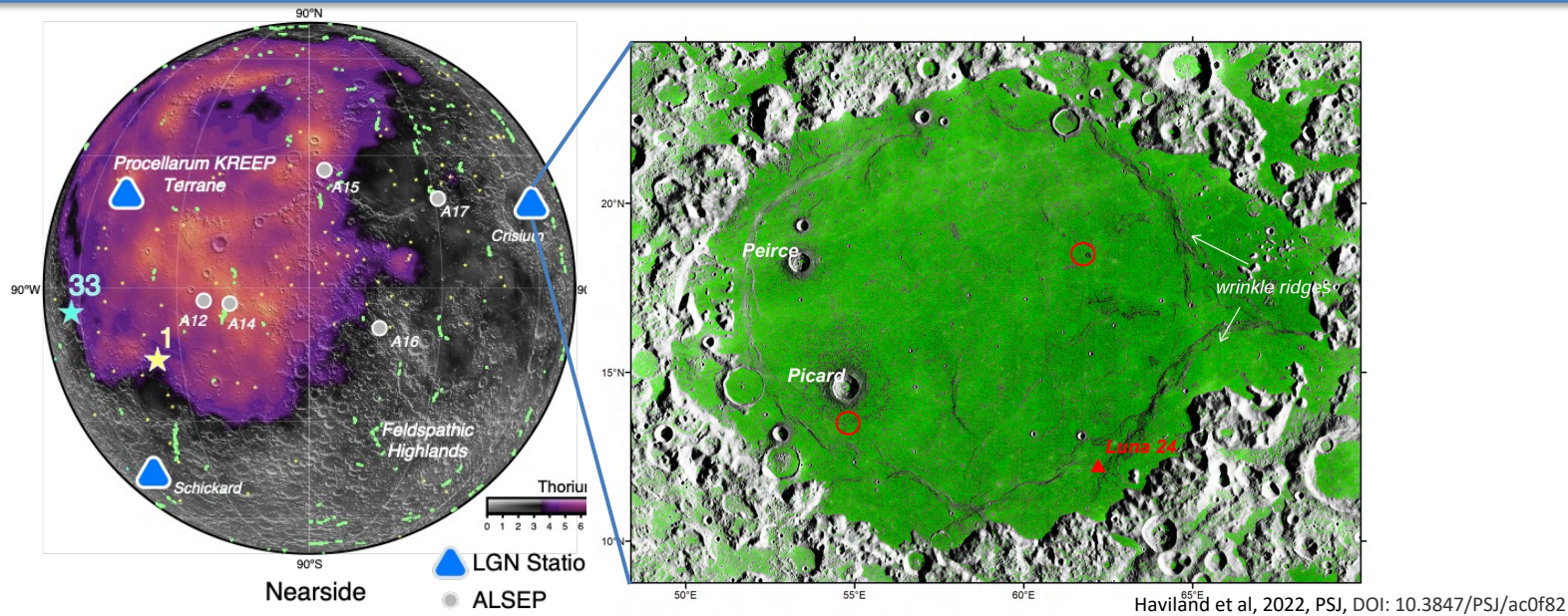




Future Lunar Missions: the Need for Future Science Observations at the Lunar Surface



Heidi Fuqua Haviland
heidi.haviland@nasa.gov
 NASA Marshall Space Flight Center,
 Heliophysics and Planetary Science Branch

UCLA
 SMART Talk
 06/06/2023

Education Path

- Beaumont Elementary School, Vista, California
- Lincoln Middle School, Vista, California
- San Marcos High School, San Marcos, California
- Bachelors of Science, Physical Science, Biola University , La Mirada, California
- Bachelors of Science, Aerospace Engineering, Univ. Southern California (USC)
- Masters of Science, International Space University, Strasbourg, France
- PhD, Planetary Science, University of California, Berkeley



Career Path



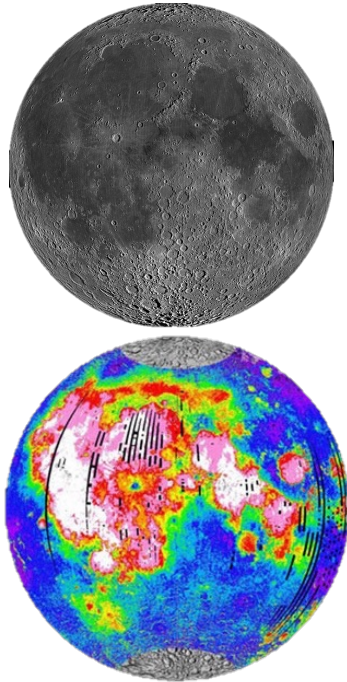
- Engineering Intern, Boeing
- Engineering Intern, Northrop Grumman
- Mechanical Integration & Test Engineer, Northrop Grumman Space Technology
- Mechanical Design Integration, Systems Engineering, Northrop Grumman Space Technology
- LADEE Engineering Intern, NASA Ames Research Center
- Graduate Student Instructor, UC Berkeley
- Graduate Student Researcher, UC Berkeley, Space Sciences Lab
- Invited Guest Researcher, Louisiana State University, Geology & Geophysics Department
- Planetary Scientist, NASA MSFC

What's the difference between science & engineering?

