# Lunar Surface Laser Ranging (LSLR), and Earth LLR, in Permanently Shadowed Regions (PSRs) for GW detection on the Moon

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5 University and INFN Naples, Italy (working on theoretical predictions)

6 University and INFN Padua, Italy (working on the ground segment with ASI-Matera)

# Outline

- Current system to be evolved for **LSGA**:
  - Next-gen lunar laser retroreflector (funded by INFN)
  - Earth-pointing actuator (funded by ESA)
  - Robotic dust cover (funded by ESA and INFN)
- Current opportunity: NASA-CLPS / PRISM-1A 2024 (NASA-ESA MoU)
- Potential opportunities (in this decade) to demonstrate an evolved/optimized system in PSRs
- Idea/proposal for LSGA enhancement: fast laser & fast-pointing & SBI LLR from Earth, in addition to local LSLR

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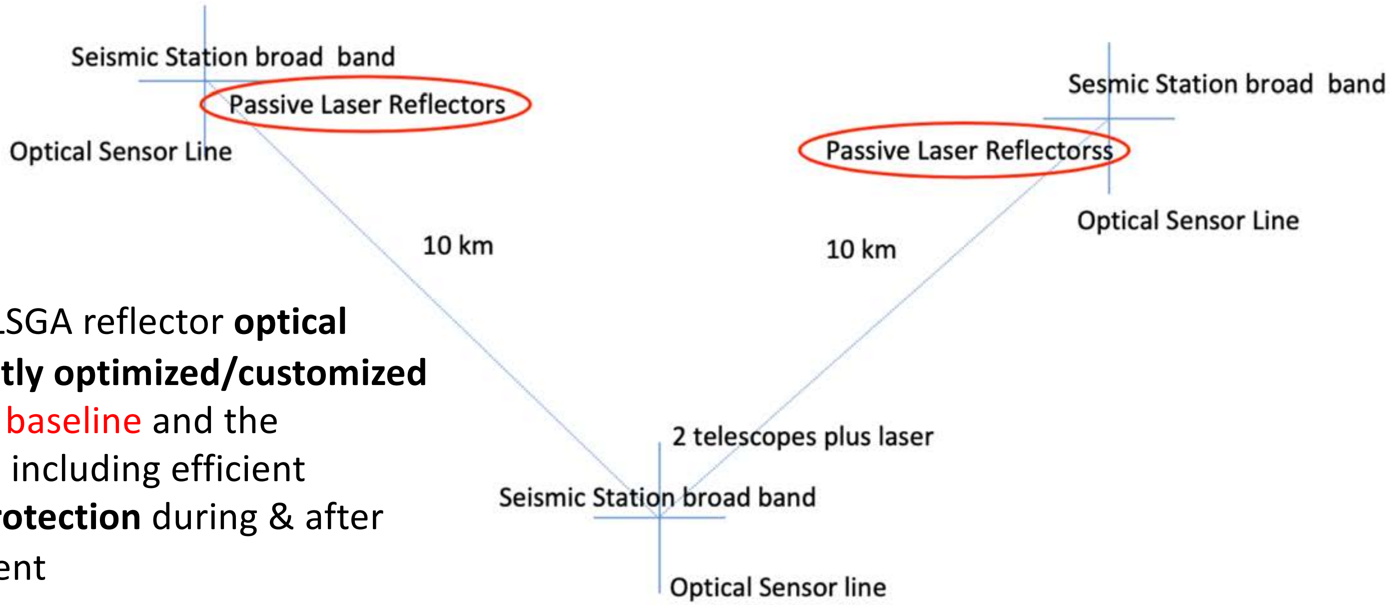
# LSGA idea, approach II: **Interferometric Detector**

**II. An interferometric detector.** The second possibility to be studied in parallel, is the possibility to deploy an interferometric detector. One would profit from the natural vacuum of the moon, provided dust issues do not become a show stopper and in case of deployment at the

PSR lunar south pole, one would also have natural cryogenic conditions diminishing the thermal noise. Thus a laser link toward a passive Laser Corner Cube receiver ~~of the Apollo 15 type~~, at 10 km with a 10 Watt 1 μm laser and 15 cm diameter, on top of super-attenuators, could give a sensitivity of $10^{-16}$ m /Hz over the distance, even with a 0.1 efficiency of the laser reflector due to long term dust deposition. This will lead to deformation of $10^{-21}$ / Hz ½ and might even be optimized with the most recent development of Lunar Laser Reflectors[m]




**Note**: the 15-cm LSGA reflector **optical specs can be greatly optimized/customized** for the very short baseline and the PSR environment, including efficient **long-term dust protection** during & after landing/deployment

# LSGA idea, approach II: **Interferometric Detector**

One would need to deploy in parallel:

**a)** a standard geophysical station (100 kg) with a geophone sensor line allowing to correct for shallow seismic waves

**b)** two telescopes with what goes with them, 35 kg per telescope with the pointing system.

**c)** It will then be necessary to have 2 passive reflectors deployed at a distance of 10 km, either with a rover or with other landers. The advantage is that they are passive. The ideal would be to have on these other tenderizers again a geophysical station to correct Moonquakes.

