International Lunar Reference System Next Steps

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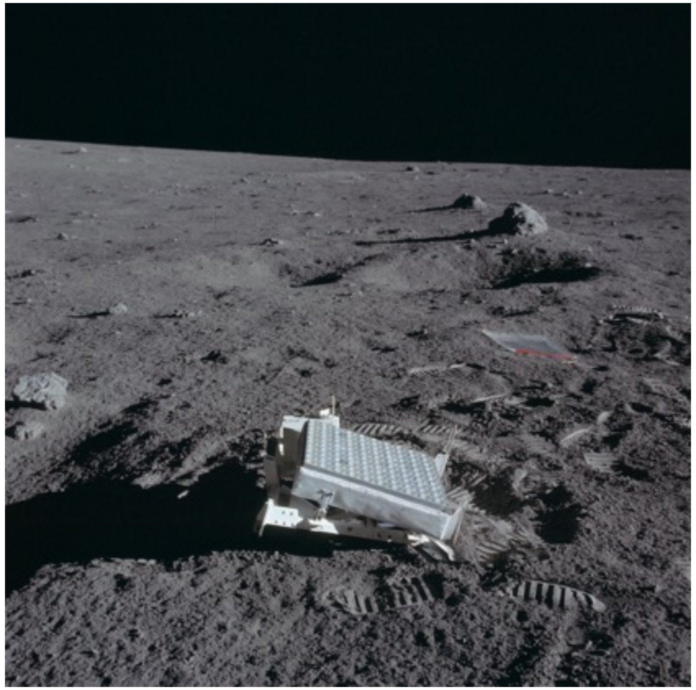
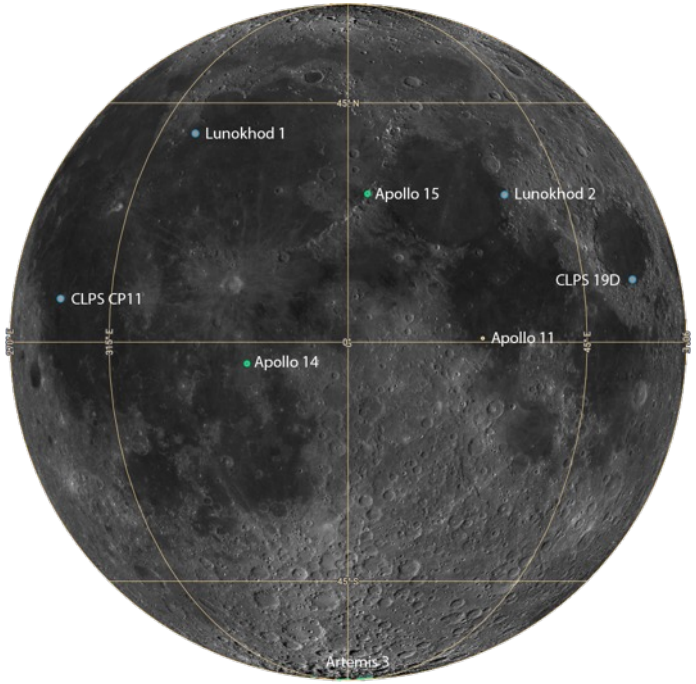
NASA/GSFC

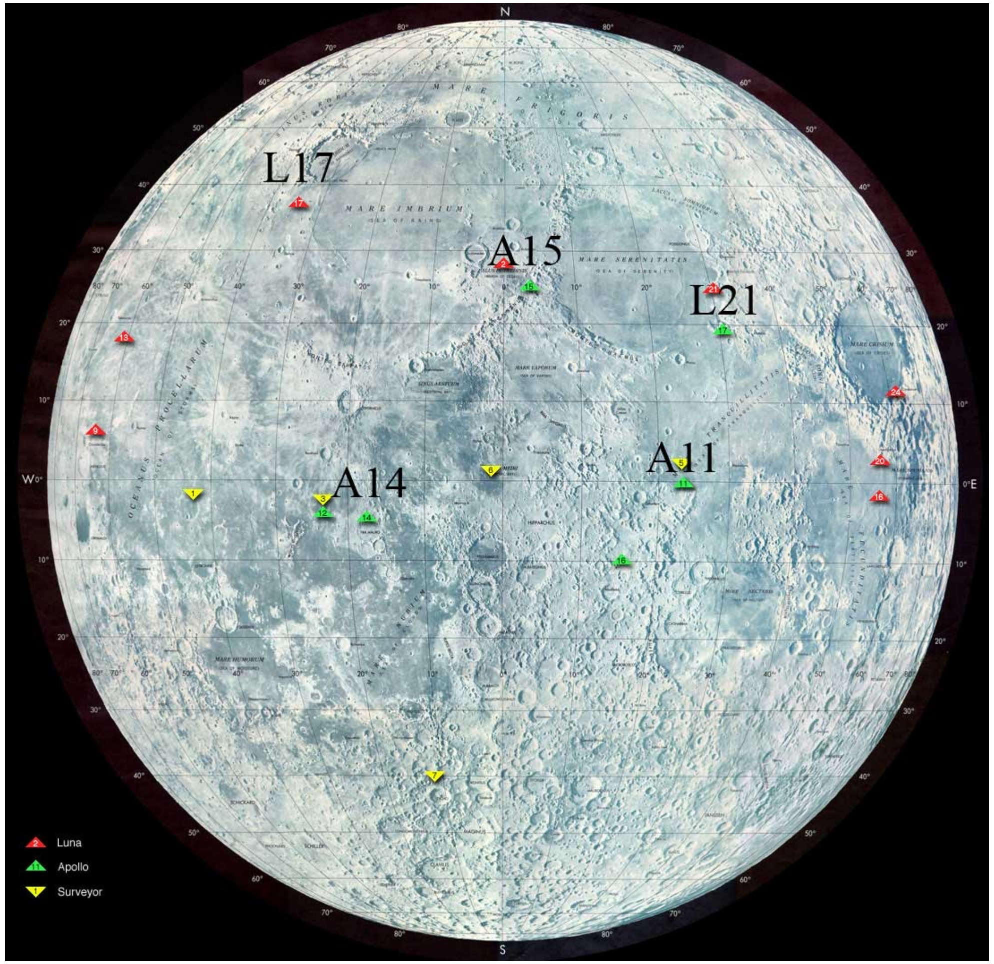
2nd Joint ICG-IOAG Multilateral Cislunar PNT Workshop
February 11, 2026