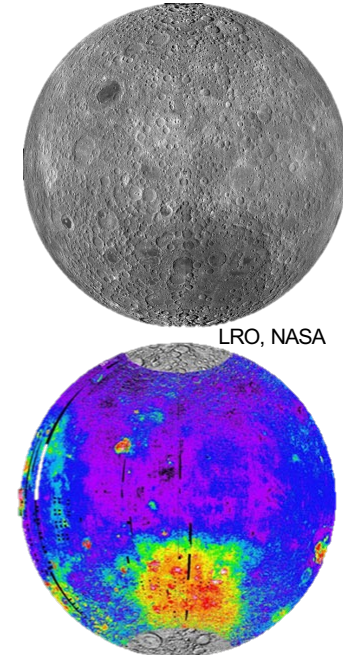
Driving Science Question

Equatorial Cross-section

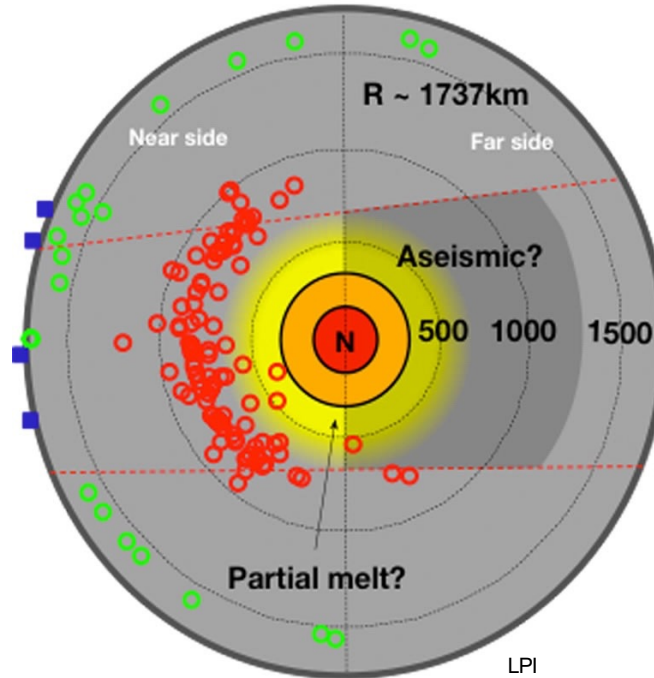
Near Side



Far Side



LRO, NASA



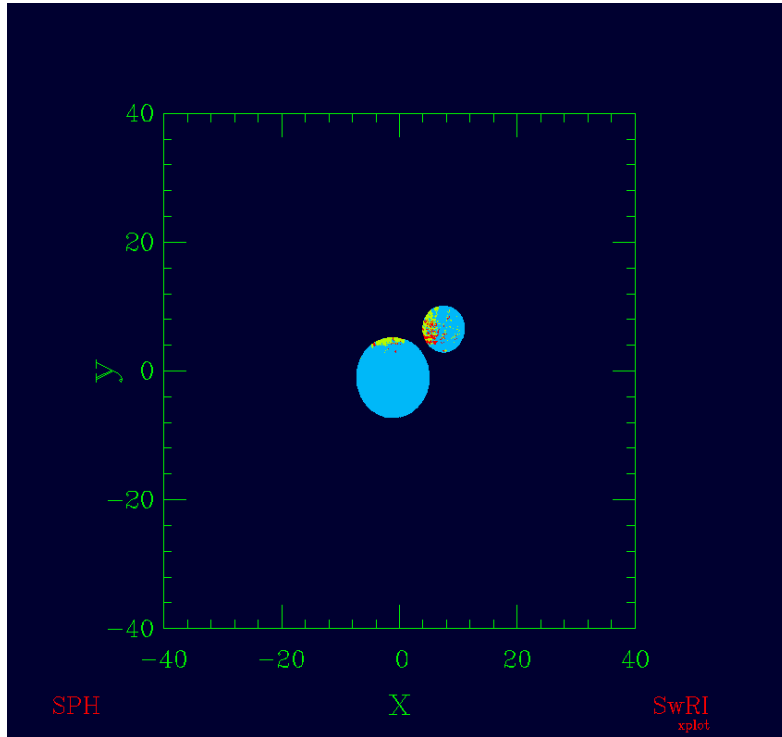
LPI

- Apollo station
- Deep moonquake nest
- Shallow moonquake event

Gillis, University of Hawaii,
<https://artemis.igpp.ucla.edu/images/moonFeOmap-global.jpg>

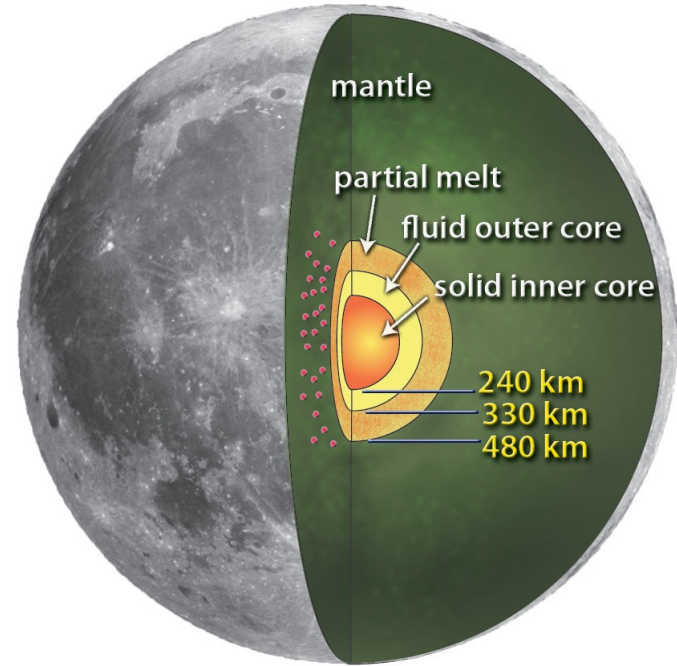
What is the current state and structure of the global lunar interior?

Lunar Origin Theories



Canup et al. 2016

<https://www.nasa.gov/ames/evidence-for-moon-forming-impact-found-inside-meteorites>



Weber et al., 2011

https://www.nasa.gov/topics/moonmars/features/lunar_core.html

The current state is key to constraining origin theories.

Magma Ocean Crystallization

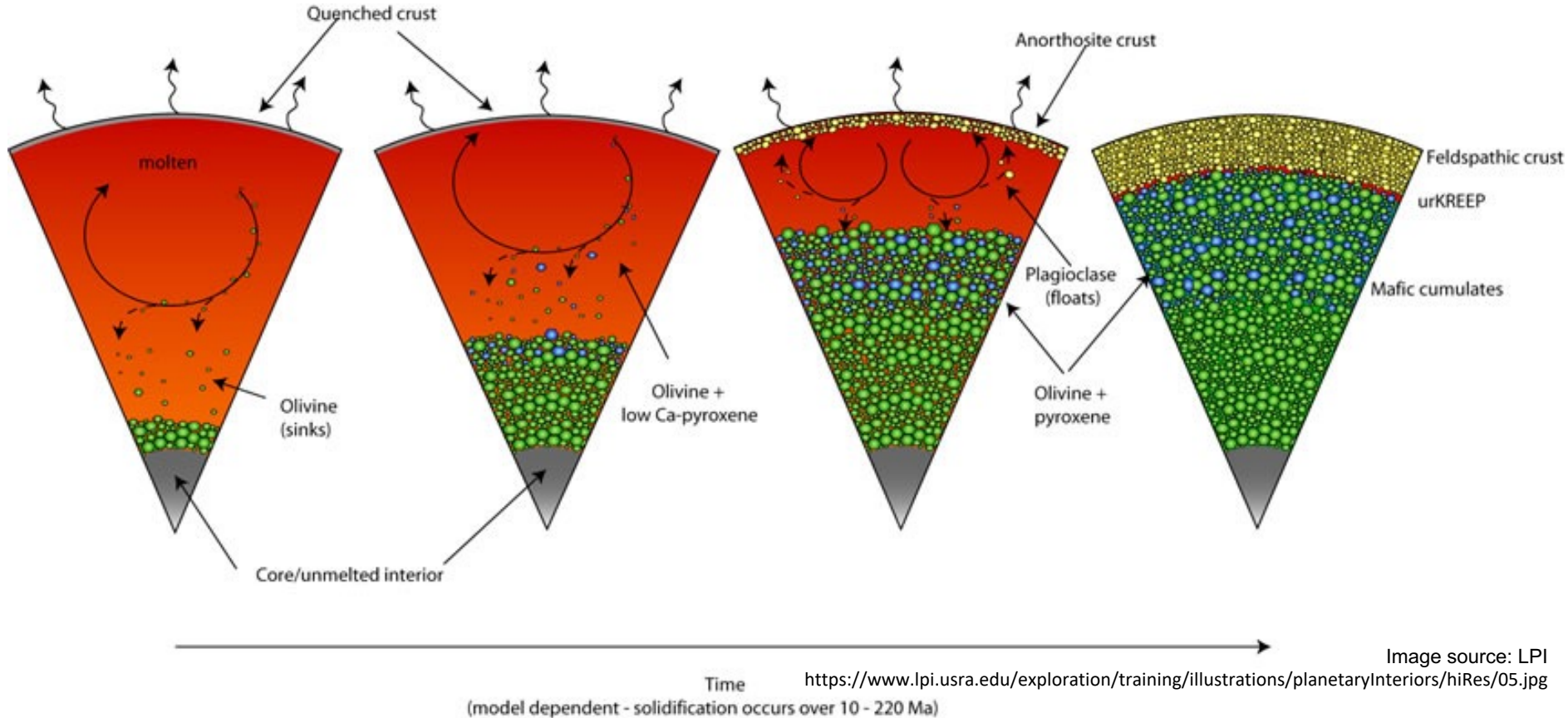
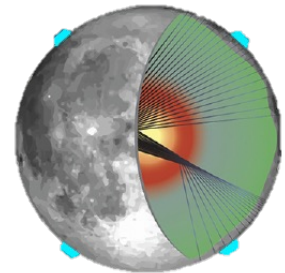


Image source: LPI

<https://www.lpi.usra.edu/exploration/training/illustrations/planetaryInteriors/hiRes/05.jpg>

Why does the Moon need a Lunar Geophysical Network (LGN)?

- Additional geophysical observations are needed to answer outstanding questions regarding lunar interior properties, formation and crystallization.
- The Lunar Geophysical Network (LGN) is a mission concept highlighted in the 2023-2032 Planetary Science Decadal Survey as a New Frontiers, medium class, mission opportunity to be accomplished in the next decade to answer key terrestrial planetary interior and formation questions.
- Alternate approaches are also being considered.



LGN Science Goal and Objectives

The main goal of LGN is to understand initial terrestrial planet evolution through defining the global interior structure and composition of the Moon.

