diameter field in Cygnus containing the Cygnus Loop nebula, the North America nebula (NGC 7000), and the H II region of the O8 star 68 Cygni. The maximum intensity in the Cygnus Loop was 100 R in the 1250–1600 Å range, and 130 R in the 1050–1600 Å range. The maximum brightnesses in the 1250–1600 Å range of the 68 Cyg H II region and of NGC 7000 were about 60 and more than 80 R, respectively, but require relatively large corrections for interstellar extinction.

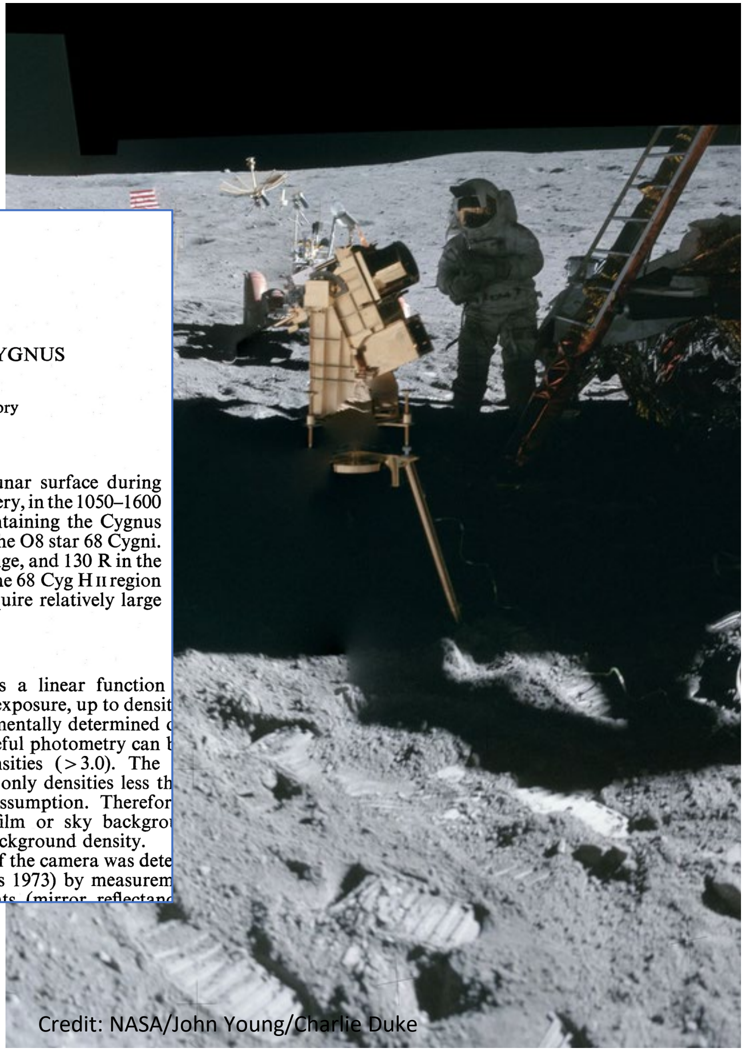
Subject headings: nebulae: general — ultraviolet: spectra

I. INTRODUCTION

One of the instruments operated on the lunar surface during the *Apollo 16* mission 1972 April 21–23 was the Naval Research Laboratory's Far-Ultraviolet Camera/Spectrograph (Experiment S-201). This instrument was based on an electrographic Schmidt camera, sensitive in two alternate wavelength ranges of 1050–1600 and 1250–1600 Å. The camera had a focal ratio of f/1.0, an aperture of 75 mm, a 20° field of view, and a limiting angular resolution of about 2′. (The instrument is described in detail by Carruthers 1973.)

emulsion, $d = \log I_0/I$, is a linear function integrated photoelectron exposure, up to densit over 1.0. With an experimentally determined exposure relationship, useful photometry can b up to much higher densities (>3.0). The results, however, involve only densities less th so linearity is a valid assumption. Therefor possible to correct for film or sky backgro merely subtracting the background density.

The spectral response of the camera was dete before launch (Carruthers 1973) by measurem the individual components (mirror reflectanc


Credit: NASA/John Young/Charlie Duke

"This experiment demonstrated the utility of the electronographic technique in space astronomy, as well as the **great potential of the lunar surface as a base for astronomical observations**." – G.R. Carruthers, Appl. Opt. **12**, 2501-2508 (1973)

Lunar Ultraviolet Telescope (LUT) on Chang'E-3

LUNAR-BASED ULTRAVIOLET TELESCOPE 1153

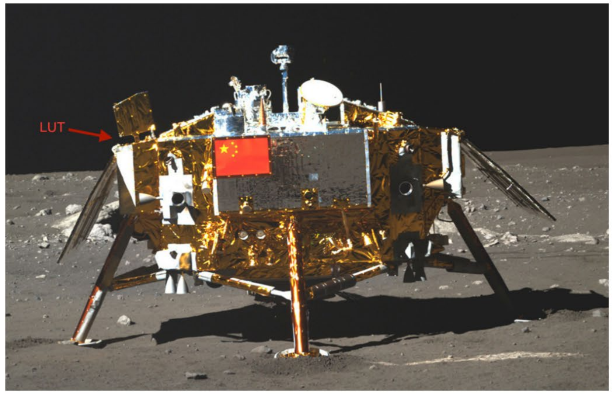


FIG. 1.—Photo of the *Chang'e 3* lunar lander taken by the rover following its soft landing on the Moon. The LUT is in a heat-insulated payload compartment on the left-hand side of this photo, with a glassless window and a protective door (shown open in the figure). The door is lifted when LUT is about to take observations, and is closed during Moon's night. The sky coverage allowed by the window is about 15° × 18°. See the online edition of the *PASP* for a color version of this figure.

