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MOONLIGHT: A NEW LUNAR LASER RANGING RETROREFLECTOR AND THE LUNAR GEODETIC PRECESSION

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Abstract. Since the 1970s Lunar Laser Ranging (LLR) to the Apollo Cube Corner Retroreflector (CCR) arrays (developed by the University of Maryland, UMD) supplied almost all significant tests of General Relativity (Alley et al., 1970; Chang et al., 1971; Bender et al.,1973): possible changes in the gravitational constant, gravitational self-energy, weak equivalence principle, geodetic precession, inverse-square force-law. The LNF group, in fact, has just completed a new measurement of the lunar geodetic precession with Apollo array, with accuracy of 9×10^{-3}, comparable to the best measurement to date. LLR has also provided significant information on the composition and origin of the moon. This is the only Apollo experiment still in operation. In the 1970s Apollo LLR arrays contributed a negligible fraction of the ranging error budget. Since the ranging capabilities of ground stations improved by more than two orders of magnitude, now, because of the lunar librations, Apollo CCR arrays dominate the error budget. With the project MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests), in 2006 INFN–LNF joined UMD in the development and test of a new-generation LLR payload made by a single, large CCR (100 mm diameter) unaffected by the effect of librations. With MoonLIGHT CCRs the accuracy of the measurement of the lunar geodetic precession can be improved up to a factor 100 compared to Apollo arrays. From a technological point of view, INFN–LNF built and is operating a new experimental apparatus (Satellite/lunar laser ranging Characterization Facility, SCF) and created a new industry-standard test procedure (SCF-Test) to characterize and model the detailed thermal behavior and the optical performance of CCRs in accurately laboratory-simulated space conditions, for industrial and scientific applications. Our key experimental innovation is the concurrent measurement and modeling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of retroreflector payloads under thermal conditions produced with a close-match solar simulator. The apparatus includes infrared cameras for non-invasive thermometry, thermal control and real-time payload movement to simulate satellite orientation on orbit with respect to solar illumination and laser interrogation beams. These capabilities provide: unique pre-launch performance validation of the space segment of LLR/SLR (Satellite Laser Ranging); retroreflector design optimization to maximize ranging efficiency and signal-to-noise conditions in daylight. Results of the SCF-Test of our CCR payload will be presented. Negotiations are underway to propose our payload and SCF-Test services for precision gravity and lunar science measurements with next robotic lunar landing missions. In particular, a scientific collaboration agreement was signed on Jan. 30, 2012, by D. Currie, S. Dell'Agnello and the Japanese PI team of the LLR instrument of the proposed SELENE-2 mission by JAXA (Registered with INFN Protocol n. 0000242-03/Feb/2012). The agreement foresees that, under no exchange of funds, the Japanese single, large, hollow LLR reflector will be SCF-Tested and that MoonLIGHT will be considered as backup instrument.

Keywords: lunar laser ranging, space test, cube corner reflector, laser technology, test of geodetic precession.

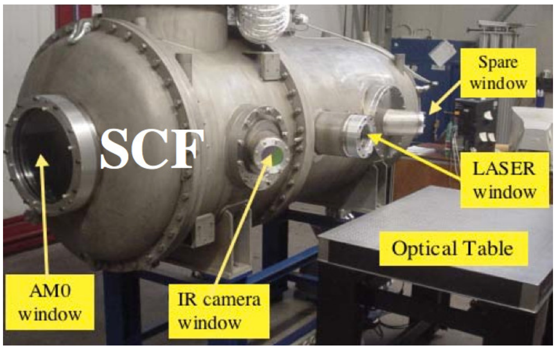

FIGURE 1. The SCF cryostat.

1. Introduction

Lunar laser ranging (LLR) is mainly used to conduct high-precision measurements of ranges between a laser station on Earth and a Corner Cube Retroreflector (CCR) on the lunar surface. Over the years, LLR has benefited from a number of improvements both in observing technology and data modeling, which led to the current accuracy of postfit residuals of ~ 2 cm.

Nowadays LLR is a primary technique to study the Earth–Moon system and is very important for gravitational physics, geodesy, and studies of the lunar interior.

