National Aeronautics and
Space Administration

Commercial Lunar Payload Services
Intuitive Machines-2
Technology Demonstrations Overview

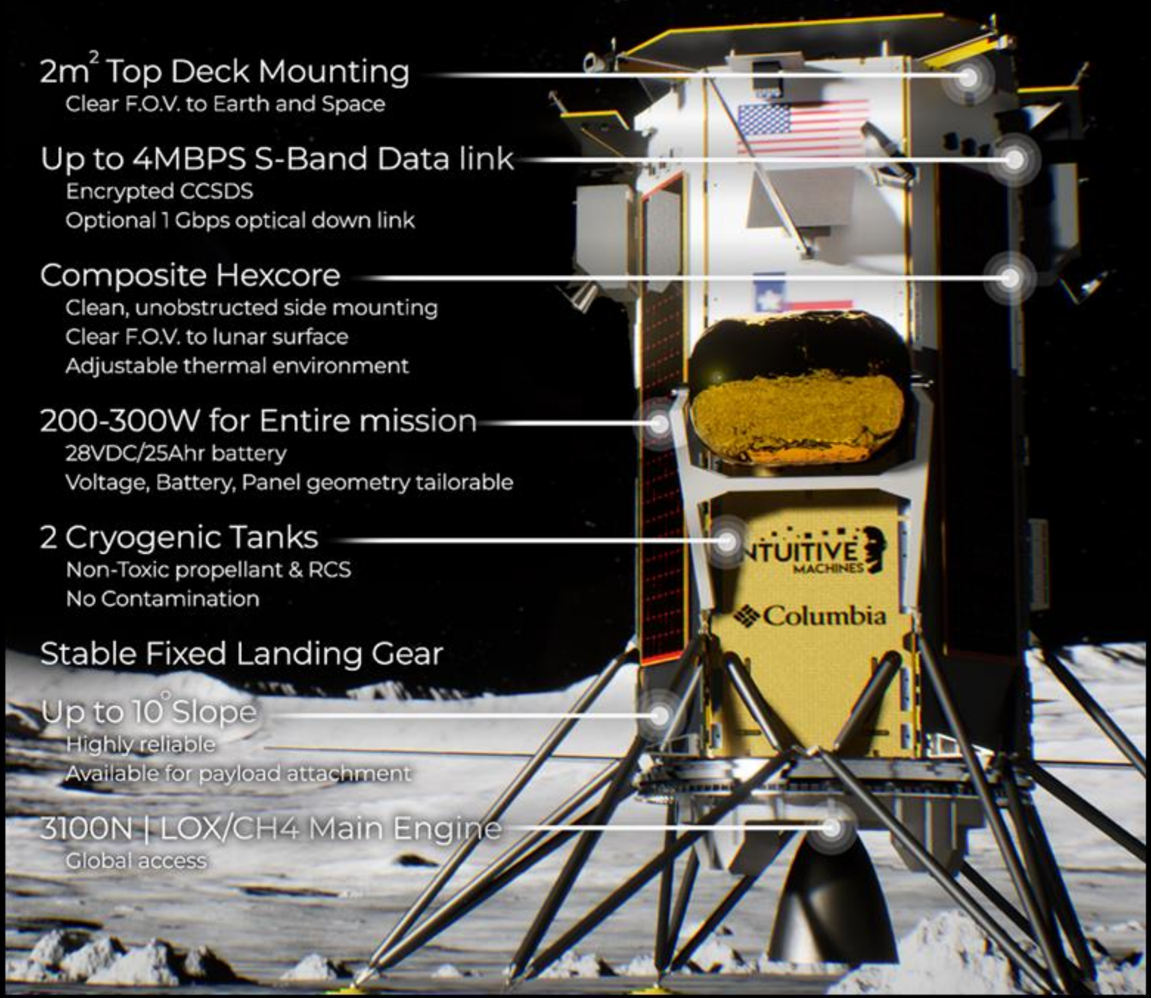
Technology, Innovation and Engineering (TI&E) Committee

Open Session

Mark Thornblom
Game Changing Development
Space Technology Mission Directorate
Deputy Program Manager, Integration
09.05.24

Intuitive Machine NOVA-C Mission Profile

IM NOVA-C Lander



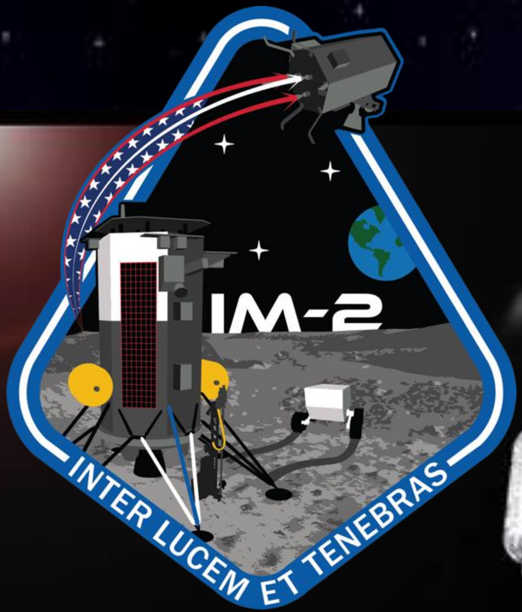
NOVA-C Capabilities as a Service

Landing Location	Nova-C	Nova-D	Nova-M*
Equatorial	130-250 kg	500-2500 kg	5,000-10,000 kg
South Pole	130-250 kg	500-2500 kg	5,000-10,000 kg
North Pole	130-250 kg	500-2500 kg	5,000-10,000 kg

