

Next-generation laser retro-reflectors and application for lunar GW detectors



M. Muccino^{1,2} (PI/Dep. PM), S. Dell'Agnello¹ (PM), G. Delle Monache¹, U. Denni¹, M. Montanari (Dep. PM), L. Porcelli¹ (CSN2 Manager), L. Salvatori¹, M. Tibuzzi¹, L. Filomena¹ (PAM), L. Mauro¹, C. Mondaini¹, M. Petrassi¹, A. Remujo Castro¹, L. Rubino¹, M. Traini¹, J. Chandler³, P. Villoresi⁴, G. Vallone⁴, S. Capozziello⁵, R. Vittori¹, P. Lognonné⁶, K. Jani⁷

ESA PoCs: N. Boersma (PM), A. Brandão and Matej Koubek (PAM), L. Cacciapuoti (Project Scientist), J. Carpenter (Program Coordinator)

NASA-CLPS Mission (CP-11) PoCs: H. Haviland (Project Scientist), R. Watkins (Program Scientist), J. Villareal (PM), P. Nile

ASI (INFN-LNF & ASI-Matera Joint Lab) PoCs: C. Benedetto (PM), G. Bianco, D. Dequal

1 National Institute for Nuclear Physics – Frascati National Labs (INFN-LNF), via E. Fermi 54, Frascati (RM), 00044, Italy

2 aeroTecno s.r.l., via dei Savonarelli 3, Rome, 00165, Italy

3 University of California San Diego (UCSD) & Centre for Astrophysics (CfA)

4 University and INFN of Padua (PD), Italy

5 University and INFN Naples, Italy

6 Institut de physique du globe de Paris, Paris, France.

7 Vanderbilt University, Nashville, Tennessee, USA



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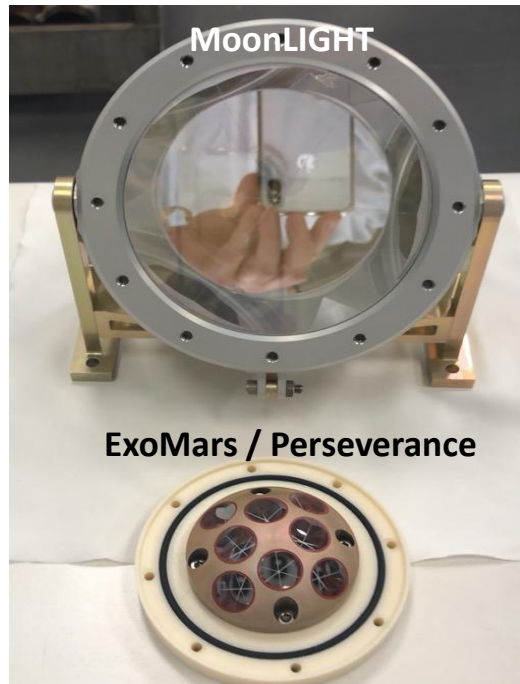
Outline

Weak field – slow motion regime in Sun-Earth-Moon system

- Next-generation lunar laser retroreflectors
 - INFN-LNF, **MoonLIGHT** (Moon Laser Instrumentation for General relativity/geophysics High-accuracy Tests)
 - UMD (USA), **NGLR** (Next-Generation Lunar Retroreflector)
designed to probe gravity through: Parametrized Post-Newtonian (PPN) β , Weak & Strong Equivalence Principles (WEP & SEP), \dot{G}/G , inverse-square law deviations (within GR and beyond)...
- Tests performed in the last decades by the network of 3 Apollo and 2 Lunokhod laser retroreflector arrays.
- Current laser retroreflector opportunities:
 - **ESA-MoonLIGHT**, NASA-CLPS/PRISM-1A (CP-11) mission in 2024 to **Reiner Gamma swirl, 7N, 59W**
(NASA-ESA MoU signed in early 2022)
INFN-LNF work supported by ESA Contract n. 4000129000/19/NL/TFD and ASI Agreement n. 2019-15-HH.0.
 - **NASA-NGLR**, CLPS/Ghost Blue mission in 2024, landing site **Mare Crisium, 17N, 59E**

GW Detection on the Moon

- Current laser retroreflector systems to be evolved for lunar GW detectors (**LGWA?**, **LSGA**, **iLILA**)
 - Next-generation lunar laser retroreflector, MoonLIGHT (funded by INFN-CSN2)
 - Earth-pointing actuator (funded by ESA)
 - Robotic dust cover (funded by ESA and INFN-CSN2)



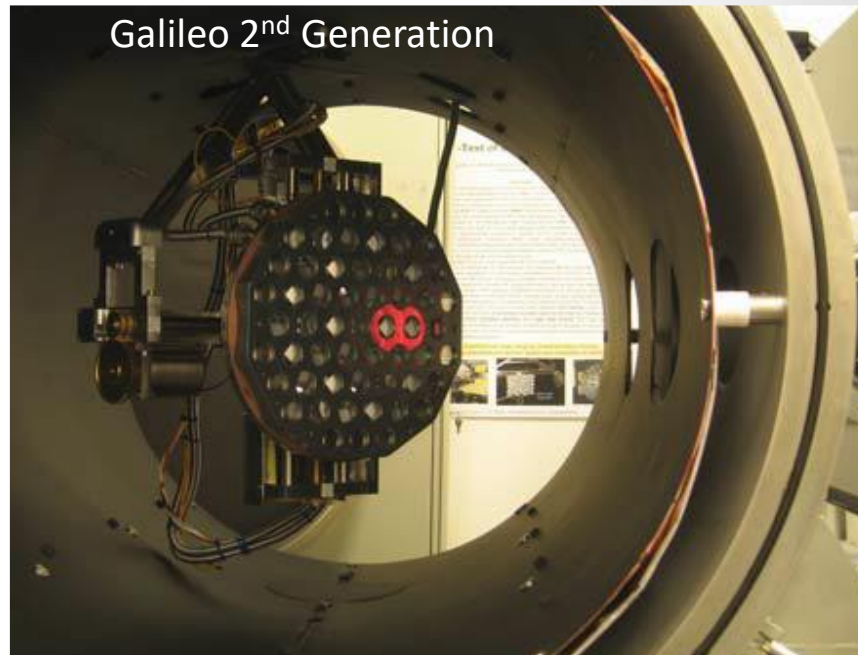
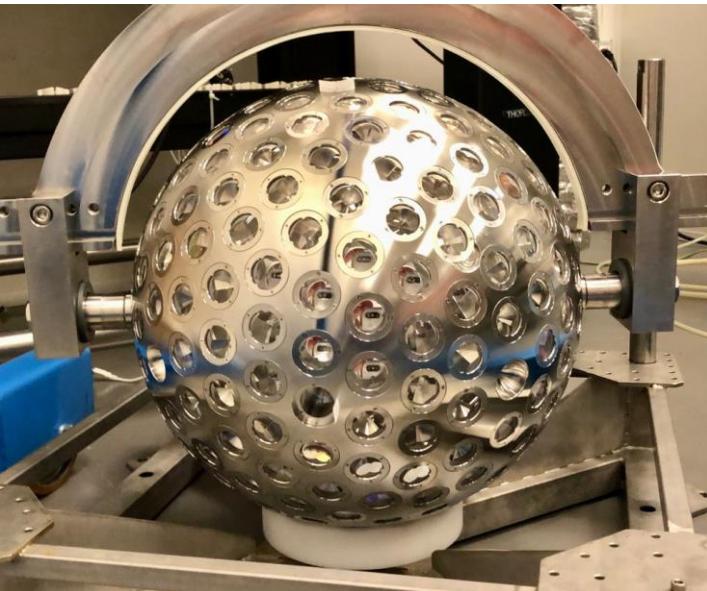
SCF_Lab Laser Retroreflector Test & Ranging

SCF_Lab@INFN-LNF: 85 m² ISO7 Clean Room Specialized Optical Ground Support Equipment (OGSE) [1]:

- Two optical benches: FFDP (diffraction), Fizeau interferometry
- Representative space environments for payloads with TRL ≥ 7
- SCF for laser ranging & SCF-G optimized for GNSS
- Two AM0 sun simulators (extended to ≈ 3000 nm)
- IR thermometry.

