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The Moon as a test body for General Relativity and new Gravitational Theories

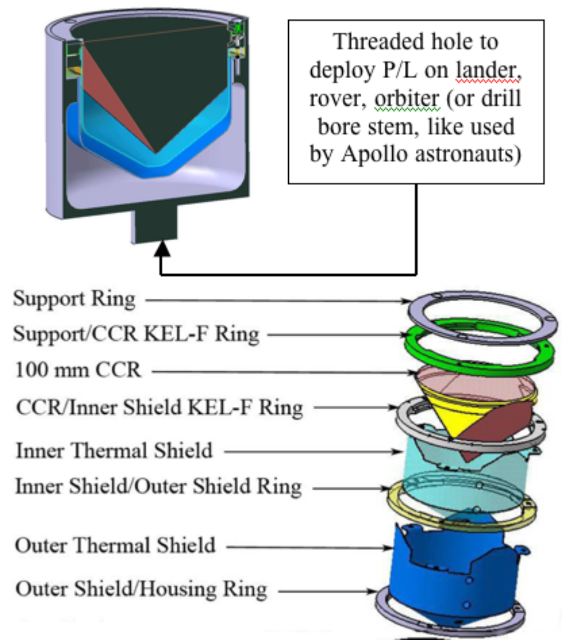
S. Dell'Agnello (1), G.O. Delle Monache (1), D.G. Currie (2), **M. Martini** (1), C. Lops (1), M. Garattini (1), R. March (3), G. Bellettini (4), R. Tauraso (4), J.B. Battat (5), G. Bianco (6), T.W. Murphy Jr (7), A. Coradini (8), J.F. Chandler (9) A. Boni (1), C. Cantone (1), M. Maiello (1), L. Porcelli (1), S. Berardi (1), N. Intaglietta (1), G. Patrizi (1)
(1) INFN-Laboratori Nazionali di Frascati (LNF), via E. Fermi 40, 00044, Frascati (RM), Italy; (2) University of Maryland (UMD), Dept. of Physics College Park Maryland 20742 MD, USA & INFN-LNF & NLSI; (3) INFN - LNF and CNR-Istituto per le Applicazioni del Calcolo (IAC), viale del Policlinico 137, 00161, Rome, Italy; (4) INFN - LNF and Department of Mathematics, University of Rome "Tor Vergata", via della Ricerca Scientifica, 00133, Rome, Italy; (5) Massachusetts Institute of Technology (MIT), Dept. of Physics 77 Massachusetts Avenue, Cambridge, MA 02139, USA; (6) ASI, Centro di Geodesia Spaziale "G. Colombo" (ASI-CGS), Matera, Italy; (7) University of California at San Diego, Dept. of Physics 9500 Gilman Drive, La Jolla, CA 92093-0424, USA; (8) INAF - Istituto di Fisica dello Spazio Interplanetario (IFSI), via Fosso del Cavaliere 100, 00133, Rome, Italy; (9) Center for Astrophysics, Harvard University, Cambridge, Massachusetts 02138, USA

Abstract

Since 1969 Lunar Laser Ranging (LLR) to the Apollo Cube Corner Reflector (CCR) arrays has supplied several significant tests of General Relativity (GR): it has evaluated the Geodetic Precession, probed the weak and strong equivalence principle, determined the PPN parameter β, addressed the time change of G and $1/r^2$ deviations.

Because of lunar librations, the Apollo arrays dominate the LLR error budget, which is a few cm. The University of Maryland, Principal Investigator for the Apollo arrays, and INFN-LNF are developing and space-testing at the Frascati "Satellite/Lunar laser ranging Characterization Facility" (SCF) an innovative CCR array design that will reduce the error contribution of LLR arrays by more than two orders of magnitude, down to tens of microns. This is the goal of the MoonLIGHT technological experiment of INFN (Moon Laser Instrumentation for General relativity High-Accuracy Tests). Current payload prototype is shown in fig. 1 (CCR provided by NASA through UMD and mechanical design and assembly provided by INFN).