	MAPP Rover	µNova Hopper	µNova-LX Hopper
Range (Max Distance from Lander)	2.5 km	25 km	25 km
Payload Mass	5 kg	1 kg	8 kg

Source: Intuitive Machines Lunar Access Services User's Guide- www.intuitivemachines.com

IM-2 NASA Payloads Overview



PRIME-1

TRIDENT

MSolo

NOKIA BELL LABS

INTUITIVE MACHINES
NOVA-C LUNAR LANDER

IM-2 Mission planned for FY25 Quarter 1

CLPS IM-2 Task Order History

Parallel Strategies

Nov. 2018

Intuitive Machines awarded indefinite duration indefinite quantity (IDIQ) contract under CLPS initiative

Oct. 2020

PRIME-1 lander selected: Intuitive Machines NOVA C

2018 — **2022**

Initial landing scheduled for Dec.2022

Feb. 2020

Space Technology Mission Directorate announces first **Tipping Point** call of the Lunar Surface Innovation Initiative (LSII)

Oct. 2020

Nokia 4G LTE and IM Deployable Hopper Selected

Landing Site Selection: NASA Memo of Record

July 1, 2021

Competing requirements drive collaboration amongst lander and payload teams for landing site selection

National Aeronautics and Space Administration

Langley Research Center
100 NASA Road
Hampton, VA 23681-2199

July 1, 2021

Mary (Niki) Werkheiser

TO: Memo of Record

FROM: Niki Werkheiser/STMD, Director, Technology Maturation

SUBJECT: Intuitive Machines Second Lunar Mission (IM-2) Landing Location

The purpose of this letter is to document the lunar south pole landing location for the second Intuitive Machines Nova-C mission (IM-2), scheduled for late 2022. In a meeting with NASA, Nokia, and Intuitive Machines (IM) held on Thursday May 6th, 2021, the team collectively agreed to an initial landing site region on the Shackleton Connecting Ridge (SCR), designated “SCR2” with coordinates of 89.4890° S, - 137.8675° E. The following forward work was identified to confirm SCR2 or identify an alternate site within approximately 200m of SCR2:

- Assess impact of 5mpp ice stability map on location selection
- Check indexing of datasets to ensure overlays are aligned
- Implement 2mpp DEM into IM LSE tool to improve resolution
- Perform Sun & Earth el/az comparison analyses between APL, ASU, and IM
- Perform lighting analysis for precision approach
- Perform detailed rover and LTE route mapping and timeline
- Perform detailed hopper route mapping and timeline

All assessment work has been completed. A new landing location within 105m of SCR2 was identified. The landing site has been designated SCR2b and has coordinates of:

-89.4875° S, -138.2350° E

SCR2b is to be used for all forward IM-2 mission design and planning. Any adjustments to this landing target must be bi-laterally approved by NASA and IM and have significant justification.

