Lunar Laser Ranging in the Artemis Era

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NASA/GSFC

AGU Session P44C: To the Moon: A New Era of Lunar Science
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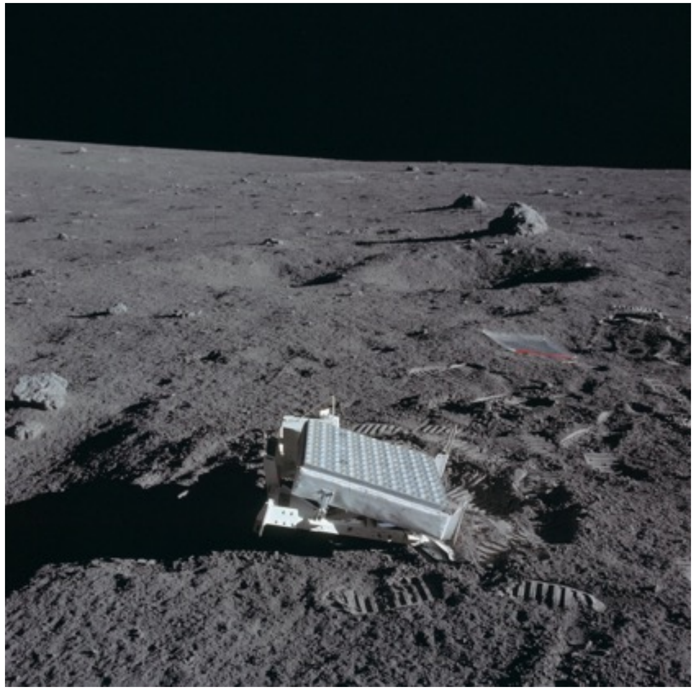
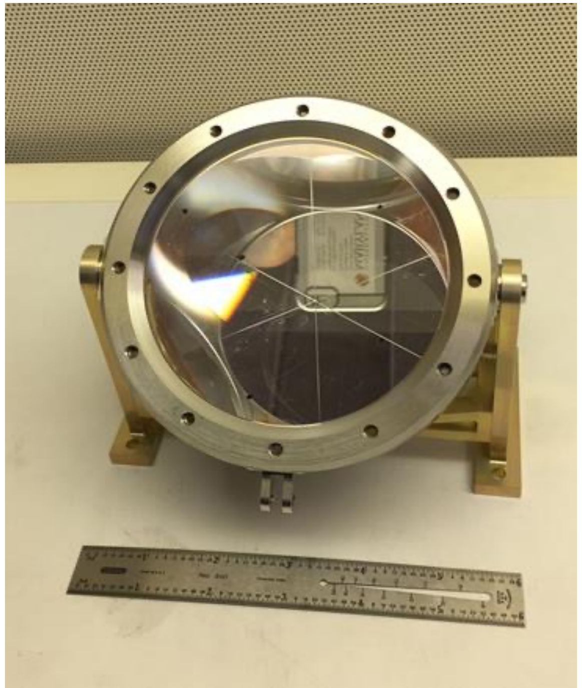
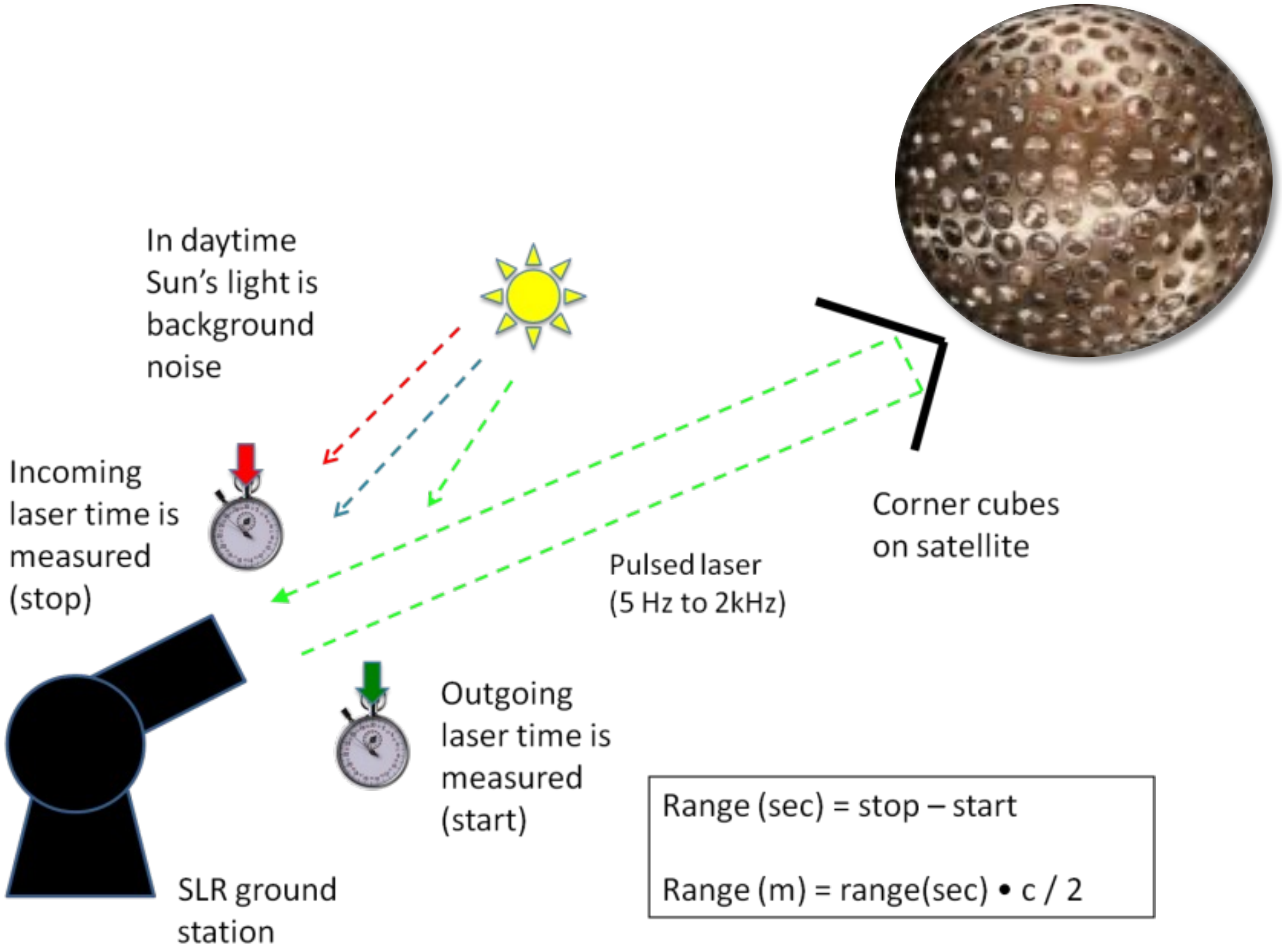
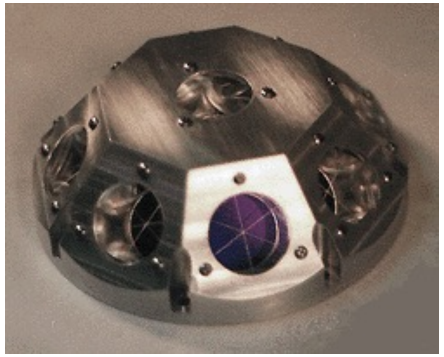



