

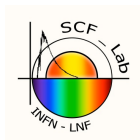
High-Precision Laser Ranging: From Lunar Reflectors to the GUEST Mission

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❶ Introduction to laser ranging

time of flight, cube corner retroreflectors, LLR & SLR

❷ LLR application: NGLR-1

the first single large CCR on the Moon and its first data analysis with PEP

❸ SLR application: geodesy

LAGEOS, LARES, the geocenter and the terrestrial reference frame

❹ SLR application: fundamental physics

GUEST – orbits as detectors of μHz gravitational waves

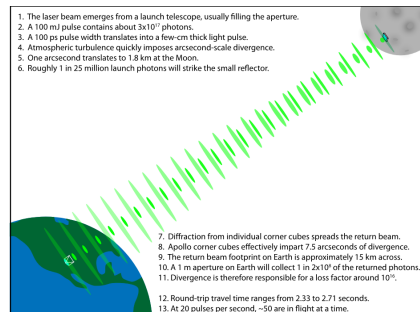
❺ Summary & outlook

Laser ranging: the principle

- Short laser pulse fired from a ground station; a *start* detector tags the departure time
- The pulse is returned by retroreflectors on the target (satellite or Moon) and collected by the telescope
- A *stop* detector tags the return; an event timer referenced to an atomic clock gives

$$\Delta t = t_{\text{stop}} - t_{\text{start}}, \quad d \simeq \frac{c \Delta t}{2}$$

- Corrections: atmosphere, relativistic delays, station and target geometry, target centre-of-mass offset
- Raw ranges are compressed into **normal points (NPs)** averaged over minutes



Murphy [1309.6294]

Orders of magnitude

LLR: $d \sim 384\,000$ km, ToF ~ 2.6 s, return flux $\propto R^{-4}$

Absolute positioning at mm–cm level, at modest cost compared to interferometric techniques

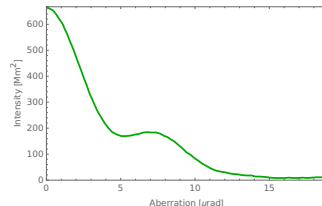
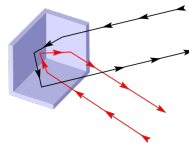
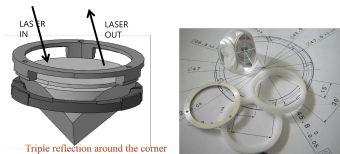
Cube corner retroreflectors (CCRs)

- Three mutually orthogonal faces: triple total internal reflection sends light back *parallel* to the incoming beam, independently of small orientation errors
- The return is spread in a **far-field diffraction pattern** (FFDP); central lobe $\theta \approx 1.22 \lambda/D$
- Relative motion shifts the return by the **velocity aberration**

$$\mu \simeq \frac{2 v_{\perp}}{c}$$

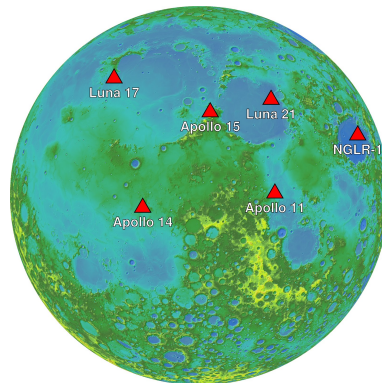
Moon: $\mu \approx 4\text{--}5 \mu\text{rad}$; low/medium orbits: tens of μrad

- Design knobs: aperture D , dihedral angle offsets (DAOs), coatings, thermal behaviour, mounting
- The optical cross section (OCS) quantifies how “bright” a target is for a station



Lunar Laser Ranging: five decades of data

- 1950s: R. H. Dicke et al. propose optical tracking to test gravity; laser invented ~ 1960 ; first lunar shots in the 1960s
- Arrays deployed on the Moon:
 - Apollo 11, 14: 100 fused-silica CCRs (3.8 cm)
 - Apollo 15: 300 CCRs
 - Lunokhod 1, 2: 14 silver coated triangular CCRs arrays on Soviet rovers
 - NGLR (single 10 cm reflector)
- Still working: the longest-lived science experiment left in space by humans
- Precision improved from tens of cm (1970s) to cm (1990s–2000s) to mm-level normal points with modern stations

