Next-generation laser retroreflectors for precision tests of general relativity

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Since 1969, Lunar Laser Ranging (LLR) to the Apollo Cube Corner Retroreflectors (CCRs) has supplied almost all significant tests of General Relativity (GR). When first installed in the 1970s, the Apollo CCRs geometry contributed only a negligible fraction of the ranging error budget. Today, because of lunar librations, this contribution dominates the error budget, limiting the precision of the experimental tests of gravitational theories. MoonLIGHT-2 (Moon Laser Instrumentation for General relativity High-accuracy Tests) is a new-generation LLR payload made of a single large CCR unaffected by librations in order to increase the precision of the GR tests compared to the Apollo CCRs. To optimize the MoonLIGHT-2 design and its lunar deployment we performed both experimental tests of MoonLIGHT-2 thermal properties in simulated space condition and GR test simulations using the Planetary Ephemeris Program (PEP) software, developed by the Center for Astrophysics (CfA). The experimental test shows the expected thermal properties and will provide useful to optimize the payload for the launch while the GR simulations suggest a significant improvement in GR test with the new CCRs and that the absence of a sunshade does not have a relevant impact on the precision of GR tests.

Keywords: Cube Corner Retroreflector; General Relativity; Lunar Laser Ranging; Planetary Ephemeris Program.

1. Introduction

Lunar Laser Ranging (LLR) provides accurate measurements of the lunar orbit through high-precision measurement of ranges between a laser station on the Earth and the Apollo Cube Corner Retroreflectors (CCRs) on the lunar surface. The LLR has provided for decades the best tests of the validity of Einsteins theory of General Relativity with measurements of the weak and strong equivalence principle, the Parameterized Post Newtonian (PPN) parameters β and γ, the time change of the Gravitational Constant $\dot{G}/G$, weak and strong equivalence principle (through the Nordtvedt parameter η), Geodetic Precession (K_{GP}) and $1/r^2$ deviations ([1] and [2]). Actually the LLR precision is around 2cm (reference[3] and reference[4]), but the current geometry of the CCR array installed on Moon significantly limits further improvements. The main reasons are the lunar librations in longitude that results from the eccentricity of the Moons orbit around the Earth. The SCF group, in collaboration with the University of Maryland, developed a new design of lunar CCR whose performance is unaffected by either lunar librations and regolith motion. The design employs a series of single large CCR (around 100 mm of front face diameter), deployed separately on the lunar surface. This arrangement creates single short reflected pulses with a final precision better than 1 mm [5]. We show in table 1 the GR tests that have been carried out using the first generation of LLR and the expected improvement for the second generation. In order to optimize MoonLIGHT-2 for the deploying, scheduled in 2018 with Moon Express mission (this will be the first of four mission each one with a MoonLIGHT-2) we are now carrying out an experimental test campaign in simulated space condition (section 2) at the SCF_Lab (Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory). In addition we are working on different GR simulation in collaboration with the CfA: one to compare GR test with and without the sunshade and another one to study the expected improvement in GR test provided by MoonLIGHT-2 (section 3).

Table 1. GR science objectives and measurements. 2^{nd} column shows current situation and measurements from [3].

Science Measurements Measurements	1st generation LLR accuracy (cm)	2nd generation LR accuracy (mm)
EP	1.4×10^{-13}	10^{-14}
SEP (η)	4.4×10^{-4}	3×10^{-5}
β -1	1.1×10^{-4}	10^{-5}
$\dot{G}/G$ $[yr^{-1}]$	9×10^{-13}	5×10^{-14}
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}
$1/r^2$ (α)	$3. \times 10^{-11}$	10^{-12}

2. MoonLIGHT-2 thermal characterization: the SCF-Test

The SCF-Test [6] key experimental innovation is the concurrent measurement and modeling of the optical Far Field Diffraction Pattern and the temperature distribution of the MoonLIGHT-2 CCR under thermal conditions produced with a close-match solar simulator. The tests apparatus includes a infrared camera for non-invasive thermometry, PT100 probes for invasive thermometry, thermal control electronics and movement systems to experimentally simulate payload orientation with respect to both solar illumination and laser interrogation beams. The aim of this analysis is to study the exponential law for CCR heating/cooling:

$$T(t) = T_0 \pm \Delta T(1 - e^{\frac{-t}{\tau_{CCR}}}) \quad (1)$$

where: T(t)is the temperature at time t, T_0 is the temperature at t=0, ΔT = is the difference between the final temperature and T_0. and τ_{CCR} is the CCR thermal constant. For the whole test the payload housing is at a fixed temperature and thermally decoupled from the climatic facility. The thermal test can be schematized in the following steps:

- **Steady state conditioning**: With the payload temperature in steady condition we take 1 IR in order to acquire initial conditions.
- **SUN ON heating phase**: The CCR faces the solar simulator beam. This phase lasts for 13h and here we take 1 IR every 5 minutes for the first 30 minutes, then 1IR every 5 minutes for the remaining minutes.
- **SUN OFF cooling phase**: The solar illumination is closed. This phase lasts for 14h and here we take 1 IR every 5 minutes for the first 30 minutes, then 1IR every 5 minutes for the remaining minutes.