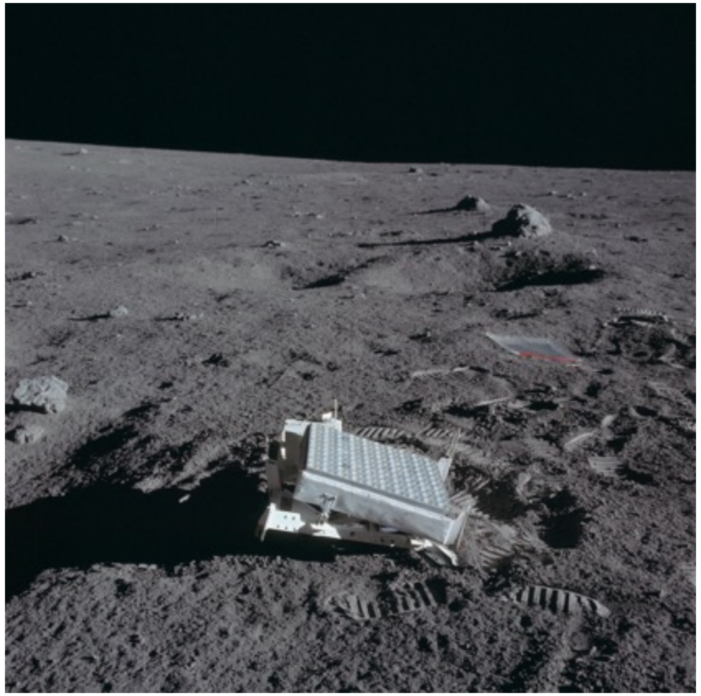
Satellite and Lunar Laser Ranging



Range (sec) = stop – start

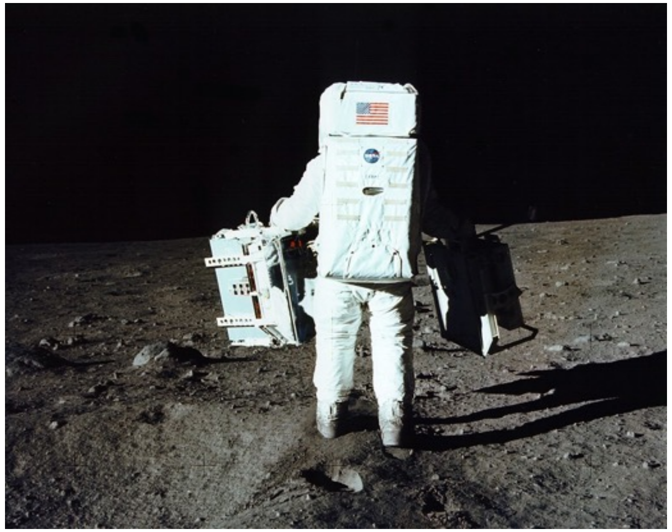
Range (m) = range(sec) • c / 2

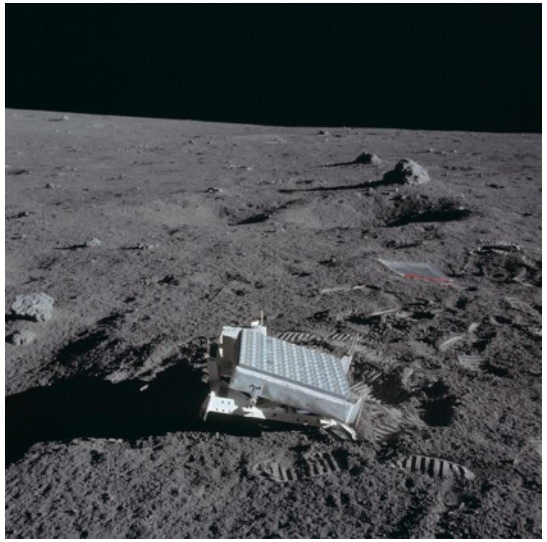


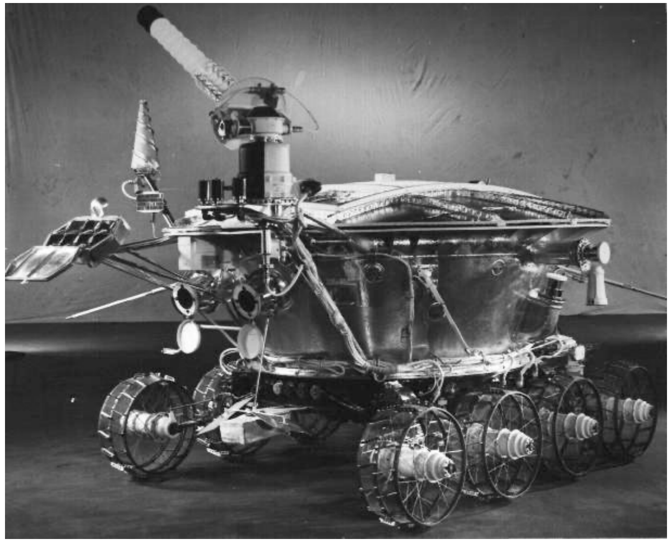


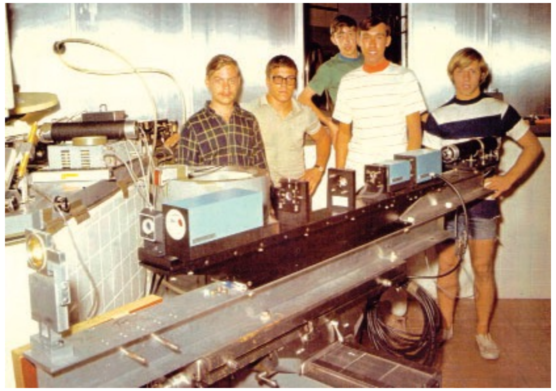
Lunar Laser Ranging (LLR) Background

- R. H. Dicke and his group at Princeton first considered precision tracking of satellites using pulsed searchlight illumination for tests of gravity in the 1950s.
- MIT and Soviet Union bounced laser light off lunar surface in 1960s.
- Retroreflectors flown on Apollo 11, 14, & 15 and 2 Soviet Luna Missions.
- Since 1969, stations around the world have been ranging to the lunar retroreflectors.