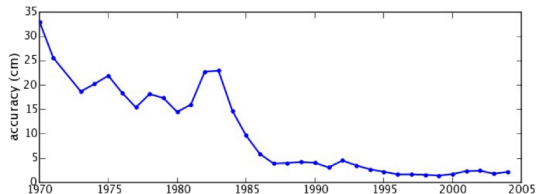


Science from LLR

Earth–Moon dynamics and tides, lunar liquid core, lunar ephemerides, equivalence principle, $\dot{G}/G$, geodetic precession, PPN β, γ

The ILRS network: SLR and LLR stations

- The **International Laser Ranging Service (ILRS)** coordinates stations, targets and data products (CDDIS, EDC)
- Dozens of SLR stations worldwide track LEO, GNSS, geodetic satellites
- Stations that can range to the Moon:
 - Grasse (MeO, France)
 - APOLLO, Apache Point (USA)
 - Wettzell (Germany)
 - Matera MLRO (ASI, Italy)
 - TianQin and Kunming (China)



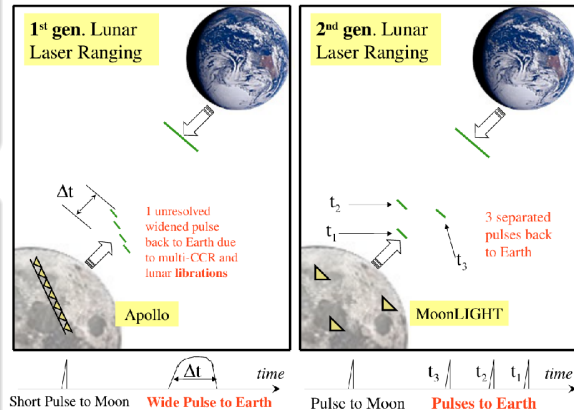
Why next-generation lunar retroreflectors?

The limit of the Apollo/Lunokhod arrays

Lunar **librations** tilt the arrays with respect to the Earth direction: CCRs at different depths along the line of sight widen the returned pulse. Today this spread dominates the instrumental LLR error budget, since station technology has improved dramatically.

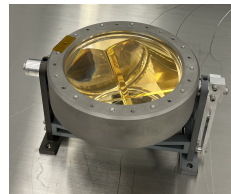
The solution: single large CCRs

- One 10 cm CCR = undispersed point reflector
- Pulses from separate reflectors return resolved in time
- Large aperture compensates the return energy ($I \propto D^4$)
- Goal: from cm to **mm** Earth–Moon accuracy



NGLR-1: the first single 10 cm CCR on the Moon

- **Next Generation Lunar Retroreflector-1**: single CCR, 10 cm optical diameter
- Developed by University of Maryland (D. Currie) in collaboration with INFN-LNF
- Landed **2 March 2025**, Mare Crisium, on Firefly's *Blue Ghost* lander
- Ranged from the first days after landing by Grasse, Wettzell and APOLLO;



LLR data analysed

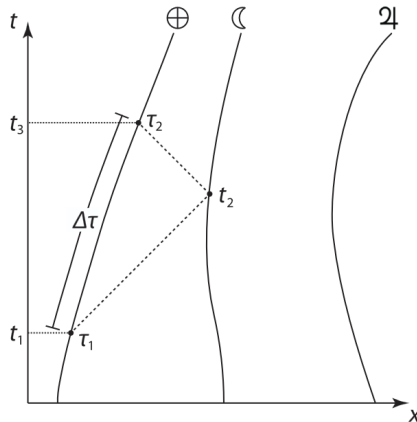
Station	λ [nm]	Data	Period
APOLLO	532	46 NPs	Mar 2025–Apr 2026
Wettzell	1064	37+32 ranges	4 Mar 2025
Grasse	532/1064	11/69 NPs + full rate	Mar–Apr 2025

