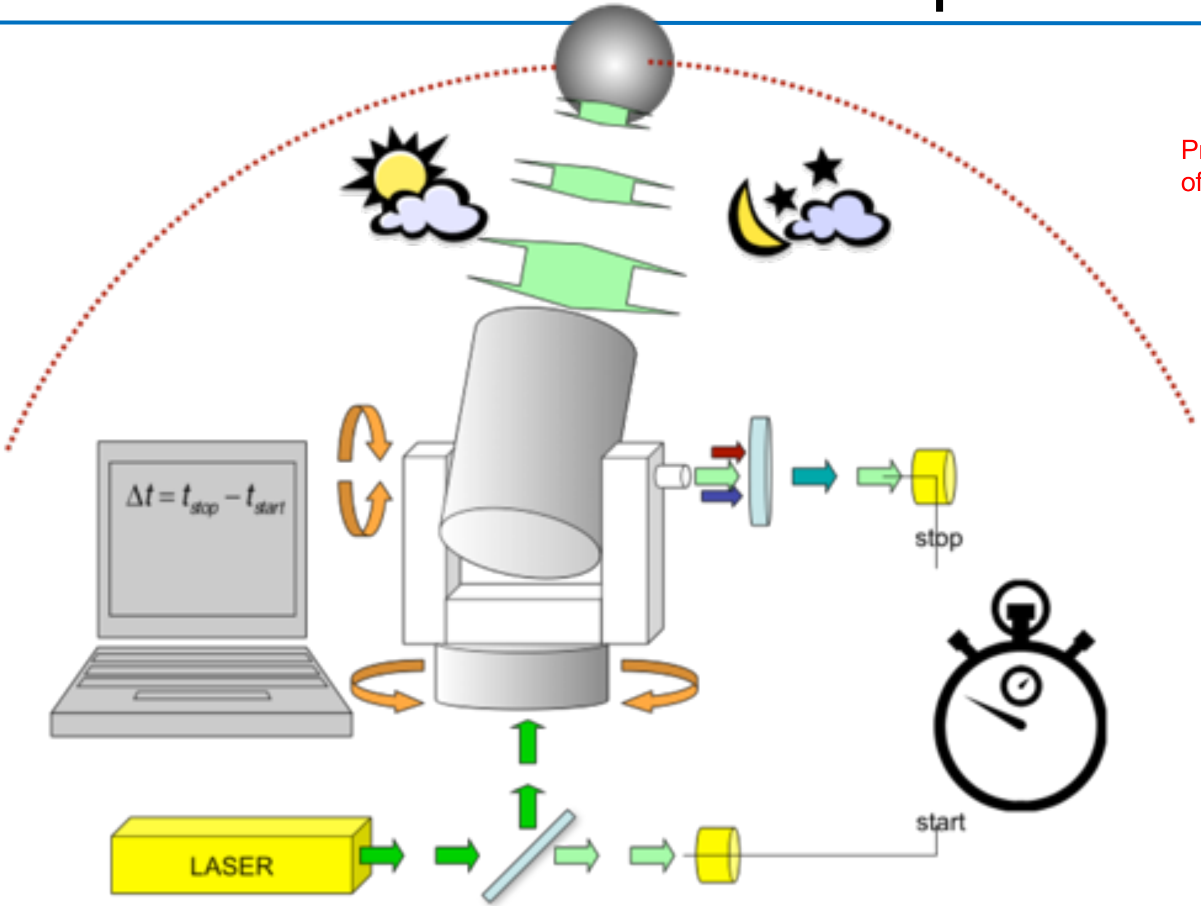
Three lunar laser ranging mission in 2023-2024 by NASA, ESA and CNSA for precision test of general relativity

PORCELLI, Luca (INFN-LNF); DELL'AGNELLO, Simone (INFN-LNF); CURRIE, Douglas (University of Maryland, College Park); BIANCO, Giuseppe (ASI-CGS); DELLE MONACHE, Giovanni Ottavio (INFN-LNF); REMUJO CASTRO, Alejandro (INFN-LNF); RUBINO, Laura (INFN-LNF); DENNI, Ubaldo (INFN-LNF); MUCCINO, Marco (INFN-LNF); MAURO, Lorenza (INFN-LNF); SALVATORI, Lorenzo (INFN-LNF); TIBUZZI, Mattia (INFN-LNF); DI PAOLO EMILIO, Maurizio (INFN-LNF); TRAINI, Marco (INFN-LNF); FILOMENA, Luciana (INFN-LNF); MORETTI, Giulia (INFN-LNF); DI, Kaichang (Aerospace Information Research Institute, CAS, Beijing, China); PING, Jinsong (National Astronomical Observatories, CAS, Beijing, China); LI, Yuqiang (Yunnan Astronomical Observatories, CAS, Yunnan, China); KANG, Zhizhong (China University of Geosciences, Beijing, China)

Vulcano Workshop 2022 - Frontier Objects in Astrophysics and Particle Physics
https://agenda.infn.it/event/30175/