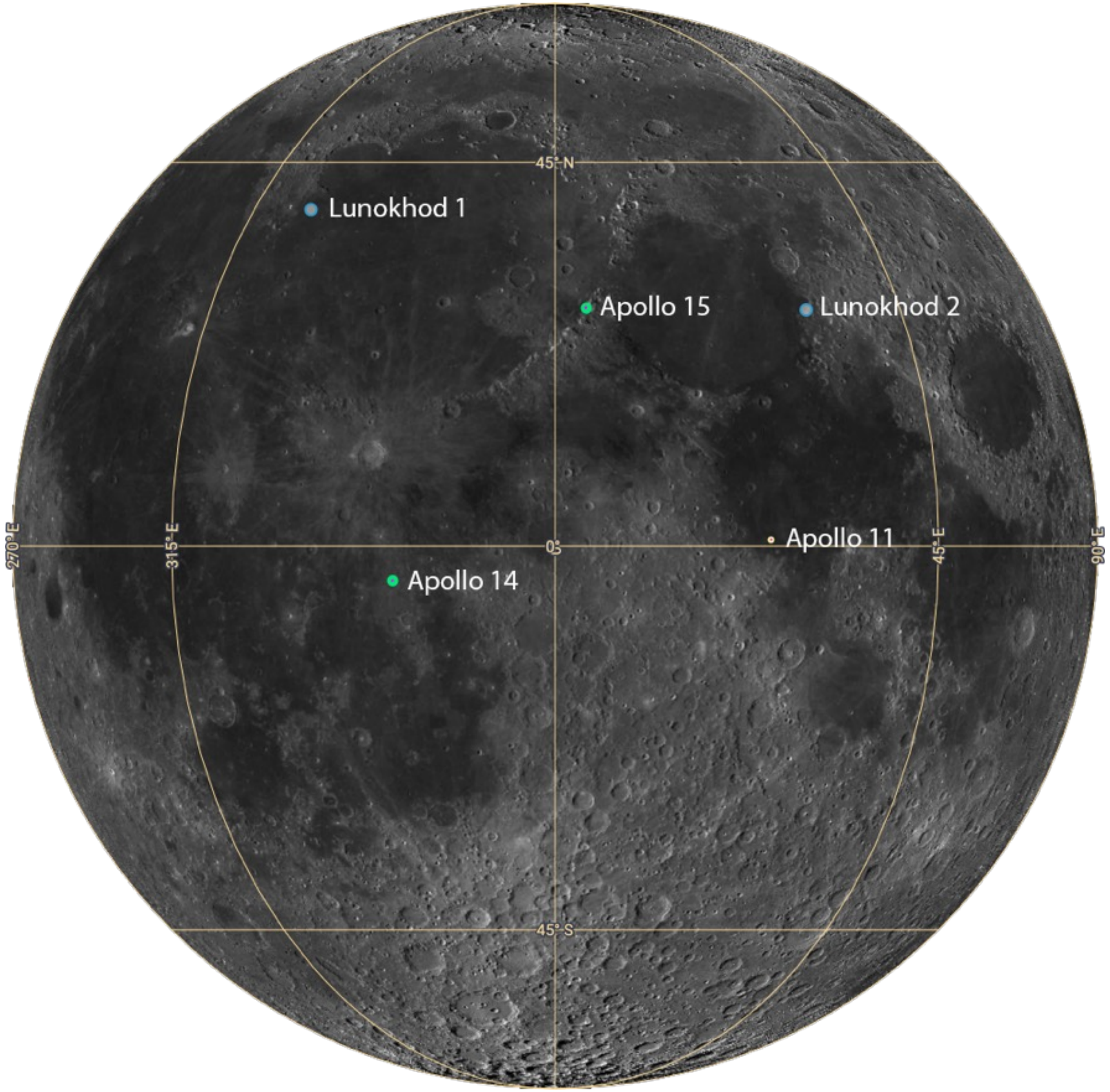
Lunar Reference Frames

- Realization of the lunar reference frames (Mean Earth and Principal Axis), used for lunar cartography, geolocation, positioning, and navigation, critically rely on the LLR measurements.
- Lunar ephemerides are also a product of LLR analysis and essential for spacecraft navigation.
- New and existing lunar retroreflectors will be an important component of future Lunar reference frame realizations.