Telescopes and passive reflectors will need isolation suspensions which mass need to be estimated as function of their efficiency.

Scaling up 10-cm to 15-cm reflector does gives ➔ 15 kg

Phasing:

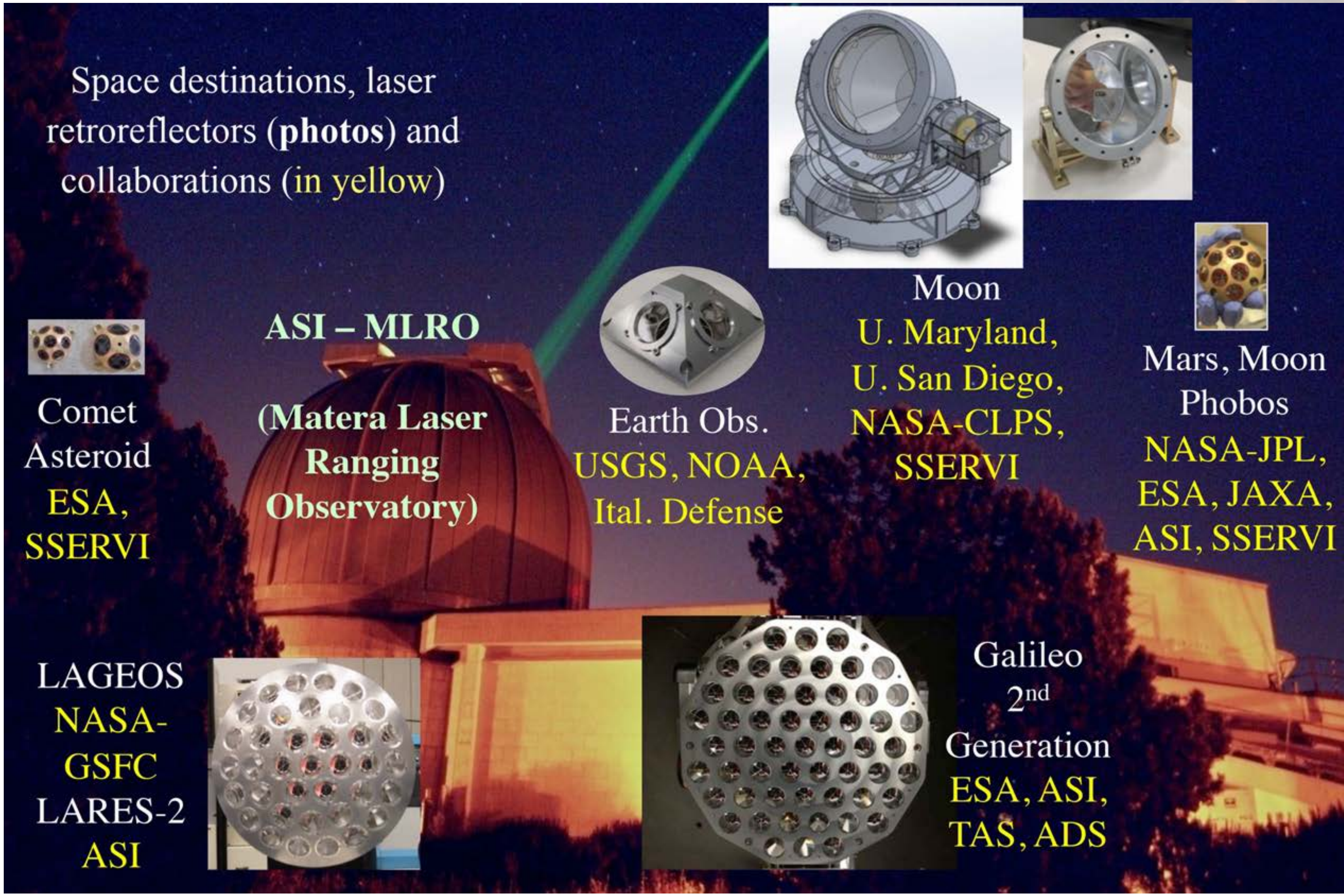
**a)** Lander 1: Geophysical station with seismic correction sensors. 100 kg for an autonomous system 2x telescopes with electronics, 2x 35 kg, with on the other hand a lander providing power and transmission.