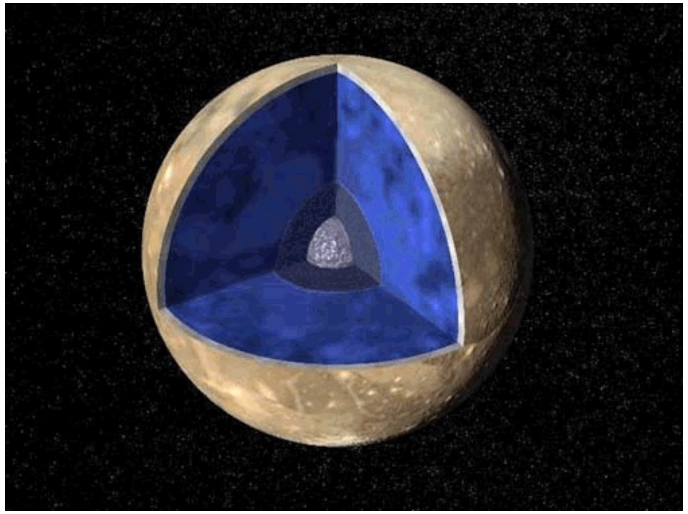


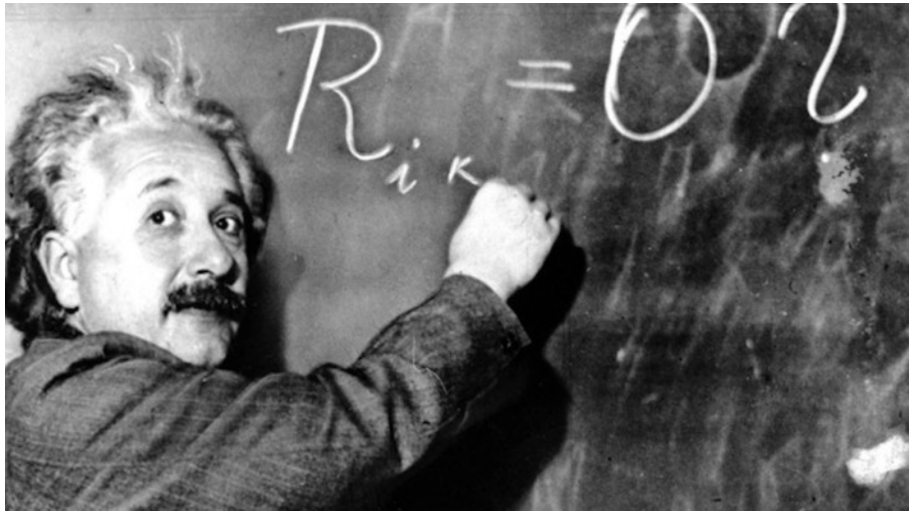




LLR Key Science Questions

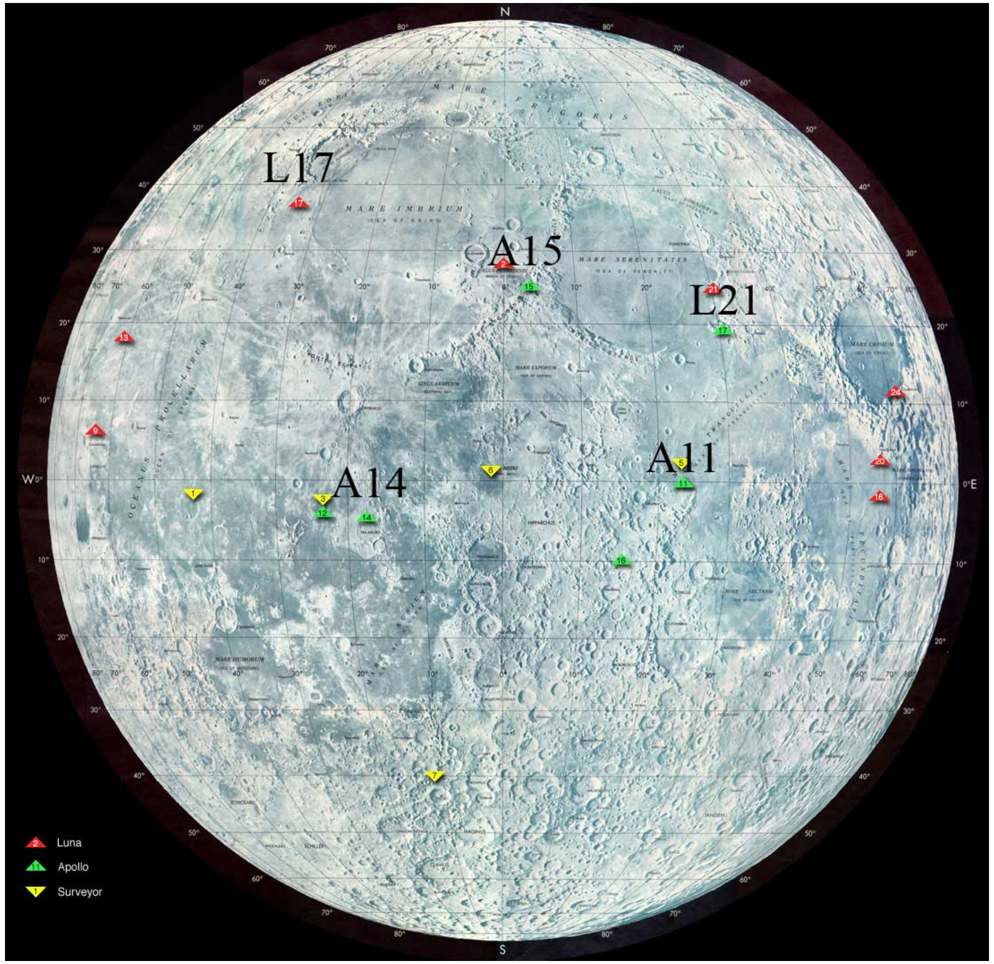
- What is the interior structure of the Moon?
- Is the Equivalence Principle exact?
- Does the strength of gravity vary with space and time?
- What is the nature of spacetime?
- Do extra dimensions or other new physics alter the inverse square law of gravity?





