MoonLIGHT: a 2nd Generation Lunar Laser Ranging Payload for Precision Gravity and Geodesy Measurements and for the ILN

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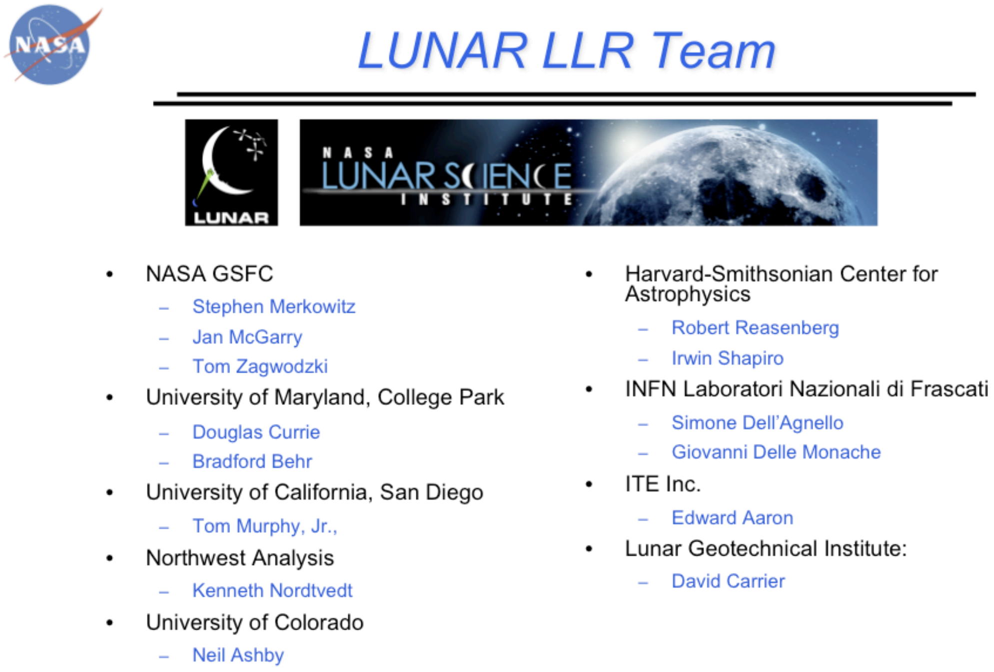
INTRODUCTION

Over the past forty years, Lunar Laser Ranging (LLR) to the Apollo Cube Corner Reflector (CCR) arrays deployed on the surface of the Moon has supplied almost all of the significant tests of General Relativity (GR), that is, it has evaluated the Geodetic Precession (de Sitter), the PPN parameter β and addressed the possible change in the gravitational constant and the self-energy of the gravitational energy and deviations from the $1/r^2$ force law. In addition, it has provided significant information on the composition (interior) and origin of the Moon through measurement of its rotations and tides. Current and future CCR payloads on the surface of the Moon will form a high-accuracy and permanent "International Moon Reference Frame (IMRF)", referenced with LLR to its terrestrial analogue, the ITRF. The IMRF, together with lunar altimetry and gravity maps provided by current orbiters, will help the lunar exploration and colonization. The ITRF and IMRF will be the reference frame for positioning metrology in the Earth-Moon system, fostering evolutionary and continuously improving gravitational and geophysics science. Initially the Apollo lunar arrays contributed a negligible portion of the error budget used to achieve these results. Over the decades, the performance of ground stations has greatly improved so that the ranging accuracy has improved by more than two orders of magnitude. Now, the existing Apollo CCR arrays contribute significantly to the current limiting error to the range measurements, which is 2 cm. The University of Maryland, which was the Principal Investigator for the original Apollo arrays is now proposing, with INFN-LNF as Co-PI, a new approach to the lunar laser CCR array technology, an innovation over the Apollo arrays and current satellite retroreflector payloads. Thus, after installation on the next lunar landing, either robotic or manned, the new arrays will reduce the error contribution of the space segment of LLR by more than two orders of magnitude, from the centimeter level to the 10 micron level. To achieve this goal we will also take major advantage of the new APOLLO LLR station at Apache Point, USA, which already now is capable of mm-level measurements, and of other ILRS stations. The MLRO station in Italy is restarting LLR operations. The new fundamental physics tests that this program can provide are described.