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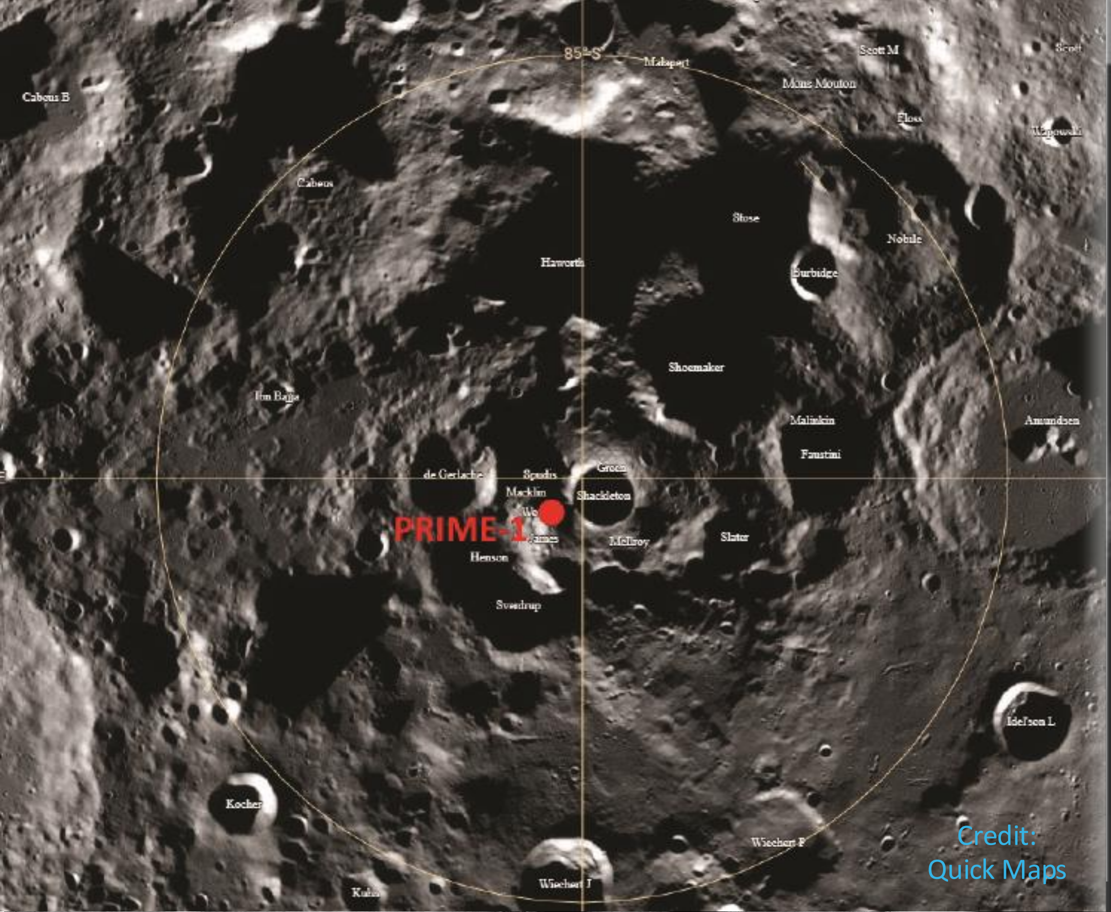
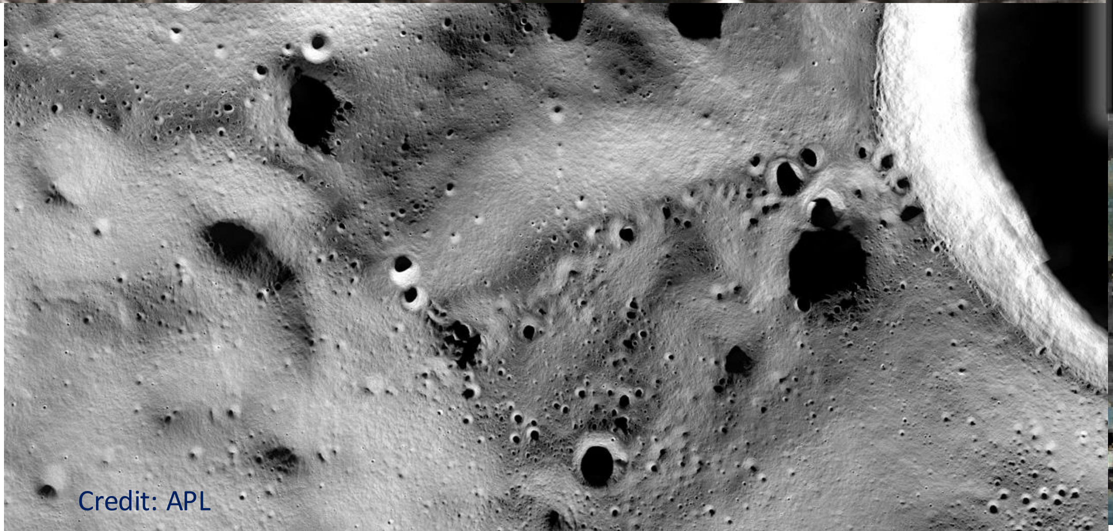
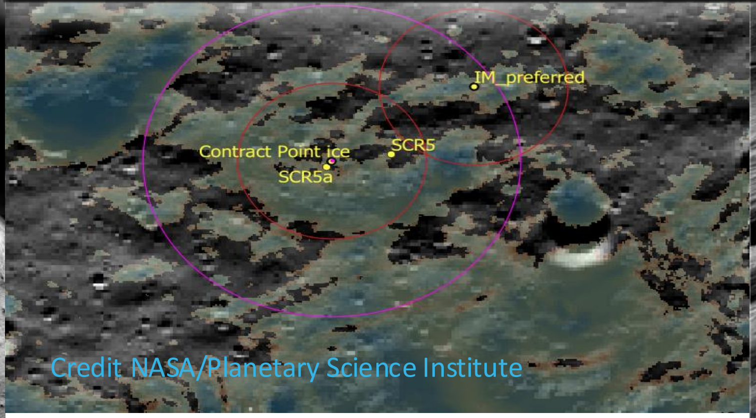


Credit: Quick Maps

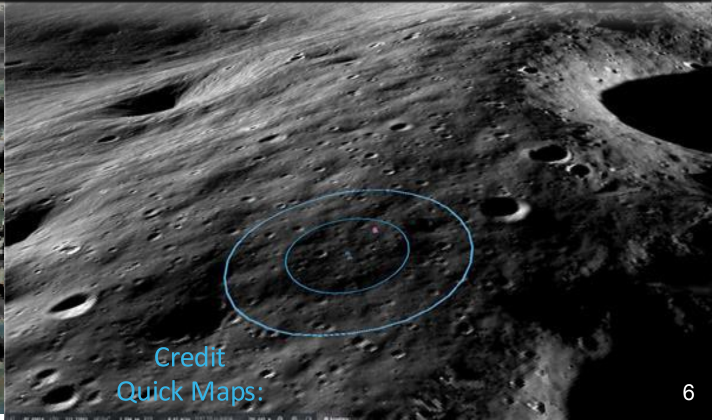
Click image to play video

Credit: APL:


Credit: APL



Credit NASA/Planetary Science Institute


Credit Quick Maps:

PRIME-1

MSolo Cross-Beam Ion Source

TRIDENT Drill Tip

PRIME-1 is the combination of two high-TRL instruments; Mass Spectrometer observing lunar operations (MSolo) and The Regolith and Ice Drill for Exploring New Terrain (TRIDENT). PRIME-1 will drill at a south pole lunar landing location where orbiting assets indicate the potential to find water ice. PRIME-1's MSolo instrument will analyze for volatiles present in lunar regolith down across a one-meter vertical profile. Demonstration of the PRIME-1 system will buy down engineering risk to the VIPER mission