[1] Dell'Agnello S. et al., J. Adv. Space Res. 47, 822–842 (2011)

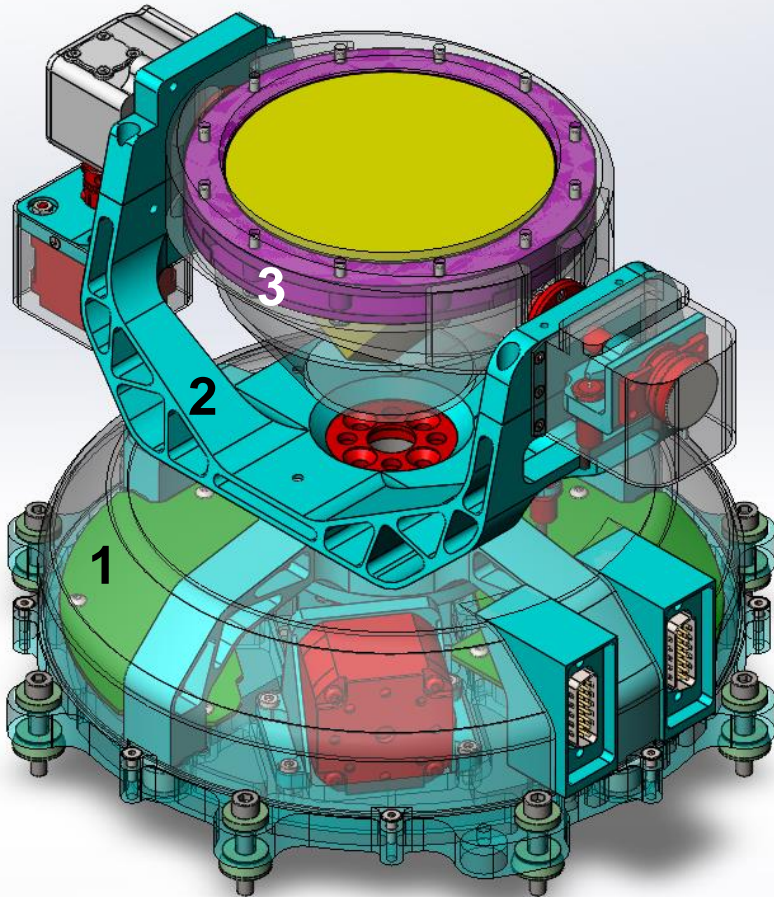
LARES-2 (Laser Relativity Satellite-2) by
INFN-LNF&Pd (ESA Vega-C, July 13th 2022)



ASI-INFN Joint-Lab on Laser Retroreflectors & Ranging



MPAc (**M**oon**L**IGHT **P**ointing **A**ctuator) in a nutshell



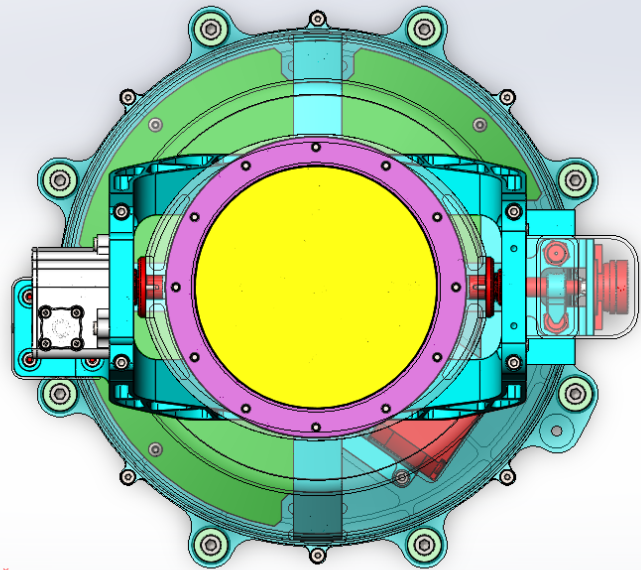
*Isometric

1. **Azimuth frame or base frame** contains most of the electronics and the “Azimuth” actuator, a stepper motor with an ideal range of movements from 0° to 180° , around the normal to the lander deck surface. These movements are confined by two limit switches.
2. **Elevation frame** holds the CCR housing and contains the “Elevation” actuator, a stepper motor with an ideal range of movements up to $\pm 90^\circ$ around an axis parallel to the lander deck. The space of movements is confined by two limit switches.
3. **CCR Housing** is a completely passive block that holds the retroreflector **MoonLIGHT** and contains its integration structure. The housing defines a coordinate system where the normal to the CCR front face points in the direction of the Earth, after pointing operations. In this direction the FoV must be free of obstructions in a cone of semi-aperture of 45° with respect to the axis of the CCR.

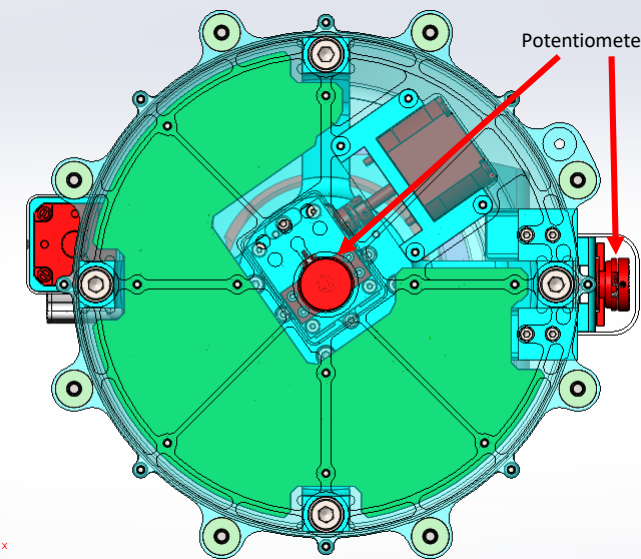
Color	Material	Finish	Absorptivity	Emissivity	Mass (Kg)
Cyan	AA6061	Surtec 650	0.13	0.06	~ 1.6
White	AA 6061	MAP® SG121FD white paint	0.18	0.88	~0.7
Yellow	Fused Silica	/	0.01	0.90	~0.6
Red	AISI 316	/	0.45	0.14	~0.95 *
Light green	FR4	/	Unknown	Unknown	~0.02
Green	35N	/	Unknown	Unknown	TBC
Purple	PCTFE (Kel-F)	/	0.5	0.92	0.08

Total Mass	4.3 kg +20% (margin) = 5.2 kg
Dimensions (h × w × d)	312.5 × 312.5 × 312.5 mm ³

