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ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Performance analysis of next-generation lunar laser retroreflectors

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Received 11 July 2016; received in revised form 3 May 2017; accepted 3 June 2017

Abstract

Starting from 1969, Lunar Laser Ranging (LLR) to the Apollo and Lunokhod Cube Corner Retroreflectors (CCRs) provided several tests of General Relativity (GR). When deployed, the Apollo/Lunokhod CCRs design contributed only a negligible fraction of the ranging error budget. Today the improvement over the years in the laser ground stations makes the lunar libration contribution relevant. So the libration now dominates the error budget limiting the precision of the experimental tests of gravitational theories. The MoonLIGHT-2 project (Moon Laser Instrumentation for General relativity High-accuracy Tests – Phase 2) is a next-generation LLR payload developed by the Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory (SCF_Lab) at the INFN-LNF in collaboration with the University of Maryland. With its unique design consisting of a single large CCR unaffected by librations, MoonLIGHT-2 can significantly reduce error contribution of the reflectors to the measurement of the lunar geodetic precession and other GR tests compared to Apollo/Lunokhod CCRs. This paper treats only this specific next-generation lunar laser retroreflector (MoonLIGHT-2) and it is by no means intended to address other contributions to the global LLR error budget. MoonLIGHT-2 is approved to be launched with the Moon Express 1(MEX-1) mission and will be deployed on the Moon surface in 2018. To validate/optimize MoonLIGHT-2, the SCF_Lab is carrying out a unique experimental test called SCF-Test: the concurrent measurement of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of the CCR under thermal conditions produced with a close-match solar simulator and simulated space environment. The focus of this paper is to describe the SCF_Lab specialized characterization of the performance of our next-generation LLR payload. While this payload will improve the contribution of the error budget of the space segment (MoonLIGHT-2) to GR tests and to constraints on new gravitational theories (like non-minimally coupled gravity and spacetime torsion), the description of the associated physics analysis and global LLR error budget is outside of the chosen scope of present paper. We note that, according to Reasenberg et al. (2016), software models used for LLR physics and lunar science cannot process residuals with an accuracy better than few centimeters and that, in order to process millimeter ranging data (or better) coming from (not only) future reflectors, it is necessary to update and improve the respective models inside the software package. The work presented here on results of the SCF-test thermal and optical analysis shows that a good performance is expected by MoonLIGHT-2 after its deployment on the Moon. This in turn will stimulate improvements in LLR ground segment hardware and help refine the LLR software code and models. Without a significant improvement of the LLR space segment, the acquisition of improved ground LLR hardware and challenging LLR software refinements may languish for lack of motivation, since the librations of the old generation LLR payloads largely dominate the global LLR error budget.

Keywords: Lunar laser retroreflector; Far Field Diffraction Pattern; Thermal relaxation time

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http://dx.doi.org/10.1016/j.asr.2017.06.005
0273-1177/

Please cite this article in press as: Ciocci, E., et al. Performance analysis of next-generation lunar laser retroreflectors. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.06.005

1. Introduction

LLR (Bender et al., 1973; Murphy, 2012) provides accurate measurements of the lunar orbit through high-precision data collected between a laser station on Earth and a CCR array on lunar surface. LLR has provided for decades the best tests of the validity of Einstein's theory of GR with measurements of the weak and strong equivalence principle (through the Nordvedt parameter η), the Parametrized Post Newtonian (PPN) parameters β and γ, the time change of the Gravitational Constant, the Geodetic Precession (K_{GP}) and $1/r^2$ deviations (Alley et al., 1970; Bender et al., 1973; Nordtvedt, 1995). Over the years, LLR has benefited from a number of improvements in both observing technology and data modeling. These improvements have led to the current precision of $\sim$2 cm (Williams et al. (2004). Actually one of the best GR test carried out using the old CCRs and LLR was provided in Williams et al. (2004) and Martini et al. (2012)). Since this paper is focused on the analysis of the MoonLIGHT-2 performance test we refer to Martini and Dell'Agnello (2016), Martini (2016) and Lops and Martini (2011) for further details about the test improvement results in General Relativity.