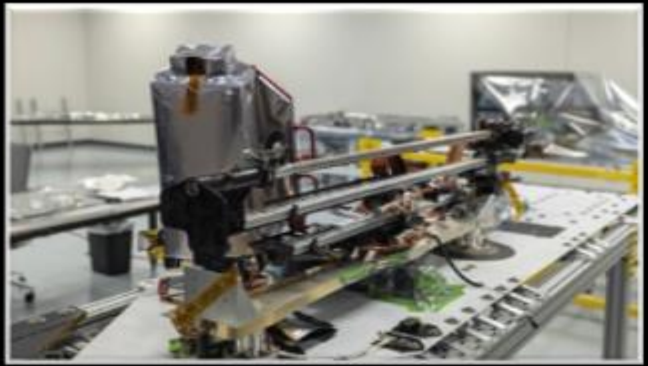
https://twitter.com/NASAMoon/status/1471889928762109953

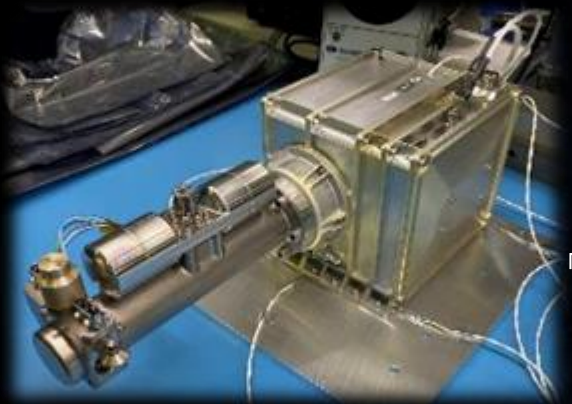
Objective #1	TRIDENT will drill into the lunar subsurface up to a meter deep and deliver regolith cuttings to the surface for water and other volatiles evaluation by MSolo
Objective #2	MSolo will measure within its field of view, the composition of gases emanating near the TRIDENT drill before, during and after drilling activities

PRIME-1 Hardware Integrated to NOVA-C Spacecraft panel ready for installation

PRIME-1

Programmatic Overview





Programmatic Status: **PRIME-1 is a NASA led project managed by KSC along with Honeybee and INFICON to provide the major flight components. The project has remained on schedule and on budget except for modest additional funds to support workforce through IM-2 mission delays.**

Technical Status: **Prime-1 Flight systems are complete and integrated to the IM-2 NOVA-C lander. Project is conducting operations training and awaiting the IM-2 mission.**

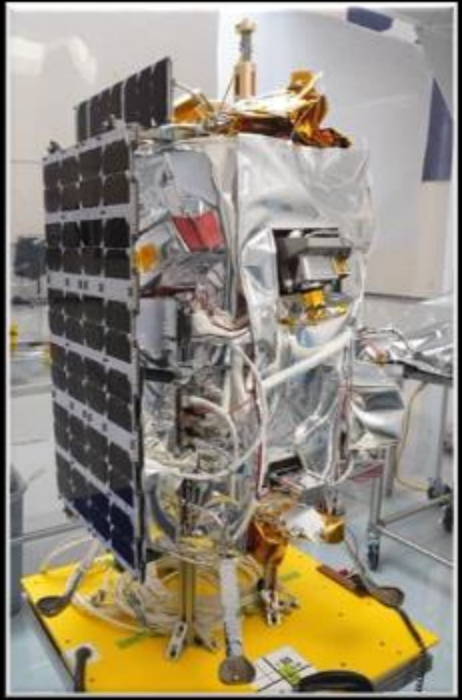
- 11/14/2022 MSolo V&V Testing Complete
- 6/15/2023 TRIDENT V&V Testing Complete
- 9/30/2023 TRIDENT Delivery to Lander
- 7/30/2024 PRIME-1 Delivery to Lander
- 7/30/2024 MSOLO Delivery to Lander
- FY25 Q1 IM-2 Mission and PL Ops

*- costs are for development of the technology and does not include SMD and STMD contributions for CLPS Task Order

Lunar Deployable Hopper Tipping Point

The lunar deployable hopper project will develop and demonstrate a small robotic hopper, deployed as a secondary payload from the IM-2 Nova-C lander, that can provide access to extreme environments and locations of interest on the lunar surface. μNova Hopper is designed to hop into and out of permanently shadowed regions (PSRs), providing a first look into undiscovered regions that may provide the critical science needed to sustain human presence on the Moon. This demonstration drives a commercial venture for IM and helps establish a space economy ecosystem economy.

https://www.youtube.com/watch?v=Ckcrn1btv8M



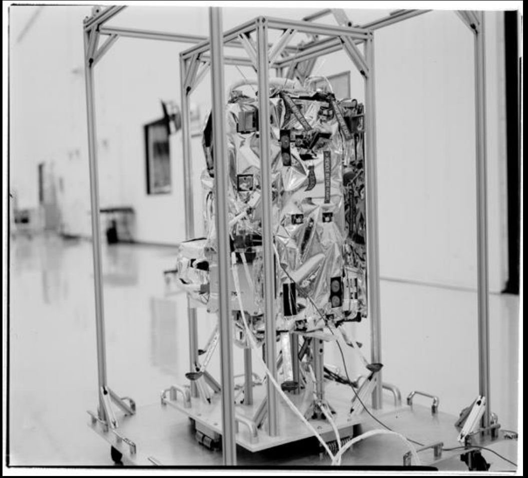
μNova Hopper vehicle on test stand

μNova tested in a TVAC Chamber

Objective #1	Enable robotic access to extreme lunar environments for scientific exploration
Objective #2	Enable regional exploration of wider areas than small rovers or other mobility platforms can cover

Deployable Lunar Hopper Tipping Point

Programmatic Overview



Programmatic Status: Lunar Deployable Hopper is an industry led tipping point project from Intuitive Machines, awarded under a firm fixed price contract. The project is on schedule to meet the current IM-2 mission timeline, and minimal costs have been incurred to NASA because of increased testing costs

Technical Status: The IM HOPPER is currently awaiting final testing and verification before being delivered for integration to the NOVA-C lander. While small risks exist for test anomalies, it is expected that HOPPER will meet the IM-2 delivery and mission schedules.