Since 1969 LLR has supplied a lot of tests of General Relativity (GR): it has evaluated the Geodetic Precession [12], probed the weak and strong equivalence principle, determined the Parametrized Post Newtonian (PPN) parameter β and γ, addressed the time change of the gravitational constant (G) and $1/r^2$ deviations. LLR has also provided important information on the composition and origin of the Moon through measurement of its rotations and tides.

Future lunar missions will expand this broad scientific program. Initially, the Apollo arrays contributed a negligible portion of the LLR error budget. Today the ranging accuracy of ground stations has improved by more than two orders of magnitude: the new APOLLO[1] station at Apache Point, USA, is capable of mm level range measurements; MLRO (Matera Laser Ranging Observatory), at the ASI (Agenzia Spaziale Italiana) Space Geodesy Center in Matera, Italy, has restarted LR operations. Now, because of lunar librations, the Apollo arrays dominate the LLR error budget, which is a few cm.

1.1. The Satellite/lunar laser ranging Characterization Facility (SCF)

In 2004, INFN started the operation to build the Satellite/lunar laser ranging Characterization Facility (SCF) in Frascati. The main purpose of this apparatus is the thermal and optical characterization of CCR arrays in simulated space conditions. A schematic view of the SCF is shown in Fig. 1.

The size of the steel cryostat is approximately 2 m length by 0.9 m diameter. The inner copper shield is painted with the Aeroglaze Z306 black paint (0.95 emissivity and low out-gassing properties) and is kept at $T = 77$ K with liquid nitrogen. When the SCF is cold, the vacuum is typically in the 10^{-6} mbar range. Two distinct positioning systems at the top of the cryostat (one for rototranslation movements in the plane of the prototype and one for spherical rotations and tilts) hold and move the prototype in front of the Earth infrared Simulator (ES, inside the SCF), the Solar Simulator (SS), the infrared camera and laser, all located outside the SCF. The SS beam enters through a quartz window (~ 37 cm diameter, ~ 4 cm thickness), transparent to the solar radiation up to 3000 nm. A side Germanium window at 45° with respect to the SS beam allows for the acquisition of thermograms of the Laser Retroreflector Array (LRA) with an IR digital camera (both during the ES/SS illumination and the laser interrogation phases).

[1]Apache Point Observatory Lunar Laser-ranging Operation

1.2. The MoonLIGHT – ILN experiment

In 2006, INFN proposed the MoonLIGHT – ILN (Moon Laser Instrumentation for General Relativity High accuracy Tests – International Lunar Network) technological experiment [5, 8], which has the goal of reducing the error contribution of LLR payloads by more than two orders of magnitude. In Tab. 1, the possible improvements in the measurement of gravitational parameters achievable through reaching the ranging accuracy of 1 mm or even 0.1 mm are reported [14–16].

After the building of the best station, APOLLO [11], in New Mexico, the main uncertainty is due to the multi-CCR arrays. The Apollo arrays now contribute a significant portion of the ranging errors. This is due to the lunar librations, which move the Apollo arrays, since that have dimensions of 1 square meter, for the Apollo 15, and half square meter, for the Apollo 11 and 14. In this paragraph we will describe the MoonLIGHT/LLRRA21 payload to improving gravity tests and lunar science measurements [3, 6]. This project is the result of the collaboration of two teams: the LLRRA21 team in the USA, led by Douglas Currie of the University of Maryland, and the Italian one led by INFN–LNF. We are exploring improvements of both the instrumentation and the modeling of the CCR. The main problem that affects the Apollo arrays is the lunar librations, in longitude, that results from the eccentricity of the Moons orbit around Earth. During the lunar phase, 27 days, the Moons rotation alternatively leads and lags its orbital position, of about 8°. Due to this phenomenon the Apollo arrays are moved so that one corner of the array is more distant than the opposite corner by several centimeters. Because the libration tilt, the arrays increase the dimension of the pulse coming back to the Earth (Fig. 2). The broadening of the pulse will be greater proportionally to the array physical dimensions and to the Moon–Earth distance increase.