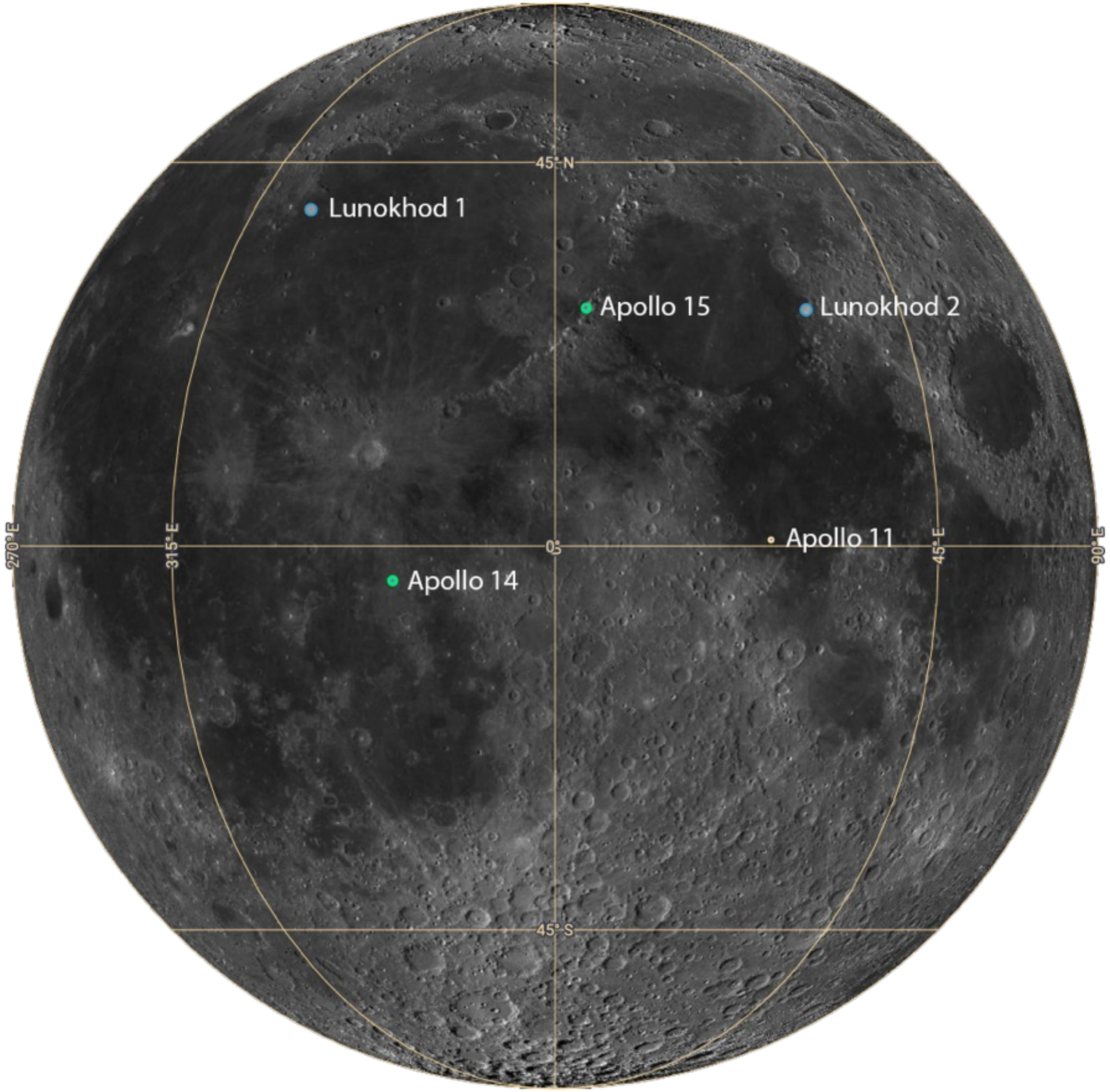
Positioning and Navigation

- 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.

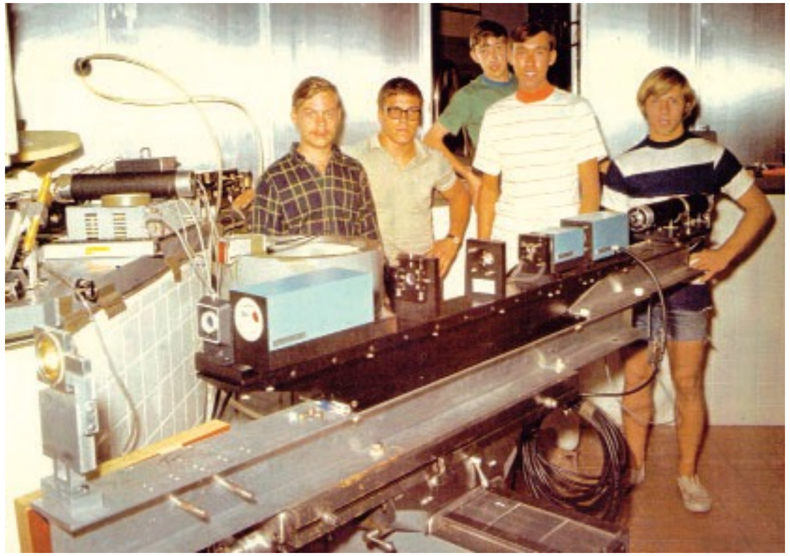


Current Lunar Retroreflectors

- All the current lunar retroreflectors 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.
- All 5 retroreflectors continue to be useful targets, but are showing signs of degradation, most likely due to dust.