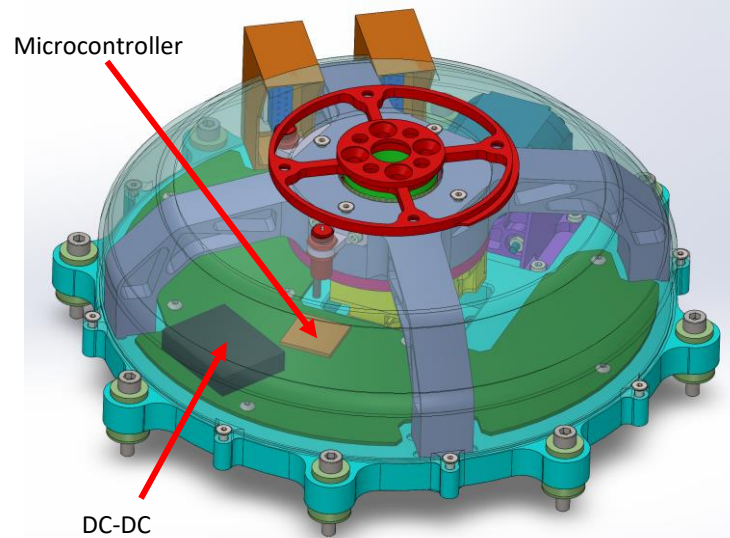
MPAc in a nutshell



*Top

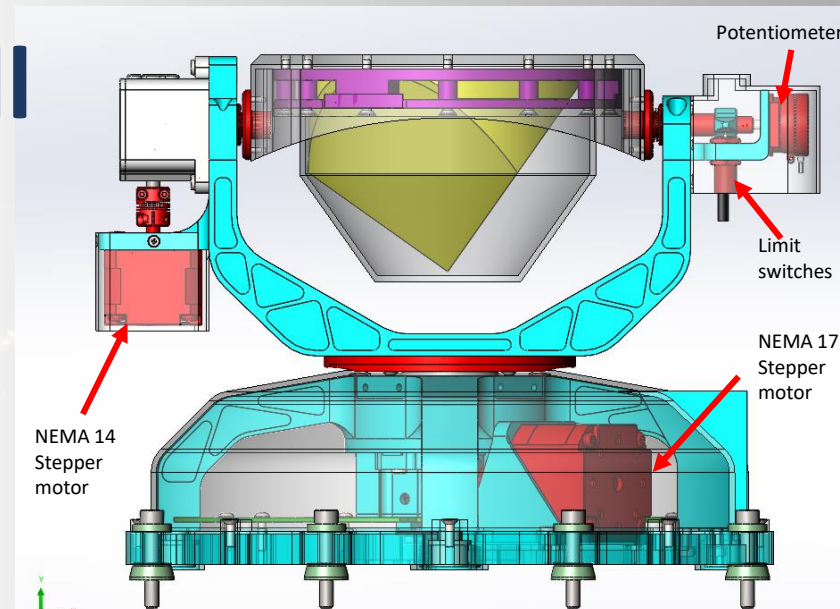


*Bottom



Microcontroller

DC-DC Converter



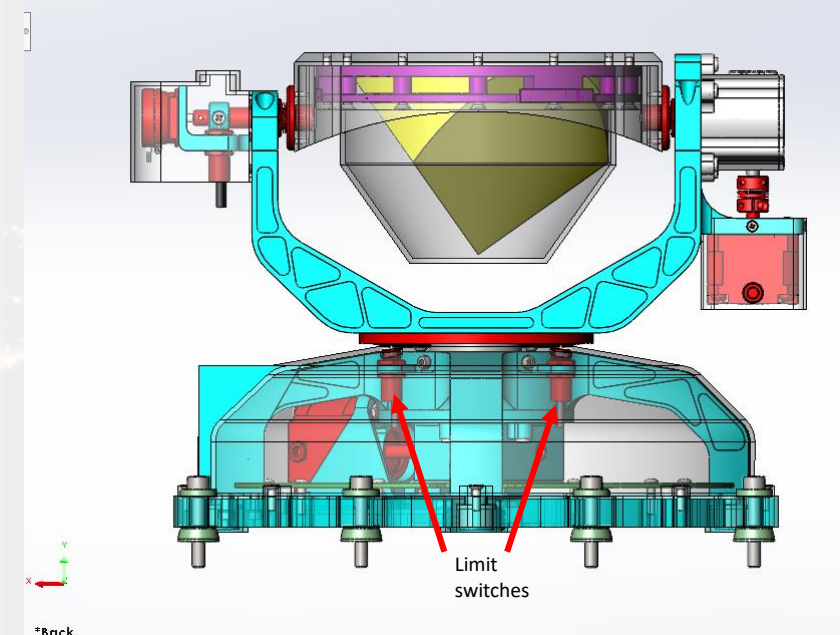
NEMA 14 Stepper motor

Potentiometer

Limit switches

NEMA 17 Stepper motor

*Front



Limit switches

*Back

“Fly MPAc to the Moon”

- MPAc is one of the two science instruments selected and funded by ESA [ESA Contract No. 4000129000/19/NL/TFD].
- Launch by NASA initiative **Commercial Lunar Payload Services/Payload and Research Investigations on the Surface of the Moon-1A (CLPS/PRISM-1A, or in short CP-11)** and the Artemis program.
- November 2021: NASA has awarded Intuitive Machines (IM) of Houston a contract to deliver research, including science investigations and a technology demonstration, to the Moon in 2024.
- The CLPS science and technology demonstration payloads on board the IM-3 Nova-C lander are: MPAc, LUSEM (high energy particles detector), CADRE (autonomous lunar rovers), and Lunar Vertex (joint lander-rover with magnetometers).
- December 8th 2021: online MAR held between IM and the teams of the PRISM 1A payloads (ESA and INFN for the MPAc payload).
- December 14th 2021: KO meeting among IM, ESA+INFN and NASA representatives officially started the exchange of information and payload requirements for MPAc.
- June 14th 2022: MPAc passed MRR with ESA.
- August 2023: TRR and delta-TRR with ESA.

Landing site: the Reiner Gamma swirl

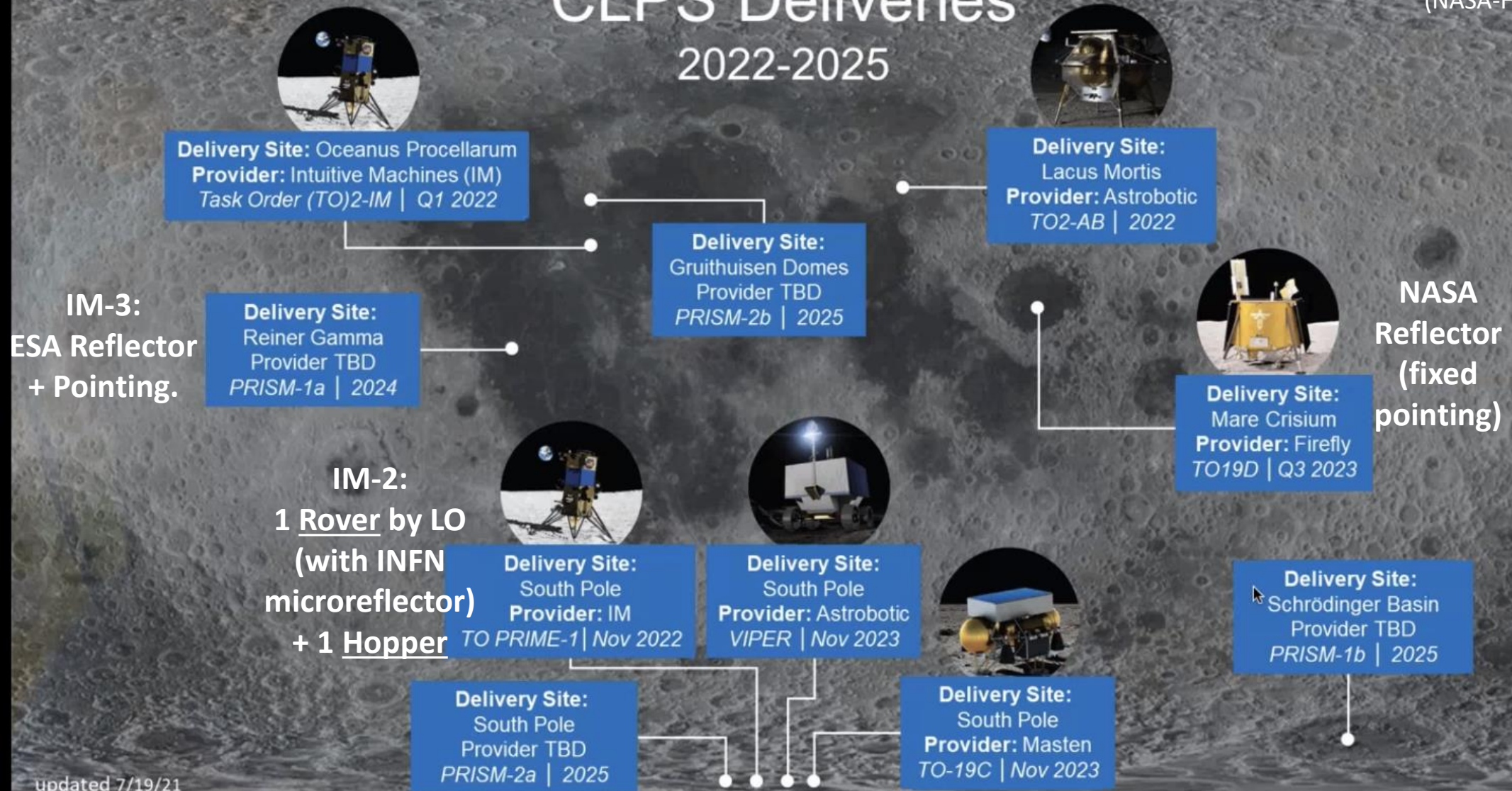
- Associated with a magnetic anomaly
- Coordinates: 7°23'24"N, 58°57'36"W
- Crater: 30 km (diameter) x 2.6 km (depth)
- No potential obstructing geological features along the line-of-sight to the Earth



Overview of NASA-CLPS missions

Courtesy of Brad Bailey
(NASA-HQ)

