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.

2 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.

2.1 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.

3 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.

Publications

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