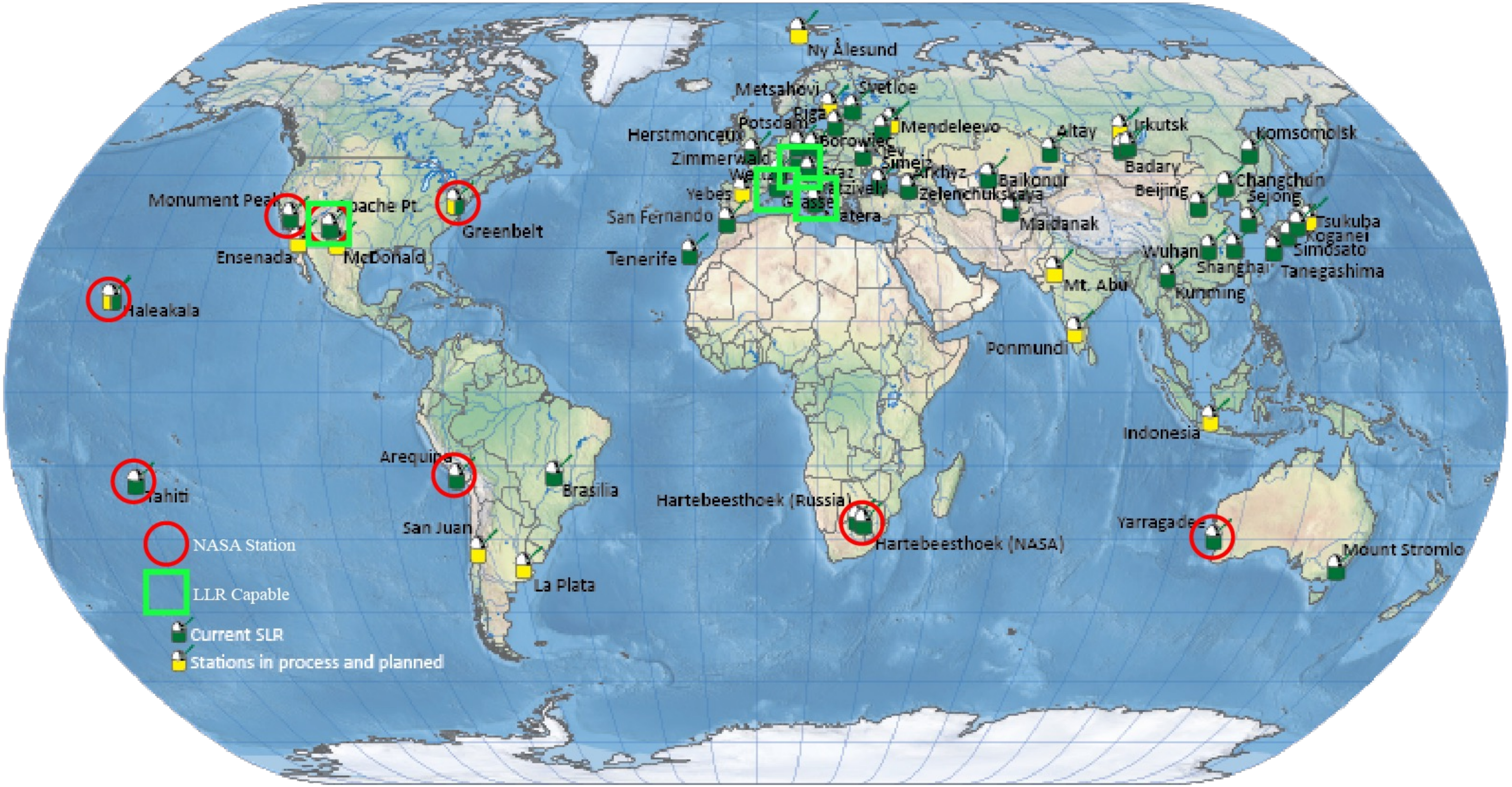


Current Lunar Retroreflectors

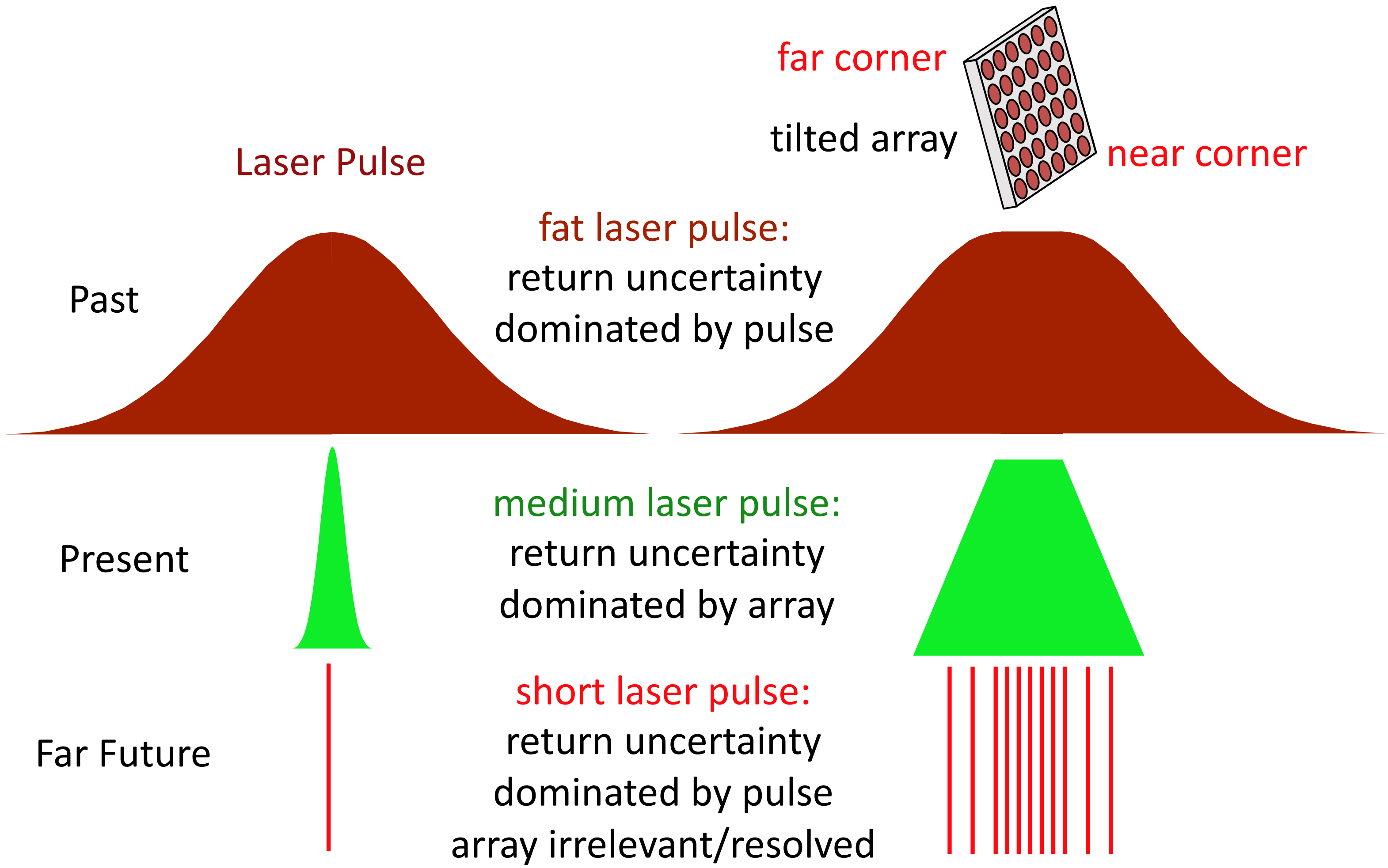
- All the lunar retroreflectors used in the current LRS lie within 26 degrees latitude of the equator, and the most useful ones (Apollo) within 24 degrees longitude of the sub-earth meridian. This clustering weakens their geometrical strength.
- The Apollo and Lunokhod retroreflectors continue to be useful targets, but are showing signs of degradation, most likely due to dust.