SCIENCE OBJECTIVES

Objectives:

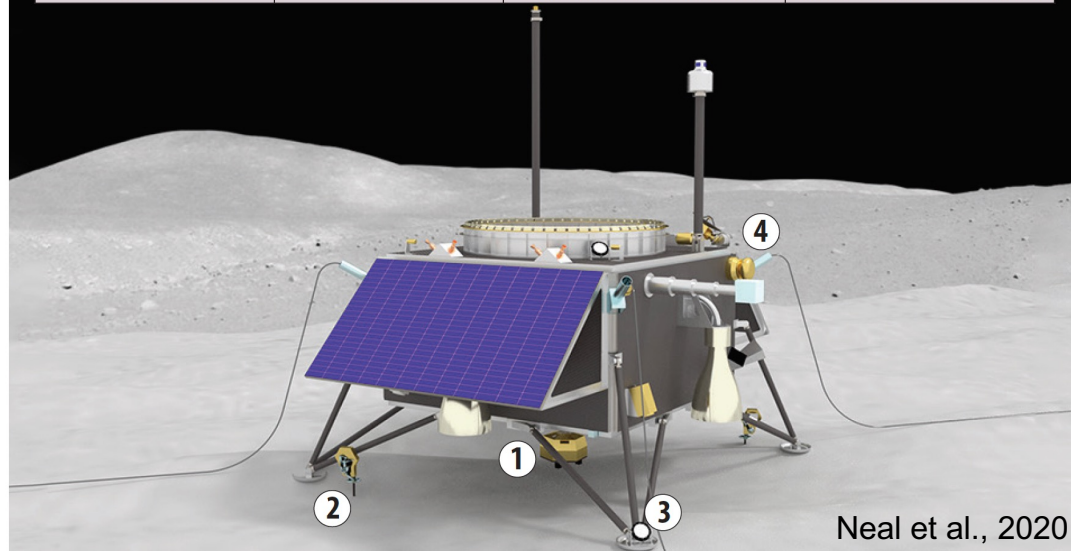
- Define the interior structure of the Moon.
- Constrain the interior and bulk composition of the Moon.
- Delineate the vertical and lateral heterogeneities within the interior of the Moon as they relate to surface features and terranes.
- Evaluate the current seismo-tectonic activity of the Moon.

Investigations:

- Determine the size, state and composition of the lunar core.
- Determine the state of as well as the chemical/physical stratification in the lunar mantle.
- Determine the thickness of the lunar crust and characterize its vertical and lateral variability.
- Determine the thermal state of the lunar interior and elucidate the workings of the planetary heat engine.
- Monitor impacts on to the lunar surface as an aid to exploring the lunar interior.

INSTRUMENT COMPLEMENT

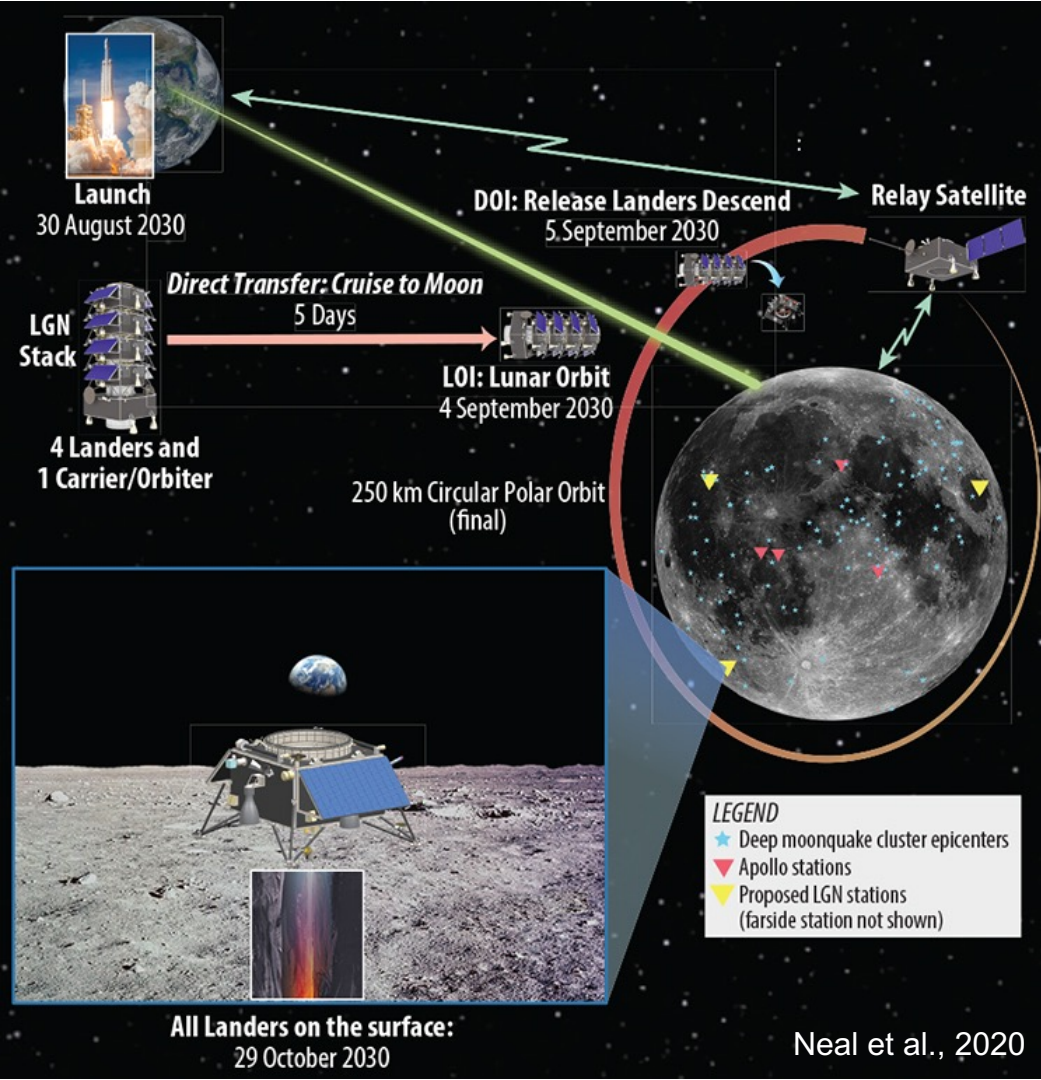
1	Seismometer	2	Heat Flow Probe	3	Retroreflector	4	Magnetotelluric Sounder
	Understand the current seismic state and determine the detailed internal structure of the Moon		Measure the heat flow to characterize the temperature structure of the lunar interior		Constrain the deep mantle environment, fluid core/solid mantle boundary conditions, and the presence/absence of a solid inner core		Determine the electrical conductivity structure of the interior to establish joint constraints on temperature and composition



Neal et al., 2020

LGN Mission Concept

- 4 identical landers deployed globally.
- Communications satellite required for the far-side station.
- Sites chosen to maximize science return.
- Sequential deployment at lunar dawn.
- Operational at all times (including night) – 6 yr minimum.
- Communications only during sunlight.
- Challenges to fit within cost cap.