**b)** Lander 2: Geophysical station with seismic correction sensors. 100 kg for an autonomous system 1x Laser reflector with pointing, 1x15 kg, passive system therefore does not require an active lander

Current: 10-cm reflector + pointing ~ 4 kg

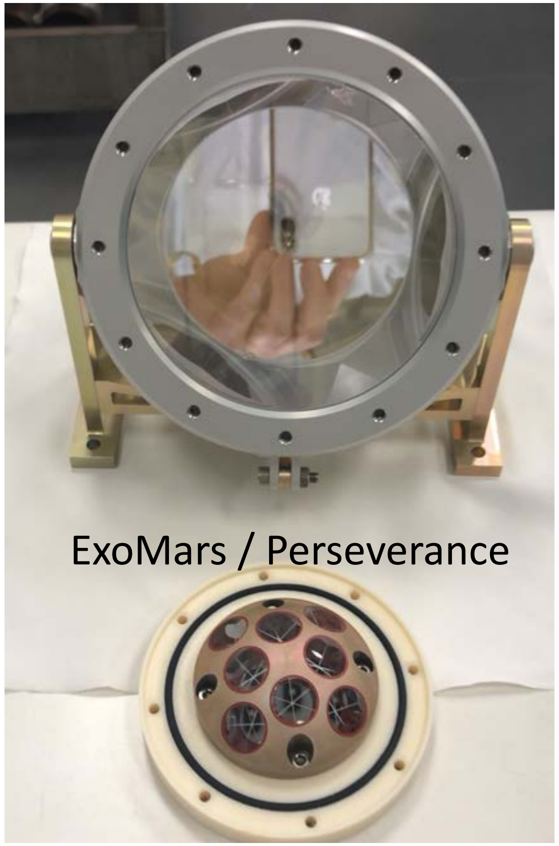
**c)** Lander 3: Geophysical station with seismic correction sensors. 100 kg for an autonomous system 1x Laser reflector with pointing, 1x15 kg, passive system therefore does not require an active lander

# ASI–INFN **Joint-Lab** on Laser Retroreflectors & Ranging
# INFN Affiliation (≥2014) & ASI Association (≥2017) to **NASA-SSERVI**



# SCF_Lab Laser Retroreflector Test Facilities @INFN-Frascati

**Moon Laser Instrumentation for General relativity High accuracy Tests MoonLIGHT**

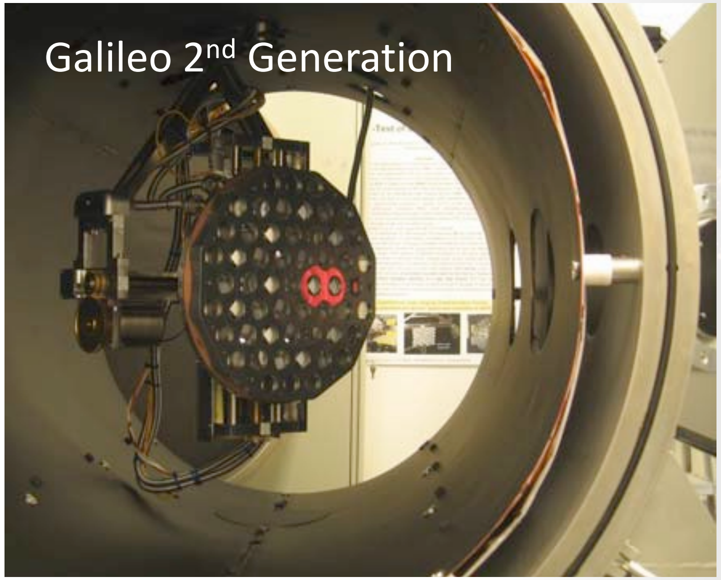


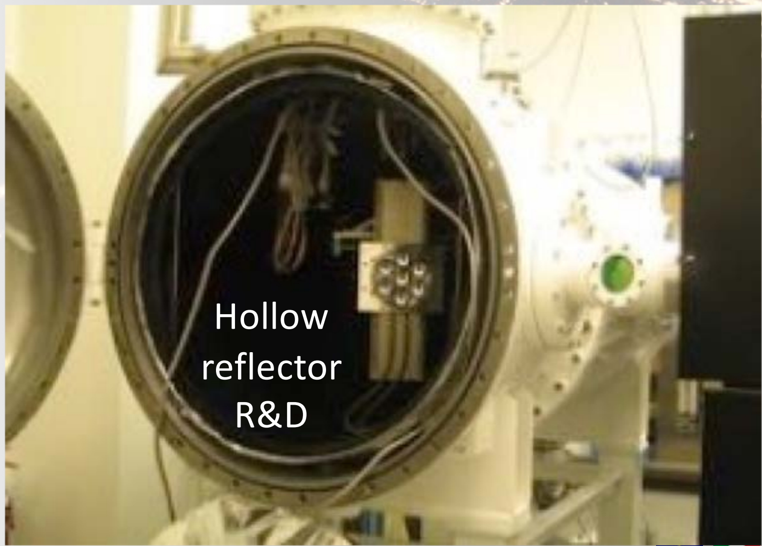

SCF_Lab@INFN-Frascati: 85 m$^2$ ISO7 Clean Room

Specialized Optical Ground Support Equipment (**OGSE**) [1]:

- Two optical benches: FFDP (diffraction), Fizeau interferometry
- Representative space environments ➔ reflector 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)**



# **MPAc** (MoonLIGHT reflector Pointing Actuator)

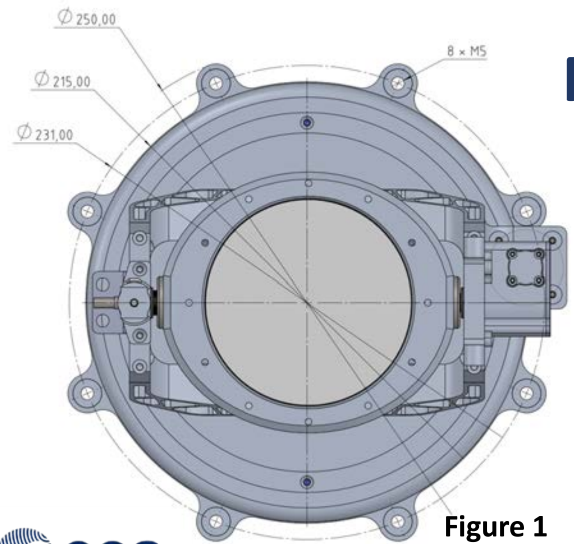


Figure 1

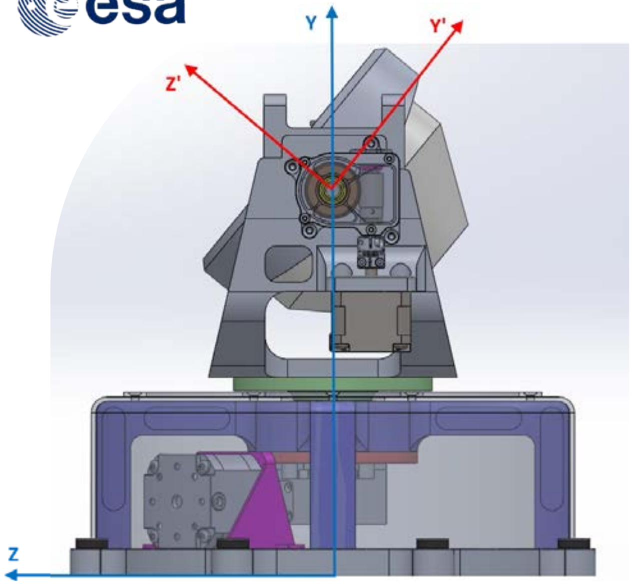


Figure 2

1. **Azimuth frame** is the interface with the lander. It contains most of the electronics and the motor for "Azimuth" movements.

2. **Elevation frame** contains a motor performing the "Elevation" rotation and holds the MoonLIGHT CCR housing.

3. **MoonLIGHT housing** contains CCR and its mounting rings. Passive block that holds and protects the CCR. Back housing: conformal (to CCR shape) or cylindrical-conical (shown).

4. **Actuated dust cover** protects the CCR front face from the regolith dust during/right after landing.

# Some MPAc Features/Parts (work in progress)

| | |
|---|---|
| **Total Mass (with reflector)** | **4000 g (~0.6 kg reflector)** |
| **Dimensions (h × w × d)** | **250 × 250 x 250 mm$^3$** (and up to 25% additional volume) |
| **Mechanical Interface to lander** | 8 x M5 screws |
| **Materials (parts)** | - Aluminum (Al 6082 T6)<br>- PCTFE (KEL-F, reflector mounting rings)<br>- Suprasil 311 (one 100 mm uncoated solid CCR)<br>- Steel (AISI 304) (reflector front housing)<br>- Silver Plated Ni alloy (reflector back housing)<br>- CRES Steel (parts for adjustable elevation) |
| **Electronic Interface** | - Power ≤ 20 W per pointing attempt (1 h time slots)<br>- Operating Voltage: 28±4 Vdc<br>- Communication Bus: RS422<br>- Stepper Motors for Azimuth and Elevation |
| **Coatings** | - MIL A8625 Anodization<br>- Alodine 1200 (gold color surfaces)<br>- Silver Coating (interior of back housing)<br>- AZ 93 white inorganic coating (exterior back housing)<br>- MLP-300-AZ primer (exterior back housing) |