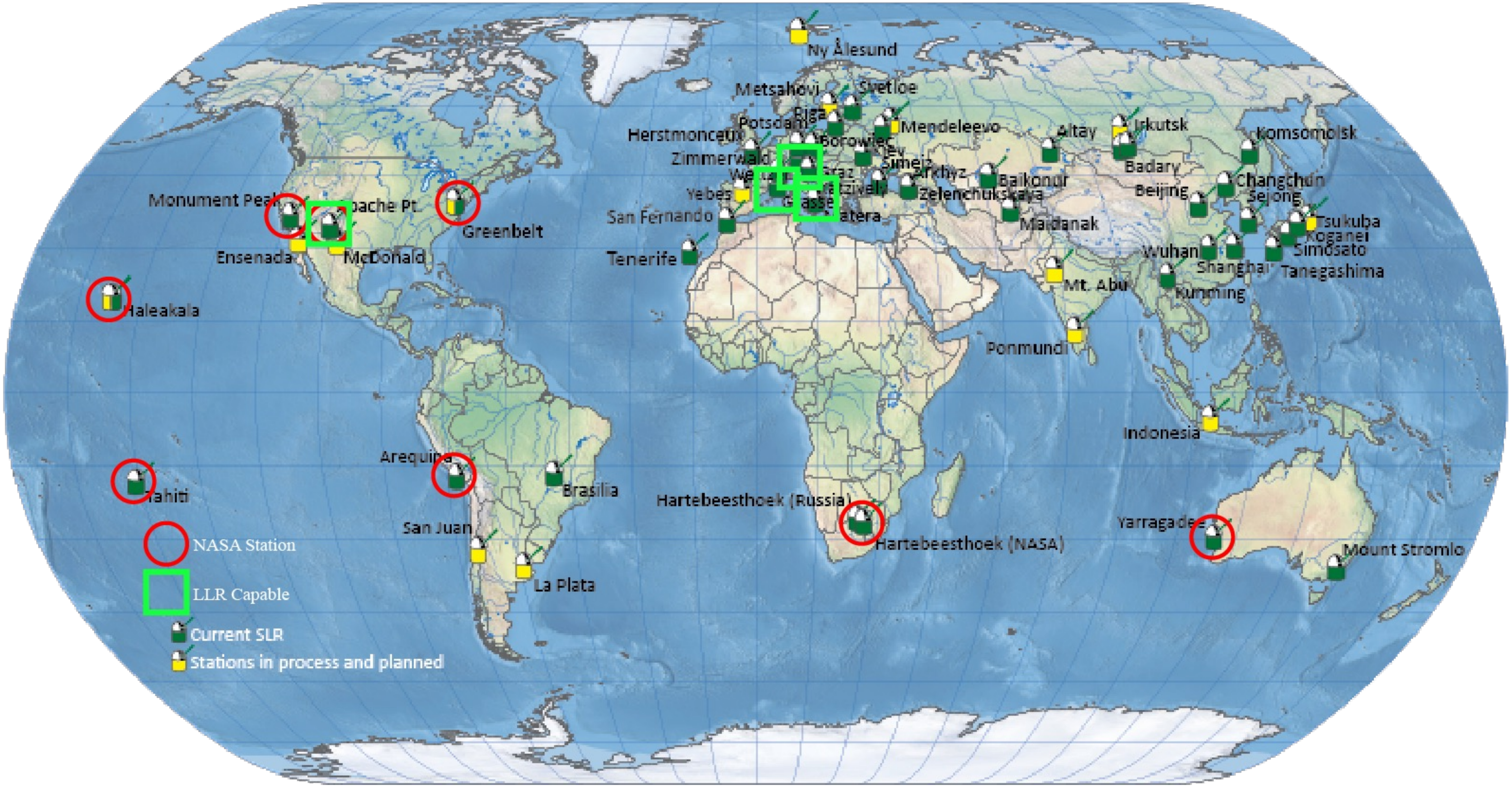


Half-Century of LLR and Still Going!



- Lick Observatory in California got first light in 1969.
- McDonald Observatory in Texas 1969 to 2015.
- Other early ranges:
  - Crimean astrophysical observatory in the Soviet Union,
  - Orroral Observatory in Australia,
  - Air Force Cambridge Research Laboratories Lunar Ranging Observatory in Arizona,
  - The Pic du Midi Observatory in France (Calame et al., 1970),
  - Tokyo Astronomical Observatory
- Orroral Observatory in Australia 1978 to 1980.
- Haleakala Observatory on Maui in Hawaii 1984 to 1990.
- Current operating stations:
  - Observatoire de la Côte d’Azur (OCA) in France 1984 to present.
  - Matera (Italy) 2003 to present
  - Apache Point Observatory (New Mexico) 2006 to present. Stewardship transferred to NASA in 2021.
  - Wettzell (Germany) 2018 to present
  - Kunming (China) reports they are taking observations but are not currently sharing the data.

International Laser Ranging Service (ILRS) Stations

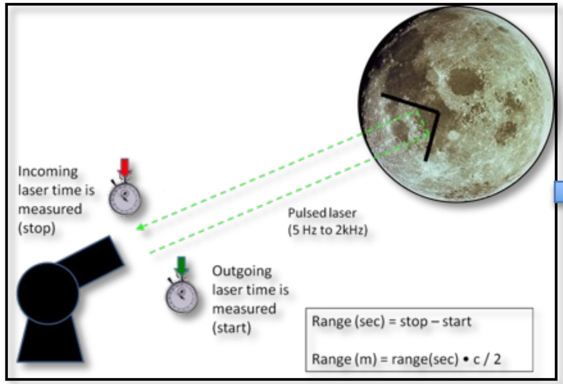


Apache Point Observatory Lunar Laser Ranging Station

- Installed on the 3.5-meter Telescope at the Apache Point Observatory in Sunspot, New Mexico
- Boasts most precise Lunar Laser Ranging capability, approaching 1 mm normal point precision
- NASA partnership with New Mexico State University for operations and maintenance
- Station being prepared to support new lunar reflectors on future CLPS missions as well as Lunar Pathfinder