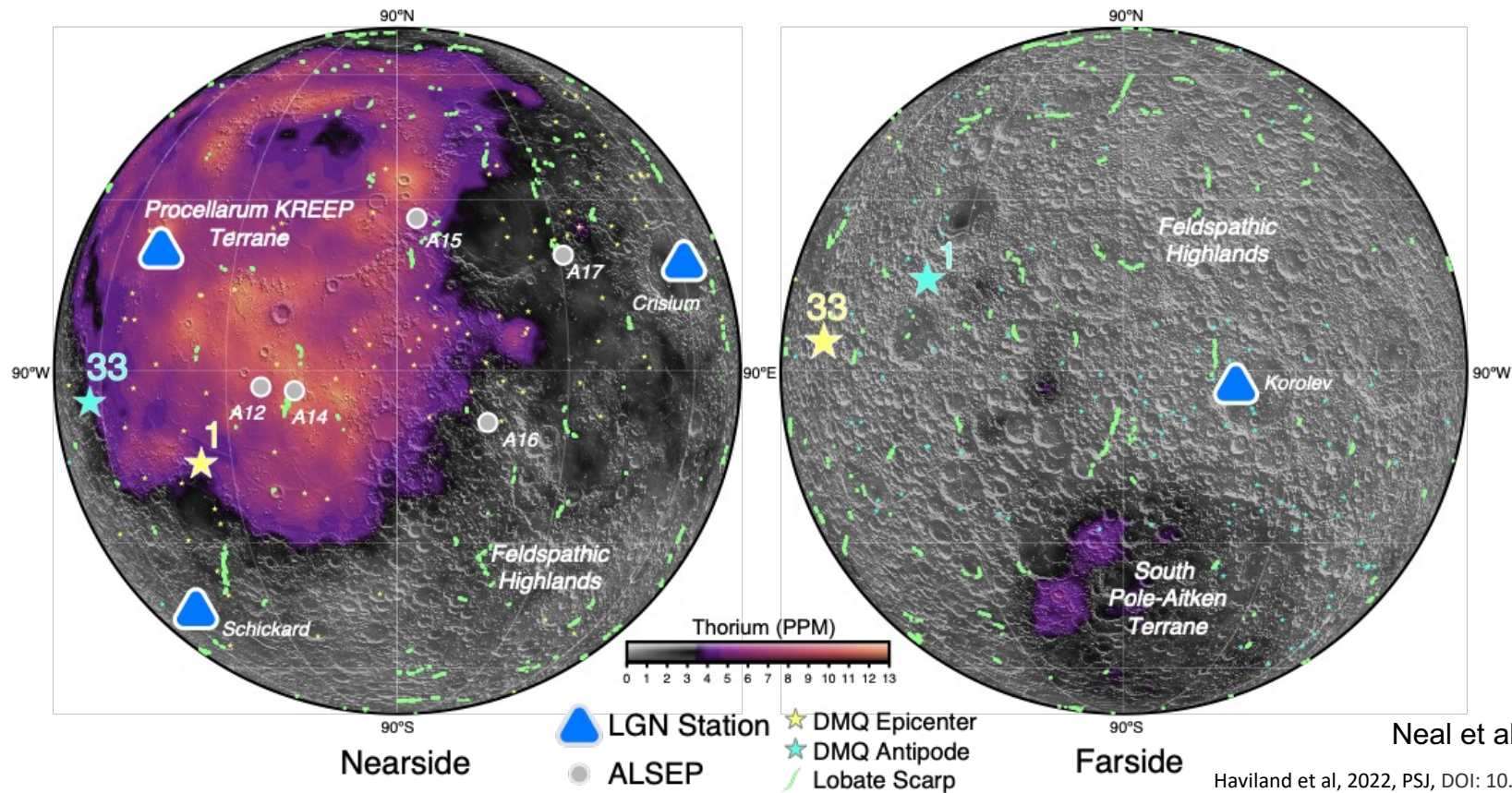


Landing Site Criteria

	LGN Landing Site Requirements	
Overarching Criteria	Broader coverage than Apollo Low-risk landing sites (i.e., low boulder and crater density)	
Measurement Type	Primary	Secondary
Seismicity	Use known seismic sources to examine the core, mantle, and crust	Proximity to thrust faults (lobate scarps, wrinkle ridges)
Laser retroreflectometry	3 nearside stations	Place nearside stations near as possible to the limb
Magnetotelluric	Location well within terrane boundaries	Benign magnetic signature at the surface
Heat flow	Location well within terrane boundaries	Regolith available for full deployment