In the design of the new array, there are three major challenges: 1) address the thermal and optical effects of the absorption of solar radiation within the CCR; 2) reduce the transfer of heat from the hot housing and from the rapid temperature changes of the regolith to the CCR and 3) define a method of emplacing the CCR package on the lunar surface such that it is stable over the lunar day/night cycle. The design approach, the computer simulations using Thermal Desktop and the housings of the new CCR that have been built by INFN-LNF are presented. Thermal and optical vacuum testing will be conducted at the "Satellite/lunar laser ranging Characterization Facility" (SCF) at INFN-LNF, Frascati. Structural payload analysis with ANSYS is in progress.

The investigation of this new technology is currently supported by two NASA programs (LSSO, the Lunar Sortie Scientific Opportunities, and NLSI, the NASA Lunar Science Institute) and by the INFN MoonLIGHT-ILN technological experiment. This new CCR concept for 2nd Generation LLR is being proposed for the robotic missions of the International Lunar Network (ILN), NASA's Manned Landings, for a precursor test on the MAGIA lunar orbiter mission proposed to the Italian Space Agency and for ESA's first lunar lander. This effort is also part of a scientific study for an LLR mission that has been submitted by an extended group of scientists (see fig. 1) to the US Astro2010's Particle Astrophysics and Gravitation (PAG) Program Prioritization Panel (PPP). This was a study, not a proposal, since no announcement of opportunity has been issued so far.



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  - Giovanni Delle Monache
- ITE Inc.
  - Edward Aaron
- Lunar Geotechnical Institute:
  - David Carrier

Figure 1. The extended LUNAR LLR group.

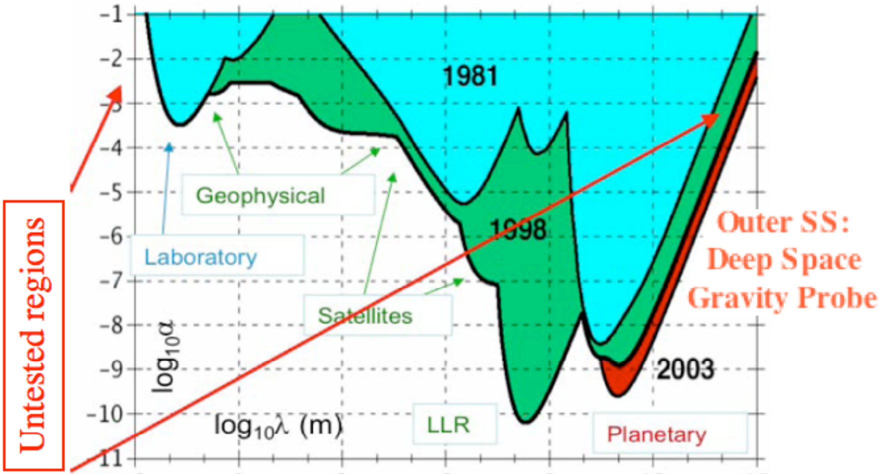
PRECISION GRAVITY TESTS WITH 2ND GENERATION LLR

The three Apollo and the Lunokhod arrays have provided the best evaluation of General Relativity of any experiment [1]. In particular, LLR gives the most accurate measurements of the De Sitter effect in GR, of the PPN parameter β and of Yukawa-like deviations from the $1/r^2$ force-law. Together with laboratory tests with torsion balances, LLR gives the most accurate test of the Weak Equivalence Principle (WEP). It also allows for a unique, 10^{-4}-level test of the Strong EP (SEP). The EP is the heart of GR. Current limits are shown in Table 1, together with the tighter constraints that can be reached with a 2nd generation CCR array.

Table 1. Limits on gravity tests based on 1st and 2nd generation LLR.