**Also a precursor for the Lunar Geophysical Network (LGN) proposal to NASA's New Frontiers 5 AO**

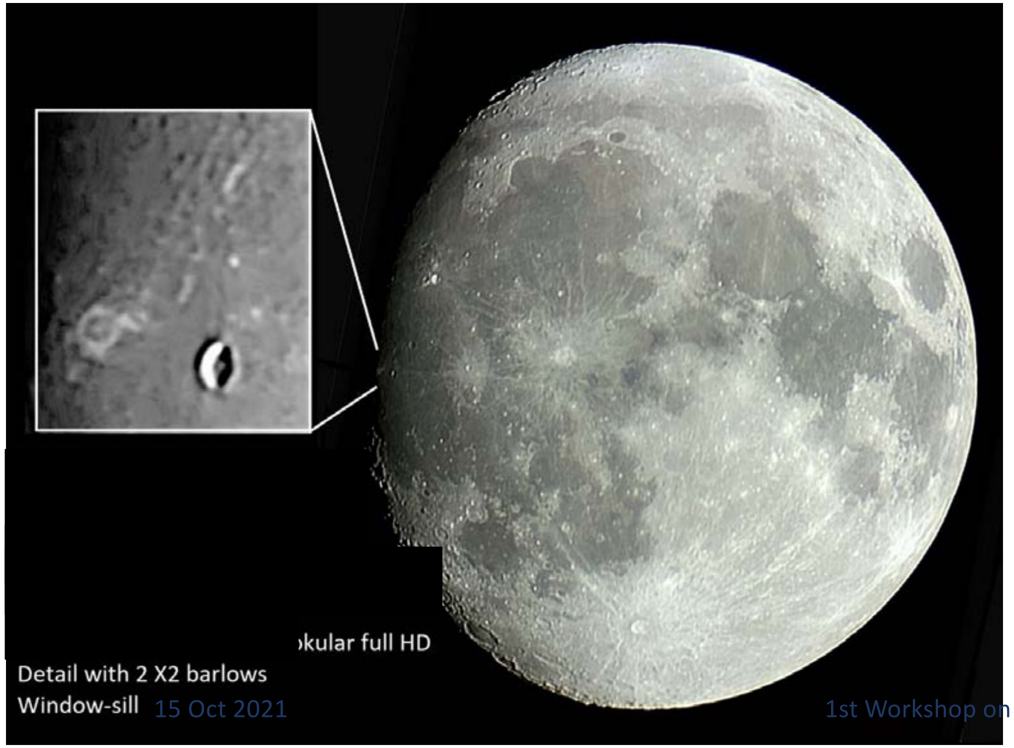
# Selections & Missions

- Core reflector instrument, MoonLIGHT / NGLR (Next Generation Lunar Retroreflector), developed together by Univ. of Maryland (D. Currie) and INFN-Italy
  - Proposed together to ESA and NASA for lunar missions
- MoonLIGHT + MPAc + Dust Cover Actuator (PI = M. Muccino, INFN): selected in 2019 by ESA with Lunar Science RFI
  - Under ESA-INFN Contract # 4000133721/21/NL/CR
  - **Launch**: NASA-CLPS / PRISM 1A mission to the **Reiner Gamma** swirl/crater (early 2024)
  - Under NASA-ESA MoU
- NGLR with fixed pointing (PI = D. Currie, U. of Maryland): selected in 2019 by NASA with LSITP AO (Lunar Science Instrument and Technology Payloads)
  - **Launch**: NASA-CLPS "Blue Ghost" mission to **Mare Crisium** (end 2023)