CLPS Deliveries 2022-2025

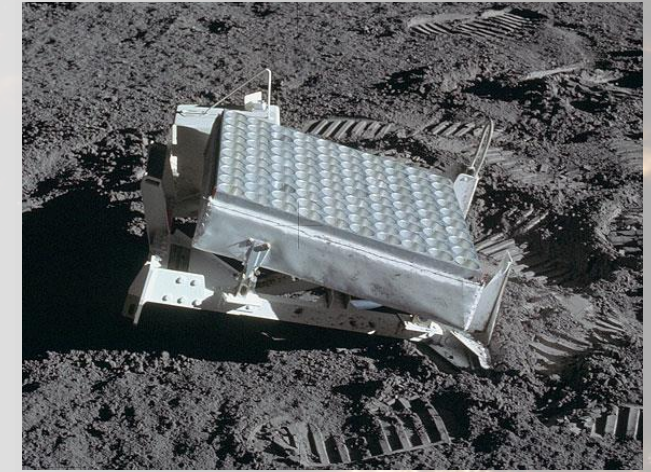
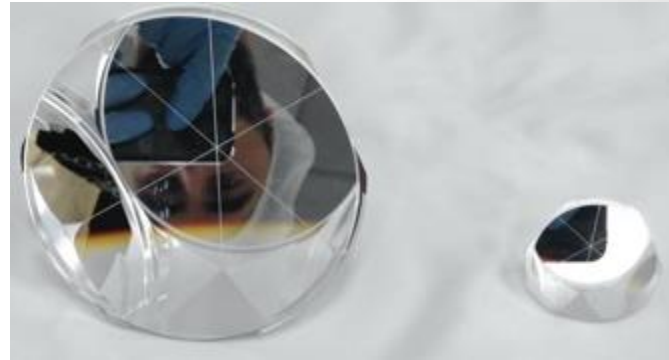
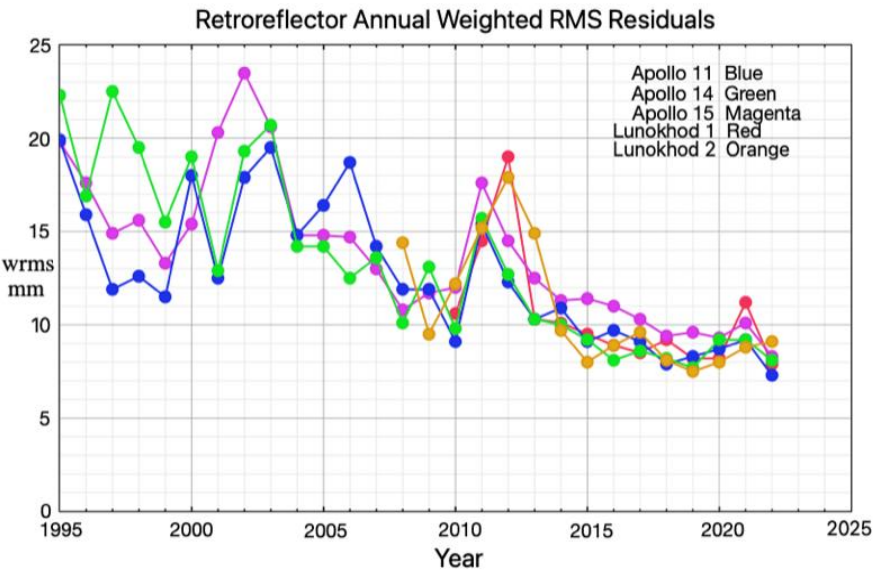


updated 7/19/21

30/08/23

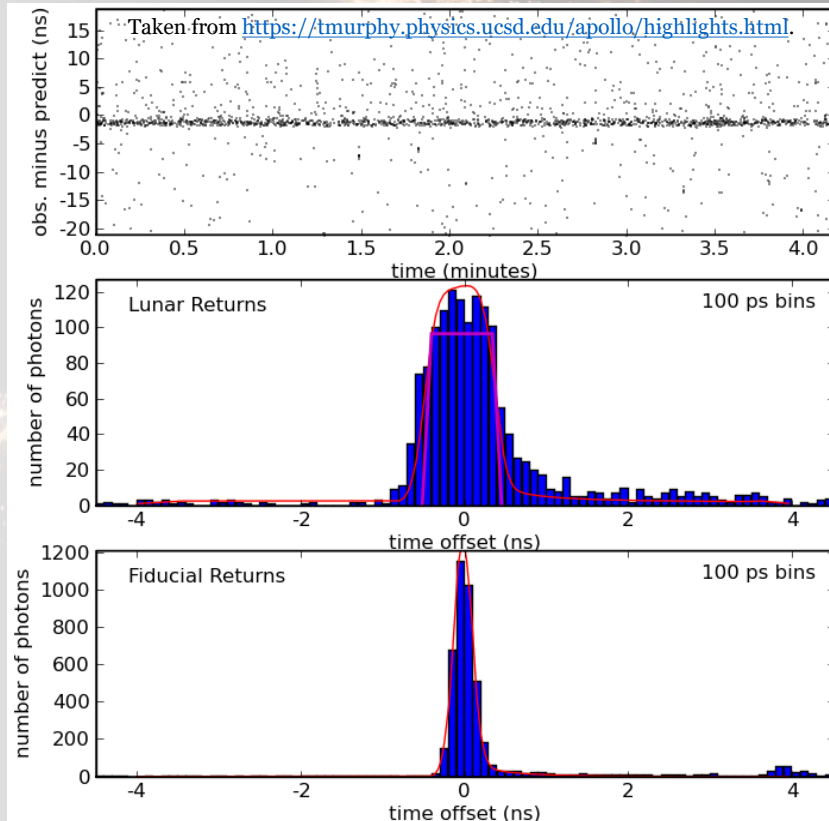
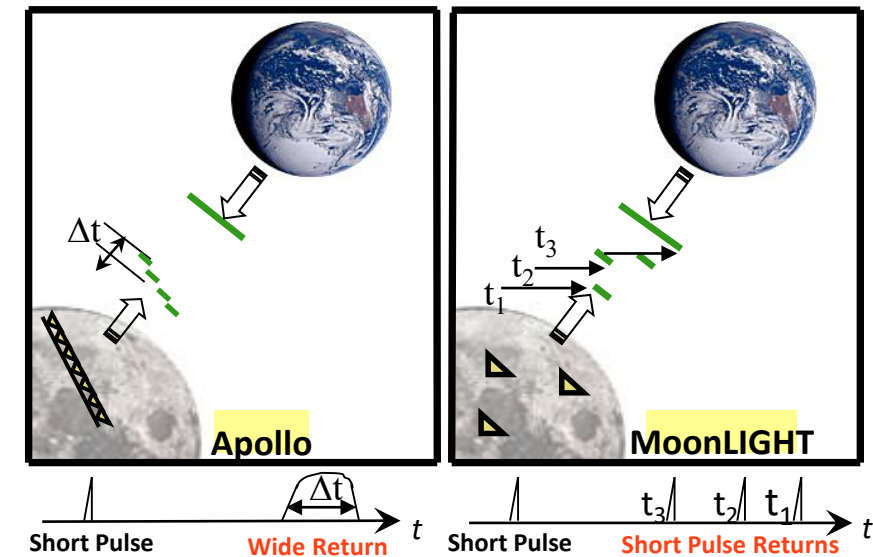
IAUP 2023