Gravity Science Measurement	**1st Gen. Limit** with Current LLR Accuracy (cm)	**2nd Gen.** Limit with 1 mm LLR	**2nd Gen.** Limit with 0.1 mm LLR	**Timescale**
Weak Equivalence Principle (WEP)	$\lvert\Delta a/a\rvert < 1.3 \times 10^{-13}$	10^{-14}	10^{-15}	Few years
Strong Equivalence Principle (SEP) Nordtvedt parameter η	$\lvert\eta\rvert < 4.4 \times 10^{-4}$	3×10^{-5}	3×10^{-6}	Few years
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert < 1.1 \times 10^{-4}$	10^{-5}	10^{-6}	Few years
Time Variation of Gravitational Constant	$\lvert dG/dt/G\rvert < 9 \times 10^{-13}$/yr	5×10^{-14}/yr	5×10^{-15}/yr	~ 5 years
Inverse Square Law (ISL), Yukawa parameter α	$\lvert\alpha\rvert < 3 \times 10^{-11}$	$\sim 10^{-12}$	$\sim 10^{-13}$	~ 10 years

Fig. 2 shows the limit on deviations from the inverse-square force law with several types of experiments. LLR gives the best limit on possible deviations due to an additional Yukawa potential (equal to $\alpha\times10^{-r/\lambda}$ times the classic Newtonian potential) at distances around the Earth-Moon distance.



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

Fig. 2. Limits on deviations from the $1/r^2$ force law (courtesy of J. Coy et al).

In 2006 a 2nd generation LLR experiment (LLRA21, Lunar Laser Ranging Retro-reflector Array for the 21st Century) has been proposed to LSSO, target to manned landings, by a US-Italy team led by UMD (PI is D. G. Currie) and co-led by INFN-LNF. The Italian team participates at zero cost for NASA. In 2006, INFN-LNF and UMD also proposed a robotic version of the project, MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests) for the ASI Study “Observation of the Universe from the Moon”. For NASA and ASI we developed a new LLR payload capable of improving the space segment contribution to LLR by a factor 100 or more. This will be achieved by replacing the 38 mm Apollo CCRs with a distributed array of single, large, 100 mm diameter CCRs, separated by few tens of meters (depending on the latitude) in order that their laser returns yield separate signals on the Earth detectors. Such an array will not suffer from the time broadening of the return pulse from the Apollo arrays due to the Moon librations. This effect currently dominates the error budget and limits the LLR accuracy to ~2 cm (see fig. 3).

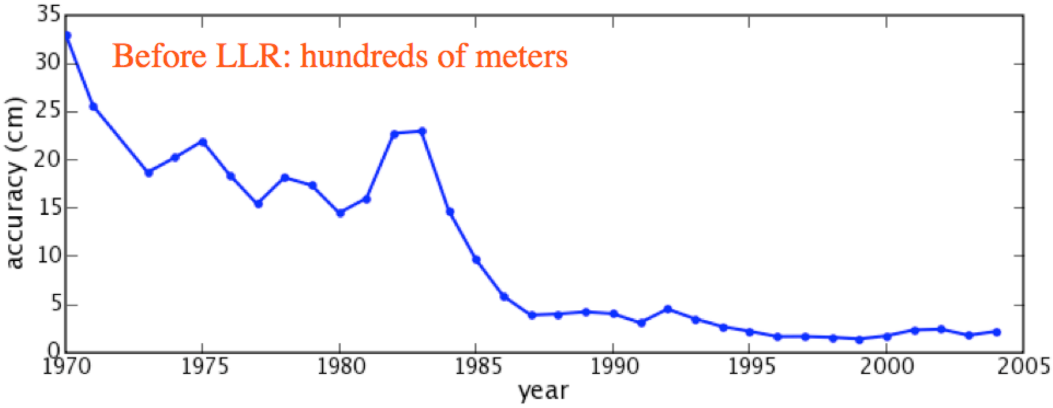


Fig. 3. Historical accuracy of 1st generation LLR.

Note that the replacement of the Apollo CCRs must be followed by improvements of the ground segment of LLR, that is, of the atmospheric corrections, hydrogeological loading of the Earth crust, laser pulse length, laser readout electronics, etc. In the decades following the Apollo missions, the wide geodesy, planetology and laser communities made very significant progress in their fields, which allowed for the major success of 1st generation LLR shown in fig. 3. SCF thermal testing of the LSSO CCR was done in 2008 (fig. 4) at INFN with the measurement of the CCR solar absorptivity. This drives the thermal distortions of the optical far field diffraction pattern back to the Earth. The CCR has been manufactured with 0.2 arcsec dihedral angle offsets specs, a factor 2.5 tighter than the standard. The FFDP test of the CCR inside the SCF is planned for spring of 2009. This SCF-Test is an effective and innovative tool for precision measurements of gravity and space geodesy and to augment the capabilities of the GNSS [2].