# MoonLIGHT + MPAc Landing Site
# Mission CLPS-PRISM 1A / **CLPS-PRISM 11** (CP-11)

## PRISM = Payloads and Research Investigations on the Surface of the Moon

NASA CP-11 PoCs:
Ryan Stephan, Paul Niles, H. Haviland



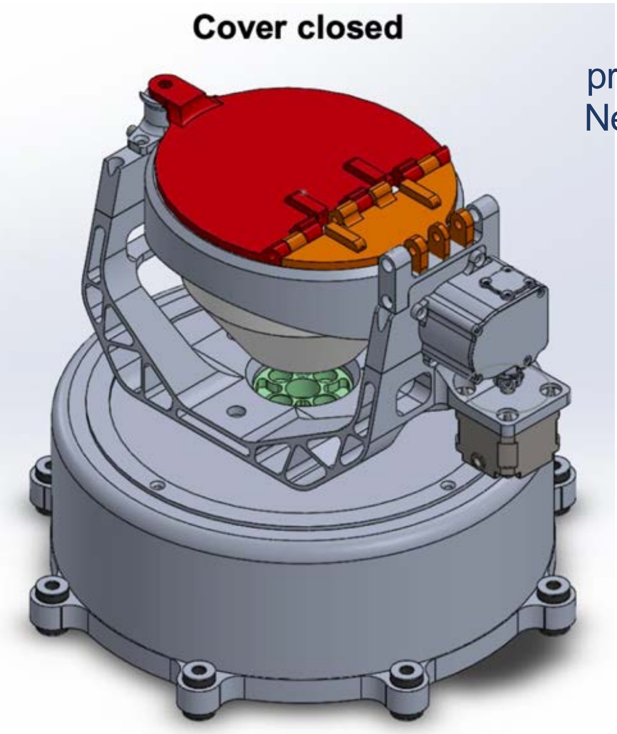

### Reiner Gamma swirl

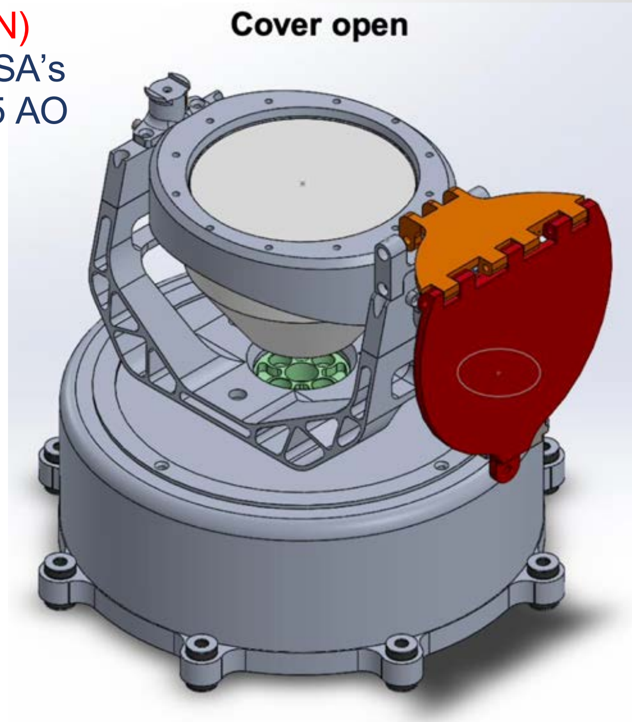
- Crater: 30 km (diameter) x 2.6 km (depth)
- Coordinates: 7°23′24″N, 58°57′36″W
- Associated with a magnetic anomaly
- No/reduced potential obstructing geological features along the line-of-sight to the Earth

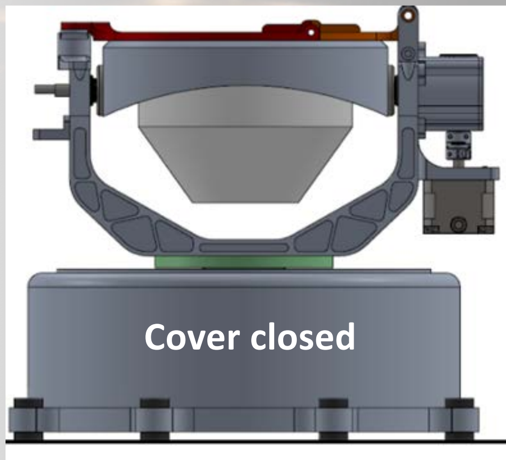
# MoonLIGHT + MPAc + Actuated Dust Cover

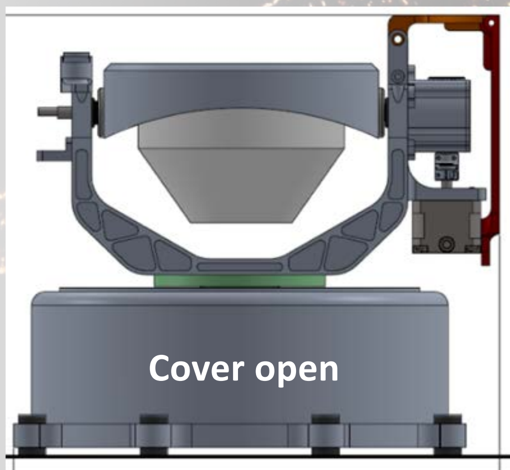
Separate actuator and third stepper motor for the cover protecting MoonLIGHT's front face from the deposition of lunar regolith dust during/right after landing

Also precursor for the Lunar Geophysical Network (LGN) proposal to NASA's New Frontiers 5 AO