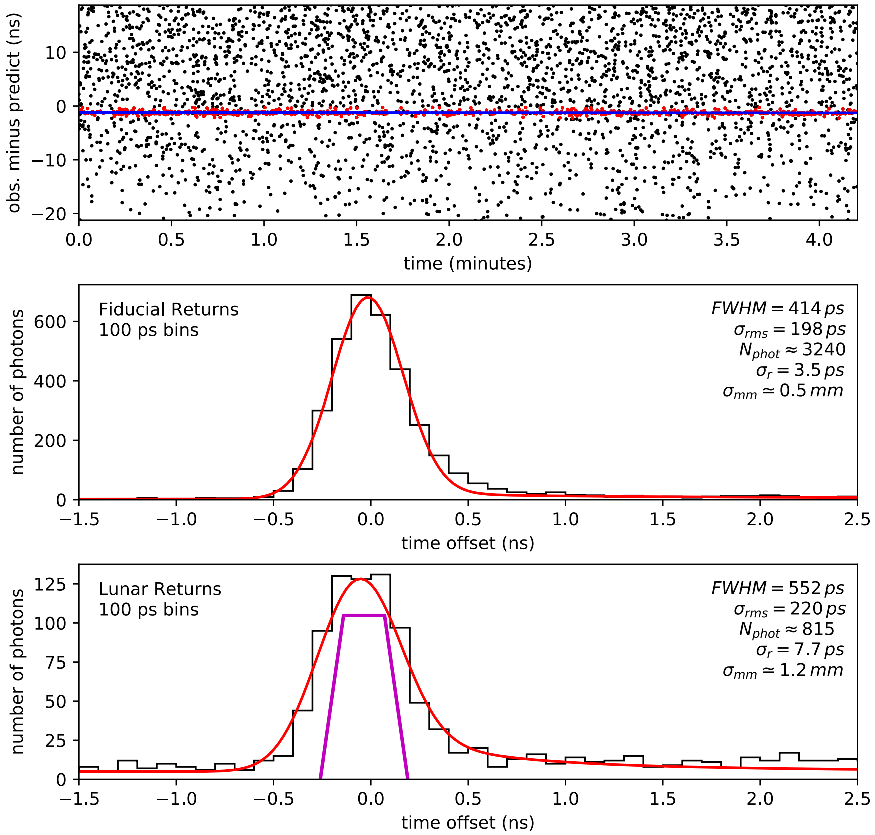


International Laser Ranging Service (ILRS) Stations



Current Limiting Error - Retroreflector Array Tilt



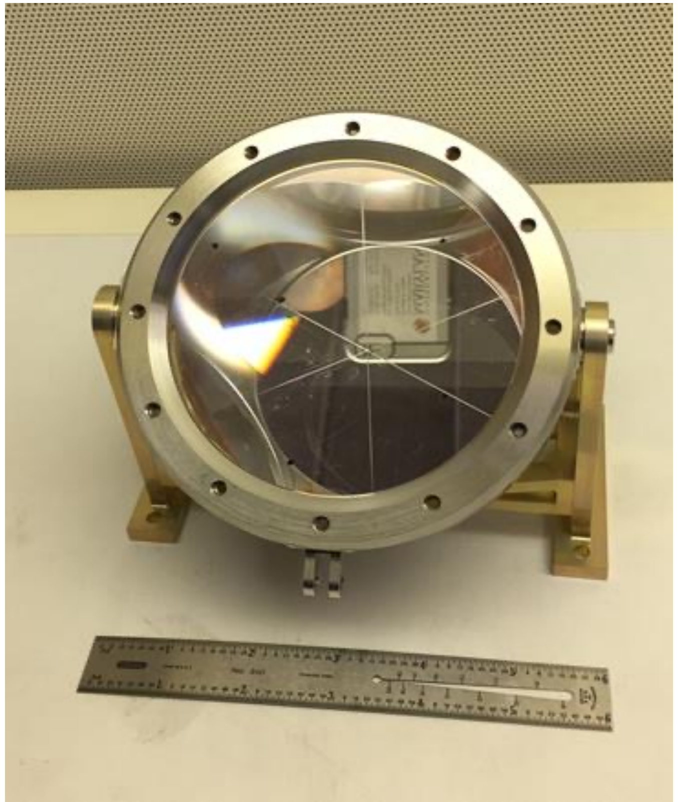


Apache Point measurements with retroreflector array timing profile

Colmenares et al.
https://doi.org/10.1088/1538-3873/acf787

Solution to Tilt Error – Single Cubes

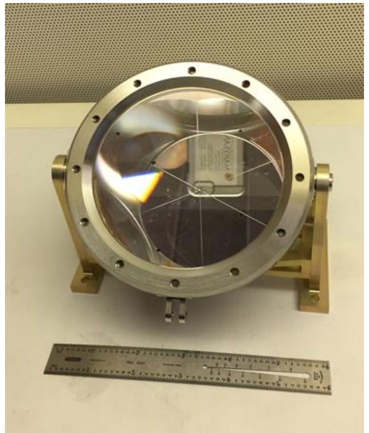
- Single cubes do not broaden return pulse thus eliminating the array tilt error.
- Central irradiance of return goes up as fourth power of the cube corner diameter, making it feasible to get comparable optical cross section to an Apollo 100 x 3.8 cm cube array with a single 12 cm cube.
- Solution does not come for free:
  - Solid cubes are susceptible to thermal and polarization effects that can impact their performance.
  - Tuning the cubes for the lunar motion (velocity aberrations) is also a challenge for single cubes versus an array.