LLR Data Flow

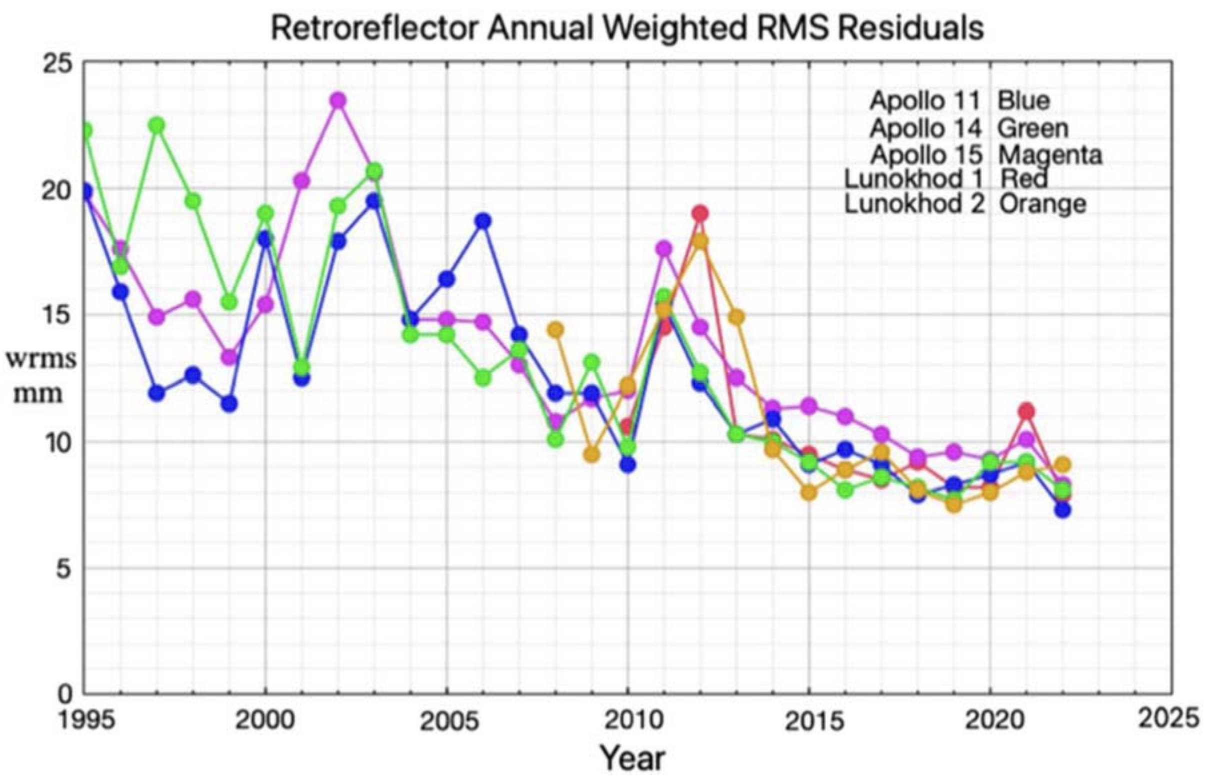
ILRS LLR Stations

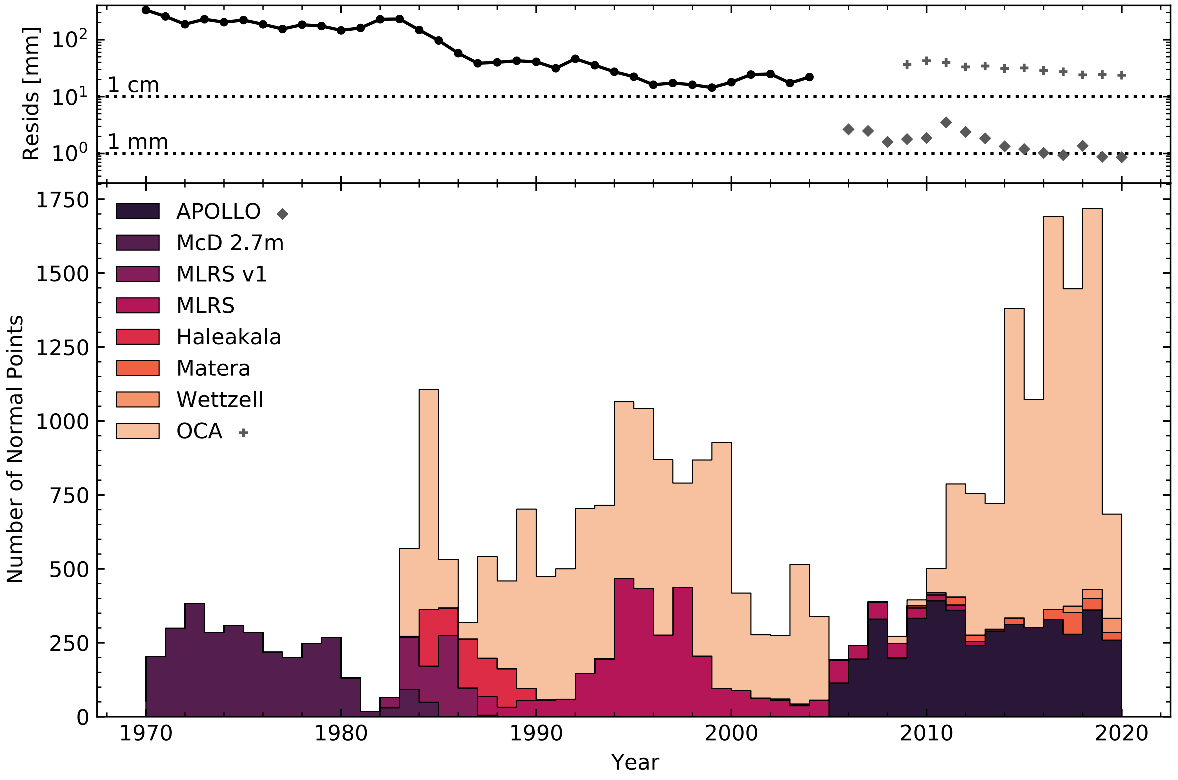


→ Calibration and Normal Point Formation → Quality Control → Submit to CDDIS ↔ ILRS Analysis Centers

LLR data available from 1969-present: https://cddis.nasa.gov/Data_and_Derived_Products/SLR/Lunar_laser_ranging_data.html