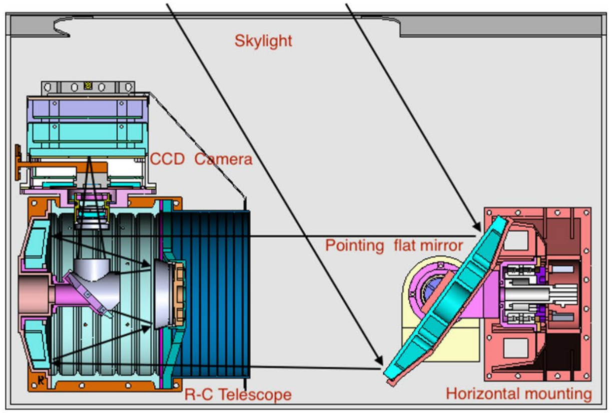


FIG. 2.—Schematic illustration of the LUT instrument showing the pointing flat mirror of 150 mm in diameter; the actual telescope is a modified Ritchey–Chrétien configuration with a square focal plane of 1.36° on a side. See the online edition of the *PASP* for a color version of this figure.

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **127**:1152–1160, 2015 November

Astrometric Support for the Lunar-based Ultraviolet Telescope

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Received 2015 April 22; accepted 2015 August 27; published 2015 October 16

ABSTRACT. The Lunar-based Ultraviolet Telescope (LUT) is an astronomical instrument aboard *Chang'e 3*, the lunar probe of China's Lunar Exploration Program that successfully landed on the northern part of the Moon's Mare Imbrium (340.4884E, 44.1214N) in late 2013. LUT is charting an ultraviolet map of the plane of the Milky Way and is also providing long-term light variability monitoring for a sample of RR Lyrae stars. However, the principal goal of the computer-controlled landing of the probe was a safe descent to a stable resting-place, and therefore, the precise orientation of LUT was never a priority. For this reason, at least theoretically, touch-down could have occurred anywhere and, for LUT, at any attitude, which would make the pointing and tracking of the wanted celestial objects practically impossible. Moreover, to reduce the data transmission load, the whole frame of every exposure could not be downloaded: only the image data containing the objects can make it to the ground; also, in order to save on electricity, the telescope does not usually track objects, which means that targets' accurate positions and velocities (within the focal plane CCD) are both needed. This paper presents the astrometric solution devised to solve these problems: feasibility is first shown with experiments done from Earth, and then confirmed with actual LUT observations from the Moon's surface.

Astrophys Space Sci (2015) 360:10
DOI 10.1007/s10509-015-2521-2

ORIGINAL ARTICLE

18-Months operation of Lunar-based Ultraviolet Telescope: a highly stable photometric performance

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Abstract

We here report the photometric performance of Lunar-based Ultraviolet telescope (LUT), the first robotic telescope working on the Moon, for its 18-months operation. In total, 17 IUE standards have been observed in 51 runs until June 2015, which returns a highly stable photometric performance during the past 18 months (i.e., no evolution of photometric performance with time). The magnitude zero point is determined to be 17.53 ± 0.05 mag, which is not only highly consistent with the results based on its first 6-months operation, but also independent on the spectral type of the standard from which the magnitude zero point is determined. The implications of this stable performance is discussed, and is useful for next generation lunar-based astronomical observations.

Programmatic Considerations for Lunar Interferometer Project(s)

- Astrophysics missions sponsored by NASA are quantized
  - Space missions supported by specific budget lines: e.g., Pioneers ($20M), SMEX (~$150M), MIDEX (~$300M), Probes (Medium Strategic, ~$1B), and Large Strategic (>$2B)
    - Also LDEP PRISM lunar payloads (~$20-30M), and contributions to international missions
- Decadal Surveys identify Large and Medium strategic missions
  - Astro2020 recommended HWO (Large), Far-IR & X-ray Probes (Medium)
  - Astro2030 will begin organizing in ~2028, with white papers solicited for science goals, strategic mission concepts, etc.
- Forthcoming competed (open topic) missions
  - Pioneers ROSES 2024 (annual), SMEX AO (2025), MIDEX AO (2027?) – *hopefully…*
- Private foundations may be capable of supporting $100-300M projects