Elba Island (Tuscany, Italy) - 26 September 2022

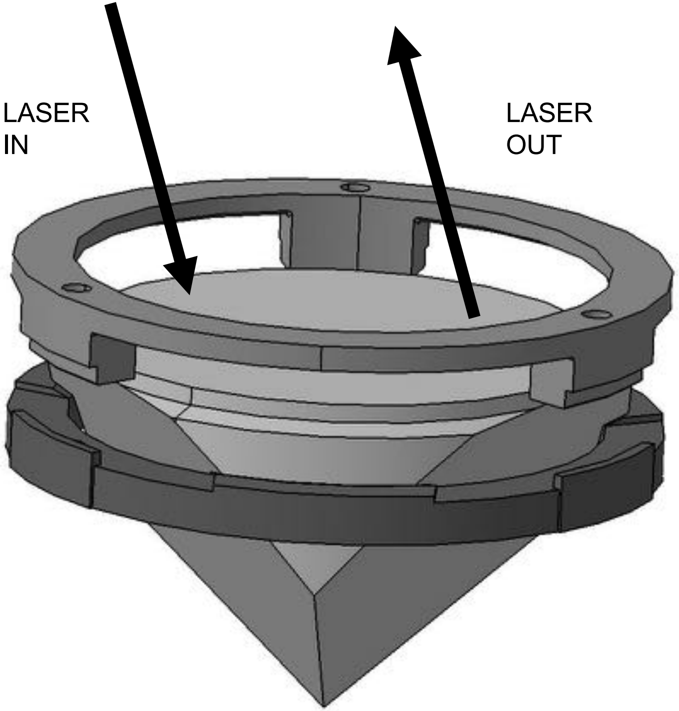
The SLR/LLR Technique



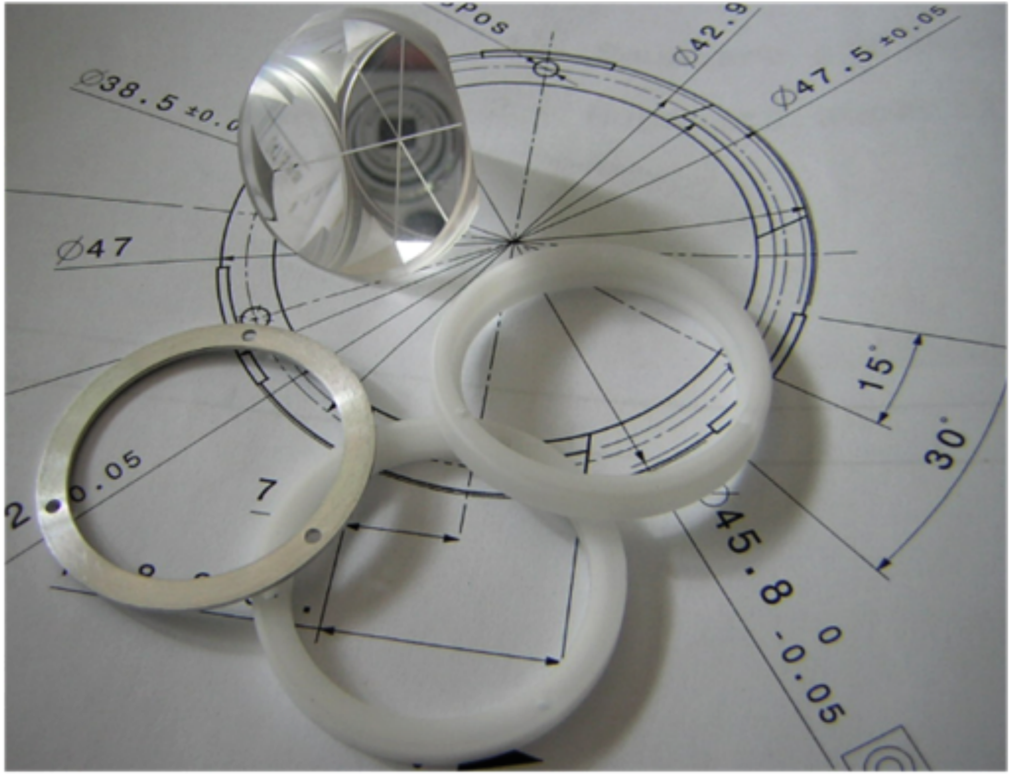
Precision for moon is of the order of 10^{-11}!

The SLR/LLR Technique

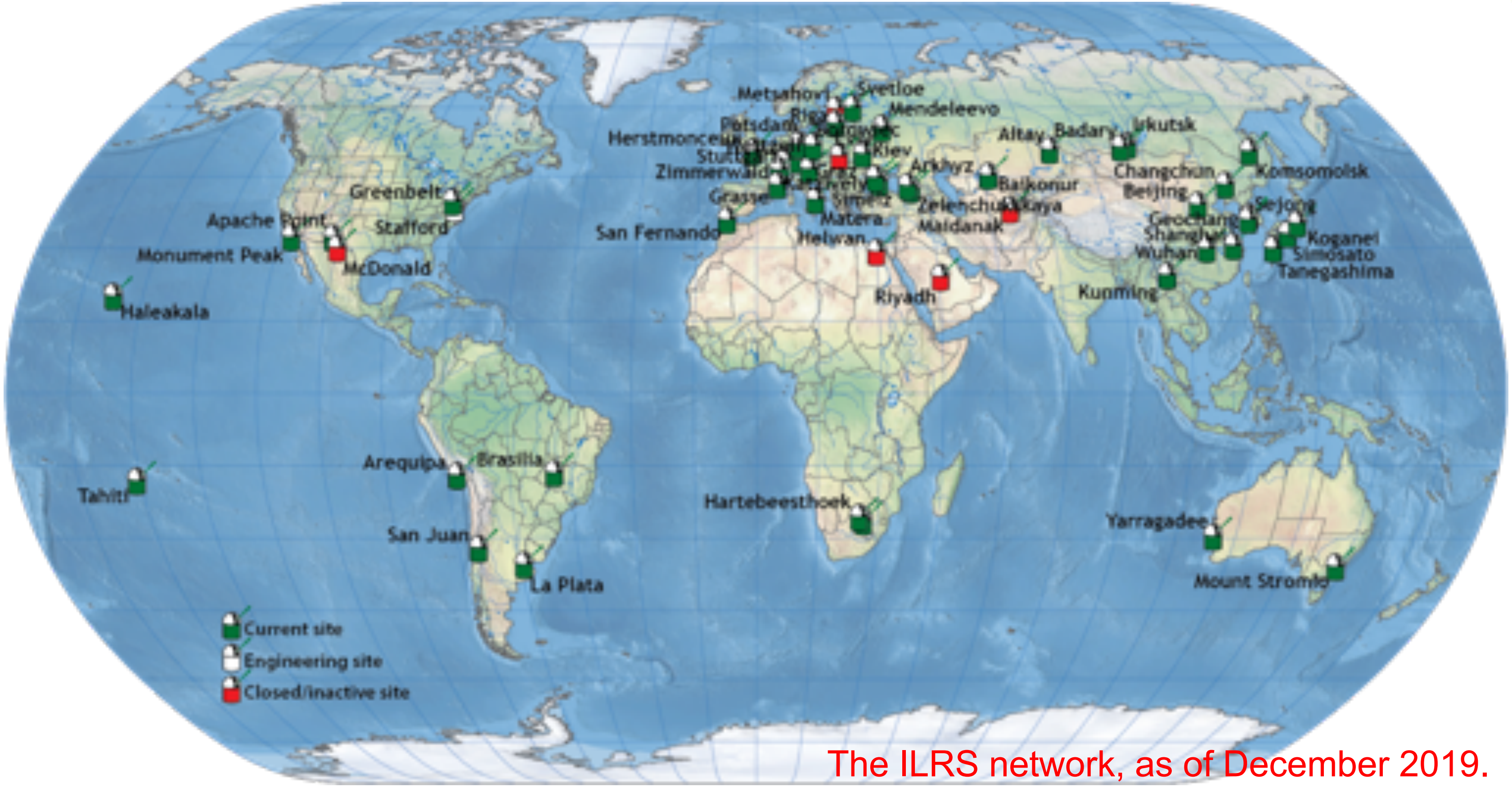
The ‘trick’ is the corner of the cube and the triple reflection of the light on the 3 back faces of the CCR.



Triple bounce w.r.t. the vertex of the cube



The SLR/LLR Technique



The ILRS network, as of December 2019.

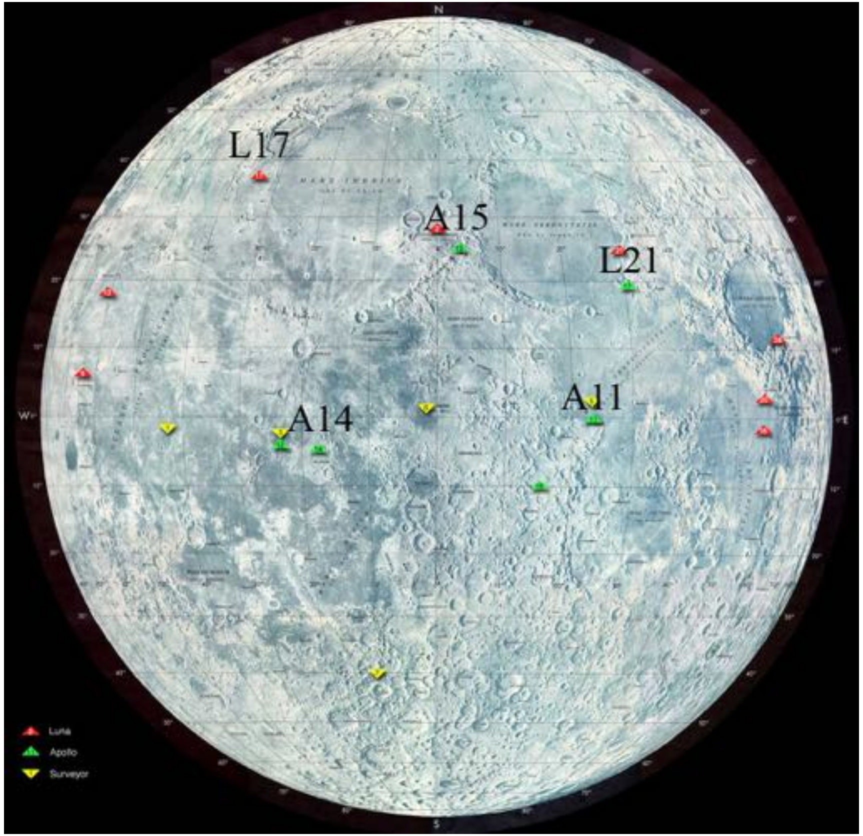
MoonLIGHT

LLR at a glance:

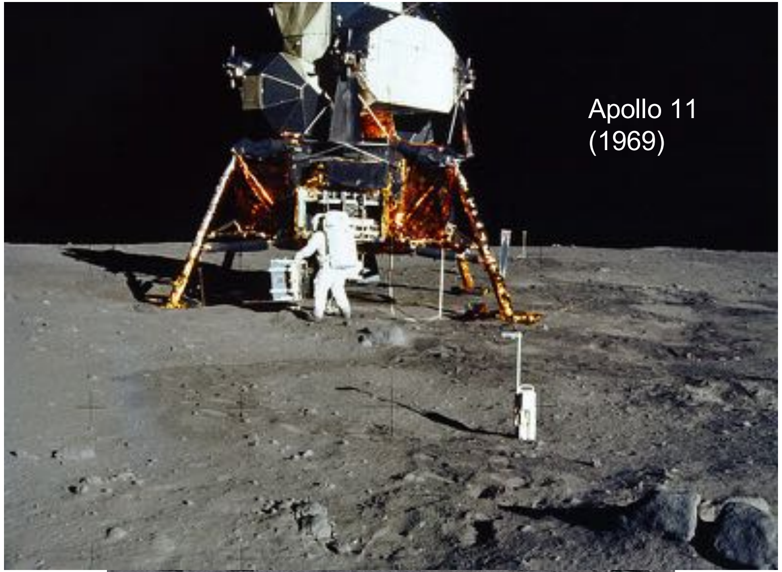
- Dicke et al. envisaged satellite POD through artificial light for gravity tests in ~ 1950.
- Laser invented in ~ 1960.
- USA and USSR light the Moon with laser light during the decade 1960-1970.
- Finally, from 1969 until 1972, LRAs of CCRs are deployed on the Moon.

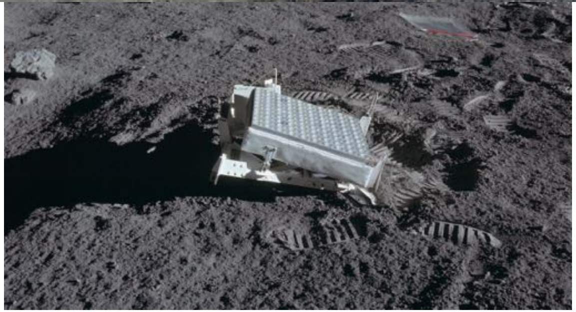
Apollo LRAs:

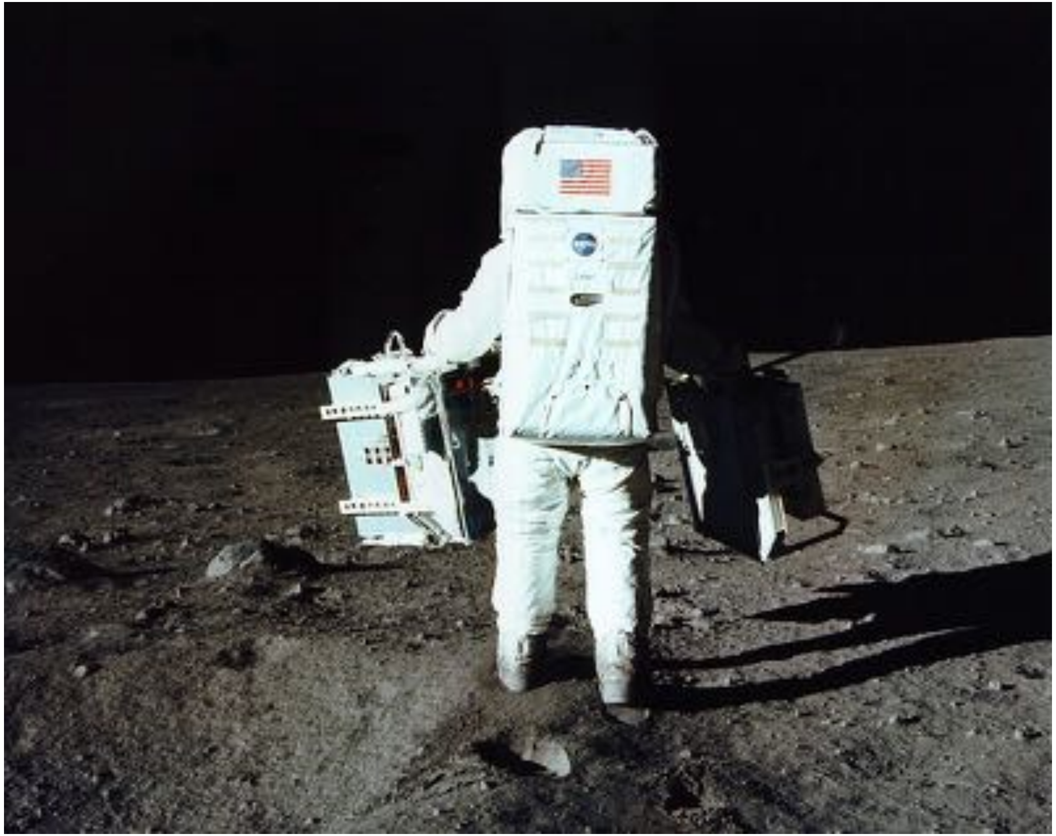
- Fused silica CCR matrices - each CCR is 3.8 cm in diameter.
- Apollo 11 e 14: 100 CCRs.
- Apollo 15: 300 CCRs.



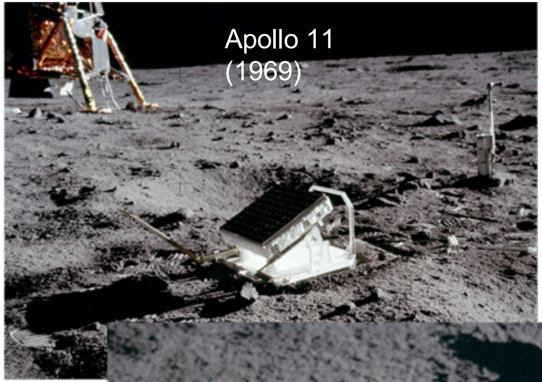
MoonLIGHT

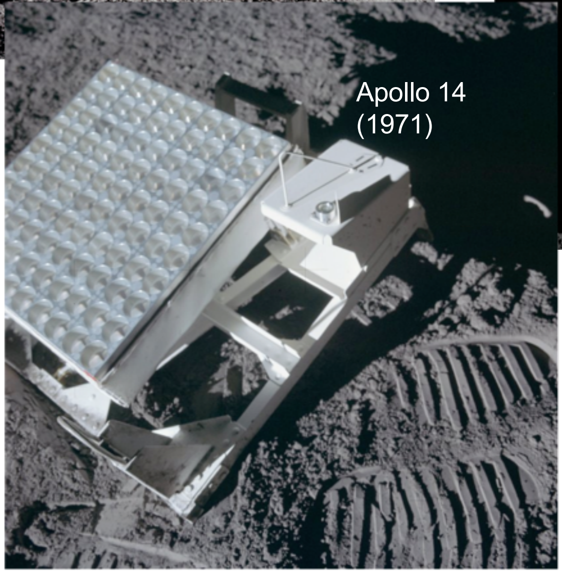


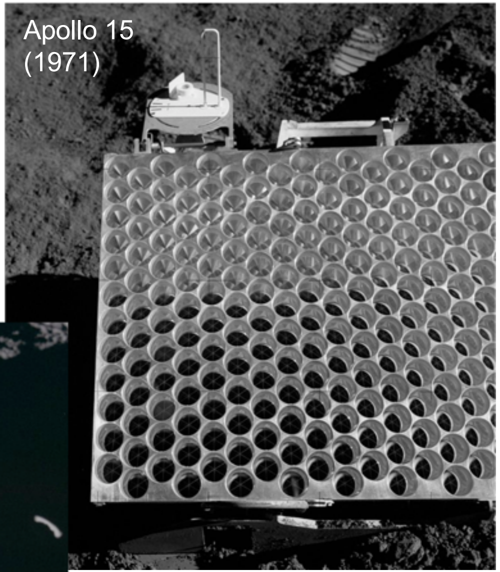


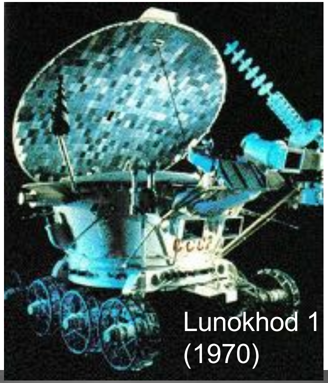


MoonLIGHT


Apollo 11
(1969)