Haviland et al, 2022, PSJ, DOI: 10.3847/PSJ/ac0f82

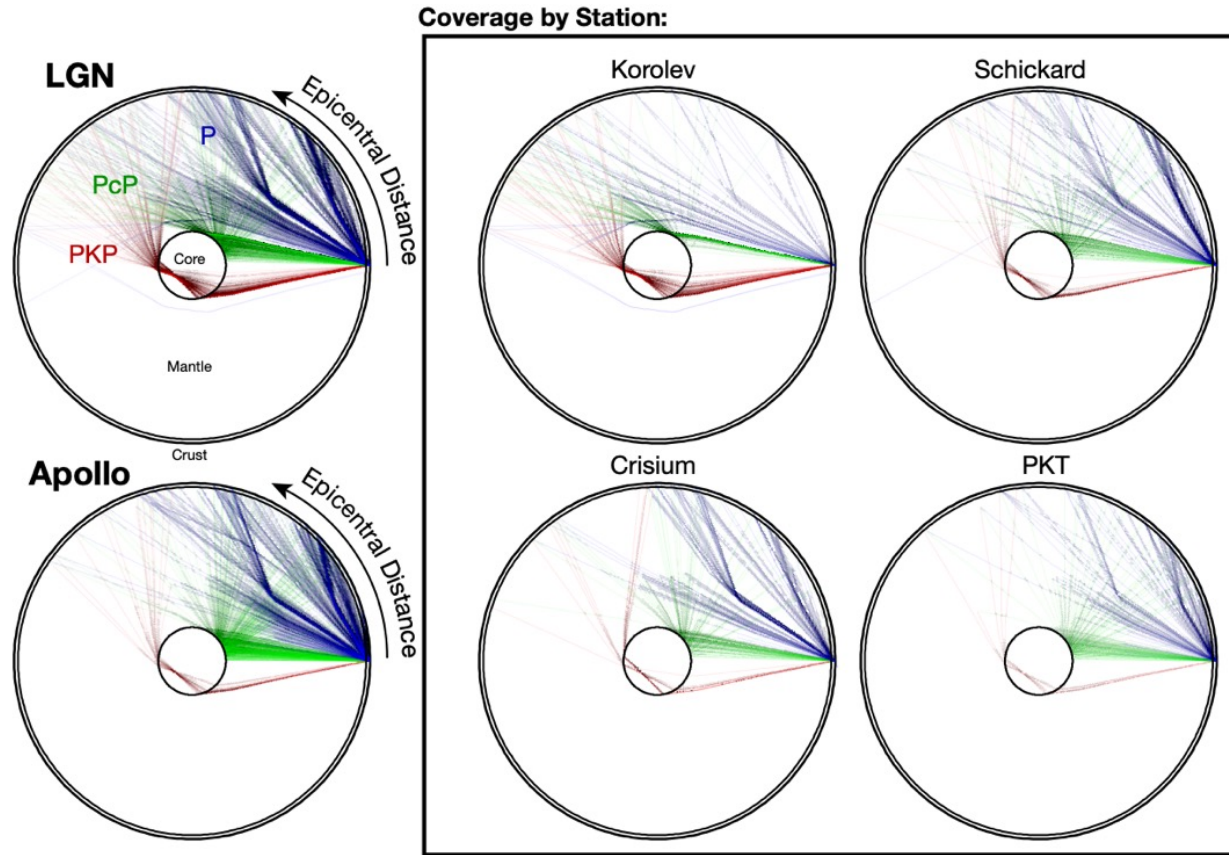
Example LGN locations



Neal et al., 2020

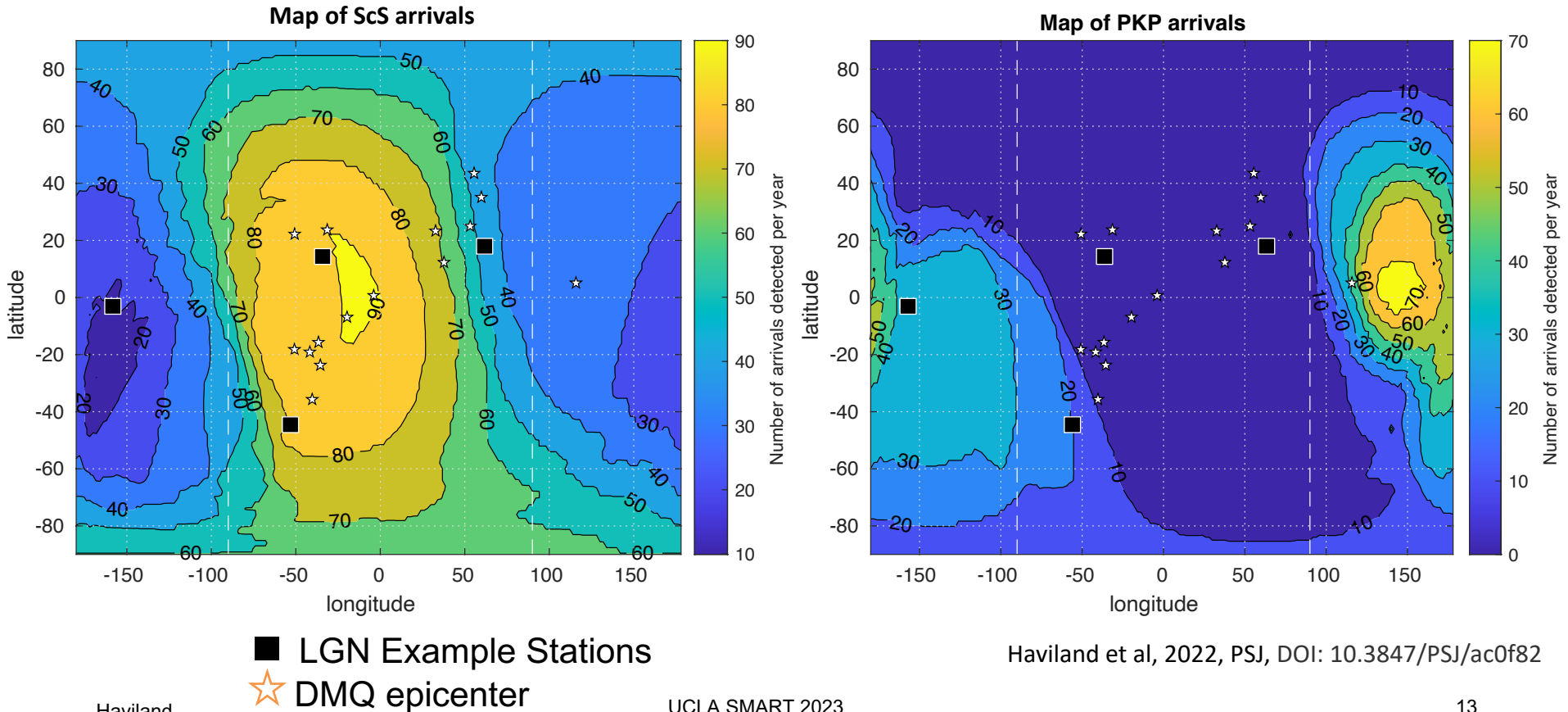
Haviland et al, 2022, PSJ, DOI: 10.3847/PSJ/ac0f82