Bargiacchi et al., *LLR analyses of NGLR-1 data with PEP (2026)* in preparation

Analysis pipeline: the Planetary Ephemeris Program

PEP (Harvard-Smithsonian CfA, open-source Fortran, since the 1960s)

- 1 integrate the equations of motion $\rightarrow$ ephemeris (all body in solar system influence the Earth-Moon range)
- 2 numerical integration $\rightarrow$ dynamical world-lines that satisfy the round-trip light propagation
- 3 compute residuals O-C of the time of flight
- 4 estimate parameters $\rightarrow$ allowing departures from GR (PPN formalism, beyond-GR models)

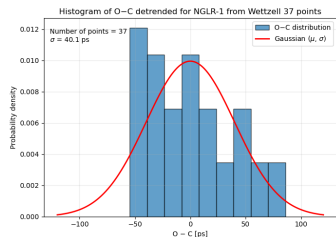
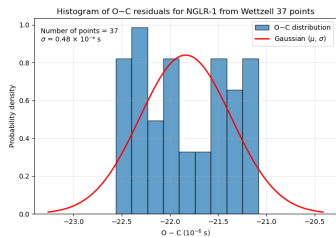
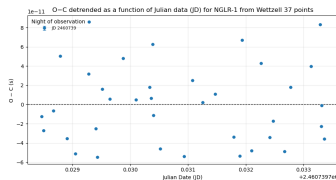
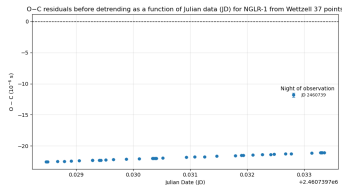


Murphy [1309.6294]

Bargiacchi et al., *LLR analyses of NGLR-1 data with PEP* (2026) in preparation

Analysis pipeline: the Planetary Ephemeris Program

Detrending of each session with a polynomial whose degree is fixed by statistical tests



Raw: $\sigma \simeq 4.8 \times 10^{-7} \text{ s} \rightarrow$
detrended: $\sigma \simeq 4.0 \times 10^{-11} \text{ s}$
Plotted σ refers to the round trip:
one-way accuracy = $\sigma/2$

Bargiacchi et al., *LLR analyses of NGLR-1 data with PEP* (2026) in preparation

Results: Grasse – NGLR-1 vs Apollo 15, same station, same night

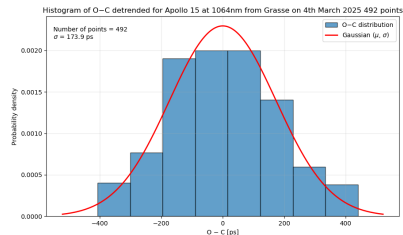
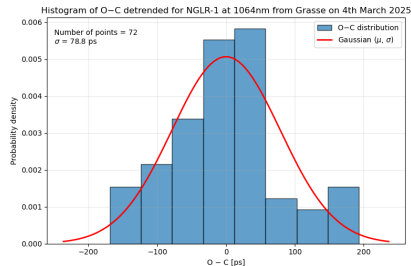
Target	λ [nm]	Points	Deg.	$\sigma_{1\text{way}}$ [ps]
NGLR-1	532	11	3	126.6 ^(*)
NGLR-1	1064	72	2	39.4
Apollo 15	1064	492	1	87.0

- All data from 4 March 2025, 10-minute windows
- At 1064 nm NGLR-1 is consistent with Wettzell and $\sim 2.2\times$ **better** than the Apollo 15 array observed with the same equipment

Main result

First direct evidence that a single large-aperture CCR outperforms legacy arrays; the error budget moves to the ground segment.