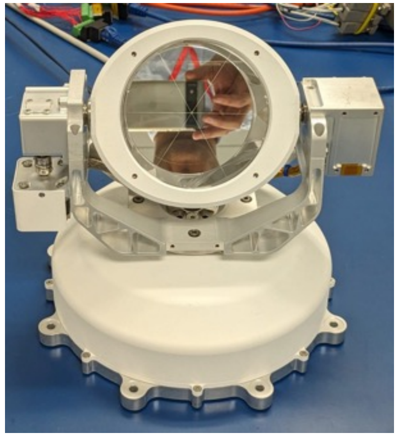
NGLR courtesy Douglas Currie

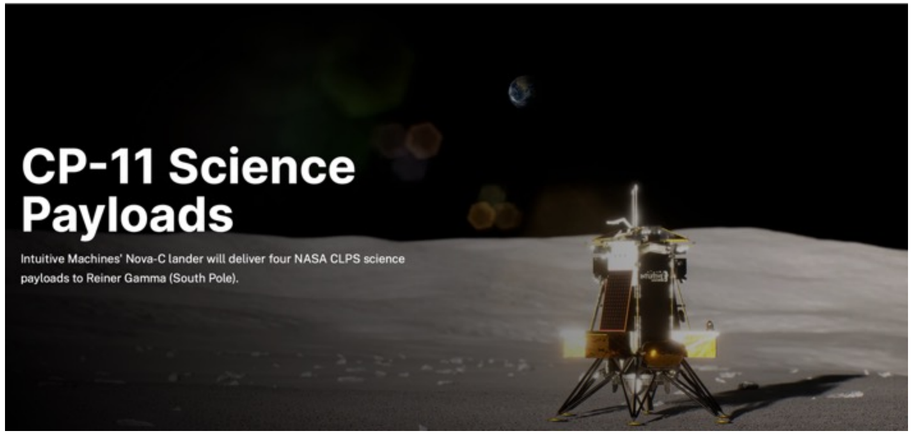
NASA Commercial Lunar Payload Services (CLPS) Deliveries

- Firefly's Blue Ghost 1 lander to Mare Crisium
  - University of Maryland's Next Generation Lunar Retroreflector (NGLR), Dr. Douglas Currie, Principal Investigator
  - Successfully landed March 2, 2025. LLR data from NASA's Apache Point station available from NASA's CDDIS.



- Intuitive Machines' Nova-C lander to Reiner Gamma
  - ESA's MoonLIGHT Pointing Actuator (MPAc)

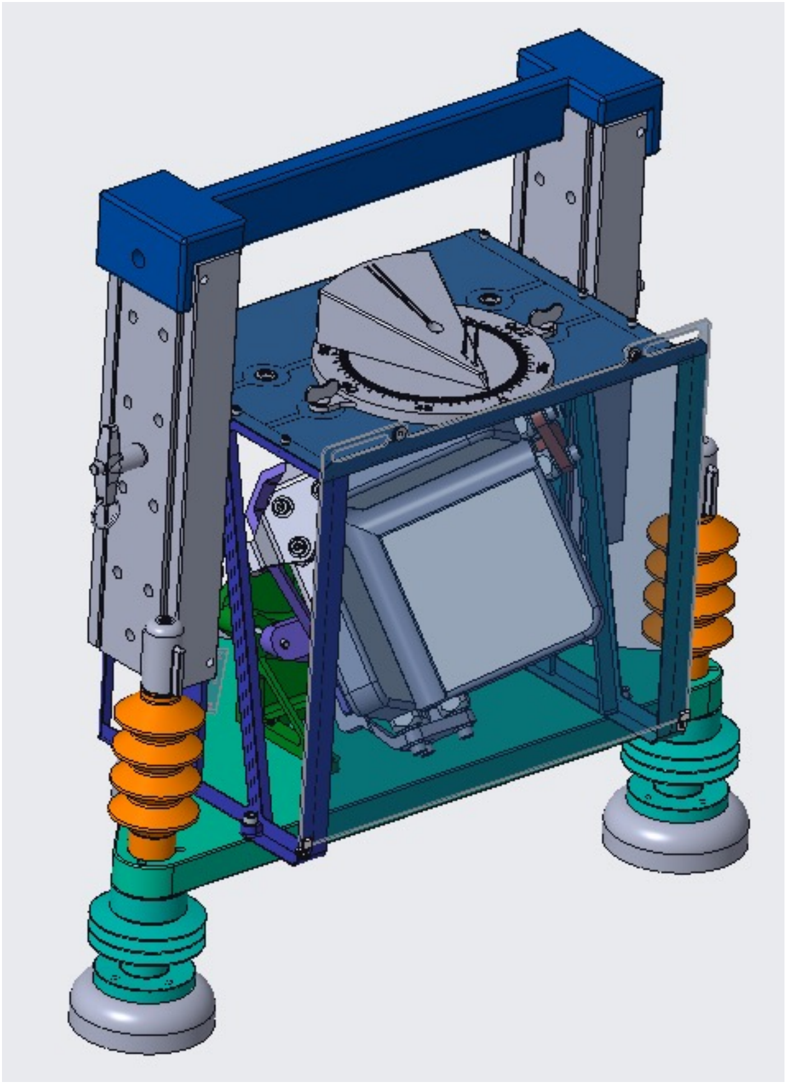




- Both CLPS missions use a single 10cm solid cube corner.