We repeat the test for two different housing temperature: 250K and 300K With this test we want to evaluate the CCR thermal constant τ_{CCR} and the thermal gradient on the CCR front face in order to study the isolation between CCR and housing.

The IR analysis is achieved with FLIR Thermacam Researcher software and a custom Matlab code. With FLIR Thermacam Researcher SW we analyze all the visible CCR front face area and extract the average temperature within this area w.r.t. test time, then using the Matlab code we obtain from the raw data the best fit parameters, including the τ_{CCR}. See figure 1 for an example of the FIT result of the heating phase.

In addition we analyze the maximum temperature difference within the CCR front face area in order to investigate in detail any thermal conductivity between CCR and housing that can decrease the optical performance. In table 2 are summarized all the thermal result for the two tests. The tests shows a large thermal constant, around $[1.0 - 1.5] \times 10^4$ seconds as expected. This feature will provide an efficient isolation of MoonLIGHT-2 from regolith during the long lunar cycle. The results for thermal analysis on the CCR front face shows a significative thermal gradient, around 4K, probably due to a hight conductivity between the CCR and the housing. This thermal gradient will affect the CCR Far Field Diffraction Pattern, so additional tests will be carried out at the SCF_Lab during 2015-2016 to improve the MoonLIGHT-2 mechanical structure.

3. MoonLIGHT-2 GR simulations with PEP

To complete the MoonLIGHT-2 optimization before the first launch, we run a number of numerical simulations using PEP. PEP is a FORTRAN software package,

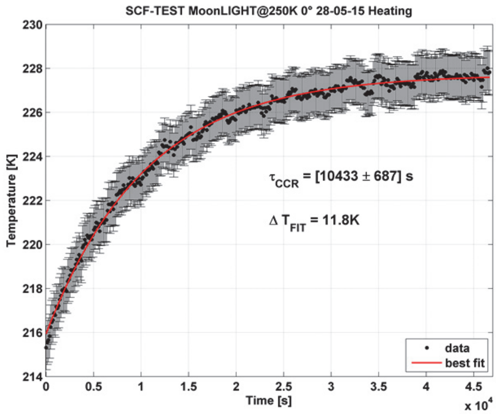

Fig. 1. Example of the FIT results for the heating phase.

Table 2. Results of the thermal analysis for the MoonLIGHT-2 SCF-Test.

Housing temperature [K]	τ_{CCR} [10^3s] Heating	Cooling	Average	Maximum ΔT [K] Heating	Cooling	Average
300	15.1±1.0	16.5±1.1	15.8±1.0	3.1±1.0	2.9±1.0	3.0±1.4
250	10.4±0.7	10.7±0.7	10.5±0.2	4.7±1.0	4.1±1.0	4.4±1.4

developed by I. Shapiro at CfA [7] and includes a detailed mathematical model of the solar system, with the masses of all solar system bodies and a large number of adjustable parameters. PEP also include the position of different Earth laser stations like APOLLO (Apache Point Observatory Lunar Laser-ranging Operation, USA) or CERGA (Centre d'Etudes et de Recherches Godynamiques et Astronomiques, France). The model parameter estimated are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C stands for Computation), O-C where: Observed is round-trip time of flight while Computed is modeled by the PEP software. The main GR tests which are being done in collaboration with CfA, are the K_{GP}, β, η and $\frac{\dot{G}}{G}$. We run two different GR simulations using the Apollo CCR array and MoonLIGHT-2 CCR.