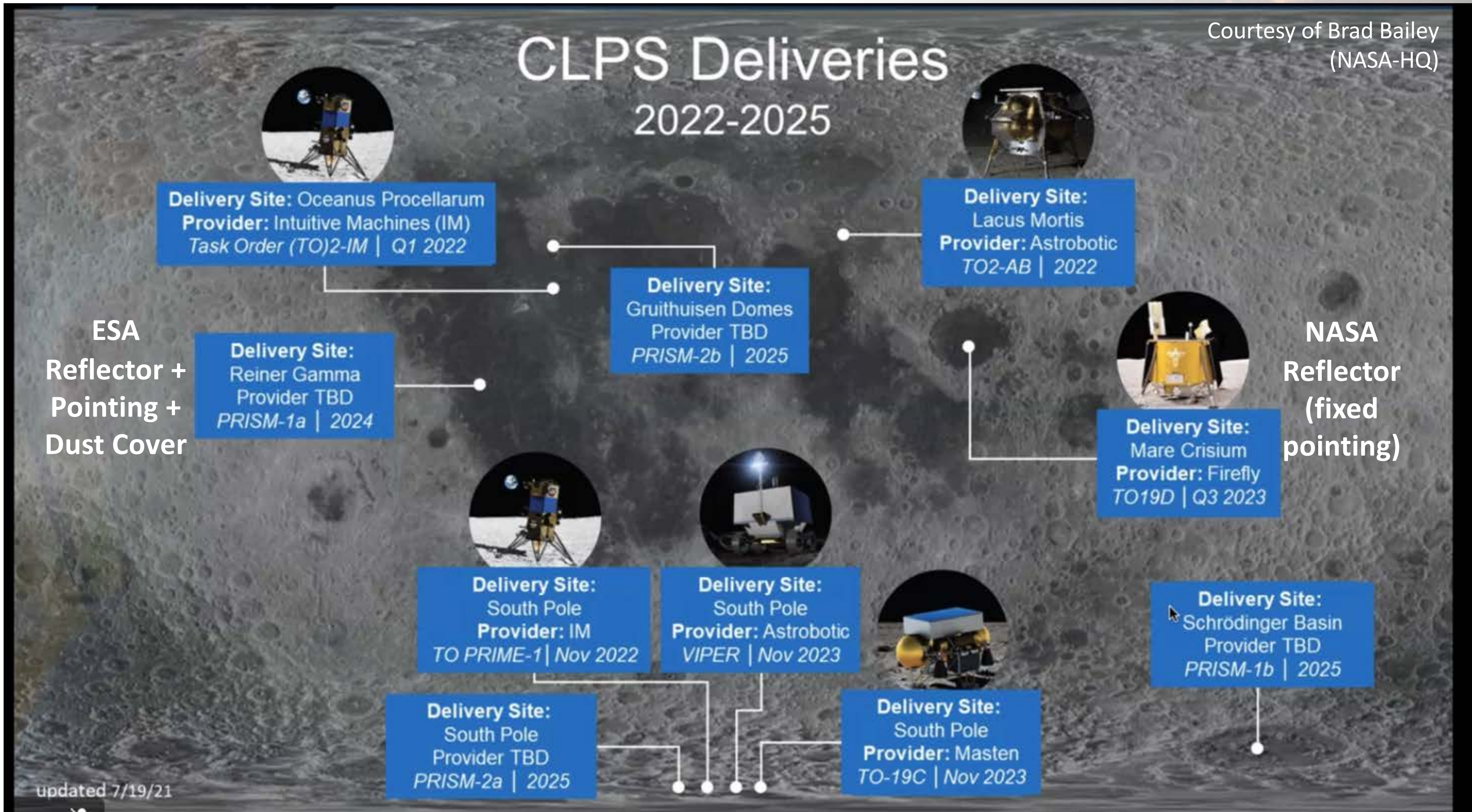
# Fundamental Physics Tests with MoonLIGHT / NGLR

Some current LLR constraints / limits (2nd column ands refs. below), with short-medium (3rd column) and ultimate-long term (5th column) expected results with future LLR data.
FULL synergism with the Lunar Geophysical Network (LGN) by C. Neal, R. Weber et al.