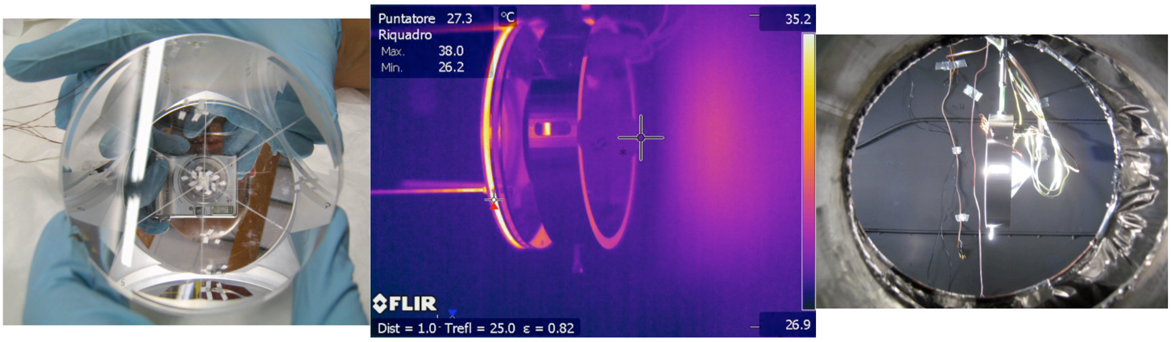


Figure 4. The MoonLIGHT CCR (left); CCR under thermal test in the SCF (left photo); CCR thermogram (central IR photo).

We are working on new gravity theories that can be tested with LLR. A new theory that can be tested with 2nd generation LLR is the braneworld theory of [3]. This is a unified quantum theory of weak gravity at horizon scales, which explains the apparent acceleration of the universe without Dark Energy and predicts a correction to the Moon geodetic precession of slightly less than 1mm/orbit. For comparison the GR geodetic precession is about 3m/orbit and is currently well measured with a precision of 2 cm. This theory cannot be tested with 1st generation LLR, but it will be well in the domain of an LLRA21/MoonLIGHT array.

THE INTERNATIONAL LUNAR NETWORK (ILN)

On July 24, 2008 many space agencies, including ASI, met for the second time at NASA-AMES and signed a Statement of Intent (SoI) to establish a network of 6 to 8 (or more) nodes of pre-agreed core instruments deployed with robotic missions. The ILN official site is http://iln.arc.nasa.gov/. The Signed statement of intent can be found at http://iln.arc.nasa.gov/statement_intent. Agency representatives are the ILN Agency Steering Group (ASG), chaired by J. L. Green, Director of NASA SMD/Planetary Science Division. The following working groups were also formed with members of the international scientific community designated by the national space agencies: Core Instrument Working Group (CIWG, in which INFN-LNF participates); Communications; Enabling Technologies (particularly devoted to the generation of power on the Moon) and Site Selection (formed in summer 2009).

NASA is preparing a mission, now in Phase A, to establish four initial “Anchor Nodes”. The US science definition team (SDT) completed a final report, which foresees a ‘baseline mission’ with four core instruments per node. The report also states: “*The SDT recommends that the Anchor Nodes operate as part of a larger network for a minimum of six years to capture the 6-year lunar tidal period*”.

The CCR developed for LSSO and studied for ASI could be a natural candidate for the ILN (if expectations on the space FFDP performance are confirmed by SCF-Testing and further modeling). To get the factor >100 improvement we need the capability of emplacing the payload such that it is in good thermal contact with the isothermal regolith at the depth of about 1 meter. Thus, a synergy is possible with the any drilling work, like the one required for the heat-flow experiment. A description of our work has been submitted by UMD on Dec. 19, 2008, in response to the Request for Information (RFI) issued by NASA for its Anchor Nodes. A similar response has been submitted by INFN-LNF on Apr. 14, 2009, for the Request for Information (RFI) issued by ESA for its first lunar lander.