3.1. *Sunshade simulation*

The first simulation analyze the original design of MoonLIGHT-2, equipped with a sunshade designed to block the direct sun into the CCR for most of the lunar day and reduce the exposure to lunar dust. We want to compare the MoonLIGHT-2 performances in GR tests using the former design with a sunshade and the actual without. We simulate 15 year of data from 3 MoonLIGHT-2 (45N 27.2E; 50S 35E; 65N 40W) on the Moon starting from 2013 plus any other existing array. We assume a cadence of accumulation of 30 days for APOLLO (Apache Point Observatory

Lunar Laser ranging Operations) station, 20 days or McDonald station, 14 days for CERGA station and 8 days for the ASI-Matera station. For the simulated observations the round trip timing uncertainties are 16 pico-seconds (around 5mm) for the APOLLO station and 33 ps (1 cm) for other stations on existing LRAs, and 3 ps (1 mm) for APOLLO and 7 ps (2 mm) for other stations on MoonLIGHT-2. Table 3 shows the results for this simulation. As we can see in table 3, the GR tests with the sunshade shows a slightly better accuracy compared with the case without the sunshade. The difference in the instruments performances is so little that we have preferred to choose the lighter structure, without sunshade.

Table 3. Preliminary test of GR using PEP. First row shows the formal uncertainty with sunshades version of MoonLIGHT-2, and the second row without the sunshade.

GR Test		2030	GR Test		2030
$\dot{G}/G$	With	1.1×10^{-15}	K_{GP}	With	5.3×10^{-5}
	Without	1.0×10^{-15}		Without	1.2×10^{-4}
η	With	4.9×10^{-4}	$\beta - 1$	With	1.2×10^{-4}
	Without	4.2×10^{-4}		Without	1.0×10^{-4}

3.2. *GR test improvements simulation*

In the second simulation we want to study the expected improvements in GR test using four MoonLIGHT-2 on the Moon, as will be after all the four Moon Express missions. First we use use same cadency and accuracy from previous one. Then defining the previous accuracy as STD we the simulate a long time analysis, 15y and 30y of dummy data, using 4 MoonLIGHT-2 (80N 0W; -80N 0W; 0N 80W; 0N -80W) plus any other CCR array actually installed on Moon. We repeat the simulation for 3 different accuracy value set: STD, double STD (the accuracy that is the double of the STD: 32 pico-seconds for the APOLLO station and 66 ps for others on existing LRAs; 6 ps for APOLLO stations and 3.5 ps for others on the MoonLIGHT-2) and half of STD (the accuracy is the half of the STD). In this way we want to evaluate the expected improvements in GR using different time span and different accuracy set. Table 4 shows the results for this simulation. K_{GP} shows the most significant improvement (about one order of magnitude) and mainly benefit from MoonLIGHT-2, while the other parameter benefit however of lesser, but important, improvements. It is important underline that all the simulations does not include the benefits of several upgrades already planned for LLR stations and does not include any PEP updates in the next 15-30y. In conclusion, the simulations we carried out shows the pessimistic case.

Table 4. Long term GR test the formal uncertainty for different time span and accuracy.

GR test	2013	STD accuracy 15y	STD accuracy 30y		
$\beta - 1$	2.1×10^{-4}	2.1×10^{-5}	1.6×10^{-5}		
$\gamma - 1$	9.5×10^{-4}	4.5×10^{-5}	3.7×10^{-5}		
$\dot{G}/G$	9.8×10^{-14}	1.6×10^{-14}	1.4×10^{-14}		
K_{GP}	1.3×10^{-3}	1.3×10^{-4}	7.8×10^{-5}		
GR test		Double STD accuracy 15y	Double STD accuracy 30y	Half STD accuracy 15y	Half STD accuracy 30y
$\beta - 1$		3.3×10^{-5}	2.7×10^{-5}	1.2×10^{-5}	8.5×10^{-6}
$\gamma - 1$		7.2×10^{-5}	5.2×10^{-5}	3.3×10^{-5}	2.5×10^{-5}
$\dot{G}/G$		1.5×10^{-14}	1.4×10^{-14}	1.4×10^{-14}	1.1×10^{-14}
K_{GP}		5.7×10^{-4}	3.1×10^{-4}	1.8×10^{-5}	1.7×10^{-5}

Conclusion and future works

To optimize MoonLIGHT-2 for the launch (in 2018 with the Moon Express, the first of 4 missions) we are characterizing the CCR thermal/optical properties with experimental tests and studying the GR performances with PEP simulations. The preliminary tests shows a long thermal constant (around $\times 10^4$ s) as expected, so the CCR will be not too much affected by the 14 days lunar cycle. The front face thermal gradient analysis suggest some conduction between CCR and housing, so additional test will be needed in order to reduce the gradient. The GR simulation shows two major points: we do not have significative differences in GR performances using a design with or without the sunshade, so we choose to remove it order to obtain a weight optimization; the expected improvements in the GR tests using a realistic configuration of MoonLIGHT-2 on the Moon are about one order of magnitude and K_{GP} has the most significative improvements. Other simulations will be carried out to better study this improvements.

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