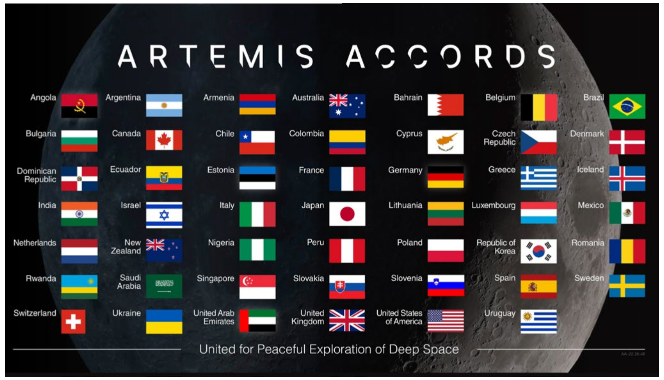
Overview of U.S. & International Lunar Plans

- NB. Much of this content comes from recent NASA presentations, Aerospace Corp report, SN articles, …

Concept animation of NASA Artemis astronauts exploring the lunar South Pole.
NASA

Figure 4. Clockwise from left, the space launch system (SLS) launching Artemis I mission, HLS design concepts from SpaceX and Blue Origin, the Orion Spacecraft, and the Axiom Extravehicular Mobility Unit (AxEMU). (Source: NASA) [From report of Center for Space Policy & Strategy, Aerospace Corp, Oct 2024]

Credits: NASA



- Main U.S. lunar surface effort is NASA's Artemis program
  - ➢ Leverage infrastructure needed to support sustainable human & robotic presence
  - ➢ Many possible paths for international participation on sparse-aperture interferometry mission

Overview of U.S. & International Lunar Plans

- For missions launching late-2020's and beyond

Center for Space Policy & Strategy, Aerospace Corp, Oct 2024

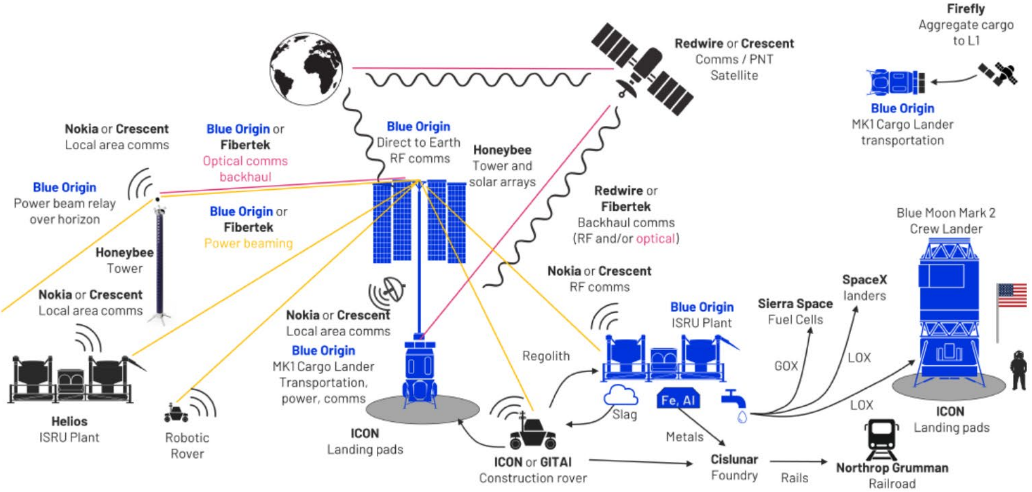
DARPA LunA-10 study (LSIC presentation, Spring 2024)

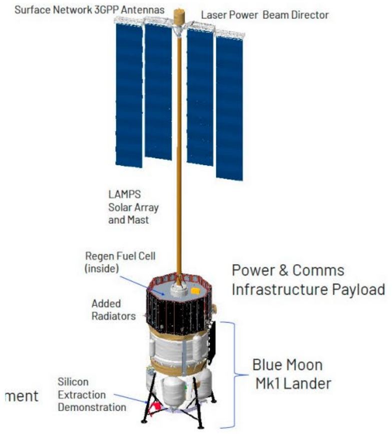
Blue Origin: lander, power, comms and ISRU

Three complementary, multi-service commercial systems:

1. Lander node as payload host and Infrastructure Platform
2. Laser-enabled Wireless power framework
3. ISRU for Construction, Mining and Energy

Features	Capability
Solar Array	> 10 kWe
Mast	20 m mast on ~10 m lander (total 30 m above surface)
3GPP Telecom Service	25 Mbps bps up to > 10 km range, max range ~100 km
Regen Fuel Cell Augmentation Kit	1.5 MWh, 7.8 kW$_e$ over 192 hrs
Laser Power Transmitter	~1 kW$_e$ delivered to 10+ km,
Silicon Extraction Experiment	Demonstrate production of silicon from regolith
Heat Rejection Augmentation Kit	Added Radiator area for payload power