- 12/14/2023 – HOPPER V&V Testing Complete
- Structural Re-Work (12/14/2023 – 9/15/2024)
- 9/15/2024 – Integrated Vibe Test
- 9/30/2024 – HOPPER Delivery to Lander
- 10/3/2024 – Integration to Lander
- FY25 Q1 – IM-2 Mission and PL Ops

Nokia LTE Tipping Point

The overall goal of the LTE-TP project is to revolutionize lunar surface communications by leveraging advances in terrestrial communications technology to both improve the quality of communications (lower power, better range, higher bandwidth) while simultaneously reducing cost and providing an on-going commercial communication solution for the lunar economy (both surface and orbital). Future uses of the LTE network will be utilized for both human and robotic missions.

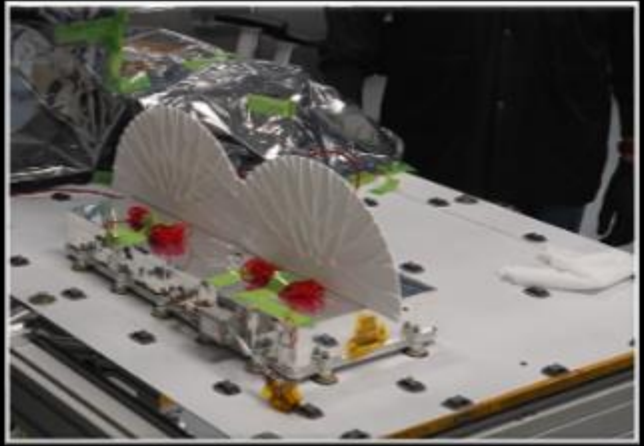
MAPP rover testing with LTE

Objective #1	Adapting Nokia's LTE technology for the lunar demonstration.
Objective #2	Integrate and test Nokia's LTE technology on Intuitive Machines (IM)s Nova-C lander/rover.
Objective #3	Demonstrate Nokia’s LTE technology on the lunar surface at short and long range
Objective #4	Provide a post mission lunar propagation model based on the lunar surface test results

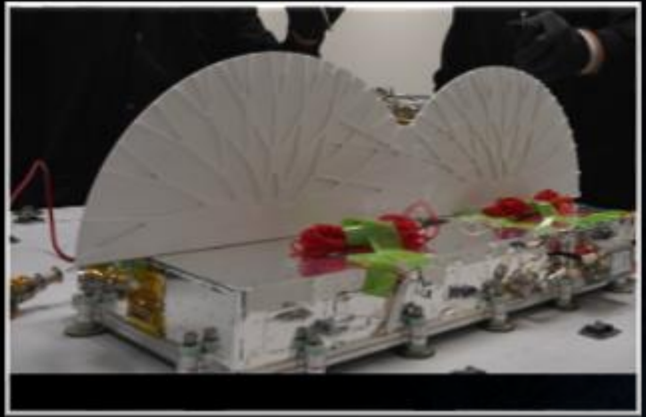
Flight Hardware Integration with IM-2 lander

Nokia LTE Tipping Point
Programmatic Overview

NOKIA BELL LABS



LTE Base Station Flight Hardware



Biologically Inspired Elephant Ear Thermal Radiators

Programmatic Status**: NOKIA LTE-TP is an industry led Tipping Point project from Nokia Bell Labs, awarded under a firm fixed price contract. The project has performed on schedule and on budget with minimal additional costs to support workforce due to IM-2 mission delays.**

Technical Status**: The LTE flight hardware is tested, delivered and integrated to the NOVA-C lander and awaiting the IM-2 Mission.**

Field Testing of the LTE System

9/29/2021
Flight LTE assets delivered to IM

9/26/2022
FlatSat Testing Complete

8/31/2023
Integrate HW on Lander

9/3/2024
Delivery to Lander

FY25 Q1
IM-2 Mission and PL Ops

Summary

- STMD-funded PRIME-1, IM HOPPER-TP, and Nokia LTE-TP projects have executed on time and on budget with minimal overrun
  - Hardware has been delivered to Intuitive Machines
  - Ready to support mission operations in FY25 Q1 on the IM-2 mission

- IM-2 is a key part of the Artemis program
  - NASA's first ISRU demo on the Moon, assessing the composition of regolith, volatiles, and collecting and returning valuable data
  - Supports Artemis surface communications architecture to enable 10km LTV communication requirement
  - Enables a commercial solution for mobility capabilities into lunar PSRs
  - Axiom Space and Nokia Partner to Develop 4G/LTE Network in Spacesuits
  - Maintains a continuity of purpose by incrementally expanding robotic and human presence

- IM-2 supports collaboration and investment across Industry
  - Intuitive Machines, Honeybee Robotics, INFICON, Nokia

Conclusion and Questions

The NASA STMD funded Prime-1, HOPPER-TP, and LTE-TP projects have executed admirably, are delivered to Intuitive Machines, and will be ready to support mission operations in FY25 Q1 on the IM-2 mission

