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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 The First Laser Retroreflector on the Lunar Far Side onboard Chinas Chang'e-6 Lander

The Chang'e-6 (CE-6) lander-ascender combination softly touched down at the designated landing site in the Apollo basin within the South pole-Aitken (SPA) basin on June 2, 2024. As one of the four international payloads onboard CE-6, the INstrument for landing-Roving Laser Retroreflector Investigations (INRRI) was installed on the top panel of the lander. Developed by INFN, with support from ASI (Italian Space Agency), this Italian instrument had already been deployed on Mars surface missions: ExoMars (ESA-ASI), InSight (NASA), and Perseverance (NASA). The piggybacking of this instrument came through the collaboration between Italian and Chinese scientists in response to an international Announcement of Opportunity issued by China National Space Administration (CNSA) in 2018. To optimize its mounting on the CE-6 lander, adaptive design and environmental qualification tests were conducted to meet the requirements of surviving on the far side lunar surface environment. The INRRI retroreflector can be observed using the laser altimeter onboard the Lunar Reconnaissance Orbiter (LRO) and future lunar orbiter missions (e.g., Change-7). The successfully landing of CE-6 establishes the first permanent location marker on the Moon's far side, it will serve as an absolute control point to support lunar surface positioning and mapping, and orbit determination and navigation of future lunar orbiters with laser ranging instruments. Chang'e-6 (CE-6) was launched on May 3, 2024, from the Wenchang Space Launch Site in Hainan province, China. The mission went through the processes of Earth-to-Moon transfer, perilune braking, Moon orbiting, and successfully landed in the Apollo basin within the South pole-Aitken (SPA) basin on the far side of the Moon at 6:23 AM on June 2. The coordinates of the landing point are $(153.9780^o W, 41.6252^o S)$ on the Change-2 base map, $(153.9855^o W, 41.638^o S)$ on a Lunar Reconnaissance Orbiter camera (LROC) narrow angle camera (NAC) base map (Image ID: M166854798LE) and $(153.9856^o W, 41.6383^o S)$ from 5 LROC NAC base maps. After completing the lunar surface sampling, the ascender took off from the far side of the Moon and docked with the orbiter. The return capsule was successfully landed in Siziwang Banner, Inner Mongolia, China on June 25. This marks the successful completion of the CE-6 mission, achieving the first unmanned automated sample return from the far side of the Moon. The CE-6 mission piggybacked four international payloads, among which the lander is equipped with a new generation lunar laser retroreflector developed jointly by the Italian National Institute for Nuclear Physics - Frascati National Laboratory (INFN-LNF) and the Aerospace Information Research Institute, Chinese Academy of Sciences (AIRCAS), known as the Instrument for landing-Roving laser Retroreflector Investigations (INRRI), as shown in Figure 1. INRRI is a completely passive instrument with advantages of compactness and maintenance free. With INRRI now deployed on the far side of the Moon, observations can be implemented from lunar orbiters, through laser ranging and altimetry, lidar atmospheric observations from orbit, laser flashes emitted by orbiters, and lasercom[3]. Through precise orbit determination and attitude adjustment, the distance from the orbiter to this microreflector can be accurately measured. Long-term repeated observations can determine precise location of INRRI, which will make it become a high-precision absolute control point on the far side of the Moon. Currently there are only seven laser retroreflector arrays in effective working condition on the lunar surface. Five of them, observed by a few sites on Earth, were deployed by the United States Apollo 11, 14 and 15 manned missions and the Soviet Union's Lunokhod 1 and 2 missions in the late 1960s and 1970s. Most of them are located in the lunar northern hemisphere and at low and middle latitudes. Other two small laser retroreflector arrays are on the Moon onboard the Indian Chandrayaan-3 lander of ISRO landed in August 2023, located in the middle-to-high latitude region close to the South pole, and onboard the SLIM (Small Lander for investigating the Moon) lander of JAXA landed in January 2024, and they have been observed by the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO). All these seven laser retroreflector arrays are located on the near side of the Moon. For the five laser retroreflector arrays for Earth-Moon observations, after long-term Lunar Laser Ranging (LLR), the ranging accuracy of these laser retroreflector arrays has reached few-centimeter level. These laser retroreflectors have become indispensable reference points on the Moon, playing a fundamental role in lunar geodesy, EarthMoon dynamics, and lunar physics, and relativistic physics, etc. In the recently concluded year of 2025, under the leadership of Editor-in-ChiefAcademician Ye Peijian, and with the collective wisdom and assistance of the entireeditorial board, peer reviewers, authors, and readers, the journal Space: Science Technology (hereinafter referred to as "SPACE") has continuously strived for progressand surpassed itself. Looking back on this year, we remember every rigorous andmeticulous review, every innovative article, and every earnest suggestion from readers athome and abroad. Based on comprehensive data such as article downloads and citations from the US Science website, Web of Science database, and Scopus database, this journal hasselected the following10 articles (arranged in chronological order) from those publishedin 2025 for readers' reference.