Apollo 14
(1971)

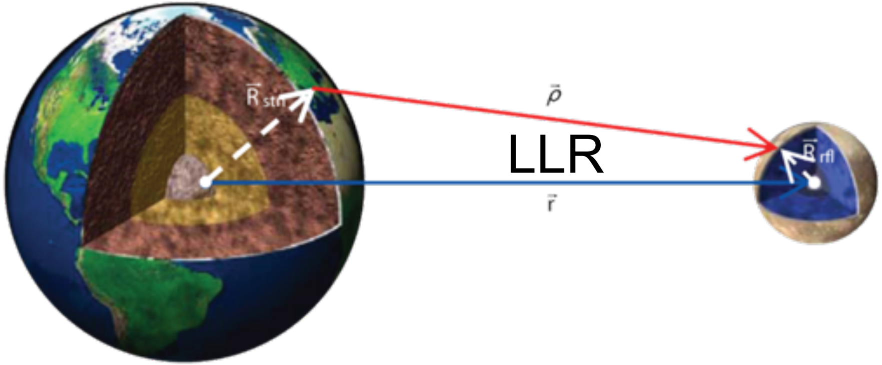

Apollo 15
(1971)


Lunokhod 1
(1970)

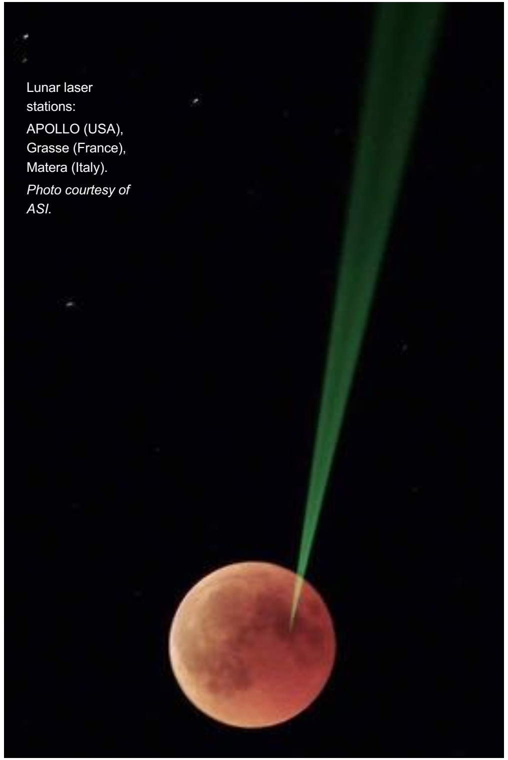

Lunokhod 2
(1973)

MoonLIGHT

Accurate Time of Flight (ToF) of short laser pulses, timed by accurate ground atomic clocks.



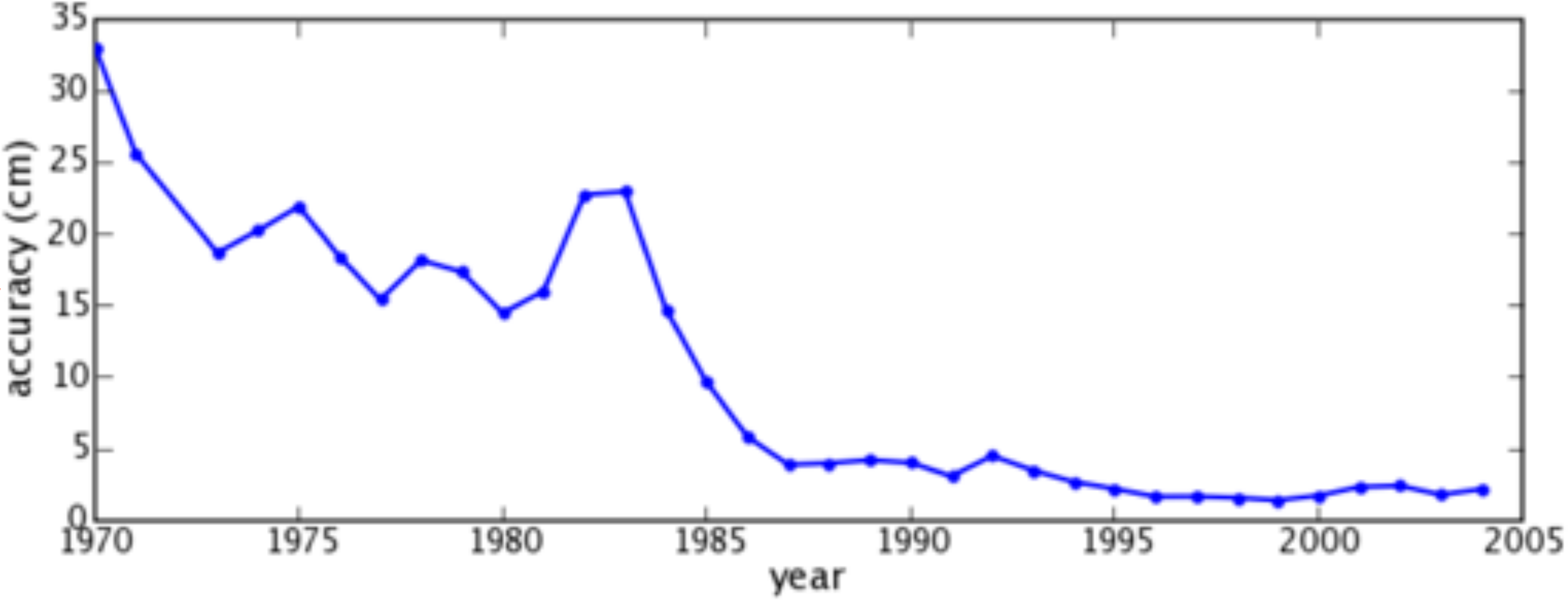
LLR during lunar eclipse of July 28, 2018 from ASI-Matera.



The most precise and cost effective distance measurement in space
(few millimeters to few centimeters) and (100K€ to M€)
Laser interferometry much more precise but much more expensive/difficult