The next-generation lunar retroreflector MoonLIGHT



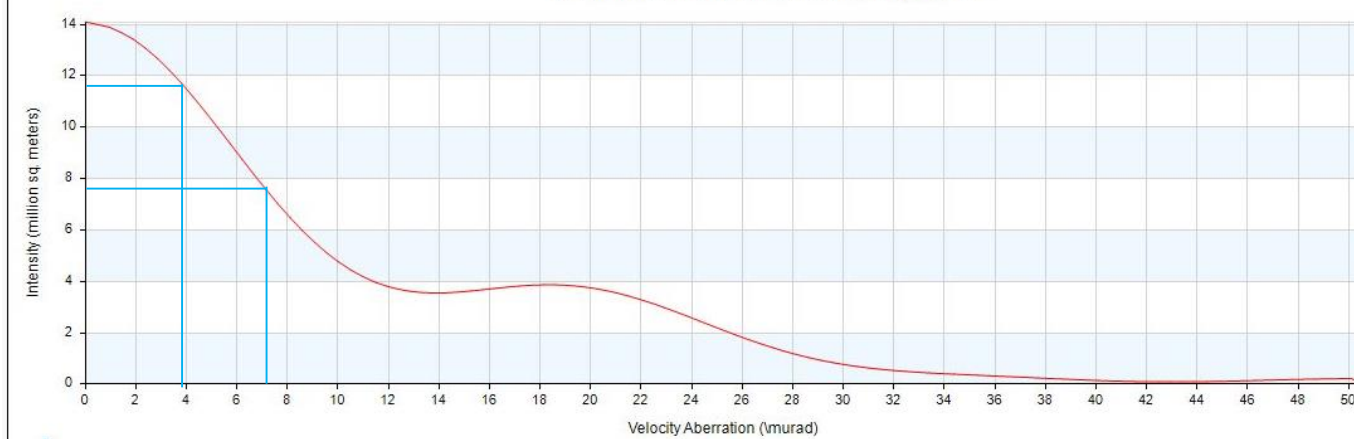
Next-generation retroreflectors (MoonLIGHT, Italy, and NGLR, USA) have specific designs that reduce in a significant way the lunar libration issue that dominates the range error budget of the Apollo arrays that cause a time spread in the laser return, leading to a range estimate with an accuracy of no better than a few cm (for a single shot).

MoonLIGHT laser returns will have shorter time spread wrt Apollo arrays. This feature represents a key factor to fully exploit the potential of laser stations firing short laser pulses of $\approx 10\text{-}20$ ps of width and achieve lunar orbit range accuracy below current cm value down to the mm level.



Apollo arrays vs MoonLIGHT

38.100000 mm CCR uncoated Intensity vs VA



code v

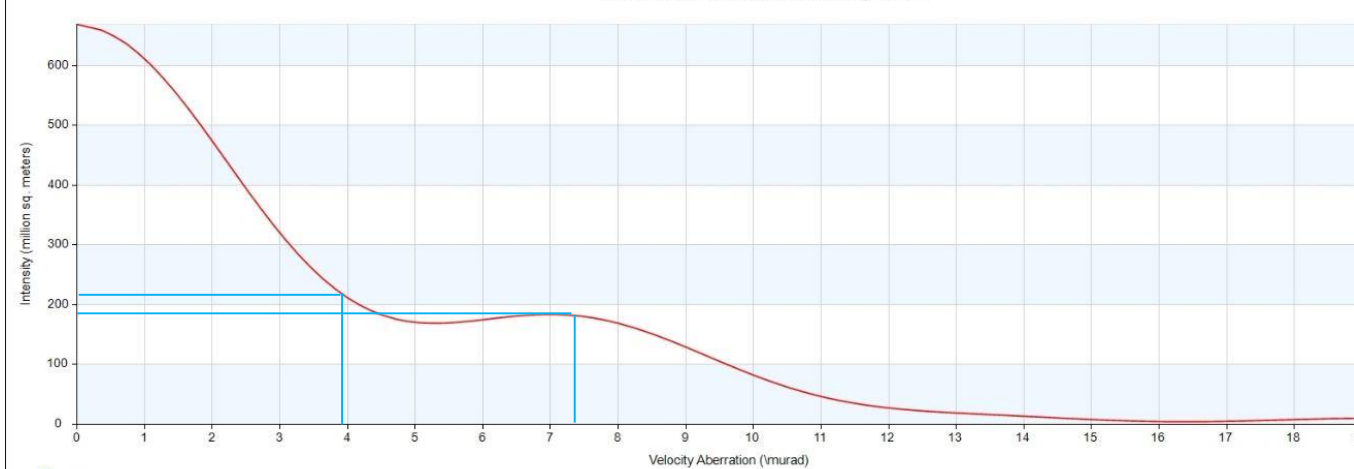
05- Jan -21

CCR 38.100000 dia.

DAO 1=0
DAO 2=0
DAO 3=0

Apodization=0
Waist Value=0
Polarization= Linear

100 mm CCR uncoated Intensity vs VA



code v

10- Jun -22

CCR 100 dia.

DAO 1=0
DAO 2=0
DAO 3=0

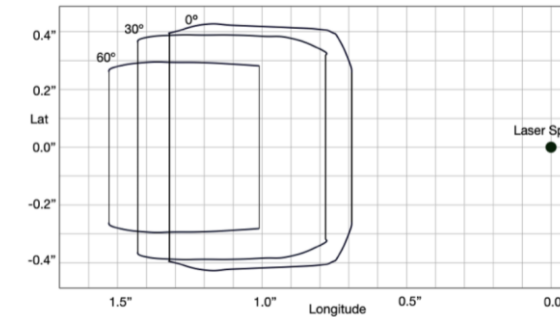
Apodization=0
Waist Value=0
Polarization= Linear

30/08/23

TAUP 2023

Assumptions:

- No DAOs for Apollo CCRs and MoonLIGHT;
- OCS taken at minimum and maximum values of VA for Reiner Gamma site, i.e., **VA = (3.88 - 7.27) μrad [1];**



VA for three Earth station latitudes as seen from the lunar center of mass vs. lunar longitude and latitude.

- Dust deposition reduced the return of the Apollo arrays by $\eta = 0.1$ [2];
- Thermal effects reduce MoonLIGHT's OCS by $\xi = 0.8$ (assuming $\Delta T = 0.5K$ between tip and face) [3];

$$\frac{I_{A11}}{I_{ML}} = 100 \frac{\eta \text{OCS}_{A11}(\text{VA})}{\xi \text{OCS}_{ML}(\text{VA})} = (0.56, 0.70) \quad \text{or} \quad (0.45, 0.56)$$

$$\frac{I_{A15}}{I_{ML}} = 300 \frac{\eta \text{OCS}_{A15}(\text{VA})}{\xi \text{OCS}_{ML}(\text{VA})} = (1.68, 2.10) \quad \text{or} \quad (1.34, 1.68)$$

[1] J.G. Williams, L. Porcelli, S. Dell'Agnello, L. Mauro, M. Muccino et al., The Planetary Science Journal, Vol 4, Issue 5, id.89, 22 (2023)

[2] Murphy et al., Icarus, 208, 31–35 (2010)

[3] D. Currie, S. Dell'Agnello, G. Delle Monache, Acta Astronautica, 68, 7, 667 (2011)

Fundamental Physics Tests with MoonLIGHT/NGLR

The aim is to obtain highly accurate measurements of the Earth-Moon distance to investigate:

- I. **The Equivalence Principle:** measuring the difference in acceleration of Earth and Moon due to Sun.
- II. **The variation of \dot{G}/G** that can relate the expansion of the solar system in relation to the external universe.
- III. **Test of theories of gravity:** through estimates of the PPN parameter β from LLR measurements can test theories proposed for acceleration of distant galaxies which is closely tied to ideas about dark energy.

Gravitational measurement	Apollo/Lunokhod LLR accuracy (\sim few cm)	Next generation LLR accuracy (\sim 1 mm)	Time scale	Ultimate goal LLR accuracy (\sim 0.1 mm)
WEP	$\left \frac{\Delta a}{a} \right < 1.4 \times 10^{-13}$	10^{-14}	Few years	10^{-15}
SEP	$ \eta < 4.4 \times 10^{-4}$	3×10^{-5}	Few years	3×10^{-6}
β	$ \beta - 1 < 1.1 \times 10^{-4}$	10^{-5}	Few years	10^{-6}
$\frac{\dot{G}}{G}$	$\left \frac{\dot{G}}{G} \right < 9 \times 10^{-13} yr^{-1}$	5×10^{-14}	\sim 5 years	5×10^{-15}
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}	Few years	6.4×10^{-5}
$1/r^2$ deviation	$ \alpha < 3 \times 10^{-11}$	10^{-12}	\sim 10 years	10^{-13}

- J. G. Williams et al. Phys. Rev. Lett. 93, 261101 (2004)
- M. Martini, S. Dell'Agnello, Springer, DOI 10.1007/978-3-319-20224-2_5 (2016)
- Currie, D. G. et al. (2013), Acta Astronautica 68, 667–680
- H. Haviland et al., The Lunar Geophysical Network Landing Sites Science Rationale (2021), arXiv:2107.06451
- Biskupek, L., Müller, J., and Torre, “Benefit of New High-Precision LLR Data for the Determination of Relativistic Parameters”, Universe, 7, 34 (2021)
- S. Turyshev et al., NASA BPS Division’s “Lunar Surface Science Workshop Fundamental and Applied Lunar Surface Research in Physical Sciences”, August 2021