Bargiacchi et al., *LLR analyses of NGLR-1 data with PEP* (2026) in preparation



Next: MoonLIGHT + MPAc (INFN-LNF)

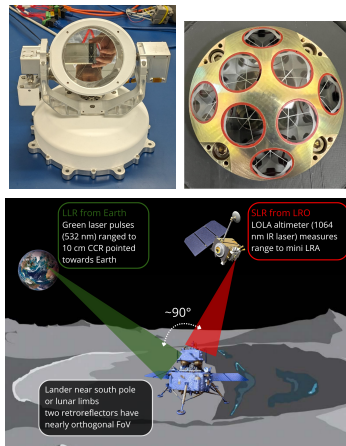
- **ML100**: single uncoated 100 mm CCR in Suprasil 311, DAOs within $0.2''$; Airy radius $\approx 6.5 \mu\text{rad}$ covers the lunar velocity aberration ($4.1\text{--}4.6 \mu\text{rad}$)
- **MPAc** (ESA): pointing actuator $\rightarrow$ points the CCR to Earth ($< 3^\circ$) autonomously after landing
- NASA CLPS CP-11, Intuitive Machines **IM-3**, Reiner Gamma; launch expected Mar 2027; with INRRI microreflector

Tests of General Relativity

Parameter	Tests	Current LLR
$\Delta(m_g/m_i)_{\text{EM}}$	EP, Earth vs Moon	$(-2.1 \pm 2.4) \times 10^{-14}$
$\dot{G}/G$	constancy of G	$(-5.0 \pm 9.6) \times 10^{-15} \text{ yr}^{-1}$
$\beta - 1$	PPN non-linearity	$(6.2 \pm 7.2) \times 10^{-5}$
$\gamma - 1$	PPN space curvature	$(1.7 \pm 1.6) \times 10^{-4}$

MoonLIGHT: instrumental error $\lesssim 1 \text{ mm} \Rightarrow 1\text{--}2$ orders of magnitude on these bounds

Biskupek et al., Universe 7, 34 (2021); Nordtvedt, Phys. Rev. 170, 1186 (1968); Nordtvedt, Icarus 114, 51 (1995); Williams et al., CQG 29, 184004 (2012)

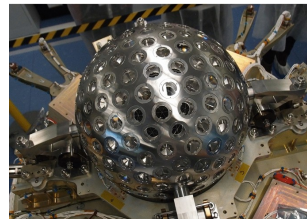


SLR geodetic satellites: LAGEOS and LARES

- Dense, passive spheres covered with CCRs: a nearly ideal *test mass* with laser “traceability”
- Small area-to-mass ratio ($\sim 7 \times 10^{-4} \text{ m}^2/\text{kg}$ for LAGEOS)
 $\Rightarrow$ weak non-gravitational perturbations
- Very long-lived orbits



LAGEOS



LARES2

Satellite	Launch	a [km]	e
LAGEOS (NASA)	1976	12 270	0.0044
LAGEOS-2 (NASA/ASI)	1992	12 162	0.0138
LARES (ASI)	2012	7 820	0.0012
LARES-2 (ASI)	2022	12 266	0.0003

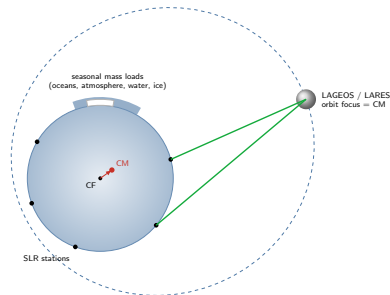
Application: Space geodesy and the geocenter

ITRS/ITRF – Cartesian frame for all positioning on Earth

- **Origin** = geocenter, the Earth's centre of mass, i.e. the focus of LAGEOS orbits → **SLR**
- **Scale** → SLR (LAGEOS) and VLBI
- **Orientation** → VLBI on quasars
- **Distribution** → GNSS (GPS, Galileo, ...),

Open problem: $GM_{\oplus}$ and the 1 mm goal

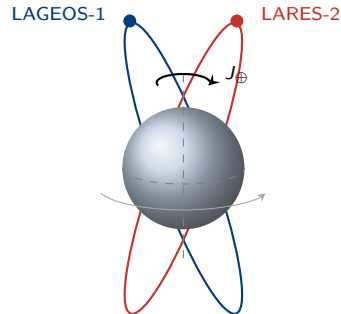
$GM_{\oplus}$ sets the dynamical scale of every Earth orbit; known to ~ 2 ppb. GGOS targets **1 mm** accuracy and **0.1 mm/yr** stability, almost an order of magnitude beyond today. For near-circular orbits, range biases, station heights and $GM_{\oplus}$ are strongly correlated.