MoonLIGHT

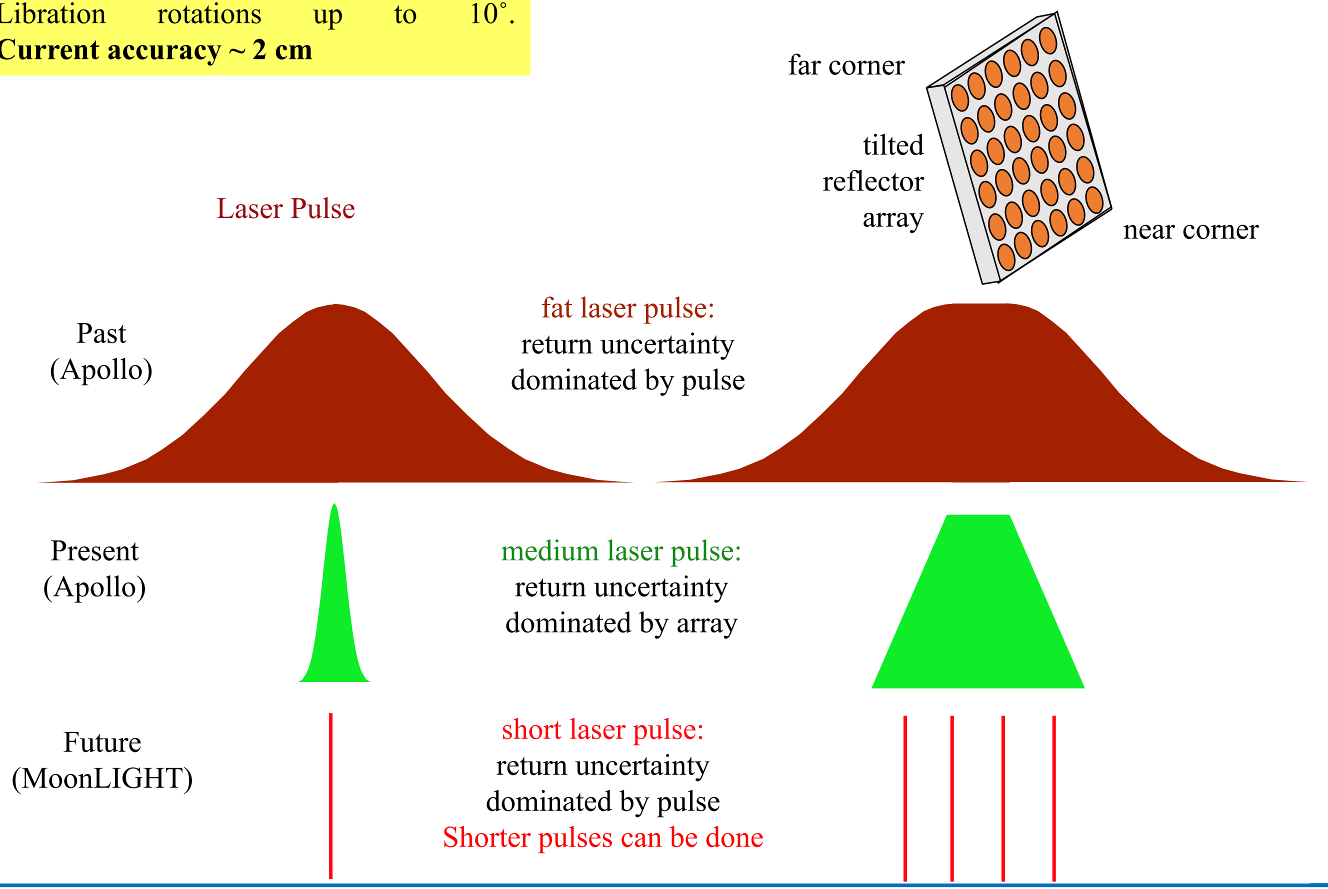
Previously: hundreds of meters.



https://tmurphy.physics.ucsd.edu/

MoonLIGHT

Libration rotations up to 10˚.
Current accuracy ~ 2 cm

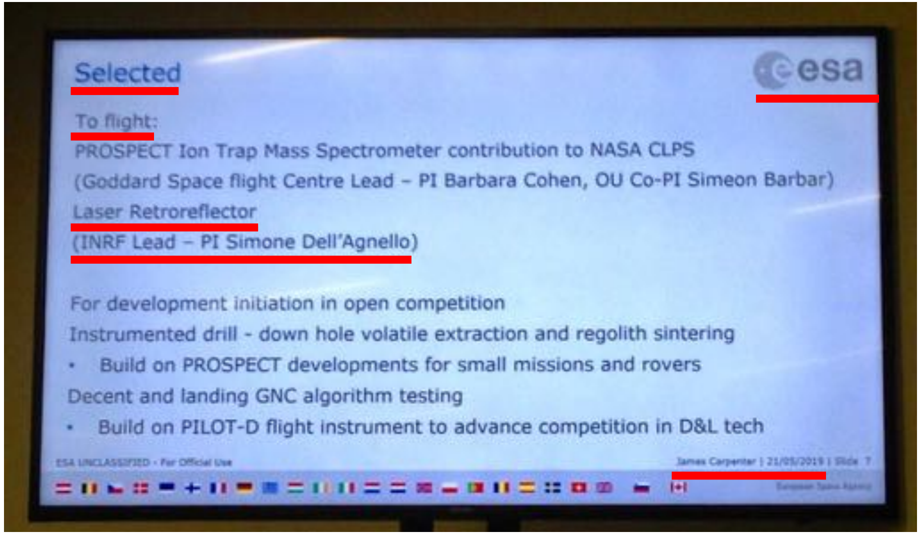


MoonLIGHT

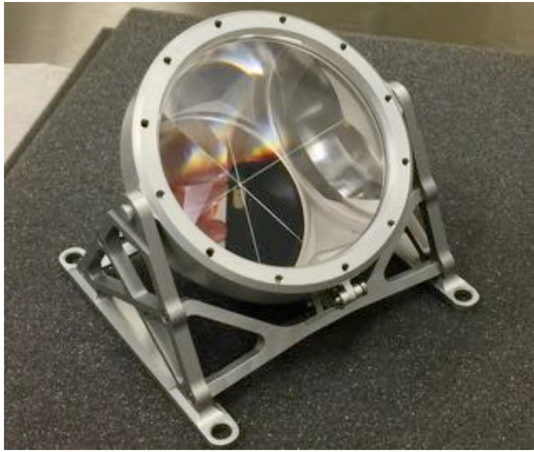
Selected for ESA MoO in May 2019 (response to the ESA RfI on Lunar Exploration Campaign Science and Technology Payloads due in late 2018):

- Publicly announced at the European Lunar Symposium 2019 by James Carpenter (ESA).
- INRF = INFN Retroreflector Frascati (another acronym ☹).
- Flight will be a NASA-CLPS (w/ MPAc = MoonLIGHT Pointing Actuator).

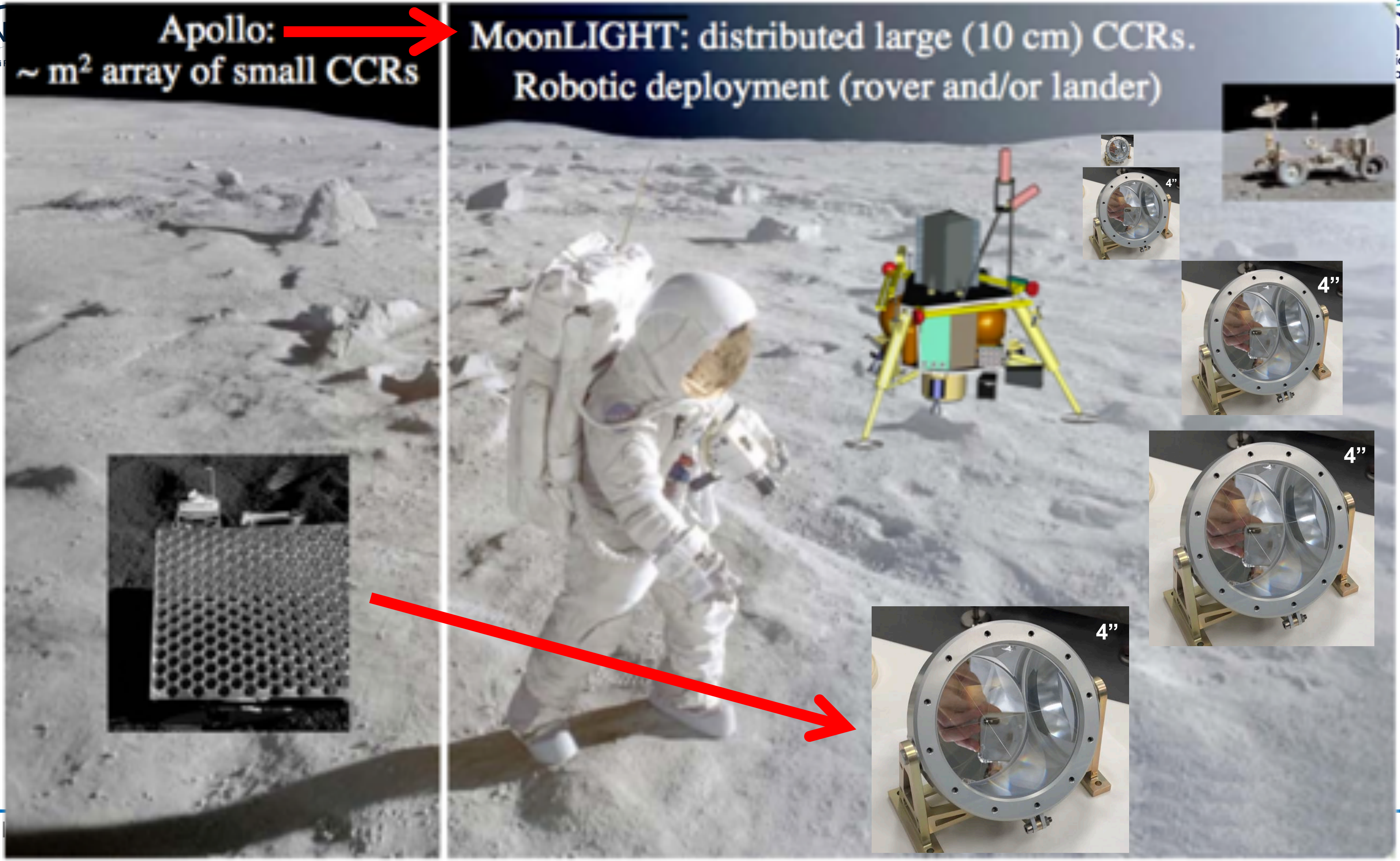
Also in 2019, arose 1+ NASA-CLPS (for fixed pointing hardware).