We report some conclusions of the CIWG work at the 3rd ILN meeting, which took place in Yokohama (Japan) on March 12-13, 2009. The CIWG finalized its Term of Reference, defined the ILN as “few-msec simultaneous and/or multi-site measurements”, identified areas of common participant interest and finalized a list of four core science objective/instruments:

- Seismometry
- Heat flow
- E&M sounding
- Laser Ranging for Lunar Geodesy and Test of General Relativity.

The CIWG also identified a list of “outer” core science/instrument list: (i) Exploring un-sampled lithology; (ii) VLBI to measure the Moon rotation; (iii) New astronomy from the Moon (including radio observations from the far side); (iv) New Fundamental Physics (including unified theories like [3] and strange quark matter [4]). Unlike for US Anchor Nodes, the above ILN lists are not prioritized. All landing site activities will require knowledge of the geological context (ie, it will required a Camera). The CIWG and the ILN Steering Group agree that this is a living list and that to finalize its work the CIWG will produce a White Paper to be approved at the 4th ILN meeting, that will take place in Europe in December 2009.

We believe that in the long-term the ILN nodes will define the International Moon Reference System (IMRF), referenced to the ITRF: near (far) side nodes will be referenced with respect to the ITRF by direct LLR and radio/mw measurements (relay satellites); ILN nodes will also provide an absolute altitude reference to orbiters instrumented with a laser or radio altimeters.

PAYLOAD THERMAL DESIGN AND EMPLACEMENT ON THE LUNAR SURFACE

Particular care has been devoted to the payload thermal design and to the choice of the materials used for the CCR mounting cavity. The payload assembly drawing shown in fig. 5 illustrates the mounting of the CCR (designed to withstand the launch environment and yet have a very low thermal conductivity) and the internal shield to prevent the hot housing from radiating heat to the CCR and thus degrading the FFDP. The internal shield is coated, inside and out, with polished gold with <2% emissivity).