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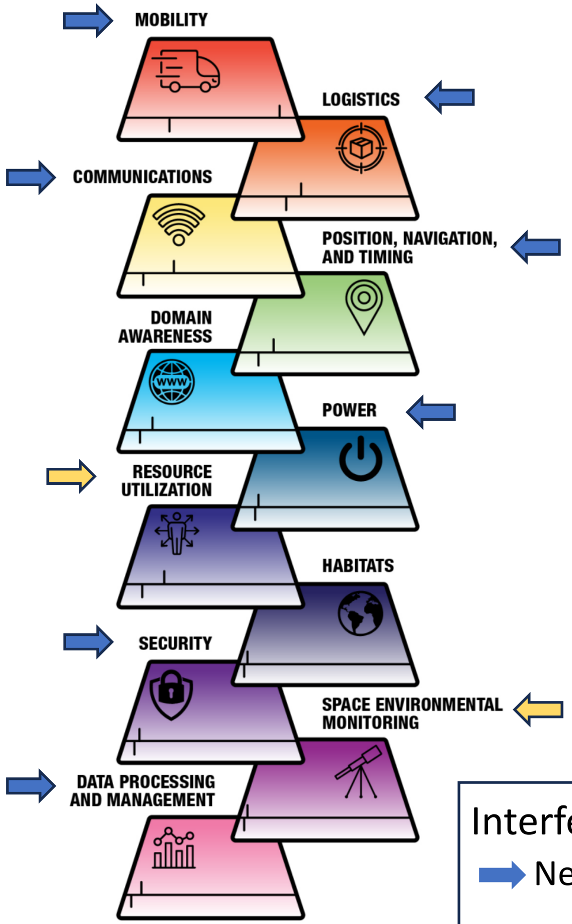


Figure 3. Cislunar infrastructure opportunities.
(Source: Guidi et al., 2022)

Interferometer
Need, BYO
Maybe

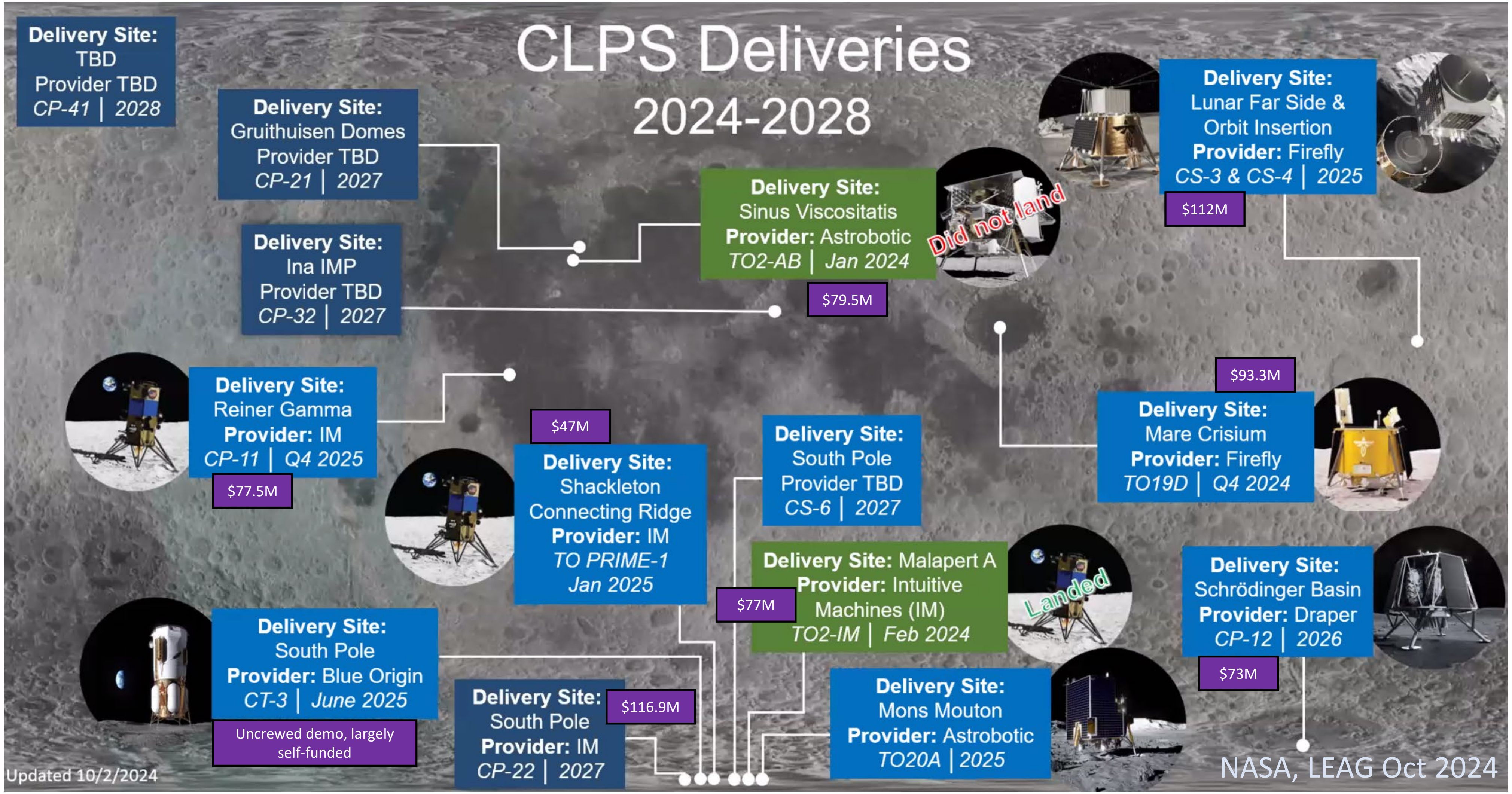
Overview of U.S. & International Lunar Plans