Unfortunately, the current multi-ccr geometry of the CCR array installed on the Moon significantly limits further improvements, mainly due to librations that results from the eccentricity and inclination of the Moon orbit around Earth (Lops and Martini, 2011; Martini and Dell'Agnello, 2016). Because of this phenomenon, one corner of the old array is more distant from the Earth by several centimeters with respect to the opposite one, broadening the pulse coming back to Earth surface as shown in Fig. 1 (Martini et al., 2012). The broadening of the pulse depends on the array physical dimensions and to the beam angle of incidence. For example, it is about 30 cm (± 1 ns time of flight increase) for the Apollo 15 array, and about 15 cm (± 0.5 ns time flight increase) for the smaller Apollo 11 and Apollo 14 arrays. Also, looking at Clarke et al. (2013), we have a significative part of the error budget coming from the laser ground stations. With the present technology one of the biggest error source comes from the RMS of the available single photons (few centimeters).

Nowadays using as reference Murphy (2012), the lunar libration contributes the largest part of the error budget, about 15–50 mm. By averaging over N lunar returns, a laser ground station such as APOLLO (Apache Point Observatory Lunar Laser ranging Operation) can reduce the range of uncertainty by the square root of N. In fact, the author claims that can reach mm level accuracy with over hour long session and that Apollo array provide a better return about one order of magnitude respect to Lunokhod ones. In order to achieve the desiderated millimeter level we need upgrade on the ground segment (laser stations) and also on the space segment (lunar retroreflectors).

From the space segment point of view, the SCF_Lab in collaboration with the University of Maryland (Currie et al., 2011), developed a new design of lunar CCR whose performance is unaffected by either lunar librations or regolith motion, thanks to its very large thermal cycle. The design employs a single large CCR (100 mm of front face diameter) instead of an array with many small retroreflector, and each "big CCR" is deployed separately on the

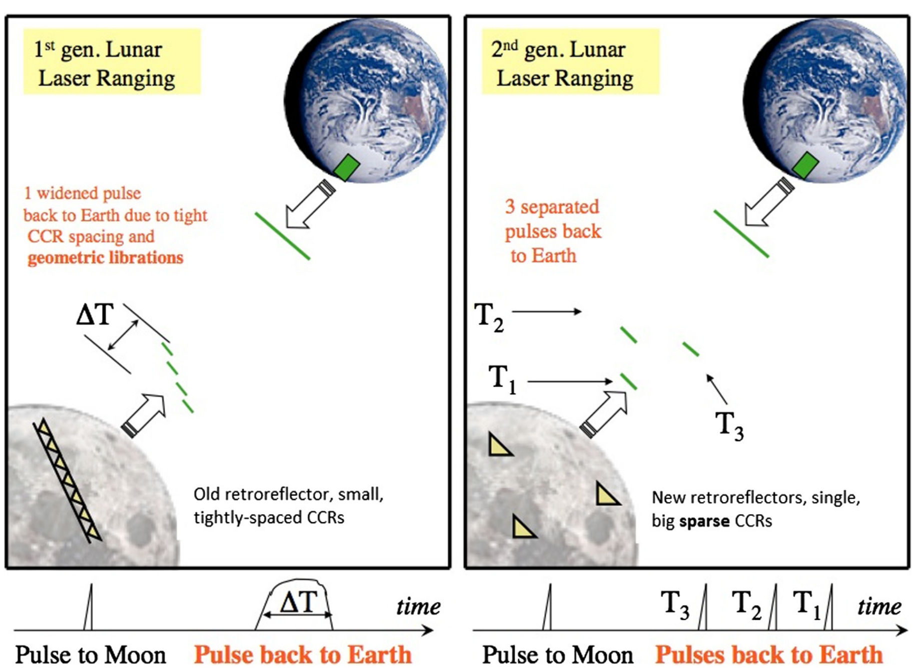

Fig. 1. Differences between first and second generation of lunar laser retroreflector.

Please cite this article in press as: Ciocci, E., et al. Performance analysis of next-generation lunar laser retroreflectors. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.06.005