Seismic network ray density theoretical comparison

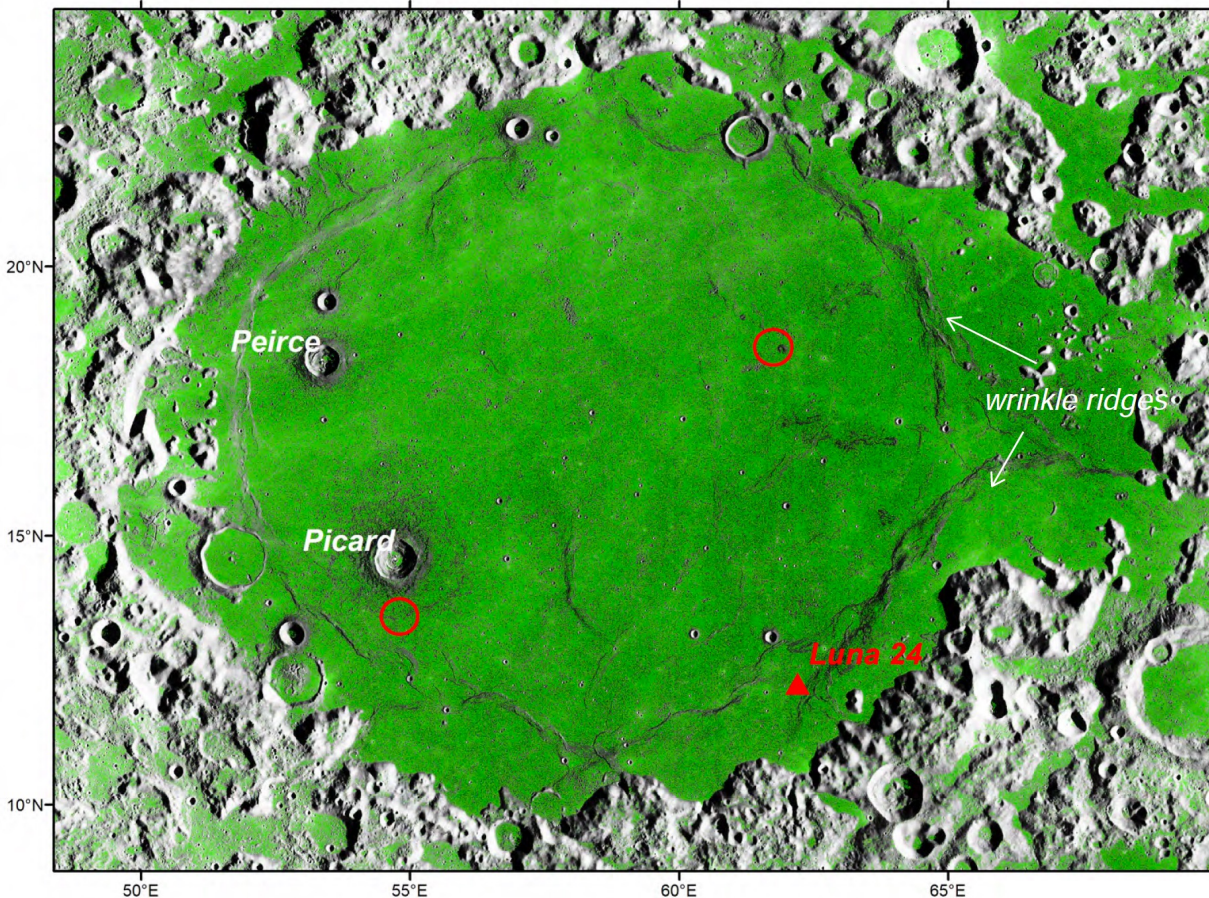


Neal et al., 2020

Seismic network optimization for core detection



Landing Site Case Study: Mare Crisium

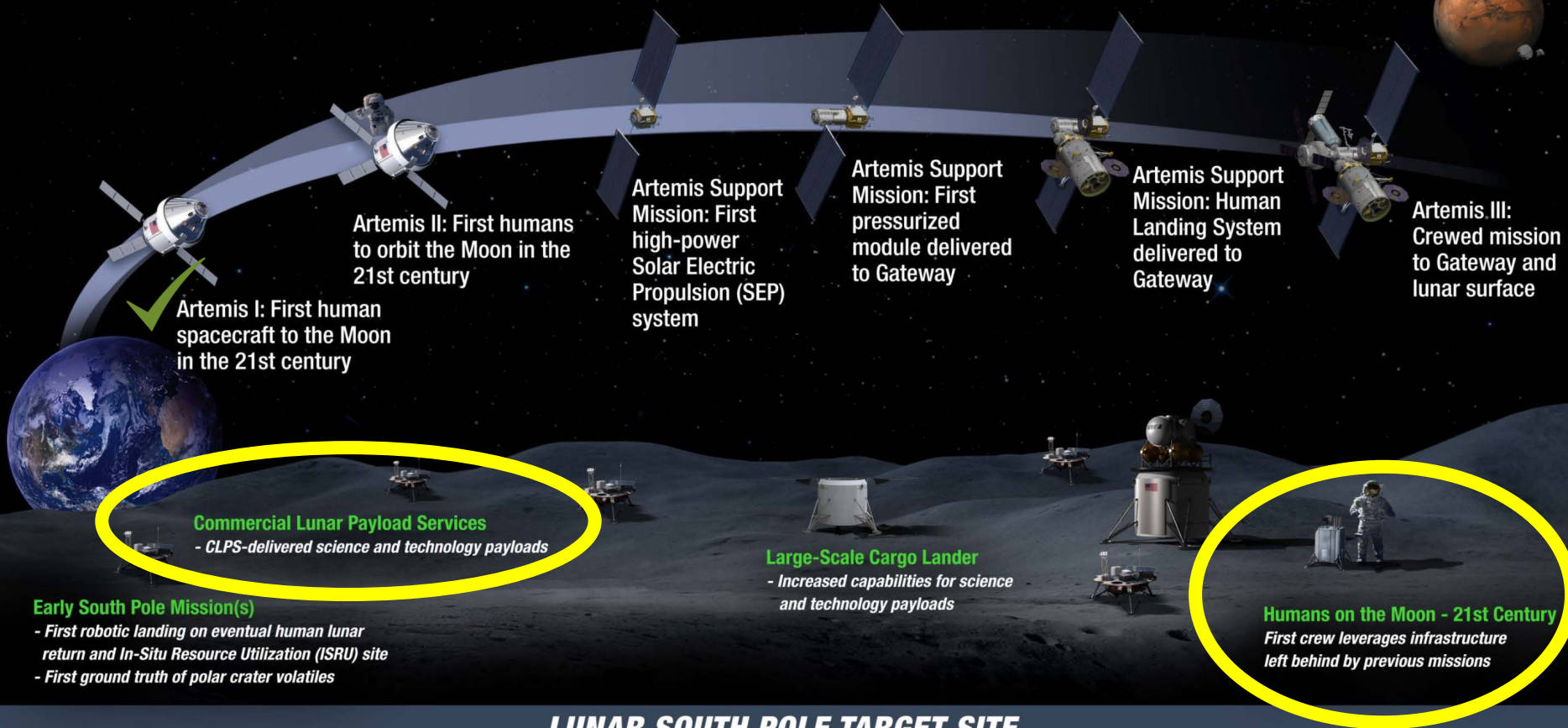


- Slopes less than 4° are plotted in green over WAC mosaic.
- Lunar 23 & 24 landing site (red triangle).
- Wrinkle ridges are noted.
- Crustal thickness, Th-abundance, rock abundance, and crustal magnetic fields were also studied.
- Two candidate landing sites are noted in red circles which optimize across site characteristics.

LGN Summary

- The LGN mission will optimize the science across seismic, geodetic, EM, and heat flow disciplines.
- These stations greatly improve upon the previous measurements made during Apollo and will provide key observations advancing knowledge of the lunar interior.
- While some of our science objectives may be accomplished with a single station, the full network, is needed to provide sufficient science return.
- Optimization of network sites will at least double the rate of detection of lower mantle and core phases over the Apollo network.
- The wide distribution of stations improves the density of seismic rays observed.
- These example landing sites will continue to be evaluated and analyzed throughout the development of the LGN mission.

Artemis Phase 1: Path to The Lunar Surface



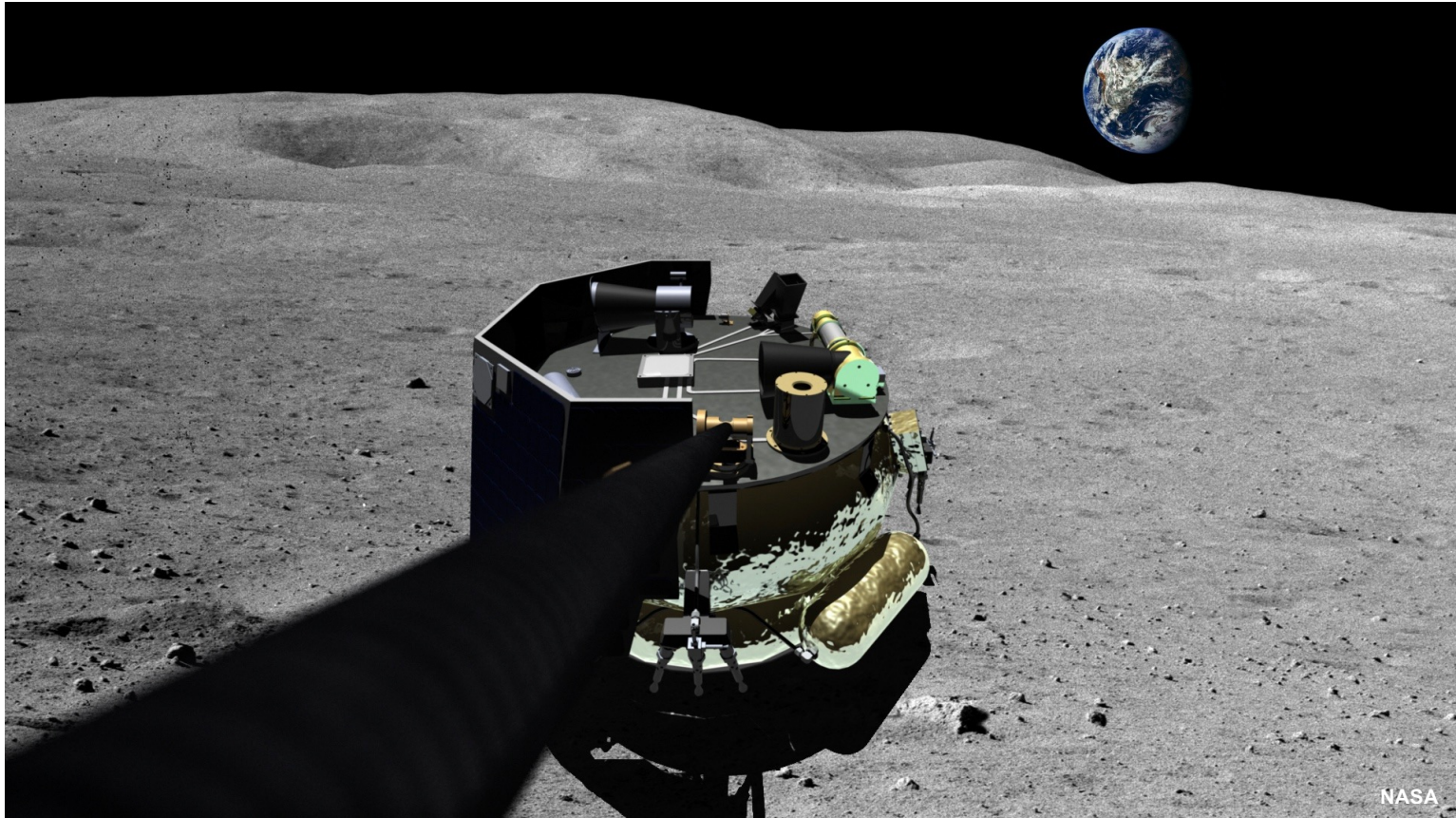
Upcoming Opportunities: Artemis & Commercial Lunar Payload System (CLPS)



NASA

- The Payloads and Research Investigations on the Surface of the Moon (PRISM) program solicits payloads annually to fly on upcoming CLPS deliveries.
- NASA's Science Mission Directorate will solicit instruments to be deployed by Artemis crew on the surface of the Moon this year (Weber et al. 2023).

Commercial Lunar Payload Services (CLPS)



CLPS Vendor Pool



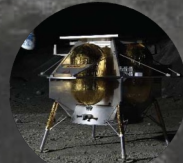
CLPS Deliveries

2023-2026

Delivery Site:
Gruithuisen Domes
Provider TBD
PRISM 2a/CP-21 | 2026



Delivery Site:
Reiner Gamma
Provider Intuitive Machines
PRISM 1a/CP-11 | April 2024



Delivery Site:
Gruithuisen Domes
Provider: Astrobotic
TO2-AB | Q1 2023



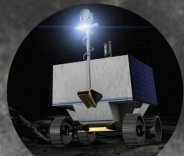
Delivery Site:
Mare Crisium
Provider: Firefly
TO19D | May 2024



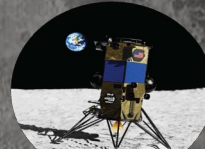
Delivery Site:
Farside
Provider: Firefly
TOCS3 | 2026



Delivery Site:
South Pole
Provider: Intuitive Machines
TO PRIME-1 | NET June 2023



Delivery Site:
South Pole
Provider:
Astrobotic
VIPER | Nov 2024



Delivery Site:
South Pole
Provider: Intuitive
Machines
TO2-IM | Mar 2023



Delivery Site:
Schrödinger Basin
Provider Draper
PRISM 1b/CP-12 | 2025

Delivery Site:
South Pole
Provider TBD
PRISM 2b/CP22 | 2025



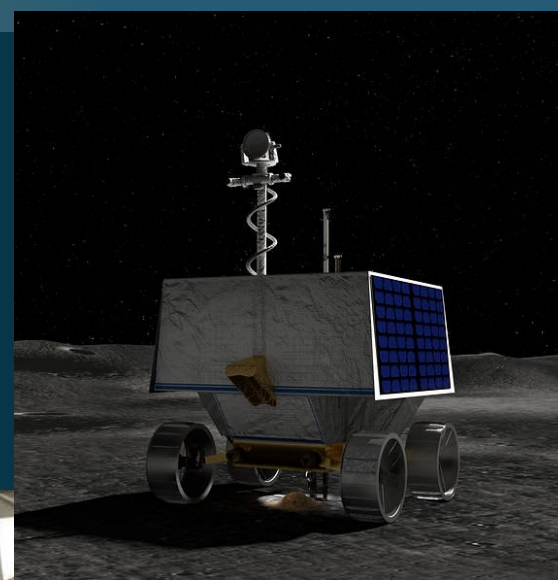
- Founded in 2013 by Steve Altemus, Kam Ghaffarian, Tim Crain
- Headquarters Houston, TX