- NASA Commercial Lunar Payload Services (CLPS) robotic lander missions

Original contract value

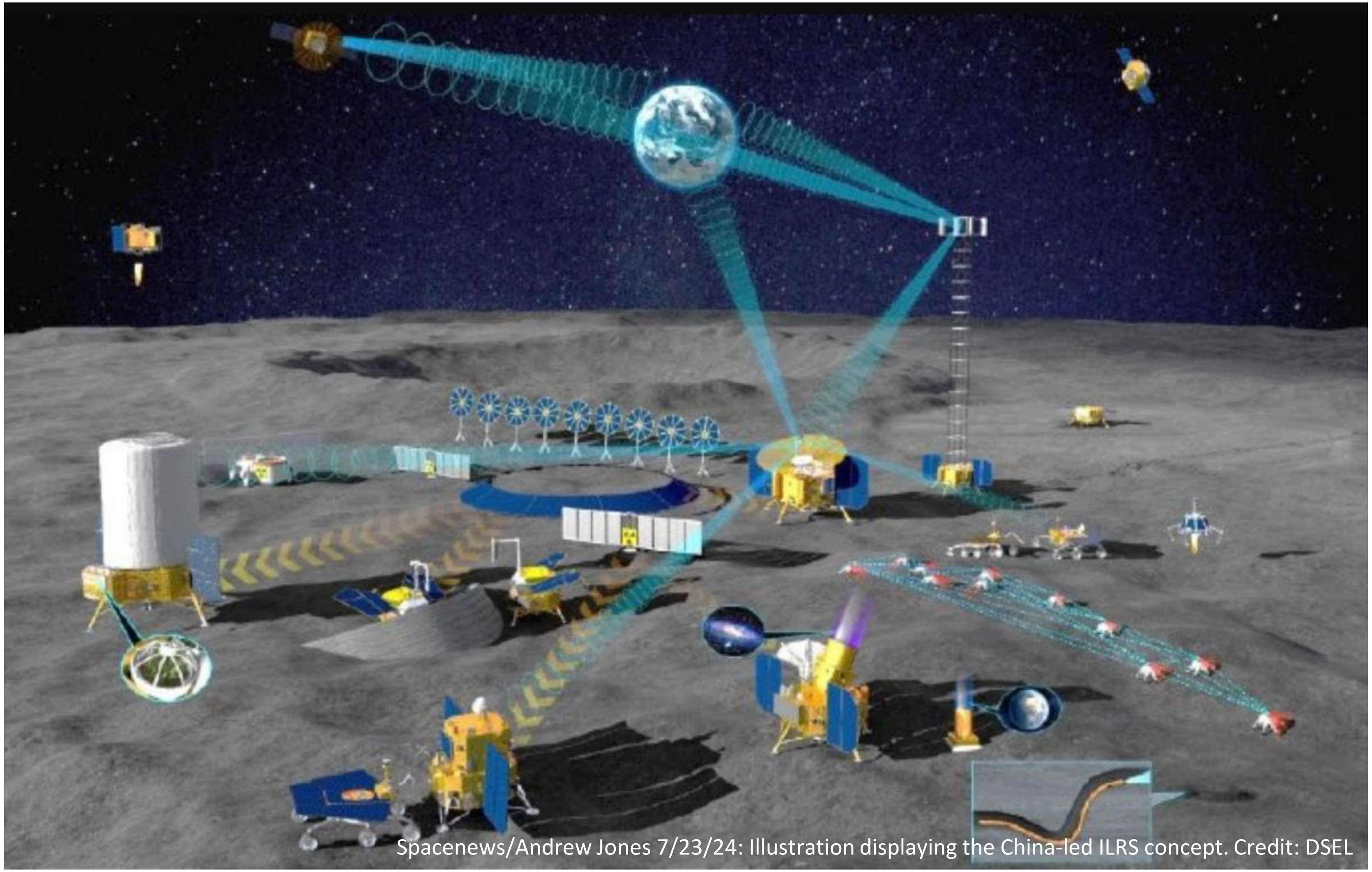
$XXXM

(Additional revenue from non-NASA payloads)



Overview of U.S. & International Lunar Plans

- China-led International Lunar research Station (ILRS)



Spacenews/Andrew Jones 7/23/24: Illustration displaying the China-led ILRS concept. Credit: DSEL

Table 4: International Lunar Research Station Signatories (as of October 2024)

China	Russia
Azerbaijan	Senegal
Belarus	Serbia
Egypt	South Africa
Kazakhstan	Thailand
Nicaragua	Venezuela
Pakistan	