1.1 Science products expected

The scientific goal of INRRI onboard CE-6 is to achieve the first-ever deployment of laser retroreflector absolute control point on the far side of the Moon, providing support for high- precision positioning on the lunar surface, and orbit determination and navigation of future lunar orbiters. After successful landing of CE-6 lander, INRRI has become a permanent location marker on the far side of the Moon. Lunar laser altimeters, including LOLA and the laser altimeter onboard Change-7 (to be launched in 2026), can precisely measure the distances to INRRI from the lunar orbit. After multiple measurements from orbital laser altimeters, the 3D position of INRRI can be determined accurately by combined processing of the laser ranging measurements and multiple imaging observations of the lander by orbital imagery such as LROC NAC and Change-7 high-resolution images. Meter level positioning accuracy (or better) is expected for INRRI after several years observations. Then, INRRI will serve as an absolute control point to support lunar surface positioning and mapping, especially for the far side of the Moon. This laser-sensitive control point will enhance the orbit determination of future orbiters that can observe it, improving the accuracy of orbit determination, especially in the radial direction. For the long run, this laser retroreflector can be linked to the laser retroreflectors on the near side of the Moon (existing ones and new ones to be deployed) by overlapped lunar orbital images to form a lunar laser retroreflector and image network. This network, with optimal solution and continual update, will become an important lunar spatial infrastructure to support multidisciplinary applications, such as lunar geodesy, lunar dynamics, lunar science (internal structure), fundamental physics (general relativity), future lunar exploration and resource utilization, etc.

2 Testing relativistic gravity with lunar laser retroreflectors and PEP

Around ten years ago, we used a past version of PEP to perform simulations of three MoonLIGHTs deployed on the Moon and to test how the predicted test of three gravity physics observables would improve over a continued time of observation.

A network of single-CCR next-generation laser retroreflectors, like $MoonLIGHT-MPAc$ in 2026 and the one deployed by the NASA-CLPS flight in February 2025 and successfully observed (by the UMD-INFN collaboration, with UMD as Principal Investigator,together with the complementary support of microreflectors. Such an expanding network of next-gen laser retroreflectors will be a powerful tool to test general relativity and other relativistic gravity theories.

3 Planetary Ephemeris Program

Planetary Ephemeris Program (PEP) is an open-source software developed and maintained since the 1960s by the Harvard-Smithsonian Center for Astrophysics (CfA), MA, USA. The program was initially thought to produce ephemeris data, but it was soon clear that other applications would mainly be implemented in the software. Indeed, among its many features, PEP uses Lunar Laser Ranging (LLR) data for precision tests of General Relativity (GR) and beyond by comparing GR predictions with observations. The use of PEP with previous and new data improve, in turn, the accuracy on the constraints of weak and strong equivalence principles, the relative variation with time of the gravitational constant (i.e. $\dot{G}/G$), the geodetic precession, Yukawa deviations from Newtonian gravity through the inverse square law, and will put more stringent constraints on departures from GR, enabling constraints on new theories beyond GR, like spacetime torsion, f(R) gravity, nonminimally-coupled gravity, Lorentz-invariance violations, etc. Indeed, PEP is based on a detailed and complex mathematical and physical model of the solar system which employs a large number (about 150) of adjustable parameters, including the ones describing fundamental physics. By estimating these parameters based on the chosen available data, we can investigate the range of allowable theories in physics and cosmology, enabling accurate constraints on departures from standard physics. As a matter of fact, PEP plays a key role in improving GR tests and pushing constraints on fundamental physics observables in the framework of possible new physics. Our group has started working on PEP by installing the publicly available version on a virtual machine. Once obtained a working version of PEP that compiles without errors, we have achieved the following results:

1. Generation of ephemerides for the entire Solar System over an arbitrary time span;
2. Implementation of recent LLR data that was not present in the original version of PEP, such as the most recent APOLLO data;
3. Calculation and plotting of the residual differences between measured flight times and theoretically predicted flight times. This is in fact the quantity that PEP minimises to estimate the best-fit parameters to be fitted;
4. Formation and resolution of normal equations to estimate the physical parameters of interest;
5. Iteration of solutions to achieve and verify convergence and obtain a reliable estimate of the uncertainties associated with the best-fit of the fitted parameters;
6. Creation of a comprehensive dictionary for all the numerous variables embedded in PEP and, more generally, a manual that clearly and efficiently describes all the steps necessary to use PEP, from installation to parameter estimation. This manual also reports possible errors, problems and their resolution based on our experience;
7. Simulation of future data from new-generation lunar retroreflectors to assess the improvement made in estimating the accuracy of physical parameters and further test theories of gravitation. These steps are fundamental and represent the starting point for achieving other important goals in the near future. The main ones are listed below:
    (a) First measurements (with associated uncertainty) of physical parameters of General Relativity and post-Newtonian formalism parameters using older, more recent, and simulated LLR data;
    (b) Implementation of observations not from Earth stations but from lunar orbiters;
    (c) PEP applications no longer limited to the lunar environment, and therefore to the Earth-Sun-Moon system, but extended to Mars.
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4 NovaMoon white paper

Our group has been involved and is currently part of the NovaMoon project. NovaMoon has been proposed as a scientific and navigation payload for ESA?s

Argonaut lander and is designed as a lunar-based local differential, geodetic, and timing station supporting both the operational needs of the Moon?s south polar region and a broad range of scientific investigations. The payload integrates a lunar laser retroreflector, a Very Long Baseline Interferometry transmitter, a receiver for lunar navigation signals compatible with LunaNet standards, high-stability atomic clocks, and direct-to-Earth radio links, making it the first lunar station to co-locate multiple ranging, tracking, and timing techniques. Figure 1 shows the Novamoon payloads and concept. NovaMoon will enable sub-metre to decimetre positioning in the south polar region, provide local differential corrections for lunar navigation users, and ensure an accurate and stable realisation of position and time for the lander. Through preliminary simulation studies, it has been shown that the resulting multi-technique dataset significantly improves the lunar reference frame, the determination of lunar orientation and ephemerides, and the estimation of interior parameters such as tidal response, core properties, and dissipation. NovaMoon will also provide the first long-duration physical realisation of a lunar time reference, enabling precise timing for lunar navigation users and contributing to the establishment of a future lunar timescale. Beyond its primary goals, NovaMoon supports improved cartography, more accurate geolocation of surface features, and higher-resolution topography in the south polar region, contributing to safer and more precise landing and surface operations. Its multi-technique measurements also open new opportunities for fundamental physics, including enhanced tests of the Equivalence Principle, improved constraints on relativistic gravity, and sensitivity to deviations from classical gravitational models or potential variations in fundamental constants. NovaMoon was approved and subscribed by the ESA Member States at the 2025 Ministerial Council. This is a major milestone and a very positive outcome, made possible by the collective effort of this community. The white paper "NovaMoon": A Strategic Lunar Reference Station for Positioning, Timing, and Largely Enhanced Science in the "Earth-Moon System" is now finalized and ready for submission to Space Science Reviews.

5 MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests-2) and MPAc (MoonLIGHT Pointing Actuator)

Since 1969, 55 years ago, Lunar Laser Ranging (LLR) has provided accurate and precise (down to 1 cm RMS) measurements of the Moon's orbit thanks to the Apollo and Lunokhod Cube Corner Retroreflector (CCR) Laser Retroreflector Arrays (LRAs) deployed on the Moon. Nowadays, the current level of precision of these measurements is largely limited by the lunar librations affecting the old generation of LRAs. To improve this situation, next-generation libration-free retroreflectors are necessary. To this end, the Satellite/lunar/GNSS laser ranging/altimetry and cube/microsat Characterization Facilities Laboratory (SCF_Lab) at the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati (INFN-LNF), in collaboration with the University of Maryland (UMD) and supported by the Italian Space Agency (ASI), developed MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests), a single large CCR with a front face diameter of 100 mm, nominally unaffected by librations, and with optical performances comparable to the Apollo-Lunokhod LRAs of CCRs. Such a big CCR (hereafter, ML100) is mounted into a specifically devised, designed, and manufactured robotic actuator, funded by the European Space Agency (ESA), the so-called MoonLIGHT Pointing Actuator (MPAc), which, once its host craft has landed on the Moon, will finely align the front face of the ML100 towards the Earth. The (optical) performances of such a piece of hardware, MoonLIGHT+MPAc, were tested in/by the SCF_Lab in order to ensure that it was space flight ready before its integration onto the deck of the host craft. After its successful deployment on the Moon, additional and better-quality LLR data (down to 1 mm RMS or better for the contribution of the laser retroreflector instrument, MoonLIGHT, to the total LLR error budget) will be available to the community for future and enhanced tests of gravitational theories.