INTUITIVE MACHINES
NOVA-C LUNAR LANDER

BACKUP

PRIME-1

Objectives and Performance Metrics

Objective #1	TRIDENT will drill into the lunar subsurface up to a meter deep and deliver regolith cuttings to the surface for water and other volatiles evaluation by MSolo
Objective #2	MSolo will measure within its field of view, the composition of gases emanating near the TRIDENT drill before, during and after drilling activities

PRIME-1 supported by Intuitive Machines' Primary Payload Precision Off-loader (3PO) platform

Parameter Name	Unit	State of the Art	Threshold Value	Project Goal	Current Value to Date	TBoE for the Provided Current Value	Expected Exit Value	TBoE for the Provided Exit Value
Regolith sample-depth resolution	Number of linear depths along single drill hole[1]	N/A[2]	3	5	5	Estimated	5	Estimated
Volatile species identification	Number of volatiles (#)	1	2	3	2	Estimated	2	Estimated
Water detection accuracy for regolith[3]	Percentage by mass water grade in regolith (%)	N/A	2	1	2	Estimated	1	Estimated

HOPPER Tipping Point

Objectives and Performance Metrics

Objective #1	Enable robotic access to extreme lunar environments for scientific exploration
Objective #2	Enable regional exploration of wider areas than small rovers or other mobility platforms can cover

Parameter Name	Unit	State of the Art	Threshold Value	Project Goal	Current Value to Date	TBoE for Current Value	Expected Exit Value	TBoE for Expected Exit Value
Excursion Data Downlinked [1]	GB	N/A	1	3.5	5	Analysis	5	Estimate based on link analysis and Nokia LTE path propagation assessment; also includes available downlink time (shared with other payloads)
Longest Flight Capability	m	N/A	10	100	280	Analysis	280	Flight simulation with processor in the loop
PSR Survival Limits	K, min	N/A	60, 15	60, 45	60, 60	Analysis	60, 60	Global thermal model (to be validated with tvac test)
Landing Capability [2]	deg, m/s	N/A	5, 1	10, 2	7[4], 2	Analysis	7, 2	Dynamic tip over model
Power Margin [3]	%	N/A	15%	30%	21%	Analysis	21%	Power balance model including detailed solar panel degradation model

Notes:
1) Downlinked to Earth
2) Slope angle, vertical landing velocity
3) Excess power capacity as a percentage of standby power draw when solar vector is normal to solar panel
4) Includes later and rotational velocity

NOKIA BELL LABS

LTE Tipping Point

Performance Metrics

Parameter Name	Unit	State of the Art	Threshold Value	Project Goal	Current Value to Date
LTE system operational on lunar surface. LTE BTS and UE telemetry received at control center.	Pass/fail	N/A	pass	pass	N/A
LTE system operational on lunar surface. Control center able to send command messages to both BTS and UE.	Pass/Fail	N/A	pass	pass	N/A
LTE UE connection to BTS at short/long range.	Meters	300/300	100/1000	300/1500	N/A
LTE UE UDP uplink (UL) to BTS at short/long range.	Mbps	N/A	10/0.5	25/5	N/A
LTE UE UDP downlink (DL) to BTS at short/long range.	Mbps	N/A	25/1.0	80/10	N/A
Key LTE UL/DL performance indicators gathered at various points on the lunar surface from 100-300m from lander and transferred to the control center.	Pass/Fail	N/A	Pass	Pass	N/A
Key LTE UL/DL performance indicators gathered at various points on the lunar surface up to 2km from lander and transferred to the control center.	Pass/Fail	N/A	Pass	Pass	N/A
Evaluate LTE system tolerance to radiation-induced errors in terms of maximum system resets/hour.	Resets/hour	N/A	5	1	N/A

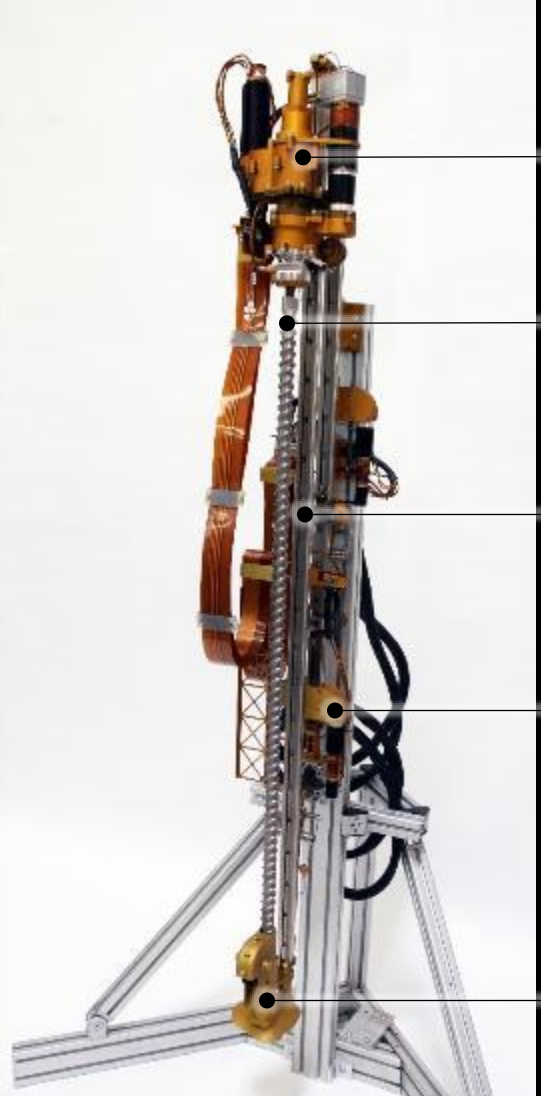
PRIME-1

TRIDENT – Commercial Drill

- TRIDENT (The Regolith and Ice Drill for Exploring New Terrains) subsystem includes the hardware to physically **excavate/extract regolith from the lunar surface up to a depth of 1 meter.**

- Excavation device will be instrumented to **measure forces/displacements** in order to determine critical bulk properties of the regolith. This information will be used to understand the working environment and **bound critical excavation parameters for future larger scale regolith mining** equipment and processes.