Geophysical Scientific Objectives with MoonLIGHT



Next-generation lunar will also contribute to:

- I. **Lunar surface geodesy (selenodesy).** Next-generation CCRs may serve as control points and improve lunar reference systems [a], including the one based on
 - ✓ Lunar Reconnaissance Orbiter (LRO) data and metric maps,
 - ✓ the future LGN (Lunar Geophysical Network) , as well as
 - ✓ positioning and navigation from orbiters equipped with laser time-of-flight capabilities,and will improve the tie to the International Celestial and Terrestrial Reference Systems (ICRS/ITRS).
- II. **Geophysical properties of the interior of the Moon.** LLR and other LGN instruments [b], will improve our knowledge of the lunar interior.
 - ✓ LLR is sensitive to the physical librations, which depend upon the moments of inertia of lunar mantle and core, lunar gravity field, tidal deformation, dissipation at the Core-Mantle Boundary, etc.
 - ✓ As done by GRAIL (Gravity Recovery And Interior Laboratory) and existing LLR data, next-generation lunar CCRs will improve our knowledge of tidal Love numbers, nature (fluid) and size of the core of the Moon.
 - ✓ A future wider distribution of next-generation lunar CCRs will help to single out the contribution of physical librations from LLR data, improving our knowledge of the core momenta and Love numbers.

[a] Kopeikin, S., <https://ui.adsabs.harvard.edu/abs/2010AcPSI..60..393X/abstract>

[b] see H. Haviland et al., *The Lunar Geophysical Network Landing Sites Science Rationale* (2021), arXiv:2107.06451, <https://arxiv.org/abs/2107.06451>

Lunar GW detectors with MoonLIGHT

In the Solar System, the Moon is ideally suited for long-term installations of GW detectors because is the **seismically quietest known place**, and offers **cryogenic temperature environments**.

Lunar GW detectors band goes from 1 mHz (set by elastic properties of the Moon) to 50 Hz (beyond the on-Earth noise level is not a major issue) and includes the **decihertz** frequencies (0.1 -1) Hz [1].

Lunar GW detectors will profit from the heritage of lunar retroreflectors like Moonlight (CP-11, 2024). For one arm with a laser and the other one with LSLR, the link budget (transmitted /received photons) gives a shot noise ΔL [2]:

$$\frac{n_{RX}}{n_{TX}} = n_q \times T_{TX} \times T_{RX} \times R_{RR} \times \left(\frac{D_t D_c}{\lambda L} \right)^4, \quad \Delta L^2 = \frac{hc}{2\pi} \frac{\lambda}{P_t}$$

$n_q = 0.3$, detector quantum efficiency, R_{RR} = reflectivity,
 T_{XX} = transmission coefficient of transmission/receiver telescope,
 $D_{t,c}$ = dimensions of transmitter/retroreflector, $L = 3000$ m, arm length,
 $\lambda = 1\mu\text{m}$, laser wavelength, P_t = received laser power.

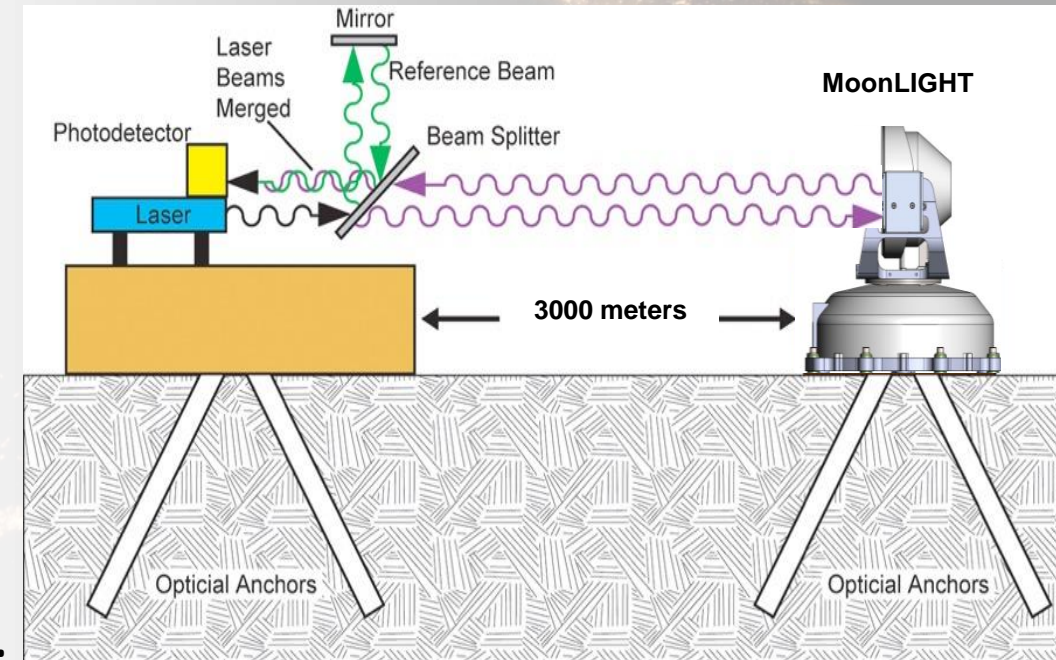
MoonLIGHT has $T_{TX}=0.1$ (worst case due to lunar dust accumulation),
 $D_t = D_c = 10$ cm, that give strain sensitivities $\varepsilon = \Delta L/L$

- **GRACE** ($P_e = 24$ mW): $\Delta L = 4.8 \times 10^{-16}$ m/ $\sqrt{\text{Hz}}$ $\Rightarrow \varepsilon = 1.6 \times 10^{-19}$ / $\sqrt{\text{Hz}}$
- **LISA laser** ($P_e = 1.22$ W): $\Delta L = 6.6 \times 10^{-17}$ m/ $\sqrt{\text{Hz}}$ $\Rightarrow \varepsilon = 2.2 \times 10^{-20}$ / $\sqrt{\text{Hz}}$.

There will be 2 retroreflectors: one on the GW detector and one for LLR (Grasse/FR, ASI-Matera/IT).