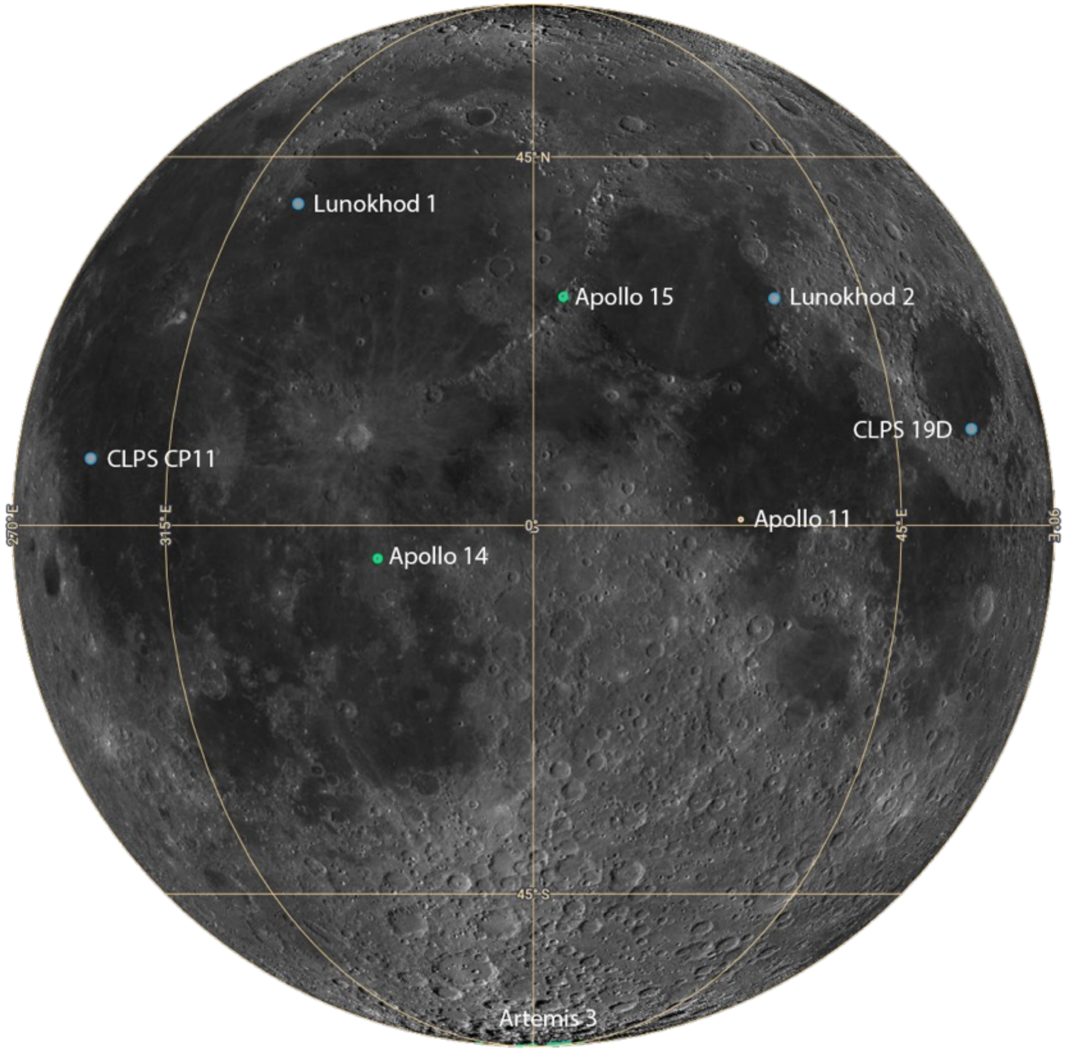
Artemis Lunar Laser Retroreflector (ALLR)

- NASA Goddard Space Flight Center developed a single large hollow retroreflector for NASA's Artemis 3 mission.
- The Artemis 3 astronauts will deploy ALLR at the lunar south pole.
- ALLR is expected to have a significantly greater optical cross section than the Apollo 11 array.