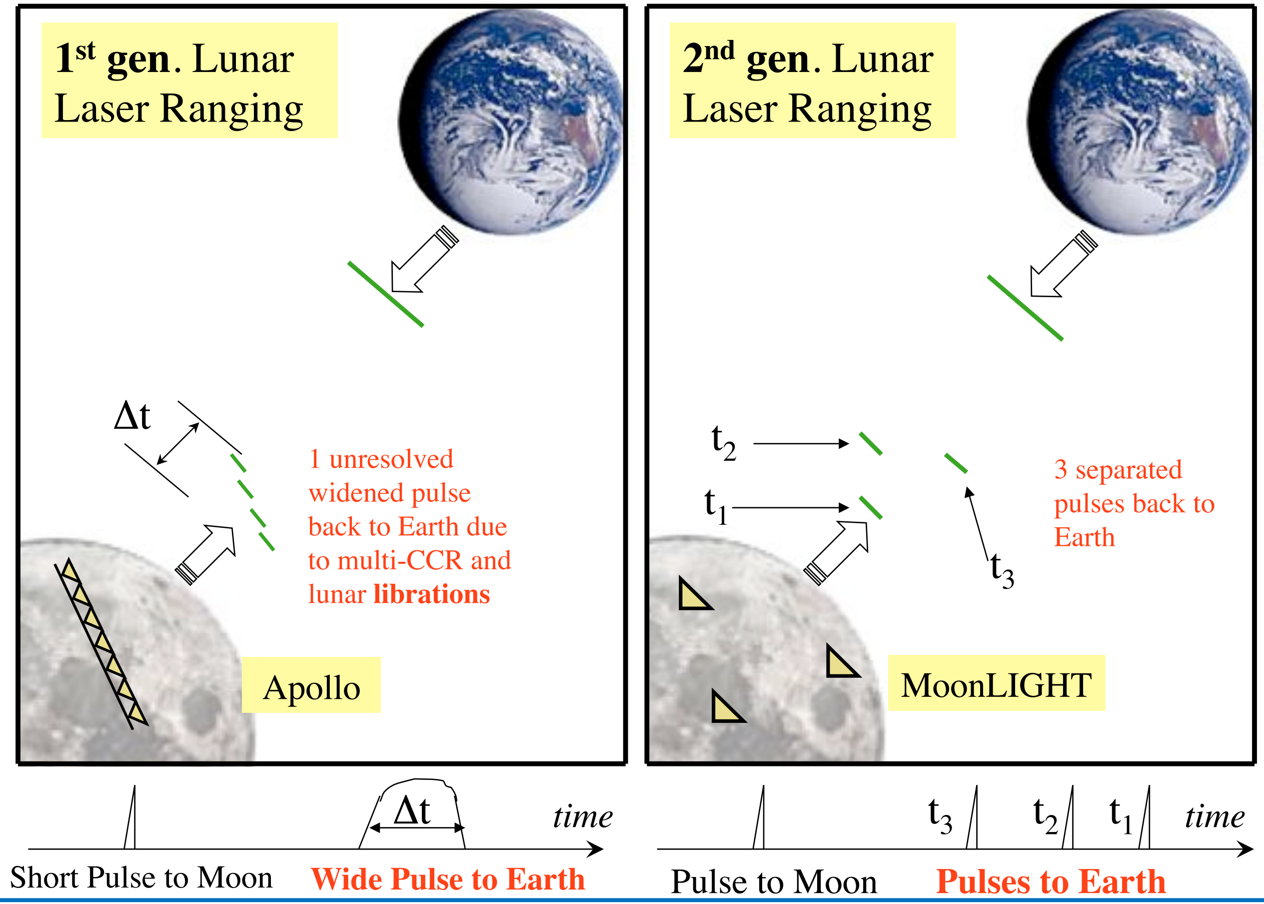
Prof. D. Currie (UMD)



MoonLIGHT-100/NGLR = Moon Laser Instrumentation for General relativity High accuracy test (INFN-LNF)/Next Generation Laser Retroreflector (UMD). This 100 mm single, solid, large reflector is intended for direct lunar laser ranging from stations in USA, Italy (ASI-CGS) and France (Grasse). Its main applications are the Lunar Geophysical Network (LGN) and precision tests of General Relativity and new theories of fundamental relativistic gravity.


Apollo:
~ m² array of small CCRs
MoonLIGHT: distributed large (10 cm) CCRs.
Robotic deployment (rover and/or lander)
4”
4”
4”
4”

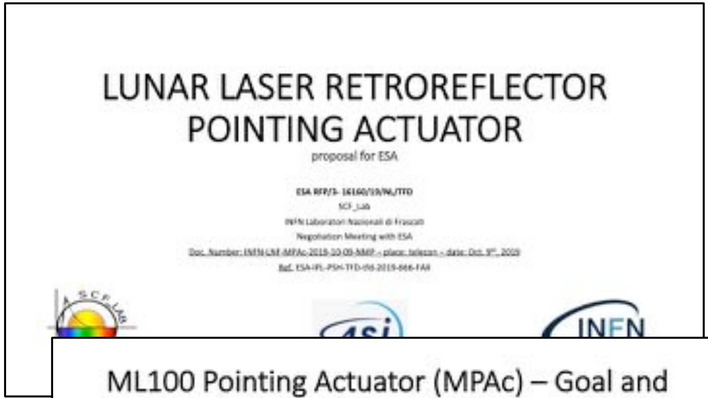
MoonLIGHT



1st gen. Lunar Laser Ranging
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**
Apollo
2nd gen. Lunar Laser Ranging
t_2
t_1
t_3
3 separated pulses back to Earth
MoonLIGHT
Δt
time
Short Pulse to Moon
Wide Pulse to Earth
t_3 t_2 t_1
time
Pulse to Moon
Pulses to Earth

MoonLIGHT+MPAc+Cover

MoonLIGHT + MPAc: actuating the system!