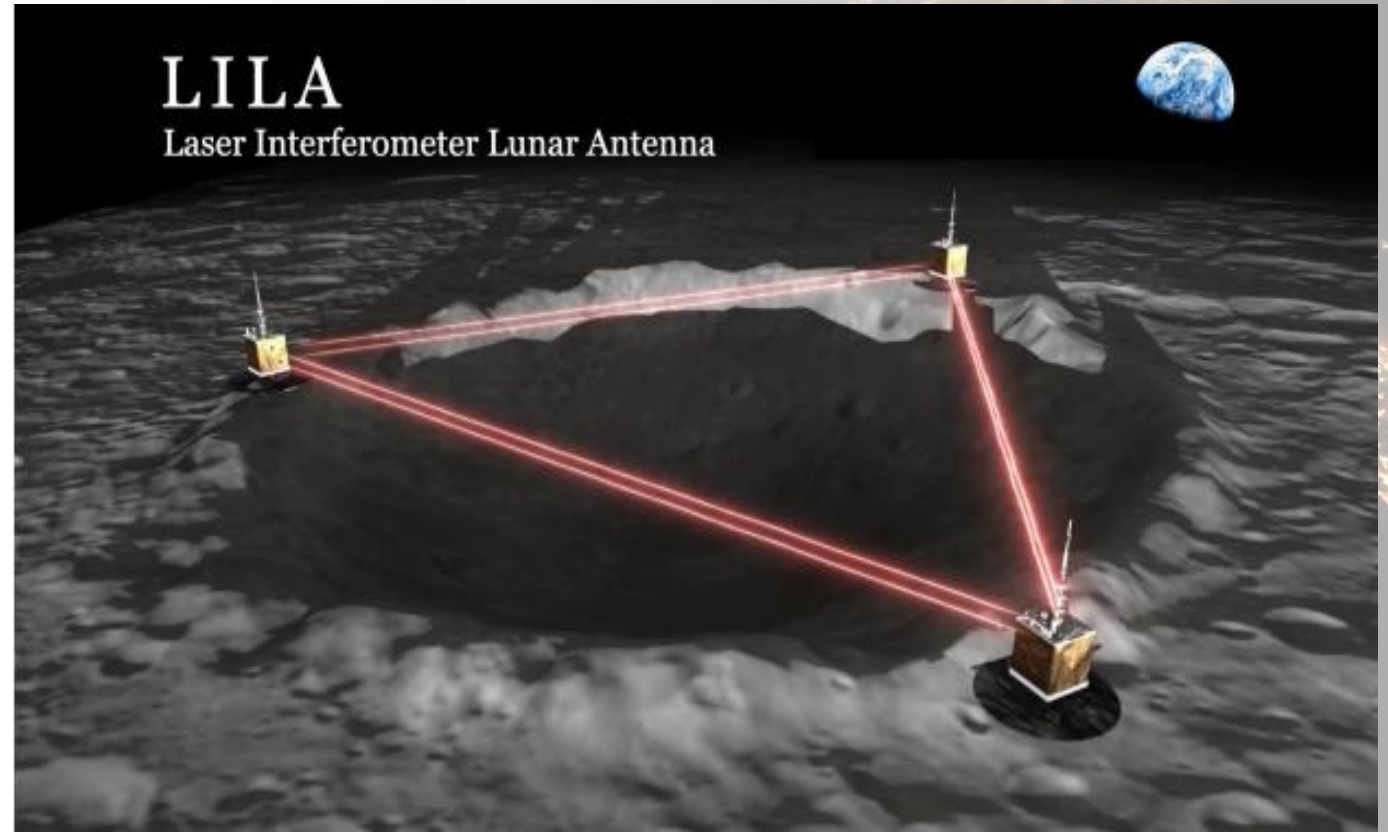
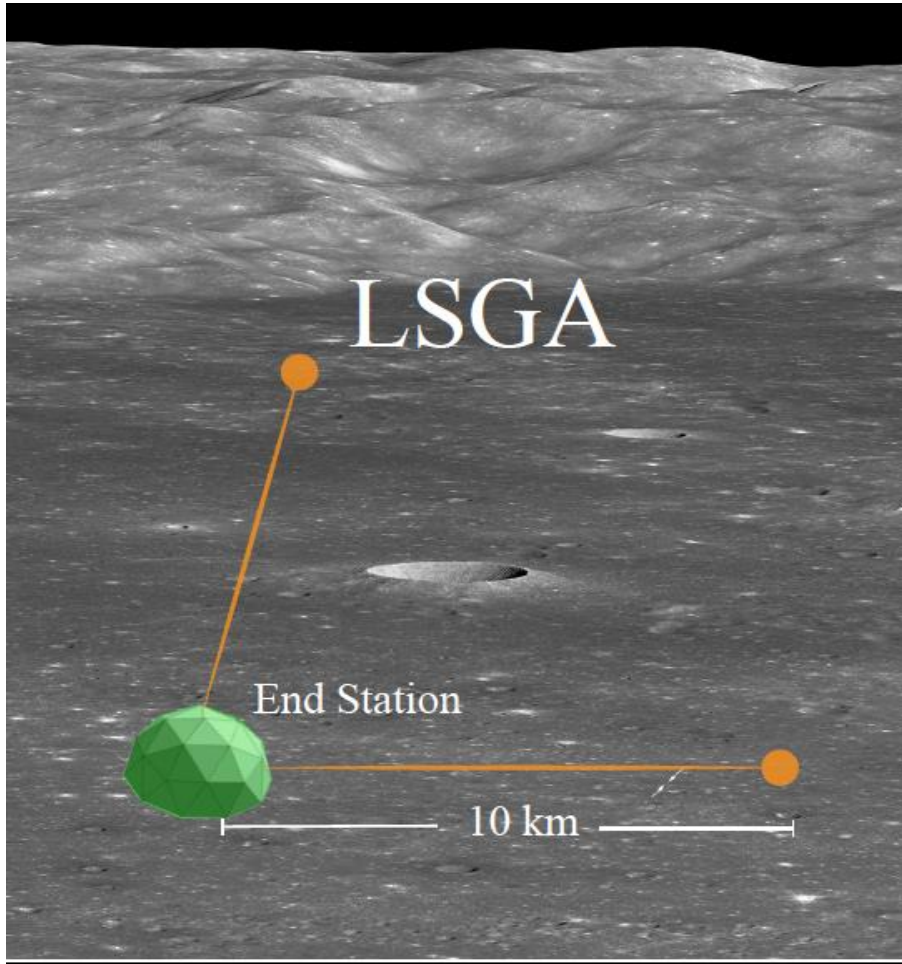
[1] Jan Harms et al. , "Decadal Survey on Biological and Physical Sciences, White Paper Topical Lunar Gravitational wave Detection" (2021).

[2] taken from Katsanevas's talk at the *Gravitational wave detection at the Moon Workshop*, Oct 14-15, 2021, EGO (Italy)



GW Detector Concepts with MoonLIGHT?

Lunar Seismic and Gravitational Antenna



Conclusions & Outlook

Next-generation lunar laser retroreflectors offer a rich science program:

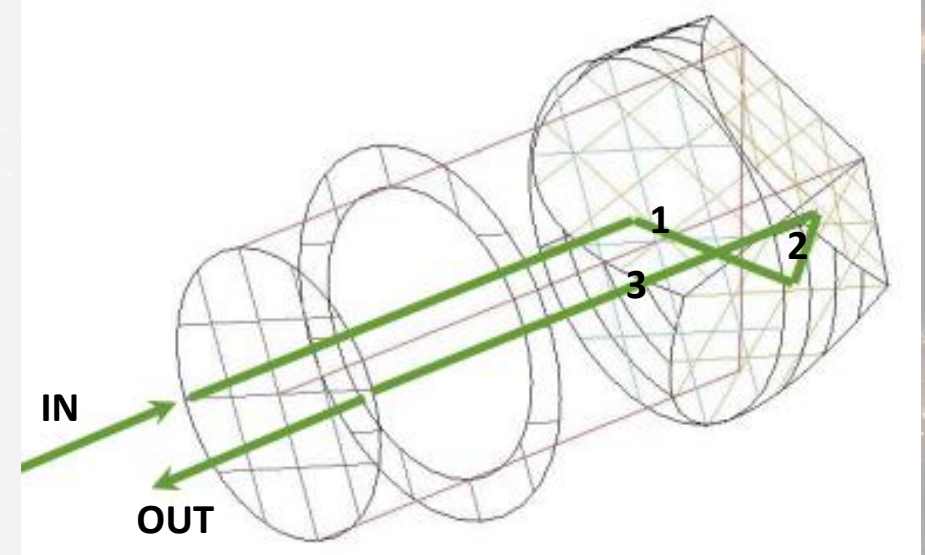
- **Weak field – slow motion regime in the Sun-Earth-Moon system**
 - ✓ **PPN β , WEP & SEP, \dot{G}/G , inverse-square law (deviations in the form of Yukawa potentials)**
 - ✓ **Tests of GR and beyond**
 - ✓ **Lunar geodesy, lunar geophysics (great synergism with seismometers, especially French)**
- **GW Detection on the Moon**
 - ✓ **Imminent lunar surface missions and collaborations with ESA, ASI, NASA, will establish a solid heritage and basis for next-generation lunar reflectors**
 - ✓ **Next-generation lunar reflectors to be evolved for LSGA, LILA,...**

Back-up Slides

Corner Cube Retroreflector and Far Field Diffraction Pattern

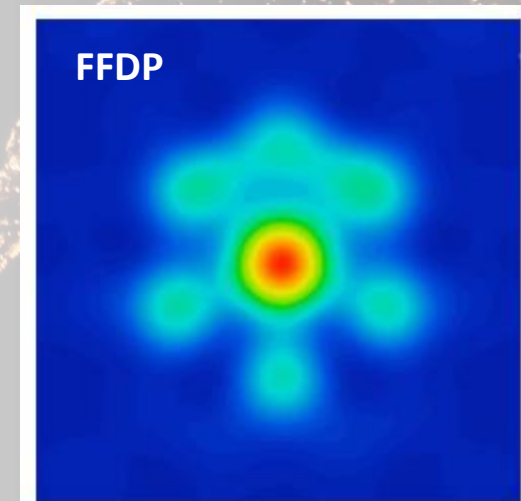
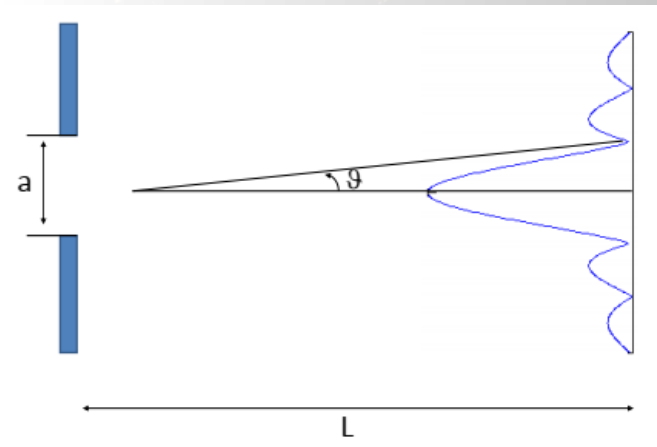


- A CCR (Cube Corner Retroreflector) is a prism of Fused Silica whose edges form a cube corner. Each back face is mutually perpendicular to each other.
- An incoming laser beam is internally reflected by the CCR by the 3 back faces. Thus, the outgoing signal is *retroreflected in the same* direction of the incoming one.



