# SCF_Lab

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## 1 Next generation lunar laser retroreflectors for fundamental physics and lunar science

Lunar Laser Ranging (LLR) data represent a powerful tool to understand the dynamics of the Earth-Moon system and the deep lunar interior. Over the past five decades, the ground station technology has significantly improved, whereas the lunar laser retroreflector arrays (LRAs) on the lunar surface did not. Current instrumental LLR error budget is dominated by the spread of the returning laser pulse due to the large size of the arrays. Next-generation single solid lunar Cube Corner Retroreflectors (CCRs) of large optical diameter (whose LLR performance is unaffected by that time spread) aim to fully exploit the current laser ranging station capabilities to attain LLR accuracy below current centimeter value down to the desired millimeter level and much higher data collection rates. Such improvements will have a significant impact, enabling more refined ephemerides, improved tests of General Relativity (GR) and of other theories of relativistic gravity in the Sun-Earth-Moon system and improved knowledge of the properties of the lunar interior.

### 1.1 Primary Scientific Objectives

Since 1969, 55 years ago, and until 1972, Apollo and Luna missions deployed Laser Retroreflector Arrays (LRAs) of Cube Corner Retroreflectors (CCRs) on the Moon. These LRAs reflect the incoming incident light back to the emitter. Thanks to a technique known as Lunar Laser Ranging (LLR), it has been possible to perform high accuracy/precision distance measurements of the Moon, firing short laser pulses from Earth ground stations to the aforementioned LRAs, and measuring the two-way time of flight (ToF) of the light. LLR outputs include accurate tests of General Relativity (GR), information on the internal structure of the Moon, its ephemerides, and geocentric positions and motions of Earth ground stations. Over the past 55 years, Earth ground stations LLR capabilities have significantly improved, and nowadays the lunar CCRs represent the main limitation for achieving more accurate/precise measurements of ToFs. The main problem affecting the Apollo and Lunokhod LRAs is represented by the lunar librations, resulting from the eccentricity of the Moons orbit around the Earth [1,2]. For this reason, the Moon Laser Instrumentation for General relativity High-accuracy Tests (MoonLIGHT) instrument was envisaged at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFNLNF), aiming at designing, prototyping, manufacturing and qualifying the next-generation of lunar laser retroreflectors, moving from a multi (small) CCR LRA geometry to a single (large, 100 mm) CCR, unaffected by lunar librations [1,2]. The MoonLIGHT 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 must be pointed accurately to the Earth (within 3 maximum). Taking into account that the industry of landers could not guarantee such an accurate pointing of the device, INFN-LNF proposed the Moon- LIGHT Pointing Actuator (MPAc) hardware to ESA in 2018. In 2019, MPAc was chosen by ESA, that issued a specifically tailored manufacturing contract in favour of INFN-LNF. In 2021, ESA agreed with NASA to launch MPAc to the Reiner Gamma swirl on the Moon, with a Commercial Lunar Payload Services (CLPS), which is part of the Artemis program, and, at the same time, NASA chose Intuitive Machines (IM) as the company that would develop and manufacture the commercial lander where MPAc would be integrated, confirming its flight for Summer 2024 (as per official NASA communication) [3]. Once on the Moon, MPAc will be able to perform two continuous perpendicular rotations to accurately point the front face of MoonLIGHT towards the Earth; the device will operate in Ultra High Vacuum space conditions, and in a wide temperature range [1,2]. Final integration of the $Moon - LIGHT + MPAc$ payload took place in 2023, and the Proto Flight Model (PFM) hardware space qualification tests were successfully passed in late 2023. The MoonLIGHT+MPAc payload was finally delivered to ESA, and NASA, and IM; it is in storage since 6th December 2023, after acceptance, and waiting for final integration on board IMs CP-11 lander.

## 1.2 Science products aspected

The science products expected from Moon- LIGHT are reported in the following for astrophysical/ gravitational sciences and for the lunar science [1,2]:
Astrophysical Sciences: o Deployment of MoonLIGHTs will support, on the LLR space segment, an improvement up to a factor 100 of several tests of GR and relativistic gravity. In fact, LLR currently provides the best, or among the best, constraints on:

Weak Equivalence Principle (WEP) at a level of 10-13.

Strong Equivalence Principle (SEP) at a level of 4 x 10-4.

Time-rate-of-change of Newtons gravitational constant, G, to better than a part in 10-12 per year.

Geodetic precession at a level of 0.1

Yukawa deviations from $1/r2$ gravity at 10-10 times the strength of gravity. o In addition, LLR currently allows to set stringent constraints on the following new theories of fundamental gravity:

Spacetime torsion [4].

f(R) gravity [5].

Non-minimally coupled gravity [6].

Lorentz-invariance violations.
Lunar Science: o Moments of Inertia, Elastic Tides, Tidal Dissipation, Dissipation at the CMB (Core Mantle Boundary), Fluid Core Oblateness, Inner Core, Free Librations. Concerning LLR data analysis, INFN-LNF authors make use of the PEP (Planetary Ephemeris Program) software package, developed and maintained since the 1960s by the Harvard-Smithsonian Center for Astrophysics (CfA), MA, USA.

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