LLR Data Quantity, Precision, and Accuracy

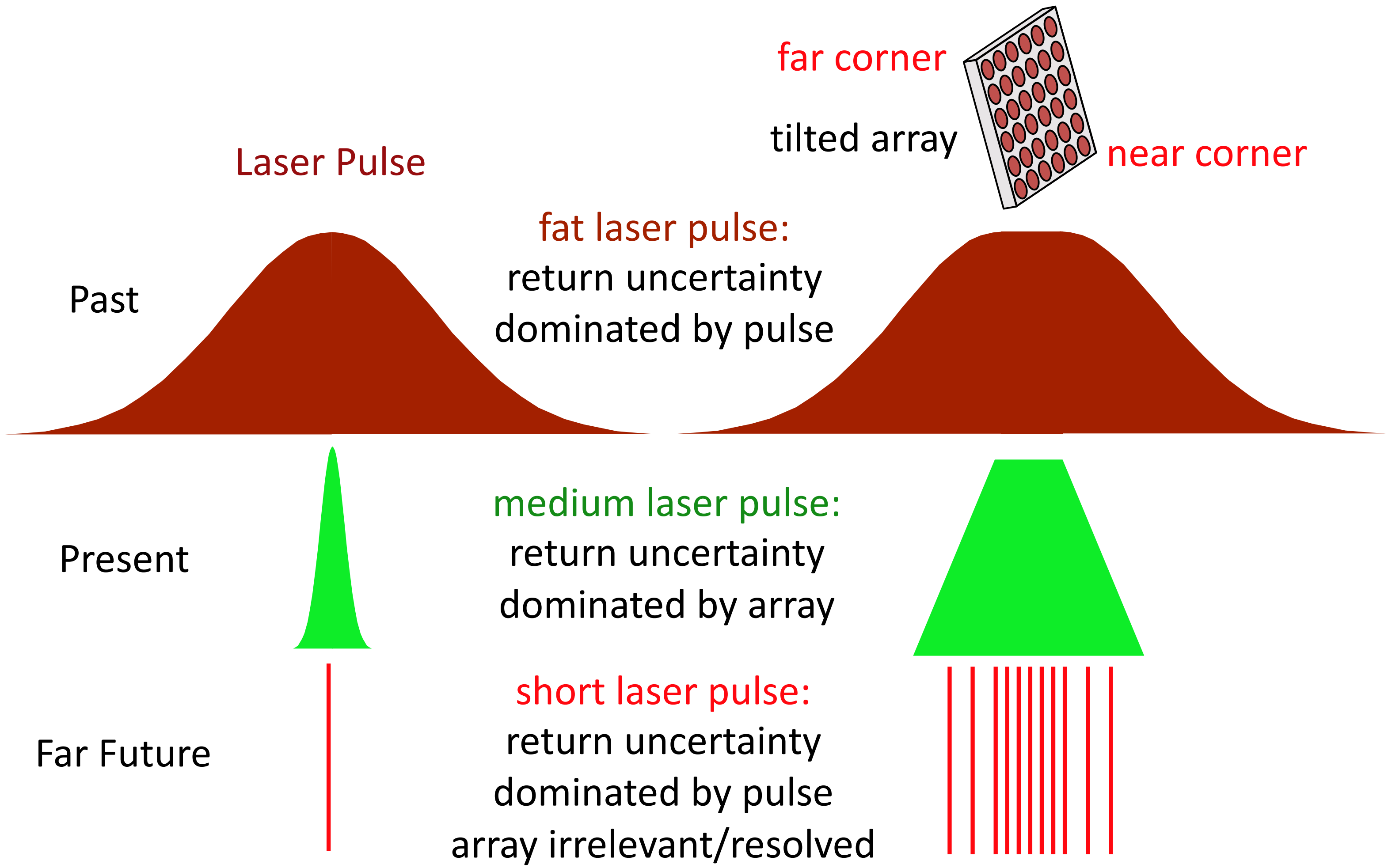


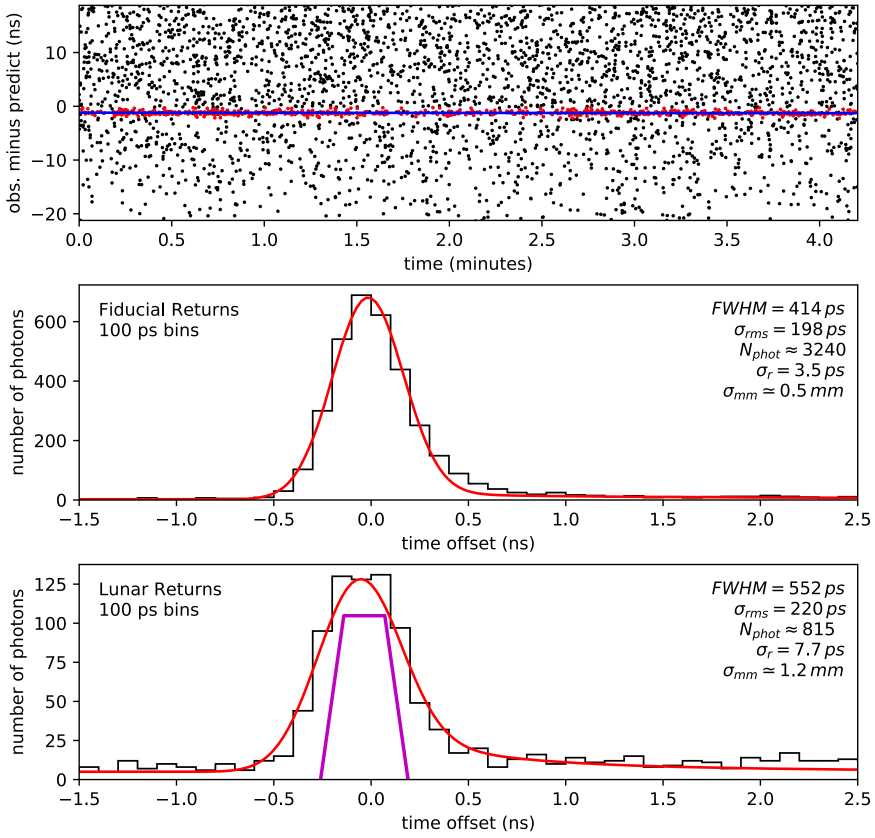


Williams et al.,
https://doi.org/10.3847/PSJ/acbeab

J. B. R. Battat et al.,
https://doi.org/10.1088/1538-3873/aceb2f

Current Limiting Error - Retroreflector Array Tilt



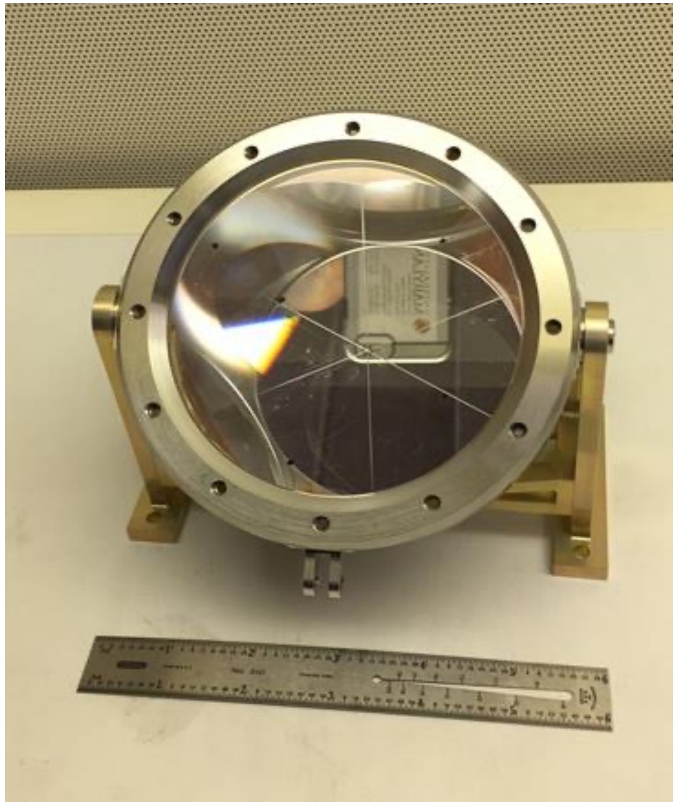


Apache Point measurements with retroreflector array timing profile

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

Solution to Tilt Error – Single Cubes

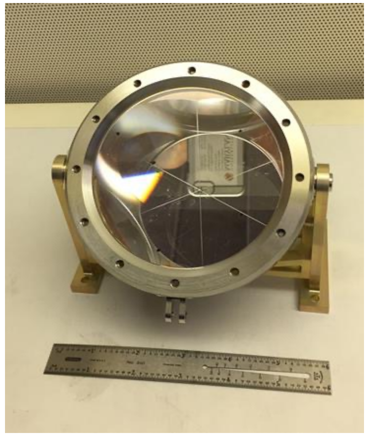
- Single cubes do not broaden return pulse thus eliminating the array tilt error.
- Central irradiance of return goes up as fourth power of the cube corner diameter, making it feasible to get comparable optical cross section to an Apollo 100 x 3.8 cm cube array with a single 12 cm cube.
- Solution does 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.