Source: Center for Space Policy & Strategy, Aerospace Corp, Oct 2024

Overview of U.S. & International Lunar Plans

- Summary of planned international missions

Table 3: Uncrewed International Cislunar Missions 2024–2033

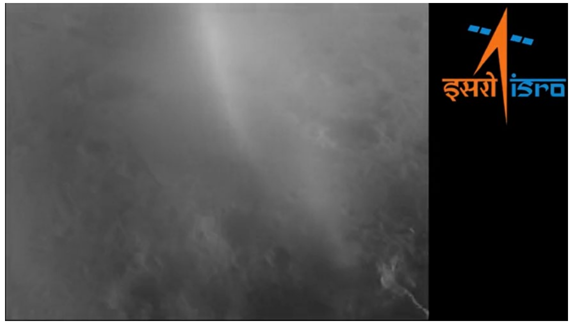
Country	Number	Mission Types
Australia	1	Rover
Canada	2	Canadarm3 (Gateway), rovers
China	6	Orbiters, relay satellites, rovers, hoppers
Europe (ESA)	4	Flyby, orbiter, relay satellite, lander
Europe/Japan	1	CubeSat
India	1	Lander/rover
Italy	1	Instrumentation for precision landing
Japan	3	Flyby, rovers
Pakistan	~~1~~ 2	Flyby/lander rover
Russia	4	Orbiters, landers, rovers
South Korea	2	Lander and rover
Thailand	1	Orbiter
Türkiye	2	Landers
United Arab Emirates	2	Rovers
Canada	2	Orbiting CubeSats
Germany	2	Landers
Germany/Israel	3	Landers
Israel	1	Orbiter, landers
Japan	3	Lander
Mexico	1	Multiple microrobot explorers

GOVERNMENT MISSIONS NON-GOVERNMENTAL MISSIONS

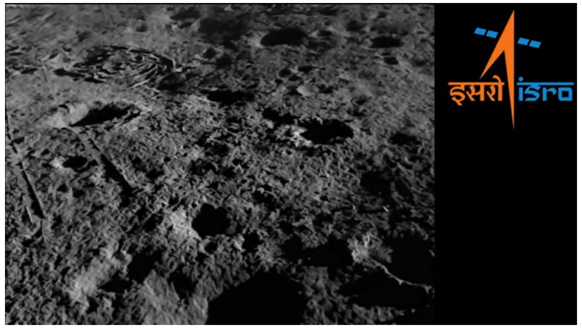
Source: Center for Space Policy & Strategy, Aerospace Corp, Oct 2024

Chandrayaan-3
Lander hop experiment successfully conducted on September 3, 2023

https://x.com/i/status/1698570774385205621



- Landing is dusty, so stay covered up
- Dust settles rapidly after landing, then deployments & ops can proceed



Q&A

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Backup

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Overview of U.S. & International Lunar Plans

Integrated Top 30 Shortfalls Compared to Stakeholder Group Rank

Higher Ranking Shortfalls	>	Lower Ranking Shortfalls				
1	30	60	90	120	150	180

Not Ranked (NR)