Gravitational measurement	1st generation LLR accuracy ($\sim$ cm)	2nd generation LLR accuracy (1 mm)	2nd generation LLR accuracy (0.1 mm)	Time scale
EP	$< 1.4 \times 10^{-13}$	10^{-14}	10^{-15}	few years
SEP	$< 4.4 \times 10^{-4}$	3×10^{-5}	3×10^{-6}	few years
β	$< 1.1 \times 10^{-4}$	10^{-5}	10^{-6}	few years
$(\dot{G}/G)$	$< 9 \times 10^{-13}$	5×10^{-14}	5×10^{-15}	$\sim$ 5 years
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}	6.4×10^{-5}	few years
$(1/r^2)$ Deviation	$< 3 \times 10^{-11}$	10^{-12}	10^{-13}	$\sim$ 10 years

Table 1. Narrowing of parameter bounds due to gains in the accuracy of ranging measurements by one or two orders of magnitude, (reaching accuracy of 1 mm or even 0.1 mm).

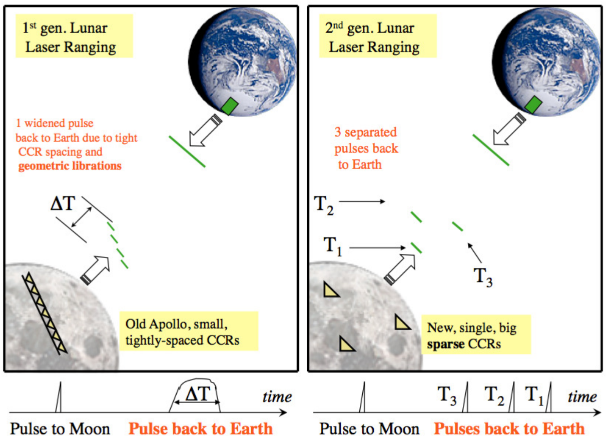

Figure 2. Comparison between 1st and 2nd generation LRAs. The librations tilt the arrays on the left, but the single big CCRs are unaffected, on the right. So we have single short pulses coming back using the MoonLIGHT payloads.

2. Analysis of lunar laser ranging data

In order to analyze LLR data we used the PEP software, developed by the CfA, by I. Shapiro et al. starting from 1970s. PEP was designed not only to generate ephemerides of the Planets and Moon, but also to compare model with observations. One of the early uses of this software was the first measurement of the geodetic precession of the Moon [12].

The PEP software has enabled constraints on deviations from standard GR physics. Here we show the first determination of the relative deviation from the value expected in GR of the geodetic precession, K_{GP}. We have used all the data available to us from Apollo CCR arrays: Apollo 11, Apollo 14 and Apollo 15.

The value obtained using only old stations (Grasse, McDonald and MLR2) vs. the value obtained using the APOLLO station is shown in Tab. 2.

This preliminary measurements are to be compared with the best result published by JPL [13] obtained using a completely different software package. On the contrary, after the original 2 % K_{GP} measurement by CfA in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

Station	Value obtained	value in GR
OLD stations	$(9 \pm 9) \times 10^{-3}$	0
APOLLO station	$(-9.6 \pm 9.6) \times 10^{-3}$	0

Table 2. Value obtained for the geodetic precession.

3. Conclusions

The analysis of existing LLR data with PEP is making good progress, thanks to the important collaboration with CfA, as shown with the preliminary measurement of the geodetic precession (de Sitter effect) with an accuracy at 1 % level.

In the future we are going to deepen our knowledge about data and software in order to better estimate the K_{GP} uncertainty and other GR parameters. A possible way to improve the precision of LLR measurements is to have lunar station to range not only to the Moon, but also to satellites around the Earth and primarily to LAGEOS, thus improving station intercalibration.

Acknowledgements

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Discussion

Jim Beall — Do you have a planned date for deploying the retroreflector on the Moon?

Manuele Martini — There are several scientific agreements for opportunities for robotic mission on the lunar surface that will deploy MoonLIGHT CCRs, but there is no firm approved planned date for deploying CCR on lunar surface.