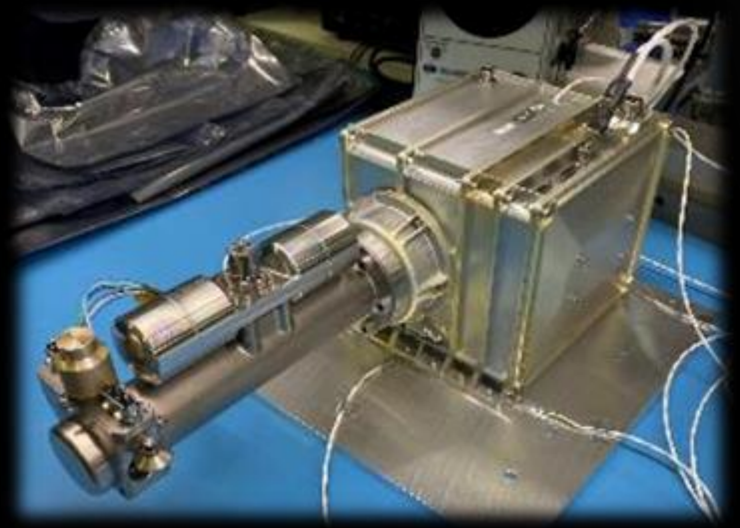
- TRIDENT captures regolith in **8-10 cm increments** down to a depth of 1 meter. Material captured by the drill is transported to the surface to be analyzed by **MSolo**. TRIDENT measures **strength of the lunar regolith as well as subsurface temperatures** during drilling operations.



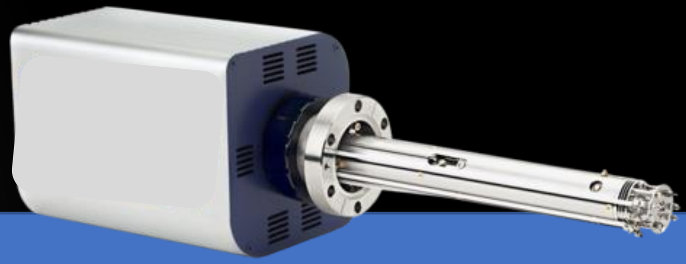
TRL6 Drill Prototype

Mass Spectrometer Observing Lunar Operations

Ruggedization for Spaceflight
- Calibration Gas System
- Thermal upgrades
- Structural upgrades
- Onboard computer designed
- Avionics board redesign
- New chassis to support COTS MS Boards, new power boards and onboard computer
- Software designed to be compatible with RS422 and COTS firmware/operation



Modified Commercial Off The Shelf Mass Spectrometer
- INFICON Quadrupole Residual Gas Analyzer
- Open or Cross Beam Ion Source (COTS)
- Electron impact ionization - Dual Y_2O_3/Ir filaments (COTS)
- Faraday Cup and Electron Multiplier Detectors (COTS)
- Calibration Gas System (KSC)
- Chassis designed to build on instrument avionics and include spaceflight control computer (SHREC) and power board



Cross Beam Ion Source

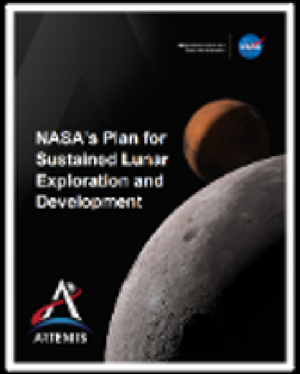
Open Ion Source

STMD Investment Aligned to Agency Goals

NASA Strategic Plan

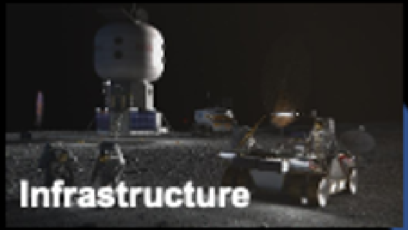
3.1 Innovate and advance transformational space technologies

Develop revolutionary, high-payoff space technologies driven by diverse ideas to transform NASA missions and ensure American leadership in the space economy