CF: centre of the station network (crust)
CM: centre of mass of Earth + oceans + atmosphere
CF $\rightarrow$ CM = geocenter motion: few mm, seasonal offsets exaggerated by $\sim 10^3$

Application: Frame dragging (Lense–Thirring effect)

- GR: a **rotating** mass drags spacetime around with it (gravitomagnetism, Lense & Thirring 1918)
- The orbital plane of a satellite slowly rotates; node drift
$$\dot{\Omega}_{\text{LT}} = \frac{2GJ_{\oplus}}{c^2 a^3 (1 - e^2)^{3/2}} \simeq 31 \text{ mas/yr (LAGEOS)} \Rightarrow \text{only } \sim 1.8 \text{ m per year}$$
- Problem: Earth's oblateness (J_2) drives the node $\sim 10^7$ times faster ($\approx 125^\circ/\text{yr}$)
- Butterfly configuration:** LAGEOS-1 ($i = 109.9^\circ$) and LARES-2 ($i = 70.1^\circ$): J_2 drifts opposite, LT drifts equal $\Rightarrow$ the sum cancels J_2 and keeps $2 \times \text{LT}$



node drift	J_2 (Newton)	LT (GR)
LAGEOS-1	$+125^\circ/\text{yr}$	$+31 \text{ mas/yr}$
LARES-2	$-125^\circ/\text{yr}$	$+31 \text{ mas/yr}$
sum	$\simeq 0$	$+61 \text{ mas/yr}$

Results

LAGEOS + LAGEOS-2 + LARES: $\mu = 0.991 \pm 0.02$ (GR: $\mu = 1$)
LARES-2 + LAGEOS-1: agrees with GR; goal $\text{few} \times 10^{-3}$

Ciufolini et al., EPJC 79, 872 (2019); Ciufolini et al., EPJ Plus 138 (2023); Sośnica et al., J. Geod. 99, 1 (2025)

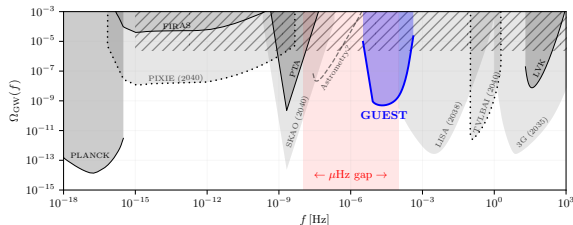
Application: GUEST proposal detecting microherz gravitational waves

- Open windows: LVK (~ 100 Hz, 2015), PTAs (nHz, evidence 2023), CMB
- Coming: LISA (mHz, late 2030s), 3G ground detectors
- 10^{-8} – 10^{-4} Hz **essentially unconstrained**: the “ μ Hz gap”
- Expected signals: SMBH binaries, early-Universe backgrounds, at $h_0 \gtrsim 10^{-16}$, $\Omega_{\text{GW}} \gtrsim 10^{-8}$

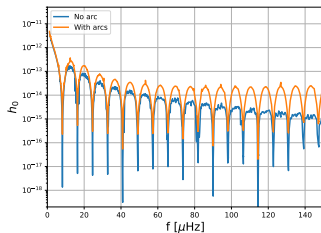
GUEST mission proposal

Gravitational Universe Exploration with Satellite Tracking:

Blas et al., *GUEST* community white paper, arXiv:2607.18390



GW landscape $\Omega_{\text{GW}}(f)$ with the μ Hz gap and the GUEST forecast



Monochromatic reach $h_0(f)$, resonance comb

The concept: orbits as resonant detectors

- A binary *emits* GWs; conversely a GW *perturbs* a binary $\Rightarrow$ Earth + satellite = receiving antenna
- Long-wavelength limit ($a/P \ll c$): tidal acceleration

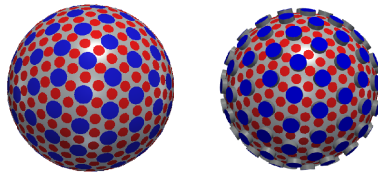
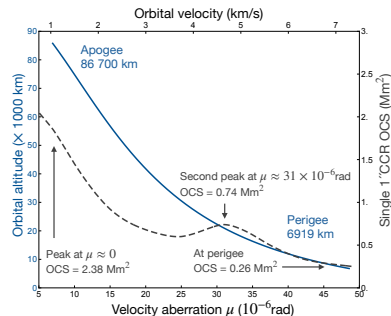
$$\delta \ddot{r}^i = \underbrace{\frac{1}{2} \ddot{h}_{ij} r^j}_{\text{GW perturb.}} + \underbrace{\text{GP} + \text{NGP}}_{\text{much larger}}$$

- **Resonance** when $\omega_{\text{GW}} \simeq 2\pi n/P$: orbital elements drift, true anomaly grows *quadratically* in time, a and e grow linearly
- High eccentricity accelerates the growth and excites higher harmonics n
- $P = 33.8 \text{ h} \Rightarrow f_1 \simeq 8 \mu\text{Hz}$, $f_2 \simeq 1.6 \times 10^{-5} \text{ Hz}$
- Closer to a resonant bar than to an interferometer: the signal accumulates over years

Blas & Jenkins, PRL & PRD (2022); Blas et al., arXiv:2607.18390; Lucchesi, GEOM Cambridge (2026)

Satellites and optical design: two CCR families on one sphere

- Speed from 9.5 km/s (perigee) to 1.4 km/s (apogee):
 $\mu \approx 48 \mu\text{rad}$ at perigee, $\approx 7 \mu\text{rad}$ at apogee
- **CCR1** (1''): optimised for large μ near perigee (LARES-2 heritage)
- **CCR2** (2''): high OCS at small μ , compensates the R^4 loss at apogee (INFN LCNS/ESA heritage)
- 3:1 mix on a Thomson-type tiling of the sphere; CCR2 on protrusions so all tips share one radius
- Spin 40–60 rpm, oblateness $\gamma \approx 12\%$ for gyroscopic stability
- Two passive spheres, different orbital planes: decorrelated systematics, near-uniform sky coverage



Orbit	h_{perigee}	h_{apogee}	AOP	RAAN	e_0	i	P
GUEST-1	6 926 km	86 700 km	270°	0°	0.75	75°	33.8 h
GUEST-2	6 926 km	86 700 km	270°	220°	0.75	50°	33.8 h

D.Blas et al. GUEST white paper [2607.18390]; Vetrano et al., GUEST optical design [2610.20298]

Summary and outlook

- **LLR:** NGLR-1, the first single 10 cm CCR on the Moon, delivers ~ 6 mm one-way accuracy and beats Apollo 15 by $\sim 2\times$ at the same station – now *station-limited*
- MoonLIGHT+MPAc (IM-3) will extend the network of point-like lunar reflectors $\rightarrow$ 1–2 orders better GR tests
- **SLR geodesy:** LAGEOS/LARES realise the geocenter and the scale of the ITRF; the 1 mm GGOS goal needs new orbits
- **GUEST:** two passive spheres on eccentric orbits turn SLR into a μHz GW detector, with DM, fifth-force and $GM_{\oplus}$ science from the same data

Timeline

2022	LARES-2 launched
2025	NGLR-1 on the Moon
2027	MoonLIGHT+MPAc on IM-3
2027	MoonLIGHT on CE-7
2028	ESA GENESIS
2030s	GUEST launch (proposed)
2030s	LISA

Thank you!