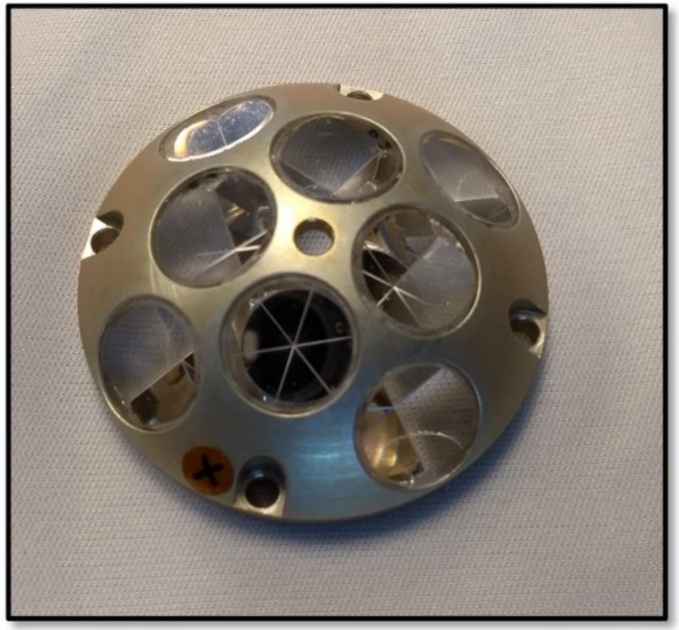
Upcoming LLR Distribution

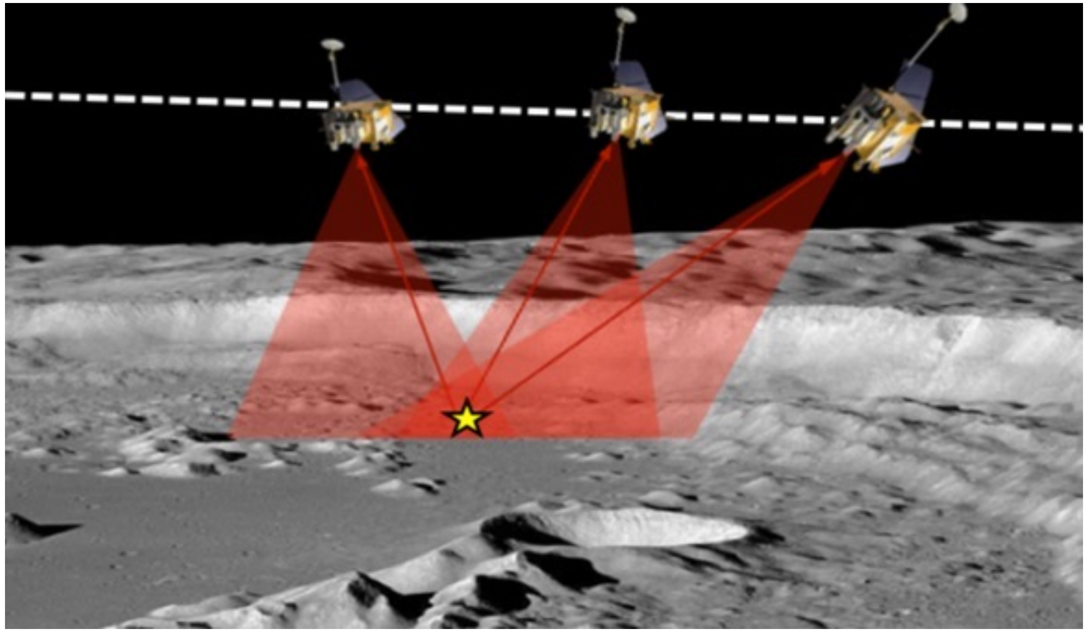
- Next-generation lunar retroreflectors deployed to new lunar sites on the NASA CLPS and Artemis missions greatly expand the geometric coverage and build upon the long legacy of LLR contributions to the lunar reference system.



Miniature Laser Retroreflector Array (mini-LRA)

- NASA Goddard Space Flight Center is also putting miniature retroreflectors on most CLPS mission that can be seen by lunar altimeters.
- The Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) has successfully.
- Mini-LRA's provide potential additional reference points for future reference frame realizations.





Xiaoli Sun et al. (2019), https://doi.org/10.1364/ao.58.009259 10

Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) Retroreflector Dataset

The larger LRAs (Apollo, Lunokohod) have larger optical cross-sections which increases the chance of return (50-100%).

The smaller arrays have more variation, also due to geometry, but generally in line or higher than predicted (~20%).

2023-2024 dataset available:
doi:10.60903/gsfcpgda-lola-lra
(expect update with 2025 data)

as of Jan.1, 2026

Array	**Total Attempts**	**Total Successes**	**Success Rate**
Apollo 11	13	10	77%
Apollo 14	30	26	87%
Apollo 15	15	8	53%
Chandrayaan-3	135	25	19%
SLIM	15	4	27%
Chang’E-6	59	12	20%
BG-1	5	4	80%
Lunokhod-1	6	5	83%
Lunokhod-2	4	4	100%
IM-1	18	0	0%

Credit: Erwan Mazarico (GSFC) & LOLA Science Team

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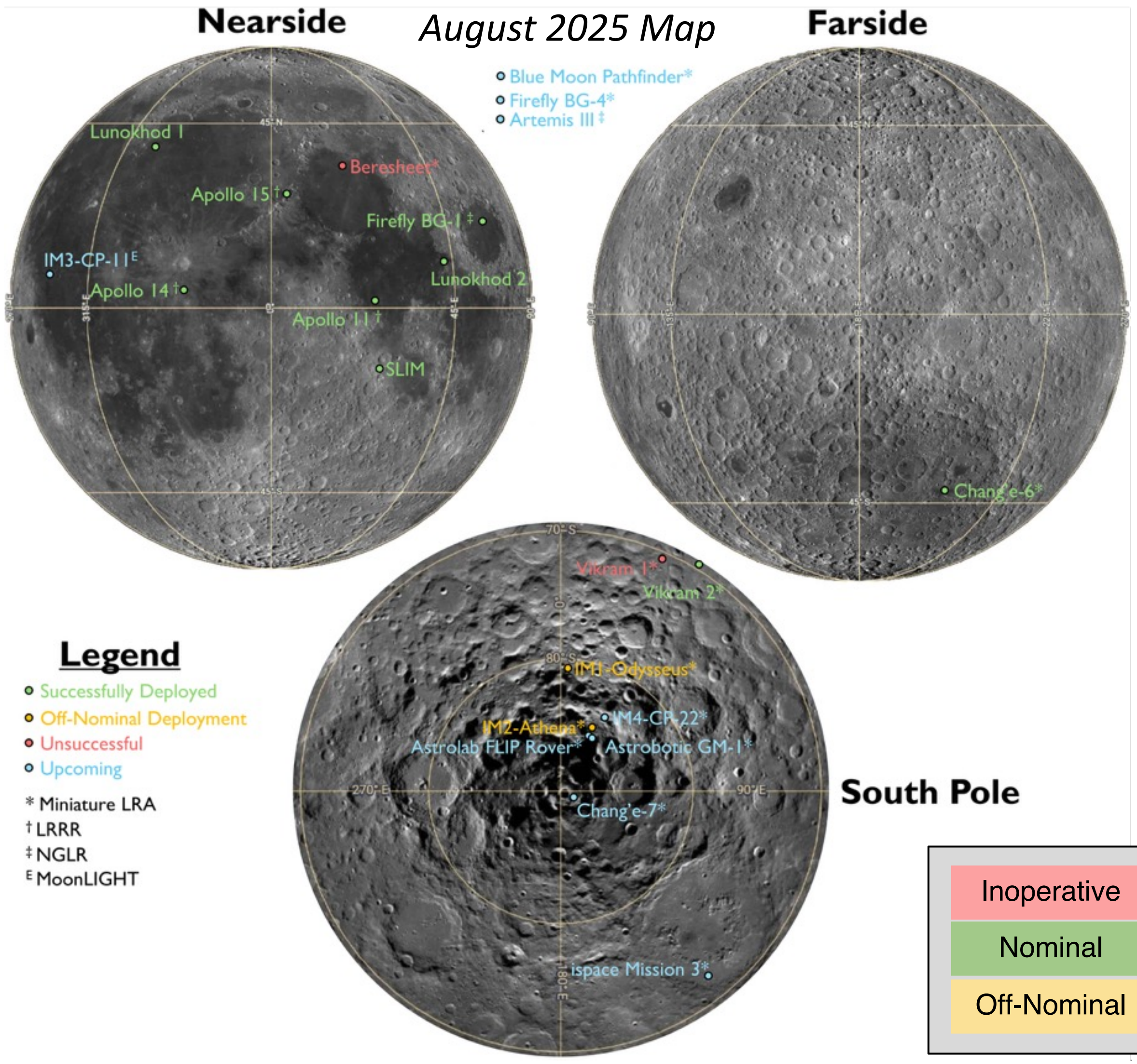
Mini-LRA Distribution