6 First flight Laser Retro Reflector (LRR) for the Galileo Second Generation (G2G) program

On December 18, 2025, INFN project personnel, specifically Enrico Scantamburlo (Project Manager) and Dalila Di Serio (Head of Optical Measurements and Analysis), traveled to the Airbus Defence and Space (ADS) headquarters in Friedrichshafen, Germany, to formally hand over the first flight Laser Retro Reflector (LRR) for the Galileo Second Generation (G2G) program. The visit took place as part of the activities planned for achieving the relevant project milestone and included the presentation of the associated technical documentation. In this context, the LRR Proto-Flight Model (PFM) was delivered. The formal acceptance of the PFM took place in the presence of Airbus Defence and Space personnel, represented by Elmar Fratianu, and with the participation of ESA personnel, connected via videoconference, who participated in the presentation of the technical documentation. The successful delivery and approval of the PFM formally completes the project milestone related to the construction and acceptance of the first flight LRR. The delivered model is therefore available for subsequent integration activities within the Galileo Second Generation (G2G) satellite system.

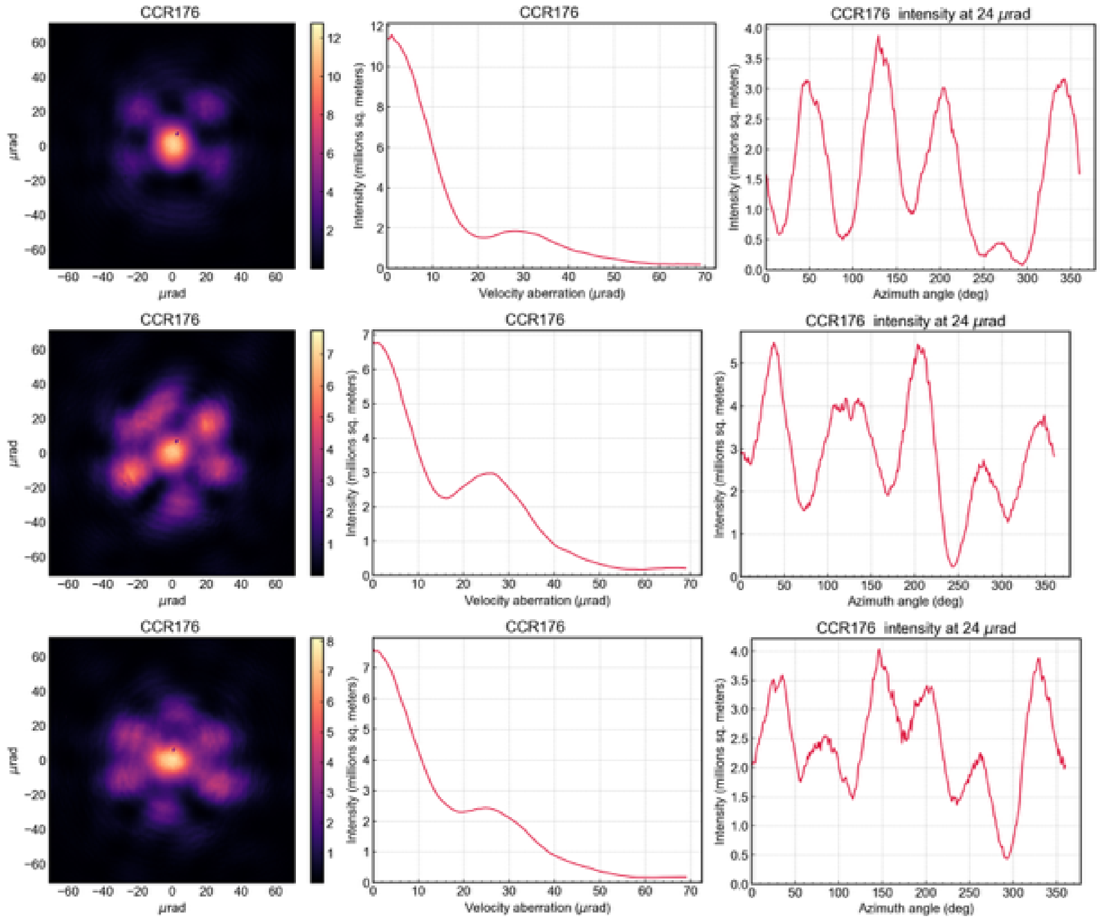

Figure 1: CCR's FFDP graphics

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