Integrated Rank	Average Score	Shortfall ID	Category	Stakeholder Group Rank: Academia	Small Industry	Large Industry	OGA	Other	NASA Centers	ESDMD	SMD	Other MDs
1	8.103	1618: Survive and operate through the lunar night	Thermal Management Systems	4	2	2	2	9	6	4	9	1
2	7.612	1596: High Power Energy Generation on Moon and Mars Surfaces	Power	13	1	1	40	20	4	21	NR	16
3	7.435	1554: High Performance Onboard Computing to Enable Increasingly Complex Operations	Avionics	80	28	21	27	13	3	34	1	56
4	7.383	1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications	Communication and Navigation	9	11	15	29	67	10	28	NR	3
5	7.247	1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation	Autonomous Systems and Robotics	34	27	28	63	10	40	13	9	49
6	7.208	1552: Extreme Environment Avionics	Avionics	176	49	6	38	23	54	6	9	62
7	7.196	1519: Environmental Monitoring for Habitation	Advanced Habitation Systems	20	101	72	75	61	49	17	19	13
8	7.168	709: Nuclear Electric Propulsion for Human Exploration	Propulsion: Nuclear	43	131	23	4	52	32	7	NR	7
9	7.114	1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility	Autonomous Systems & Robotics	27	42	30	121	91	34	25	25	66
10	7.095	1520: Fire Safety for Habitation	Advanced Habitation Systems	23	24	78	12	12	12	29	55	14
11	7.052	1531: Autonomous Guidance and Navigation for Deep Space Missions	Autonomous Systems & Robotics	47	67	24	3	89	42	64	23	15
12	7.045	1591: Power Management Systems for Long Duration Lunar and Martian Missions	Power	40	12	10	52	24	68	35	NR	27
13	7.034	702: Nuclear Thermal Propulsion for Human Exploration	Propulsion: Nuclear	36	114	36	14	78	62	7	NR	11
14	7.031	1559: Deep Space Autonomous Navigation	Communication and Navigation	62	129	27	5	120	38	64	23	10
15	6.968	1527: Radiation Countermeasures (Crew and Habitat)	Advanced Habitation Systems	5	23	22	6	2	5	63	NR	6
16	6.948	1526: Radiation Monitoring and Modeling (Crew and Habitat)	Advanced Habitation Systems	6	53	41	81	1	13	27	38	35
17	6.946	879: In-space and On-surface, Long-duration Storage of Cryogenic Propellant	Cryogenic Fluid Management	21	37	3	95	22	1	59	NR	2
18	6.843	1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions	Autonomous Systems & Robotics	42	17	26	90	16	44	14	26	57
19	6.804	1558: High-Rate Communications Across The Lunar Surface	Communication and Navigation	25	73	29	77	162	20	5	NR	51
20	6.792	1626: Advanced Sensor Components: Imaging	Sensors and Instruments	18	75	12	45	160	22	NR	18	68
21	6.784	792: In-space and On-surface Transfer of Cryogenic Fluids	Cryogenic Fluid Management	17	29	4	51	26	2	62	NR	29
22	6.720	1569: High-Mass Mars Entry and Descent Systems	Entry Descent and Landing	152	156	48	117	5	33	16	NR	12
23	6.711	1525: Food and Nutrition for Mars and Sustained Lunar	Advanced Habitation Systems	8	32	116	41	45	30	11	NR	58
24	6.695	1571: Navigation Sensors for Precision Landing	Entry Descent and Landing	14	62	37	23	4	31	45	28	9
25	6.689	1573: Terrain Mapping Capabilities for Precision Landing and Hazard Avoidance	Entry Descent and Landing	30	31	9	12	8	11	45	28	53
26	6.662	1562: Advanced Algorithms and Computing for Precision Landing	Entry Descent and Landing	54	65	45	23	3	25	45	28	8
27	6.593	1597: Power for Non-Solar-Illuminated Small Systems	Power	85	26	5	39	125	47	93	12	20
28	6.592	1568: Entry Modeling and Simulation for EDL Missions	Entry Descent and Landing	101	115	76	60	15	50	45	5	45
29	6.584	1516: Water and Dormancy Management for Habitation	Advanced Habitation Systems	49	98	127	158	53	69	26	51	22
30	6.569	1524: Crew Medical Care for Mars and Sustained Lunar	Advanced Habitation Systems	12	64	94	1	11	21	58	NR	17

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ESDMD and SMD provided ranked lists (numbers shown above) in addition to shortfall scores (used for integrated list).
ESDMD and SMD did not score all shortfalls. Unscored shortfalls were also not ranked.

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Overview of U.S. & International Lunar Plans

NASA Manifest (10 Instruments)

- Next Generation Lunar Retroreflector (NGLR)
- Radiation Tolerant Computer System (RadPC)
- Regolith Adherence Characterization (RAC)
- Lunar Magnetotelluric Sounder (LMS)
- Lunar Environment heliospheric X-ray Imager (LEXI)
- Lunar PlanetVac (LPV)
- Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER)
- Stereo Cameras for Lunar Plume Surface Studies (SCALPSS)
- Electrodynamic Dust Shield (EDS)
- Lunar GNSS Receiver Experiment (LuGRE)

Science Goals

- **Lunar fiducial markers**
- **Test dust adherence on different materials and dust mitigation using electrodynamic fields**
- **Investigate the heat flow of the lunar interior**
- **Study plume-surface interactions**
- **Acquire X-ray images of Earth's magnetosphere**
- **Constrain temperature structure and thermal evolution by studying crustal electric and magnetic fields**

Technology goals

- **Test a radiation tolerant computer system**
- **Investigate the first use of GNSS (Global Navigation Satellite System) in transit to and on the lunar surface**
- **Test regolith sampling technologies**

CLPS TASK ORDER – 19D

Mission Details

- *Lander Provider*: Firefly Aerospace/ Blue Ghost
- *Launch Date:* **4Q 2024**
- *Landing Date:* **1Q 2025**
- *Landing Site:* Mare Crisium