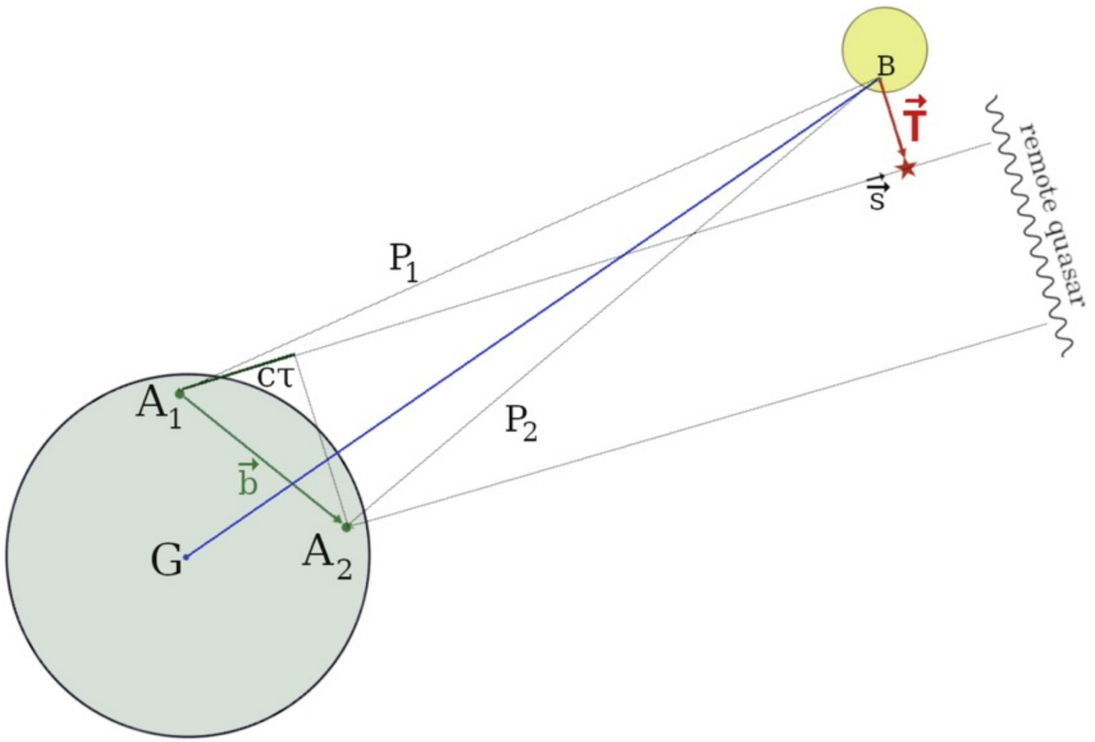
Inoperative
Nominal
Off-Nominal

Mission (Org.)	Launch Date	Surface Location
Beresheet (SpaceIL)	February 21, 2019	32.5956°N, 19.3496°E
Chandrayaan-2 (ISRO)	July 22, 2019	70.8810°S, 22.7849°E
Chandrayaan-3 (ISRO)	July 14, 2023	69.3735°S, 32.3199°E
SLIM (JAXA)	September 6, 2023	13.31549°S, 25.24889°E
CLPS TO-2AB (Astrobotic)	**January 8, 2024**	**N/A**
CLPS TO-2IM (Intuitive Machines-1)	**February 15, 2024**	**80.1277°S, 1.4357°E**
Chang'e-6 (CNSA/ESA)	May 3, 2024	41.6385°S. 153.9852°E
CPLS PRIME-1 (Intuitive Machines-2)	**February 26, 2025**	**84.7754°S, 29.1264°E**
CLPS TO-20A GM-1 (Astrobotic)	**2026**	**Mons Mouton**
FLIP Rover (Venturi Astrolab)	2026	Mons Mouton
Blue Moon Mk-1/CT-3 (Blue Origin)	**2026**	**South Pole Region**
Chang'e-7 (CNSA/ESA)	2026	Shackleton Rim
CLPS CP-11 (Intuitive Machines-3)	**2026**	**Reiner Gamma**
CLPS CP-22 (Intuitive Machines-4)	**2027**	**Mons Mouton**
ispace Mission 3	2027	Schrödinger Basin
Artemis III (NASA)	2028	South Pole Region
CLPS CS-6 (Firefly BGM4)	**2029**	**South Pole Region**

Updates of this map and list for the NASA GSFC mini-LRAs are available: doi:10.60903/GSFC-miniLRAs

VLBI to Lunar Landers

- Radio beacons on the lunar surface can be observed by VLBI along with nearby quasars to provide a transverse component. LLR provides the radial component.
- Around 1W power (similar to cell phone) is sufficient for observations.
- Expected accuracies of ~3cm with 5 hours of observations and ~1cm after 1 month.
- VLBI is not susceptible to weather like LLR.



Leonid Petrov, NASA/GSFC