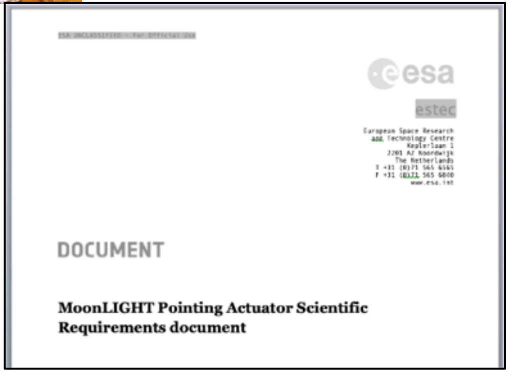
Contract for development of MPAc (MoonLIGHT Pointing Actuator)

ESA Contract No. 4000129000/19/NL/TFD

with

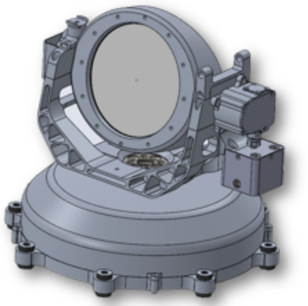
INFN - Laboratori Nazionali di Frascati

LUNAR LASER RETROREFLECTOR POINTING ACTUATOR



MoonLIGHT+MPAc+Cover

MoonLIGHT Pointing Actuator (MPAc)



The CCR field of view, in far field conditions, is quite narrow (a cone with an opening angle of about 34˚, whose apex is geometrically located in the vertex of the CCR), and it needs to be pointed precisely to the Earth. On account of the fact that the industry of landers could not guarantee such an accurate pointing of the device, INFN proposed the MoonLIGHT Pointing Actuator (MPAc) project to ESA in 2018. In 2019 ESA chose MPAc (and another instrument) among 135 eligible scientific project proposals.

The MPAc design aims to implement a modular configuration, being able to isolate the CCR from the electronics and moving elements. It must operate in Ultra High Vacuum space conditions, in a wide operating temperature range. The MPAc is divided into three main blocks with very different functions and characteristics.

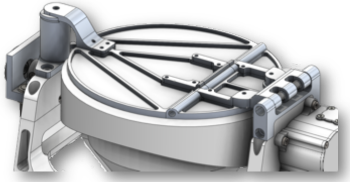
1. The CCR Housing contains the MoonLIGHT retroreflector and its integration structure.
2. The elevation frame, is responsible of the generation of the “Elevation” rotation and contains some actuators and sensors.
3. The base frame represents the interface with the lander and contains most of the electronics and the motor responsible of generating the “Azimuth” rotation.

MPAc can be activated and commanded from Earth. Pointing is performed after knowing the actual attitude of the lander on the lunar surface, sending a command that the integrated microcontroller uses to move the two stepper motors to the desired position.

Mechanics, electronics and software have been tested with the 3 first prototypes, two in plastic and one in aluminum. The next step for the qualification is the design and manufacturing of the Engineering Model.

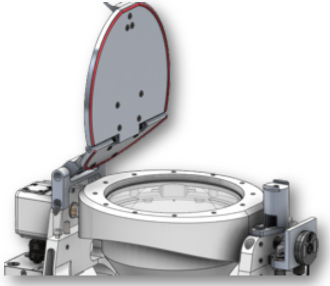
MoonLIGHT+MPAc+Cover

Dust Shield

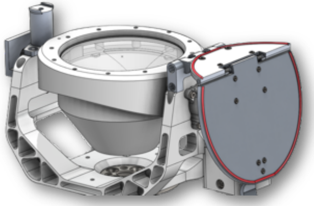


Lunar dust proved to be a challenge for many lunar projects. In particular, optical devices may see their performance degraded by the deposition of these particles. During 2021, the necessity of protecting MoonLIGHT from this danger was answered with the design of a removable dust shield.

The MPAc cover consists of a divisible plate pulled by torsion springs. Once the release mechanism actuator is activated, the cover folds by itself, representing no disturbance for the subsequent operations.



In order to study the behaviour of the dust shield during the aperture of the shield and individuate the possible flaws of the model, tests were made with a plastic prototype, allowing a faster evolution of the design.

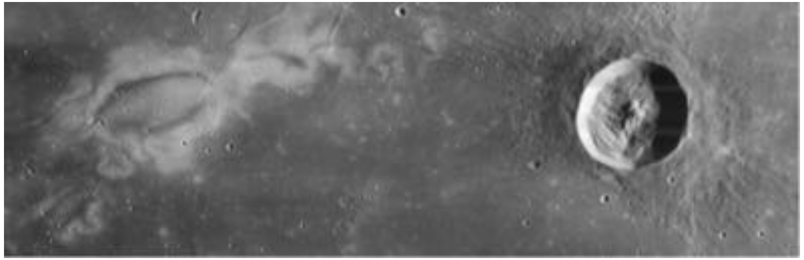


MoonLIGHT+MPAc+Cover

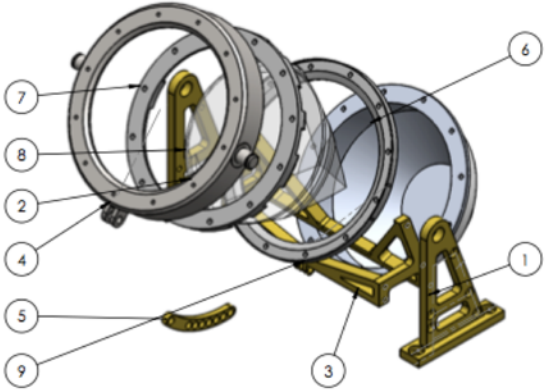
CLPS Mission

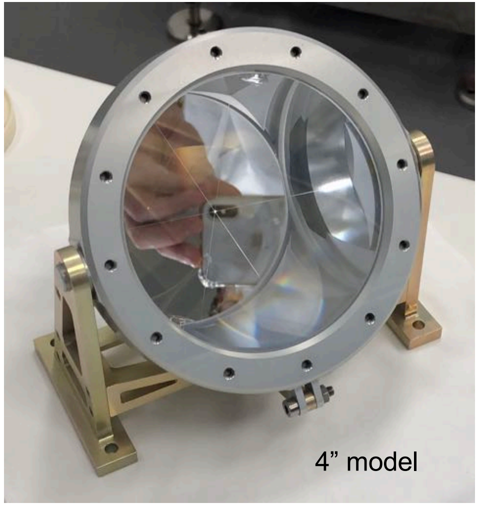
MPAc will fly, together with other 3 scientific payloads as part of NASA's Commercial Lunar Payload Services (CLPS) initiative and the Artemis program. The investigations aboard Intuitive Machines' Nova-C lander include exploration rovers, a high-energy particles detector and a magnetic field measurement device.

The landing site is Reiner Gamma, one of the most distinctive and enigmatic natural features on the Moon. Known as a lunar swirl, Reiner Gamma is on the western edge of the Moon, as seen from Earth (7.5°N, 59.0°W). It is still to be understood what lunar swirls are, how they form, and their relationship to the Moon's magnetic field.