Mission: BGM-1
MARE CRISIUM

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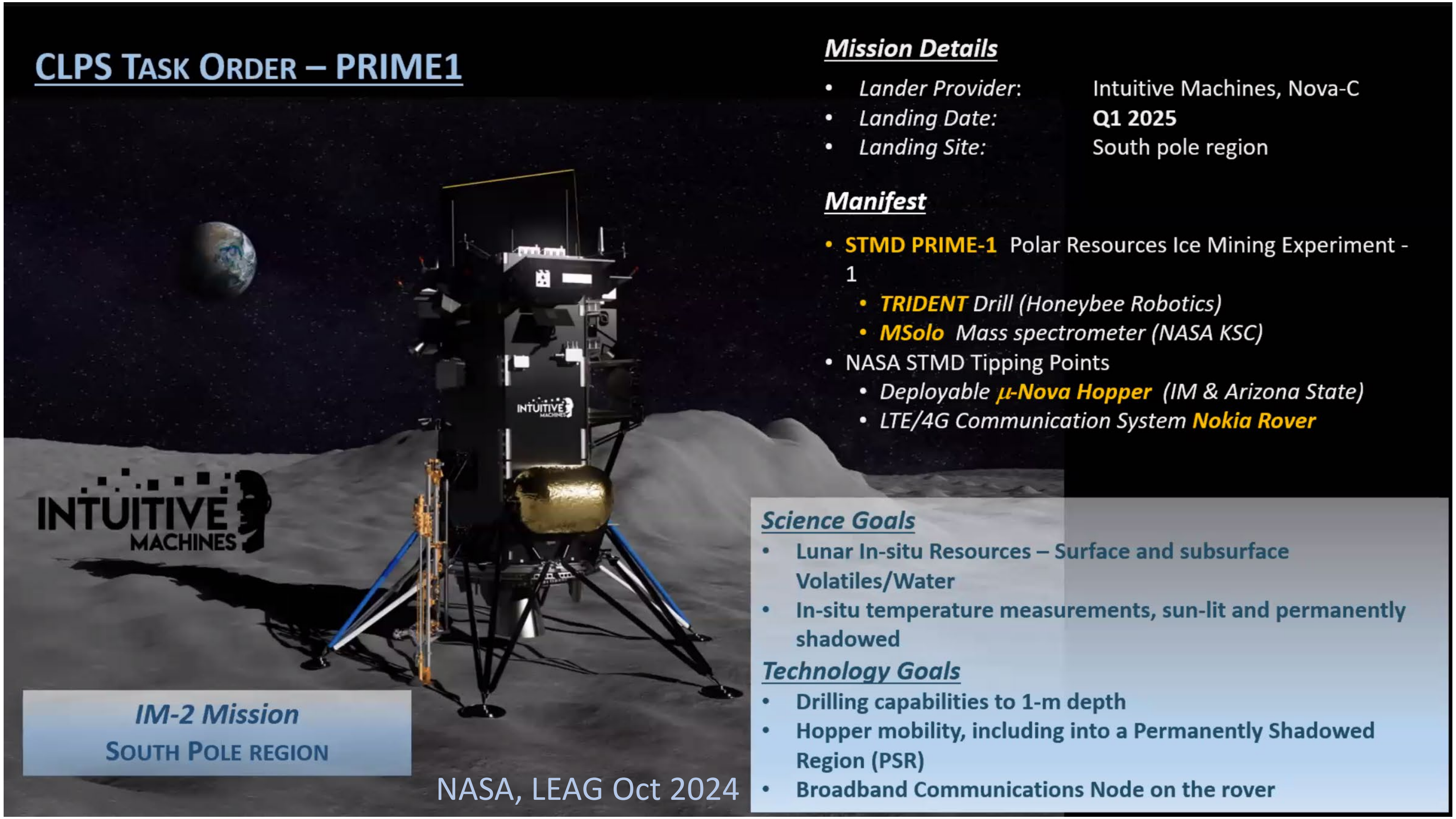
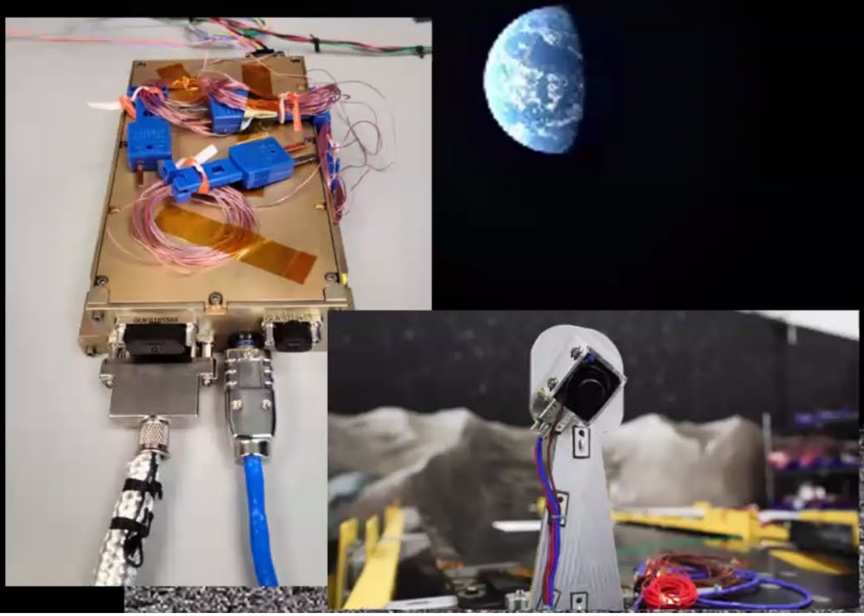
Overview of U.S. & International Lunar Plans



Overview of U.S. & International Lunar Plans

NASA Manifest (1 Instrument)

Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS)
- Collect validation data for plume-surface interaction analysis.
- Capture stereo video/images from the time of plume impingement through touchdown and after engine shutoff.
- Return data for the onset, rate, shape, and volume of plume crater formation



CLPS Task Order – CT-3

Mission Details

- *Lander Provider*: Blue Origin
  Blue Moon Mk-1 SN1
- *Launch Date*: **2025**
- *Landing Site*: South Pole Region

Mission: Blue Moon MK-1 SN1
South Polar Region

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