- Founded in 2007 by Red Whittaker and Associates
- Carnegie Mellon
- Headquarters Pittsburgh, PA



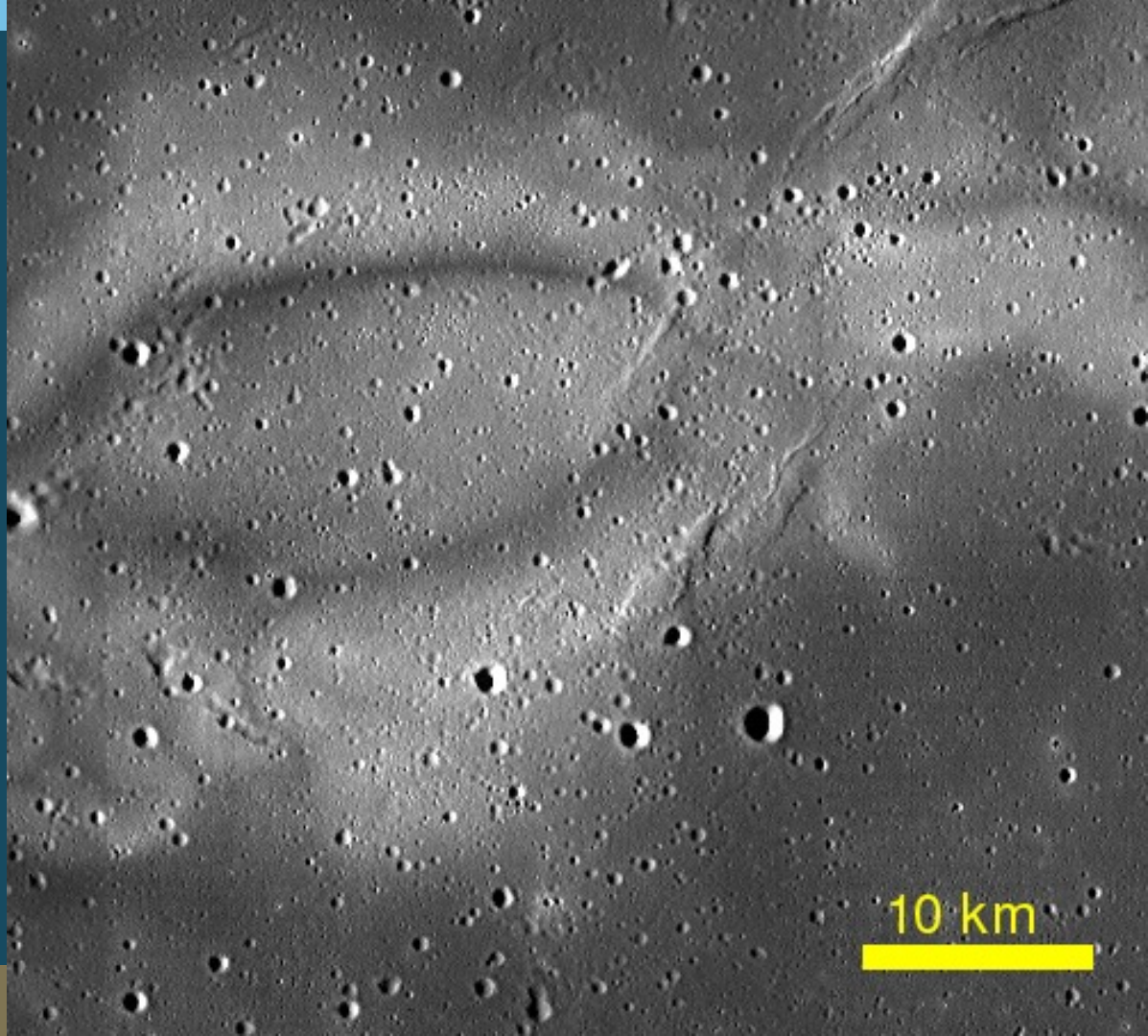
VIPER Rover

- Mission duration: 100 Earth days, covering 3 cycles of lunar day and night
 - Distance goal: 12 miles (20 kilometers)
 - Rover size: Similar to a golf cart: 5 feet by 5 feet by 8 feet (1.5 meters by 1.5 meters by 2.5 meters) and 992 pounds (450 kilograms)
 - Power: Solar-charged battery, peak power of 450 watts
 - Top speed: 0.45 mph (0.72 kph)
- Onboard instruments:
 - 3.28-foot (1-meter) drill
 - NIRVSS – Near Infrared Spectrometer
 - MSOLO – Mass Spectrometer
 - NSS – Neutron Spectrometer



Lunar Swirls – Reiner Gamma

- Reiner Gamma is one of several lunar “swirls”
- It is visible from Earth telescopes
- Origin is not well understood
 - Associated with crustal magnetic fields
 - Does not correspond to features on the surface
 - Could be impact related
- Lunar Vertex payload will explore this with a lander and rover scheduled for 2024



Mission Details

Lander/ Launch Provider: Intuitive Machines/SpaceX

Landing Date: **April 2024**

Landing Site: Reiner Gamma

Surface Ops Duration: 318 Hours

Manifest

- **Lunar Vertex Suite**
 - Magnetometer
 - Camera
 - Electron Spectrometer
 - Ion Spectrometer
 - Rover w/magnetometer + multispectral microscope
- **CADRE** (3 autonomous Swarm Rovers with Ground Penetrating Radar/JPL)
- **LUSEM** (Radiation detector) provided by the Korean Space Agency KASI
- **MPAc** (Actuated Retroreflector) provided by the European Space Agency