- Plane electromagnetic (EM) waves are *diffracted* by the CCR. The diffraction pattern due to the retroreflection by the CCR is known as FFDP (Far Field Diffraction Pattern). The angular dimensions and the intensity of the FFDP depend upon the physical dimension of the active optical aperture, namely, the CCR front face diameter

$$L \gg \frac{a^2}{\lambda} \quad \sin \theta_{\min} = \pm \frac{\lambda}{a}$$



LLR tests of WEP & SEP and implications on PPN β

- WEP violation would displace the lunar orbit (along the Earth-Sun direction) with a synodic period $D = 29.53$ days. Fitting LLR data with the solutions of the JPL SW for Earth-Moon-Sun, the Earth-Moon range radial variation is **[1]**

$$\Delta r = S \left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{WEP} \cos D = (2.8 \pm 4.1) \text{ mm} \times \cos D \quad \text{with} \quad \left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{WEP} = (-1.0 \pm 1.4) \times 10^{-13}.$$

- LLR alone does not provide a pure test of SEP, because is sensitive to *both* composition and self-energy. The University of Washington (UW) experiment with *miniature* Earth and Moon gives $(1.0 \pm 1.4) \times 10^{-13}$ **[2]**, leading to

$$\left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{SEP} = \left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{WEP} - \left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{UW} = (-2.0 \pm 2.0) \times 10^{-13}.$$

- SEP can be also tested by $U/(Mc^2) \propto M$, and the Earth-Moon system is the perfect laboratory. Numerical models yield $U_E/(M_E c^2) = -4.64 \times 10^{-10}$ **[3]** and $U_M/(M_M c^2) = -1.90 \times 10^{-11}$ **[4]**. In this way the SEP test writes **[5]**

$$\left[\left(\frac{M_G}{M_I} \right)_E - \left(\frac{M_G}{M_I} \right)_M \right]_{SEP} = \left(\frac{U_E}{M_E c^2} - \frac{U_M}{M_M c^2} \right) \eta = -4.45 \times 10^{-10} \eta \quad \Rightarrow \quad \eta = 4\beta - \gamma - 3 = (-4.4 \pm 4.5) \times 10^{-4}.$$

- The space curvature parameter γ has been measured by the Cassini mission, $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$ **[6]** and leads to one of the best constraint of the PPN β , describing the non-linearity of gravity, derived from LLR WEP test

$$\beta - 1 = (-1.2 \pm 1.1) \times 10^{-4}.$$

[1] Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

[2] S. Baeßler, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, U. Schmidt, H.E. Swanson, *Phys. Rev. Lett.*, **83**, 3585–3588 (1999); doi: 10.1103/PhysRevLett.83.3585.

[3] J.G. Williams, X.X. Newhall, J.O. Dickey, *Phys Rev D Part Fields*, **53**, 6730–673 (1996).

[4] J.G. Williams, D.H. Boggs, S.G. Turyshev, J.T. Ratcliff, *Lunar Laser Ranging Science*, in: J. Garate, J.M. Davila, C. Noll, M. Pearlman, *14th ILRS Workshop*, Greenbelt, CDDIS/NASA GSFC, pp. 155–161 (2005).

[5] K. Nordtved Jr., *Phys. Rev.*, **170**, 1186 (1968); doi: 10.1103/PhysRev.170.1186.

[6] J.D. Anderson, J.G. Williams, *Classical & Quantum Gravity*, **18**, 2447 (2001).

\dot{G}/G , geodetic precession and r^2 deviations with LLR

- In superstring theories G may vary with time. For the Moon, tidal friction and G variation influence the semi-major axis a_M . Thus, from Kepler's third law (neglecting the **mass-loss term**) and using LLR data, it is set [1]

$$\frac{\dot{G}}{G} = 3 \frac{\dot{a}_M}{a_M} - 2 \frac{\dot{P}}{P} - 2 \frac{\dot{M}}{M} = (4 \pm 9) \times 10^{-13} \text{ yr}^{-1}.$$

($\lesssim 1\%$ variation over the 13.7 Gyrs). Secular change in the orbital period P is a dominant effect for \dot{G}/G and evolves quadratically with time, therefore continued LLR data will significantly improve this limit.

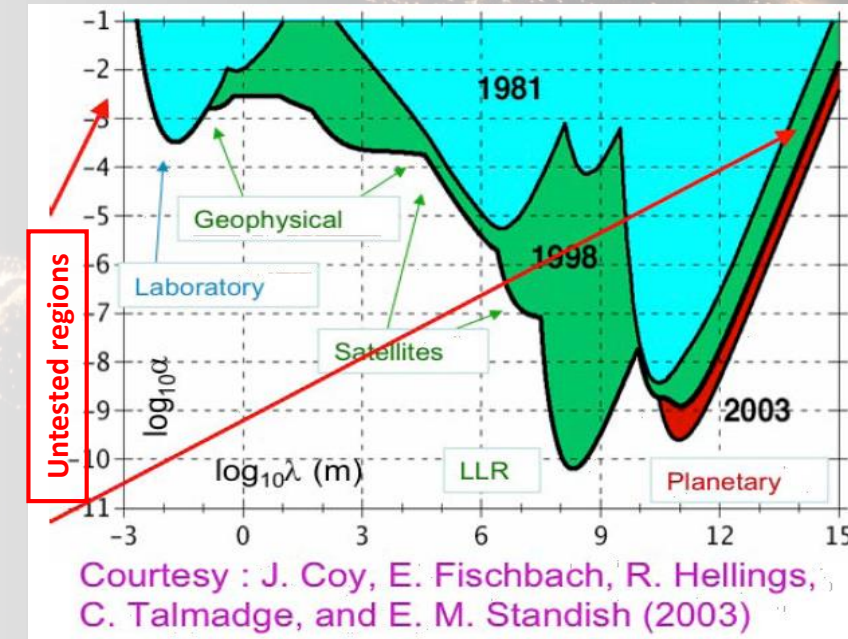
- In the Sun-Earth-Moon system, the GR prediction on the (de Sitter) geodetic precession is **19.2 msec/yr** [2] and, from LLR data, the deviation from the GR prediction is $K_{GP} = (1.9 \pm 6.4) \times 10^{-3}$ [1].
- The Yukawa additional contribution to the gravitational potential with strength α and length scale λ is

$$V(r) = -G \frac{M_1 M_2}{r} (1 + \alpha e^{-r/\lambda}).$$

At LLR scale, generates a the lunar perigee precession with frequency $\delta\omega$ [3]

$$\frac{\delta\omega}{\omega} = \frac{\alpha}{2} \left(\frac{\rho}{\lambda} \right)^2 e^{-\rho/\lambda}.$$

The Moon mean distance ρ and the above K_{GP} leads to $\delta\omega/\omega < 1.6 \times 10^{-11}$. Fits of LLR data lead to $\alpha = (3 \pm 2) \times 10^{-11}$ at $\lambda = 4 \times 10^8$ m.



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 [2] B. Bertotti, I. Ciufolini, P.L. Bender, *Phys. Rev. Lett.*, 58, 1062-1065 (1987).
 [3] E.G. Adelberger, B.R. Heckel, A.E. Nelson, *Annu. Rev. Nucl. Part. Sci.*, 53, 77-121 (2003).