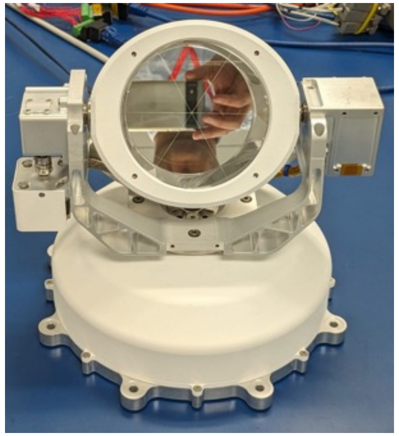
NGLR courtesy Douglas Currie

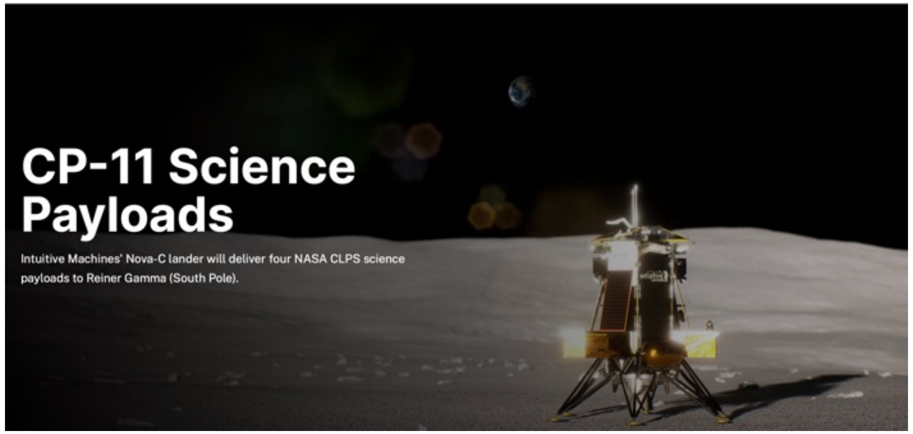
NASA Commercial Lunar Payload Services (CLPS) Deliveries

- Firefly's Blue Ghost 1 lander to Mare Crisium
  - University of Maryland’s Next Generation Lunar Retroreflector (NGLR), Dr. Douglas Currie, Principal Investigator
  - Relies on the Firefly lander and communications antenna to point it towards Earth



- Intuitive Machines' Nova-C lander to Reiner Gamma
  - ESA's MoonLIGHT Pointing Actuator (MPAc)
  - Adjusts pointing using lander’s determination of orientation

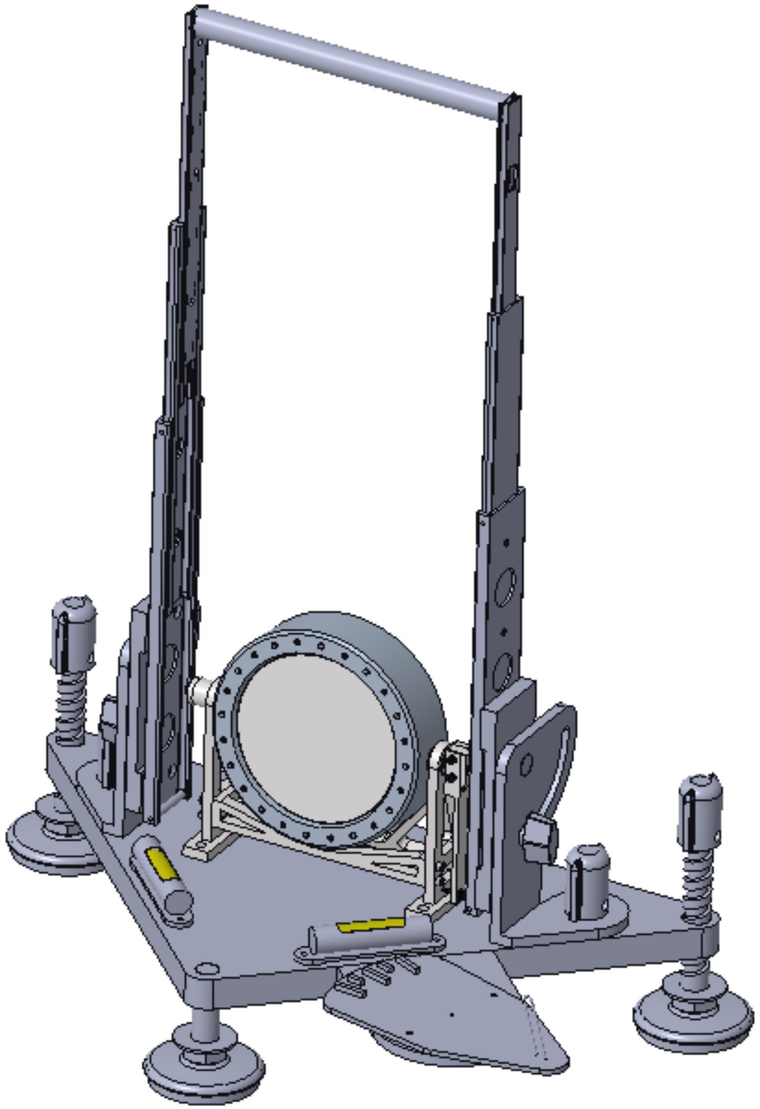




- Both missions use a single 10cm solid cube corner.

Artemis Lunar Laser Retroreflector (ALLR)

- Retroreflector selected for Artemis 3 Instruments program.
- Astronaut deployed at the lunar south pole.
- Baseline is identical 10cm cube as NGLR but investigating option for 12cm hollow retroreflector.



Summary

- For the past 55 years, LLR to the Apollo and Luna retroreflectors has produced a wealth of data supporting positioning and navigation, tests of gravitational theories, and studies of the Moon's interior structure.
- Next-generation lunar retroreflectors deployed to new lunar sites will further extend the science, positioning, and navigation applications.
- The CLPS and Artemis retroreflectors greatly expand the geometric coverage and build upon the long legacy of LLR.