We also show that the Moon equipped with retroreflectors can be used effectively to test new gravitational theories beyond GR, like spacetime torsion (developed by some of the authors; paper in preparation).



1. Introduction

Over the past 40 years, lunar laser ranging from a variety of observatories to retroreflector arrays placed on the lunar surface, have increased our understanding of gravitational physics.

At present, technological improvements in the ground-based segment of LLR are rendered futile by the 40 year old arrays on the moon. Installation of retroreflectors was a key part of the Apollo missions and it is natural that future lunar missions should include them[1].

Progress in LLR enabled science is limited by the properties of current retroreflectors arrays and by their distribution on the lunar surface.

2. General Relativity with LLR

In table 1 we show the general relativity test that have been carried out using LLR.

Science Measured	Time scale	Accuracy (cm) [2]	1 mm	0.1 mm
PPN, β	Few years	$1.1\text{x}10^{-4}$	10^{-5}	10^{-6}
WEP	Few years	$1.4\text{x}10^{-13}$	10^{-14}	10^{-15}
SEP	Few years	$4.4\text{x}10^{-4}$	$3\text{x}10^{-5}$	$3\text{x}10^{-6}$
Time variation of G	5 years	$9\text{x}10^{-13}$	$5\text{x}10^{-14}$	$5\text{x}10^{-15}$
$1/r^2$	10 years	$3\text{x}10^{-11}$	10^{-12}	10^{-13}
K_{GP}	Few years	$6.5\text{x}10^{-3}$	$6.5\text{x}10^{-4}$	$6.5\text{x}10^{-5}$

Table 1: General Relativity science objectives

In collaboration with J. Chandler, J. Battat and T. Murphy, we are using a software called PEP (Planetary Ephemeris Program) developed by Center for Astrophysics. This software is designed not only to generate ephemerides of the planets and Moon, but also to compare models with observations.

There are a diverse set of observations that PEP can handle, but we care primarily about LLR observations. In particular, the software is able to calculate the residuals of the distances between observed data, coming from measurements acquired by LLR, and computed data, derived from expectations of GR and of terrestrial and lunar Geodesy. We have performed a very preliminary analysis of LLR data from three stations: McDonald Observatory in Texas (USA), Grasse in France and APOLLO in New Mexico (USA). The latter station provides the best quality data since 2006.

In fig.2 [3] we show an example of single LLR normal point. In the top panel we show a window of observed round trip time minus the predicted range; the middle panel shows the lunar returns and the bottom panel shows the fiducial CCR return.

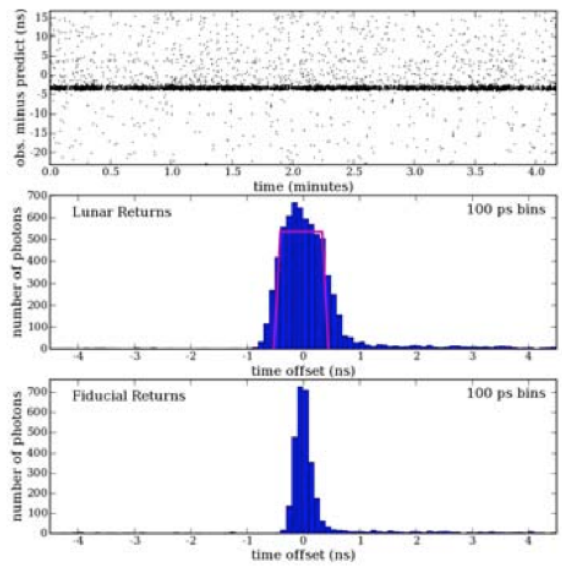


Figure 2: Single LLR normal point.

Using PEP is also possible to solve partial equations to estimate parameter values. For example, we have set the values of PPN parameter β and γ to 1.0 and the best fit output are:

$\beta = 0.999591$

$\gamma = 0.99798$

At this stage, this is not meant to be any kind of measurement or error analysis, but some figure of merit of our initial understanding of PEP, in view of a long-term work in collaboration with CfA and the APOLLO team.

References

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