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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

Several lunar ephemeris and orbit determination software packages have been developed over the decades by expert analysts who are among the co-authors of this white paper. Historically, one of the very first such packages was the Planetary Ephemeris Program (PEP) by CfA, which estimates the orbits of solar system bodies and of many artificial satellites/probes. One of the first GR measurement with LLR data was the lunar geodetic precession in 1988. Other original software packages have been developed and are actively used at JPL and in Europe (France and Germany). UCSD and INFN-LNF use PEP. All these packages are state-of-the-art and in different ways they constantly keep improving GR tests and pushing constraints on fundamental physics observables in search for new physics, one US decadal plan and one ESA roadmap after the other. Finally, LLR is also a powerful tool to test gravity theories beyond GR, like spacetime torsion, through its potential manifestations in two-body systems like: Earth-Moon and Sun-Mercury and Earth-LAGEOS/LARES artificial satellites. The physics observables can also be used to probe extended theories of gravity beyond GR, like the so-called f(R) gravity and Nonminimally Coupled gravity (NMC). These gravity theories are well motivated by cosmological models alternative to dark matter and dark energy, whose apparent effects are explained by modifications of GR, and that may have observable manifestations in the solar system dynamics (and always in the weak-field, slow-motion regime). Recently, to support the need for accurate and sufficient LLR observations, investigations were carried out in order to assess the benefit of many high-precision infrared (IR) data

1.2 Secondary Scientific Objectives

Extending the reach of Apollo and Lunokhod LRAs, next generation CCRs will greatly contribute to lunar surface geodesy (selenodesy) by improving the local lunar cartesian reference system and its tie to the International Celestial and Terrestrial Reference Systems (ICRS/ITRS). Currently LLR determines the coordinates of Apollo and Lunokhod LRAs w.r.t. the center of mass of the Moon with decimeter level uncertainties. Up to date, these five sites have the most accurately known positions on the Moon and may serve as control points for lunar reference systems, including the one based on Lunar Reconnaissance Orbiter (LRO) data and metric maps, the future LGN, as well as positioning and navigation from orbiters equipped with laser time-of-flight capabilities. LLR is one of the core technologies of the LGN mission (to be proposed by C. Neal, R. Weber et al. for NASAs New Frontiers 5), where it contributes to the improvement of the determination of the lunar interior structure together with the other LGN instruments. Concerning lunar inner structure, next-gen single large CCR will contribute in improving the uncertainties of the core momentum and Love numbers of the Moon. Lunar core and inner structure have been probed by several techniques. The lunar mean density and moment of inertia values permit a small dense, solid or liquid core, but not a large one. Seismic data provides information on the elastic properties of the lunar crust and mantle: S-waves damp out for the deep mantle, possibly due to a deep partial melt; P-waves penetrate the deepest mantle better, but are not able to unambiguously detect a core. Magnetic induction data indicates a small conducting core. LLR is sensitive to the physical librations, i.e. the 3-axis lunar rotation and orientation . The rotation of the Moon is sensitive to moments of inertia of lunar mantle and fluid core, lunar gravity field, tidal deformation, dissipation at the CMB (Core-Mantle Boundary) and flattening at the CMB. LLR physical libration analysis indicates a liquid lunar core, first detected from dissipation at the CMB and more recently from detection of CMB flattening and core moments of inertia; according to the core moments values and CMB flattening, the fluid core radius is determined to be $380km$. Next-gen CCRs will further significantly contribute to the determination done by GRAIL (the Gravity Recovery And Interior Laboratory mission) and existing LLR data of tidal Love numbers which are sensitive to internal elastic properties and structure including a core: in particular the displacement Love number h_2, which is compatible with the foregoing core size though the k_2 Love number would work better with a smaller core. A future wider selenographical distribution of next generations CCRs would help to single out the contribution of physical librations from LLR data and would lead to the increase in sensitivity not only of physical librations, but also of tides. Correspondingly, this would improve the uncertainties of the core moments and Love numbers.

1.3 First Approved Missions and Decadal Recommendations

The first NGLR (with fixed pointing) will be launched with a NASA-CLPS mission dubbed Ghost Blue and the lander provider will be Firefly. The launch is scheduled for Q4 2023 and the landing site will be the Mare Crisium. The first MoonLIGHT (equipped with MPAc and the robotic dust cover) will be launched the NASA-CLPS/PRISM1A (CP-11) mission and the lander provider will be assigned in the November 2021 timeframe. The launch is scheduled for Q1 2024 and the landing site will be the Reiner Gamma swirl region. This topical white paper wishes to recommend to the BPS decadal survey the state-of-the-art objectives of fundamental physics and lunar science described in sections II and III, that are enabled by next generation single, large diameter CCRs deployed by means of NASA-CLPS missions, through the international Artemis Accords, the EL3 lunar program and the LGN during the decade 2023-2032. The science return will continue for the following decades because CCR are passive, long-lived instruments and as demonstrated during the past 50+ years by Apollo and Lunokhod LRAs (one of which was rediscovered in 2010 by APOLLO thanks to LROC, the LRO Camera). Since all existing LRAs are north of the lunar equator, we recommend one or more southern landing or roving sites, especially towards the limbs or the south pole, as they would be most helpful both for lunar science and for fundamental physics. Concerning rover opportunities, if (for example) NASAs Volatiles Investigating Polar Exploration Rover (VIPER) does not include one, it could deploy a next-gen CCR of increased performance, like the one in Figure 1 in a fixed-pointing mount with pre-launch selectable elevation (middle and right photos). At its end-of-life VIPER could maneuver to align the CCR to Earth, avoiding the need for MPAc (i.e. an active pointing). Such a next-gen CCR would be a cost-effective, science-effective (because deployed at the south pole), compact and light instrument (¡2kg, dust cover included). ESAs robotic, removable CCR cover (Figure 4 or a version simplified/optimized for VIPERs 85oS latitude) would be most useful to avoid regolith dust accumulation over the 10-cm diameter CCR face during the rover traverses.

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