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

# Scheduled NASA-CLPS / LSITP / PRISM missions



# Potential opportunities to demonstrate an evolved/attenuated 15-cm reflector with pointing and dust protection in PSRs

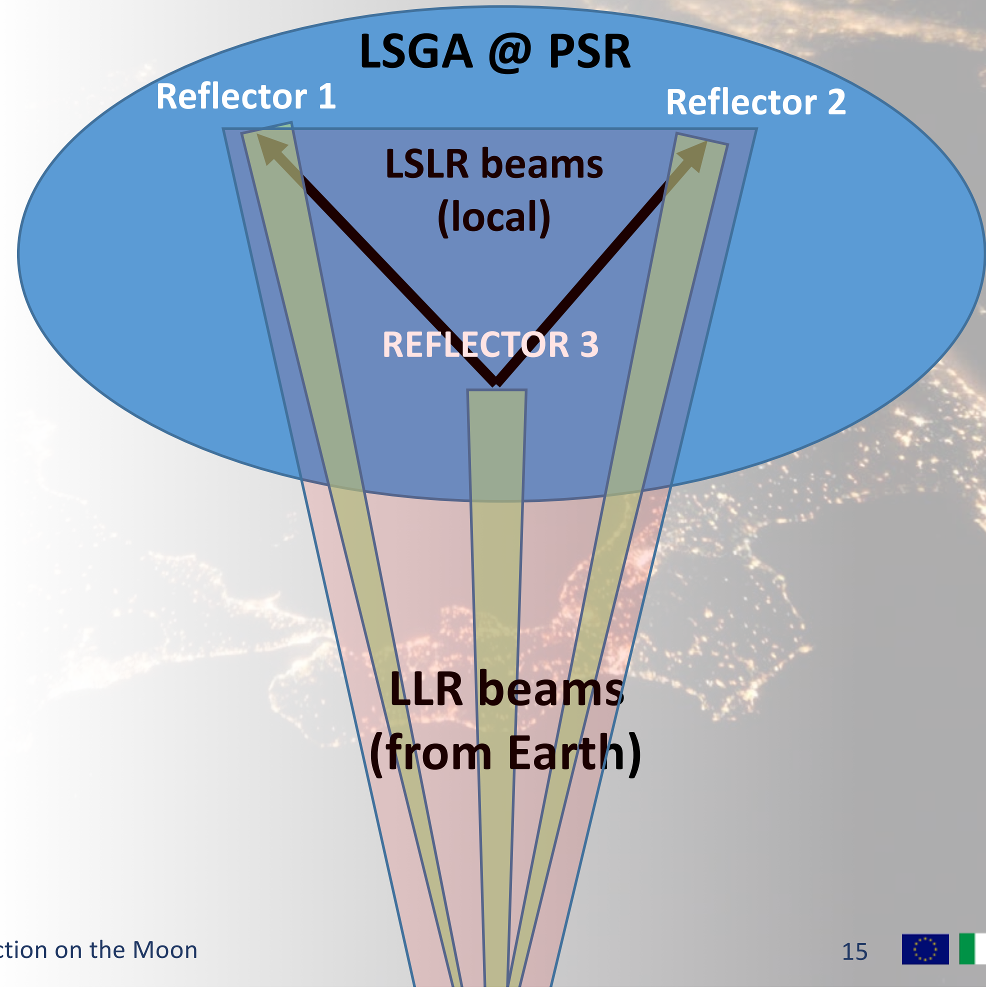
## CLPS Evolution and On-Ramping

- The menu of CLPS services is expected to expand as the market forces and company capabilities evolve
  - Estimating periodic on-ramp opportunities going forward depending upon need and service availability
  - The existing CLPS IDIQ maintains the flexibility to award task orders for upcoming capabilities, as well as data buys
  - Possible evolution areas include:
    - Survive / Operate through the lunar night
    - Increased delivery mass/volume
    - On-orbit delivery
    - Mobility services
    - Return delivery
    - Permanently Shadowed Regions (PSR)/Cold Operation

Courtesy of Brad Bailey (NASA-HQ)

# Idea to be developed with laser stations: fast laser & fast-pointing &/OR SBI LLR from Earth to LSGA, in addition to LSLR

- Using lunar maps (for ex. of NASA-LRO): try to find a PSR (if any) with free LoS to Earth
- Orient the 2 LSGA reflectors to allow for LLR form Earth stations (for ex. Grasse/FR, APOLLO/US, Matera/IT)
- ADD a 3rd reflector for LLR from Earth
- Use fast lasers (available), capable of fast pointing/switching among the reflectors
- &/or laser Same-Beam Interferometry (SBI)



# Summary / what next on **LSLR / LLR @PSRs for GWs**

- <u>LSGA interferometric approach</u>: 2 large, single reflectors with dust protection
- We can scale up the "<u>MoonLIGHT + MPAc + Dust Cover</u>" to be flown by ESA-NASA-INFN
- We can optimize reflector optical specs (our core business for all Solar System) for LSLR
- <u>We propose to upgrade/enhance LSGA by ADDING a 3rd reflector AND LLR from Earth</u>
- 3 methods to detect GWs on the Moon:
  - **LSLR** (Lunar Surface Laser Ranging)
  - **LLR** (Lunar Laser Ranging, from Earth)
  - **LSBI** (Laser Same-Beam Interferometry)