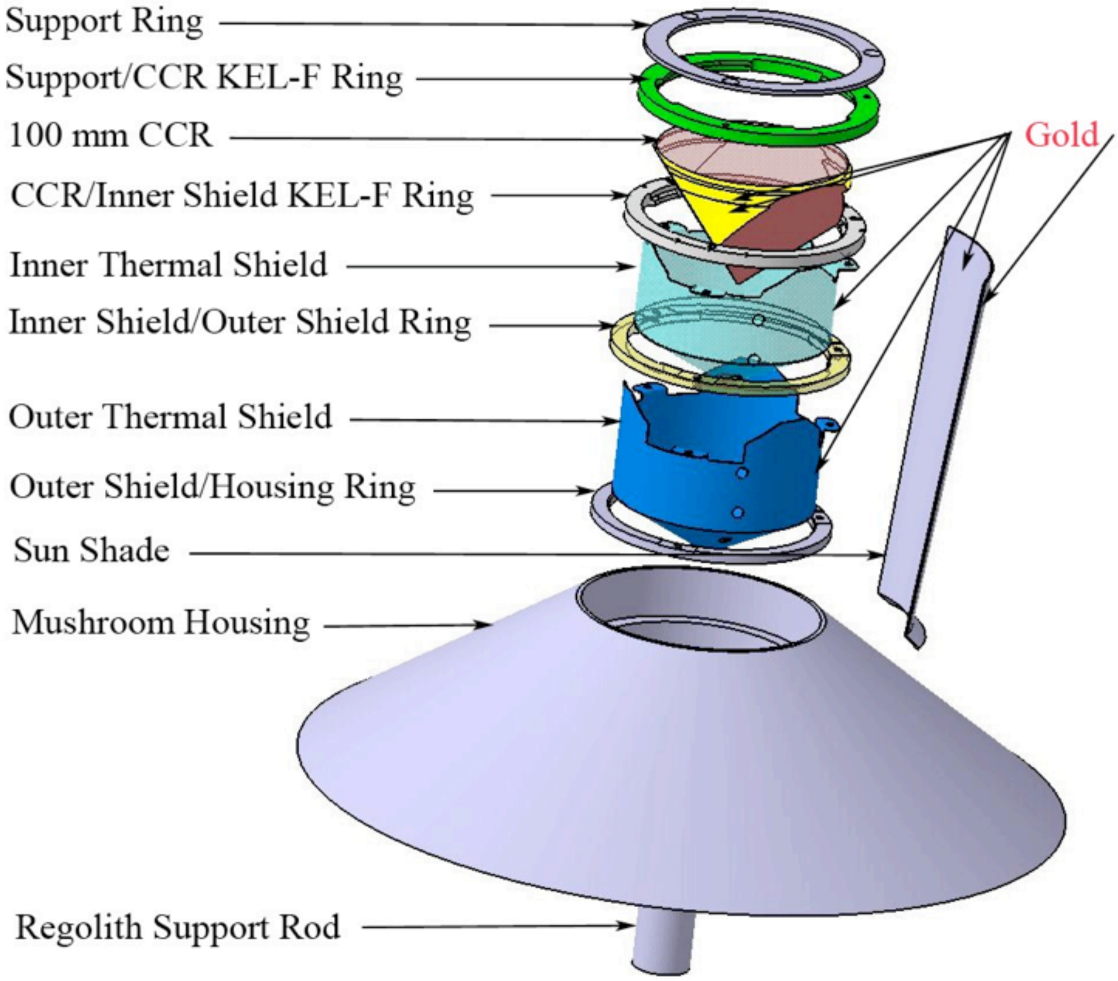


Figure 5. Illustration of current MoonLIGHT payload design. The lower ring KEL-F plastic has line inserts to reduce heat flow from the cavity to the CCR. This is an improvement of the Apollo and LAGEOS design.

The assembly scheme of fig. 5 is to be completed by an outer housing (Mushroom or “Bubbola”, in Italian), which surrounds the inner housing and optimizes the response to the external thermal environment (solar and IR radiation from regolith). It absorbs little of the solar radiation and has a high emissivity on the top. The angle prevents strong heating from the lunar regolith. The bottom is close to the surface to shield the portion of the thermal blanket under the outer housing from the solar radiation.

The emplacement into the lunar soil will be done with an Invar or ULE foot (which could be the drilling tool itself), inserted ~1m meter deep into the regolith, where the temperature has only a few degree K excursion. A 2m×2m thermal blanket will be deployed around the CCR to stabilize locally the environment. We are performing detailed simulations to model the temperature distribution in the regolith to address the effect of the proposed MLI thermal blanket. The purpose of this thermal blanket is to isolate the regolith mounting of the CCR from the thermal and mechanical effects of the lunar day/night cycle in the regolith. Simulations indicate that the temperature under the blanket changes very little.

THE ASI LUNAR ORBITER MISSION MAGIA

In February 2008 ASI approved for Phase A study five proposals presented in response to the call for "Small Missions" issued in 2007. One of these is MAGIA (Missione Altimetrica Gravimetrica GeochImica Lunare), an altimetry, gravimetry and geochemistry lunar orbiter mission. The MAGIA Principal Investigator is A. Coradini of INAF-IFSI Rome, the Prime Contractor is Rheinmetall Italia S.p.A.

Using two retroreflector, atomic clock, accelerometer and radio science payloads, INFN and UMD proposed for MAGIA the improved measurement of the gravitational redshift, a precursor test of the functionality of the MoonLIGHT CCR and a direct measurement of the position of the selenocenter with respect to the ITRF. The latter will reference the altimetry and the gravity models of MAGIA to the ITRF, thanks to the precise and absolute positioning granted by two onboard CCR arrays. The redshift measurement will provide a high-level validation of the gravity model built with the MAGIA radio science experiment and the accelerometer. In the future accurate Moon altimetry models will be needed to select landing sites, while more and more accurate gravity models will ensure that spacecrafts can safely navigate to and return from the Moon. Concerning the ILN goals, the MAGIA PI expressed the hope that the science goals of current and future orbiter missions and of the ILN be kept complementary and synergetic.

The Phase A study was completed and the proposal for the following B/C/D/E/F Phases was submitted to ASI in December 2008. The MAGIA industrial and scientific team is now awaiting the ASI decision.

ACKNOWLEDGMENTS

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