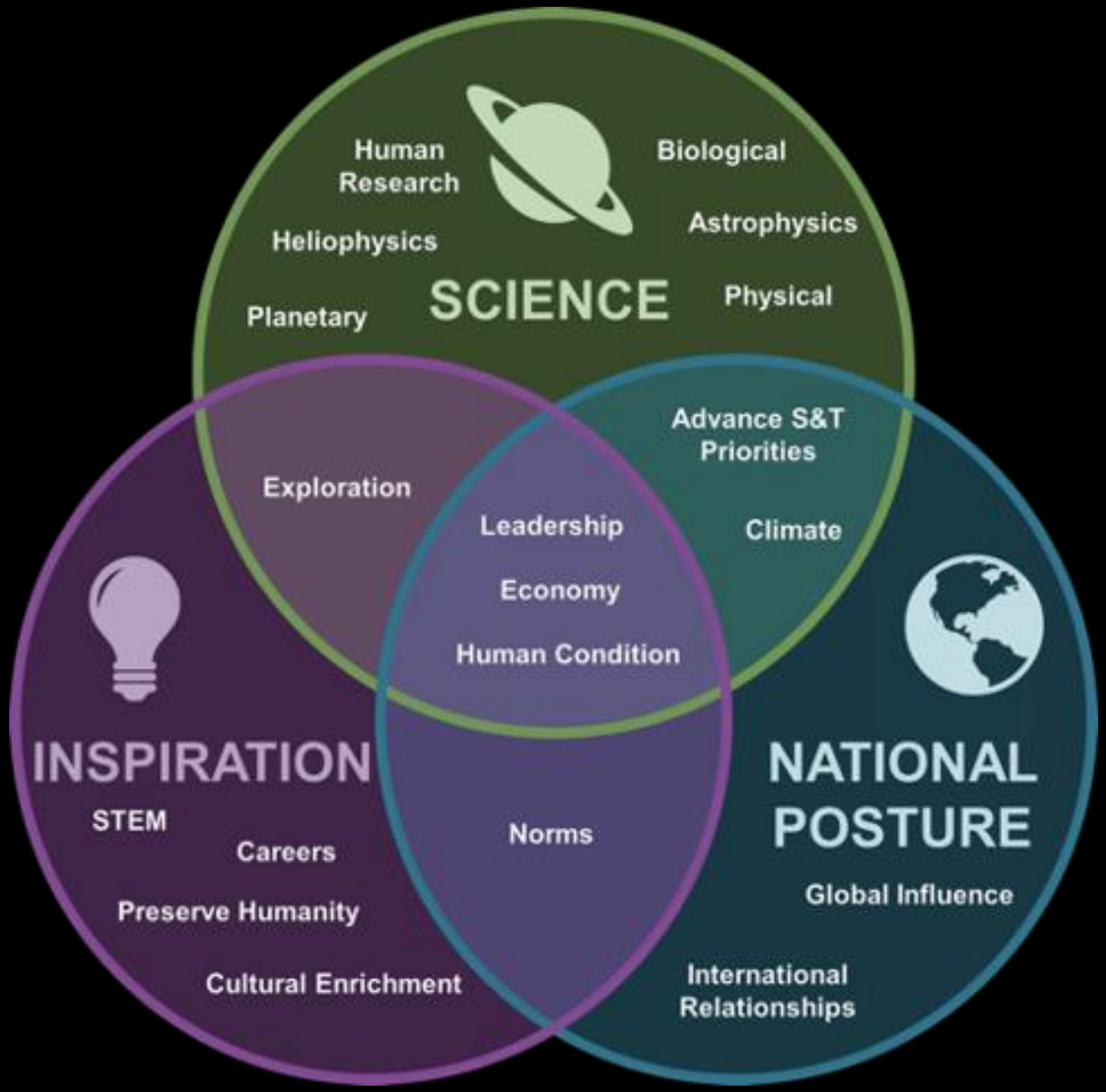
Draws from Artemis architecture, science decadals, and industry identifying technology gaps for investment to develop needed capabilities to support NASA missions and commercial space sector

Moon to Mars Blueprint Objectives

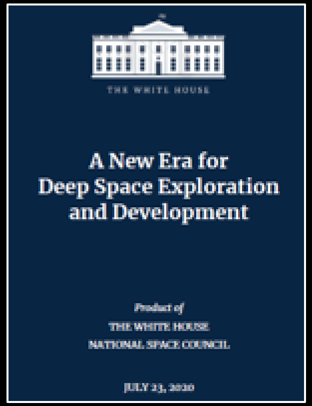


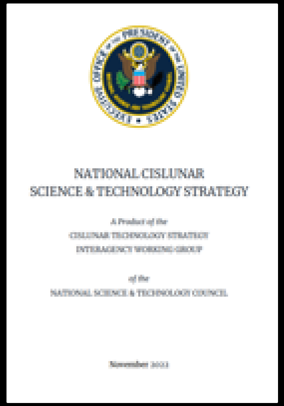
STMD Strategic Framework

National Policy and External Drivers



Recent US Policy on Space Exploration and Resources





China/Russia Cislunar Strategy

ILRS-3 MISSION	Establishment of lunar in-situ resource utilization technology verification facilities

China
Chang'e 7, 8

Russia
Luna 26, 27

STMD Investment Strategy

Advancing U.S. space technology innovation and competitiveness

Encouraging technology-driven economic growth emphasizing expanding the space economy

Inspiring and developing a diverse and powerful U.S. aerospace technology community

- **Bring innovative technologies** to flight and infuse them to industry and NASA missions
- Invest in paradigm-shifting technologies that **build a strong U.S. industry,** create good paying jobs, and support a strong national posture
- **Develop a global lunar utilization infrastructure** for sustained operations on the lunar surface
- Create partnerships with industry to **establish commercial space capabilities**
- Transfer the widest possible use of all NASA technologies **to spur economic growth**
- **Support high growth businesses** of the future through small business research
- **Empower a broad community of innovators** through emphasis on early-stage investments

LSII/LIVE: Surface Infrastructure & Exploration

The Surface Infrastructure and Exploration (LIVE) Domain is responsible for managing Capability Portfolios that will enable humans to live and work sustainably in the extreme lunar and Mars environments.

- Formulate and integrate technology maturation activities across Technology Readiness Levels
- Utilize surface flight opportunities to inform key technology development
- Work across industry, academia and government through in-house efforts and public-private partnerships to develop transformative capabilities for surface exploration
- Grow the Lunar Surface Innovation Consortium (LSIC) to foster innovation and collaboration across sectors