MoonLIGHT/NGLR

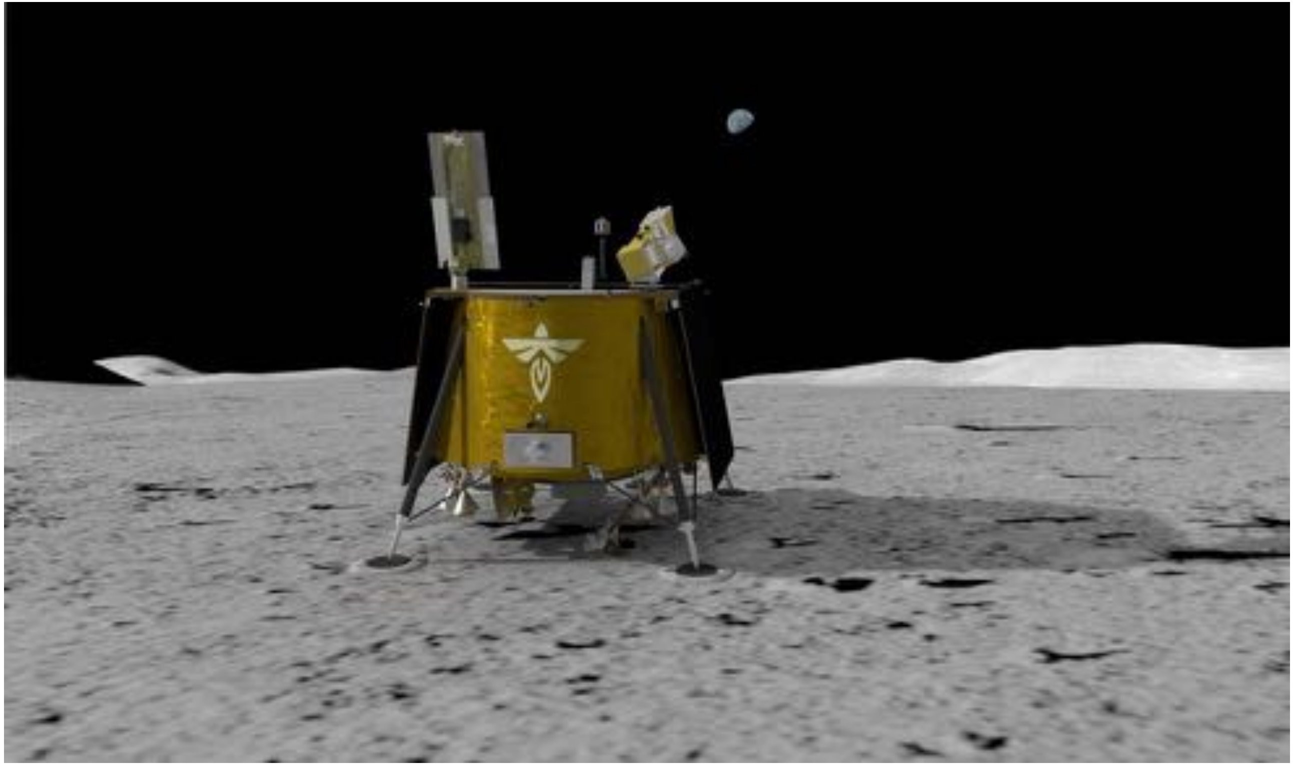




NGLR Selected by NASA for LSITP

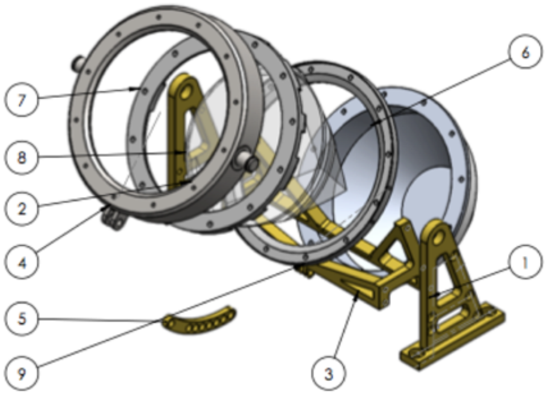
PI = D. Currie of University of Maryland
Co-PI group = SCF_Lab of INFN
July 2, 2019: Next-Gen Lunar Reflector selected by NASA for a CLPS flight as a "... target for lasers on Earth to precisely measure the Earth-Moon distance ... and address questions of fundamental physics."
Q2-Q3, 2024: landing on the Moon.

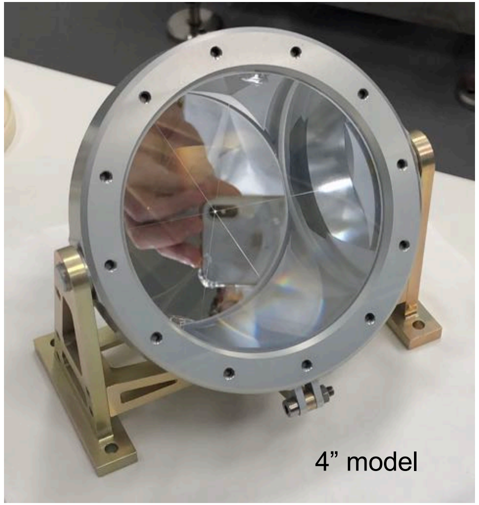
MoonLIGHT/NGLR



MoonLIGHT/NGLR will fly to the Moon on board Firefly's Blue Ghost lander.

Payloads for Chang’E-6 Mission





Payloads for Chang'E-6 Mission

INRRI, LaRRI & LaRA

- μreflector array: 8 silver/Al coated 12.7mm CCRs on a frame of aluminium alloy.
- Weight and size: 25 g for 5 cm of radius and 2 cm of height.

Goals

- Laser-location of lander/rovers on Moon/Mars/asteroids/comets from orbiters.
- Global and local exploration, planetary science, geodesy and test of fundamental gravity.

MoonLIGHT

Lunar Exploration & Science Assets:

- *Big, single laser retroreflector observed from Earth*
  - Italy/US: **MoonLIGHT** = Moon Laser Instrumentation for General relativity High accuracy Tests - unaffected by lunar librations.
- *Lunar Laser Ranging*
  - **APOLLO** (USA), **GRASSE** (France), **MLRO** (Matera Laser Ranging Observatory, ASI, Italy).
- *Orbital, positioning SW*
  - **PEP** (Planetary Ephemeris Program) for Moon/Mars positioning: developed since 1960/70s at the Harvard Smithsonian Center for Astrophysics (CfA): PEP is an open source sophisticated software package to estimate the orbits of the solar system natural bodies and of many artificial satellites.

MoonLIGHT

Lunar Science Case
Primary Goals

LLR determination of the lunar ephemeris with an increasing accuracy represents a unique laboratory for gravitational physics since:

1. Verifies to a very high accuracy terms in the relativistic PPN equations of motion.
2. Provides the only current solar system means for testing the SEP.
3. Constraints the time variation of Newton constant $\dot{G}/G$ and the geodetic precession.

Future data with higher accuracy from the new generation lunar CCRs will continue to improve the LLR tests/constraints of gravitational physics.

Secondary Goals

LLR technique can also contribute in defining a LGN and in determining the interior structure of the Moon.

MoonLIGHT

Lunar Science Primary Goals

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod * (cm-level accuracy)	MoonLIGHTs ** (mm-level accuracy)
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert < 1.1\times10^{-4}$	10^{-5}
Weak Equivalence Principle (WEP)	$\lvert\Delta a/a\rvert < 1.4\times10^{-13}$	10^{-14}
Strong Equivalence Principle (SEP)	$\lvert\eta\rvert < 4.4\times10^{-4}$	3×10^{-5}
Time Variation of Gravitational Constant	$\lvert\dot{G}/G\rvert < 9\times10^{-13}\mathrm{yr}^{-1}$	5×10^{-14}
Inverse Square Law (ISL) - Yukawa	$\lvert\alpha\rvert < 3\times10^{-11}$	10^{-12}
Geodetic Precession	$\lvert K_{gp}\rvert < 6.4\times10^{-3}$	6.4×10^{-4}

* Williams et al., PRL 93, 261101 (2004).
** Martini et al., Plan. & Space Sci. 74 (2012), 276-282.
** Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.
** Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).

Summary

Lunar 'big' single-CCR retroreflector payload:

- An innovative payload: our fully-fledged 4" (100 mm) model, approved for flight by ESA Selection (w/ active MPAc) and NASA (Fixed Pointing).
- At least two flights approved from 2024 onwards.
- Passive, 50-year lifetime, laser retroreflector-based enhancement of the Lunar Geophysical Networks (LGN), together with the 'microreflector' for CNSA.
- Improved 'use' of the Moon as a test body for:

1. Lunar surface geodesy and deep lunar interior studies.
2. Accurate test of General Relativity (and beyond).