Science Goals

- To determine the origin of lunar swirls

Technology Goals

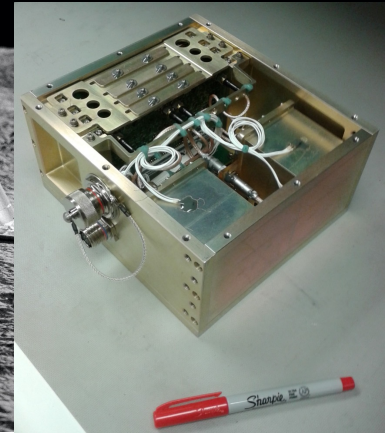
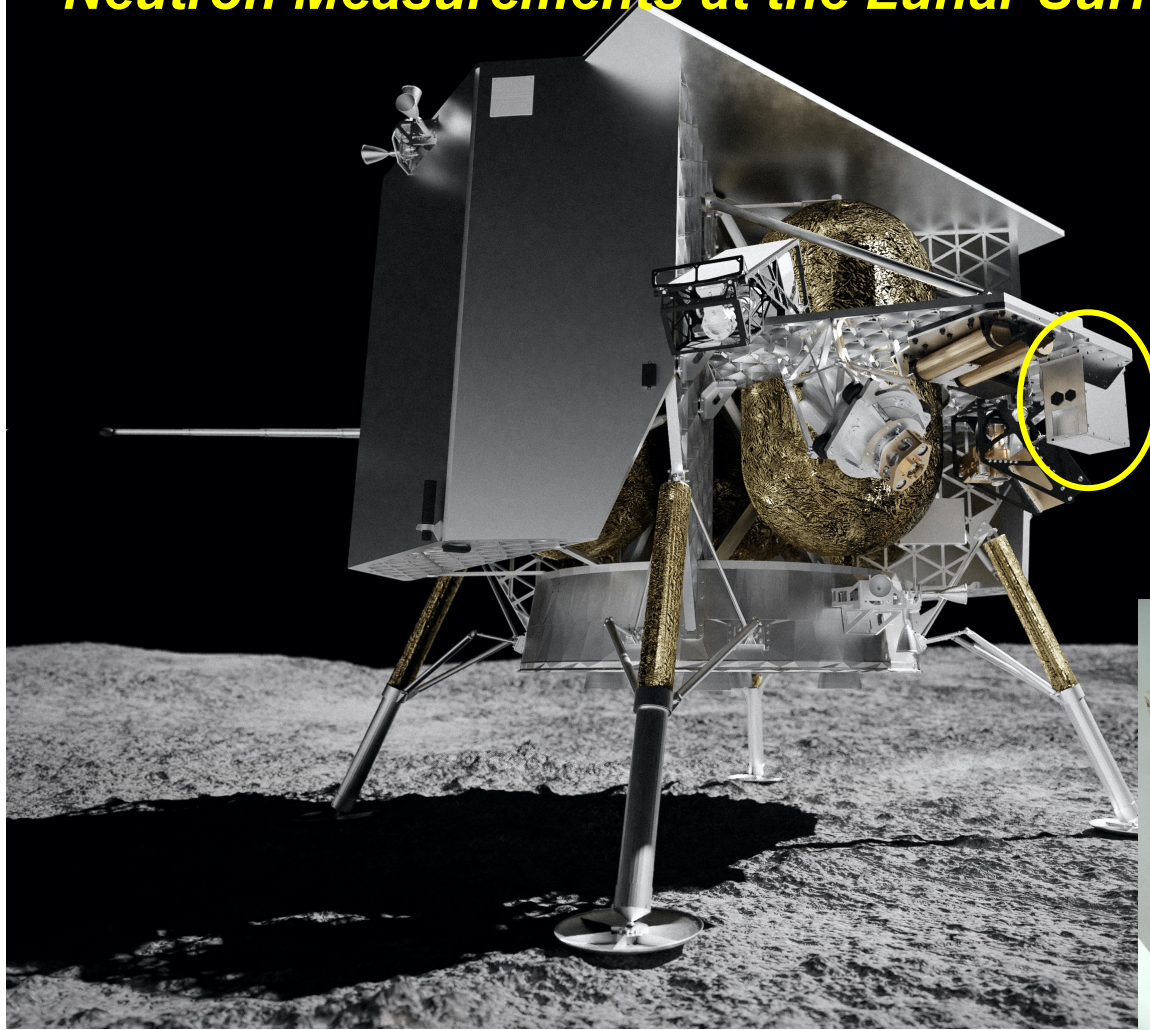
- To demonstrate autonomous roving and decision making

CLPS TASK ORDER CP-11 (PRISM 1A)

Nova-C Lander

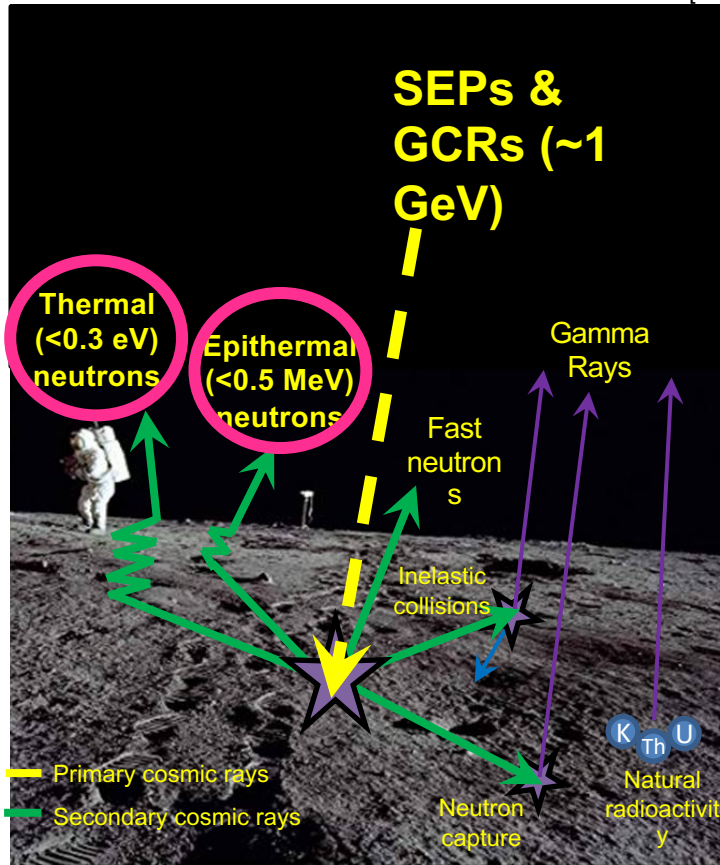


Neutron Measurements at the Lunar Surface (NMLS)



Neutron Spectroscopy

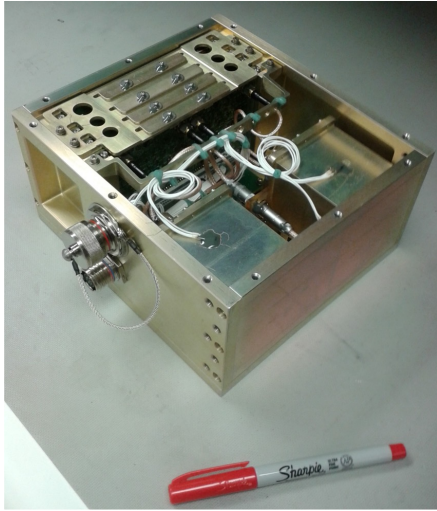
After Curran [2017]



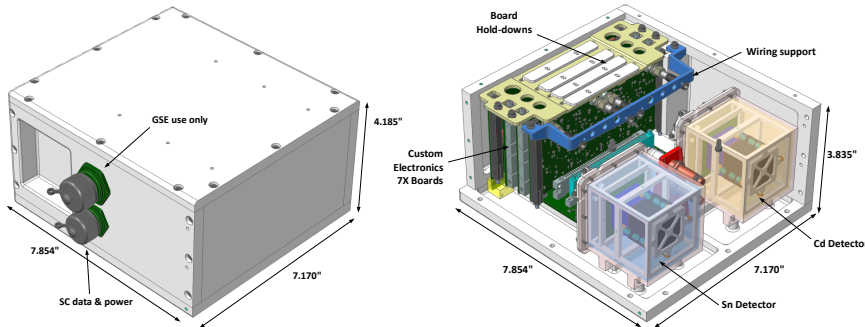
- “Epithermal neutrons”
 - Medium energy
 - ~constant for most lunar compositions (except H).
- “Thermal neutrons”
 - low energy
 - absorption cross section increases by nuclei
 - is highly composition dependent (flux is large for Fe, Ti)
 - Flux is greater in mafic materials (mare basalts, Mg or Fe-rich, of igneous/volcanic origin, dark in color, olivine, pyroxene)
 - Flux is smaller in the Fe-poor highlands (farside).
- MSFC scintillator technology effectively discriminates between pulse shapes and distinguishes between neutron and gamma ray (as well as other false) triggers.

Neutron Measurements at the Lunar Surface (NMLS)

PI Peter Bertone/ST12, Project Scientist Heidi Haviland/ST13, Lead System Engineer Jeff Apple/ES11



- Originally slated to fly on the Astrobotic Peregrine Mission 1 Lander in 2023. Due to Astrobotic's under performing engines, NMLS and other NASA payloads were removed.
- NMLS is currently awaiting a ride to the Moon.
- NMLS will measure thermal and epithermal neutron count rates using composite scintillator detectors.
- NMLS will infer surface composition from counting rates.
- Thermal neutron count rates are sensitive to minerals such as KREEP (Potassium K, Rare Earth Element, and Phosphorous).
- Epithermal neutron count rates are sensitive to hydrogen including water.



Conclusions

- Lunar geophysics relies on heavily on observations and instrumentations from the Apollo era.
- Additional seismic and geodetic observations are needed to improve knowledge of the lunar interior, including lunar geophysical networks.
- The CLPS missions are scheduled to land science instruments on the lunar surface in 2023 through 2026.
- Artemis missions will also bring science instruments to the lunar surface.

What novel science instrument(s) and instrument suites would you like to send to the Moon and possibly in the future to Mars or other terrestrial bodies?



EXPLORE MOON_{to}MARS

MOON LIGHTS THE WAY

[https://www.nasa.gov/clps/
discovery/elements/clps](https://www.nasa.gov/clps/discovery/elements/clps)

<https://science.nasa.gov/lunar->

