A Lunar Laser Ranging Array for NASA's Manned Landings, the International Lunar Network and the Proposed ASI Lunar Mission MAGIA

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Abstract

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 PPN parameters and addressed, for example, the possible change in the gravitational constant and the self-energy of the gravitational energy. In addition, it has provided significant information on the composition and origin of the Moon through measurement of its rotations and tides. 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, after forty years, the existing Apollo retroreflector arrays contribute significantly to the limiting error to the range measurements. The University of Maryland, which was the Principal Investigator for the original Apollo arrays, is now proposing a new approach to the lunar laser CCR array technology. The investigation of this new technology is currently being supported by two NASA programs (LSSO, the Lunar Sortie Scientific Opportunities, and CAN, a NASA Lunar Science Institute Cooperative Agreement Notice) and by INFN. Thus, after installation on the next lunar landing, the new arrays will reduce the contribution of the lunar emplacement by more than two orders of magnitude, from the centimeter level to the micron level. The new fundamental physics and the lunar physics that this can provide will be discussed. 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 will be presented. Thermal and optical vacuum testing will be conducted at the "Satellite/lunar laser ranging Characterization Facility" (SCF) at INFN-LNF, Frascati. Finally, we also discuss the innovations over the Apollo arrays and current satellite retroreflector packages. This new concept for a CCR for Lunar Laser Ranging is being considered for the NASA Manned Lunar Landings, for the NASA Anchor Nodes of the

International Lunar Network and for the MAGIA lunar orbiter mission proposed to the Italian Space Agency.

Second Generation Lunar Laser Ranging for the 21st Century

The three Apollo and the Lunakhod arrays have provided the best evaluation of General Relativity of any experiment. In particular, LLR gives the most accurate measurements of the De Sitter effect in GR (PPN parameter □) and of Yukawa-like deviations from the $1/r^2$ force-law. Together with laboratory tests at very small distances, LLR gives the most accurate test of the Weak Equivalence Principle (EP). It also allows for a unique, 10^{-4}-level test of the Strong EP. 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 current, first generation LLR data and expected physics reach for second generation LLR.

Phenomenon	1st Generation Limit with current LLR accuracy	2nd Generation Limit with 1 mm LLR	2nd Generation Limit with 100 ⌈m LLR	Measurement Time scale
Weak Equivalence Principle, WEP ($\otimes a/a$)	10^{-13}	$\sim 10^{-14}$	$\sim 10^{-15}$	2 yr
Strong Equivalence Principle, SEP (Nordvedt parameter)	4×10^{-4}	$\sim 10^{-5}$	$\sim 10^{-6}$	2 yr
Gdot/G	10^{-12}/yr	$\sim 10^{-13}$/yr	$\sim 10^{-14}$/yr	4 yr
Geodetic Precession (PPN param. ®)	$\sim 5 \times 10^{-3}$	5×10^{-4}	$\sim 5 \times 10^{-5}$	6-10 yr
Deviations from $1/r^2$ (Yukawa parameter $\langle$)	10^{-10}	$\sim 10^{-11}$	$\sim 10^{-12}$	6-10 yr

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 UMCP (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 UMCP also proposed a robotic version of the project,

Figure 1. Limits on Yukawa deviations from the $1/r^2$ force-law.
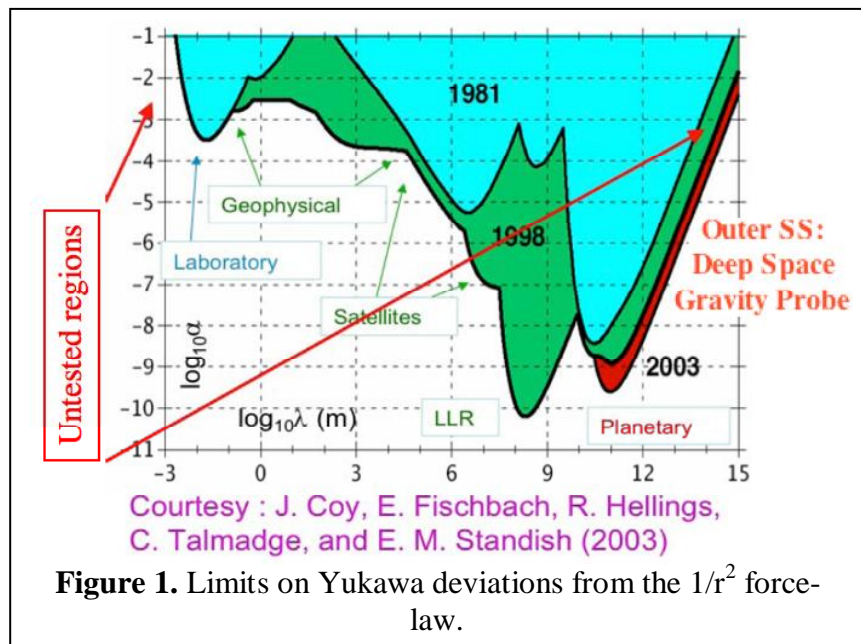
MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests) for an ASI Study (Observation of the Universe from the Moon). For NASA and ASI we developed a new LLR payload capable of improving the space segment contribution to LLR by a factor 100 or more. This will be achieved by replacing the 38mm Apollo CCRs with a sparse array of single, 100mm CCRs, separated by few tens of meters 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. 2). 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

Figure 2. Historical accuracy of 1st generation LLR.

the Earth crust, laser pulse length, laser readout electronics, etc. In the decades following the Apollo missions, the wide geodesy, planetology and laser-user communities made very significant progress in their fields, which allowed for the major success of 1st generation LLR shown in Fig. 2.
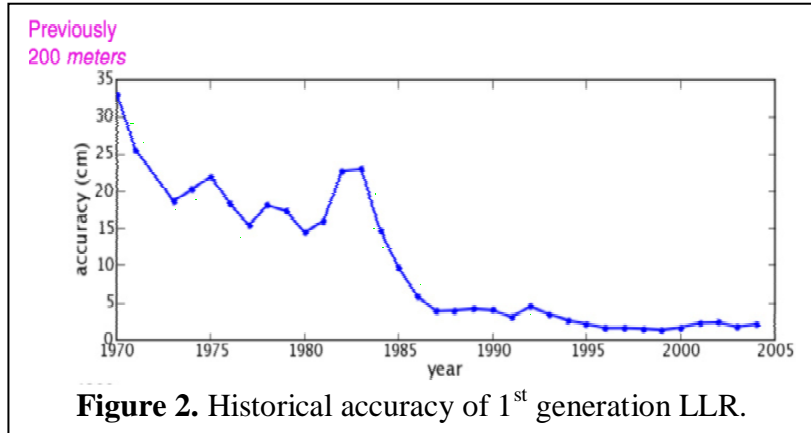
SCF thermal testing of the LSSO CCR was done in 2008 (fig. 3) at INFN with the measurement of the CCR solar absorptivity (3-4%). This drives the thermal distortions of the optical far field diffraction pattern back to the Earth. The CCR has been manufactured with 0.2 arcsec dihedral angle offsets specs, 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 experimental tests of gravity, GNSS and space geodesy [1].
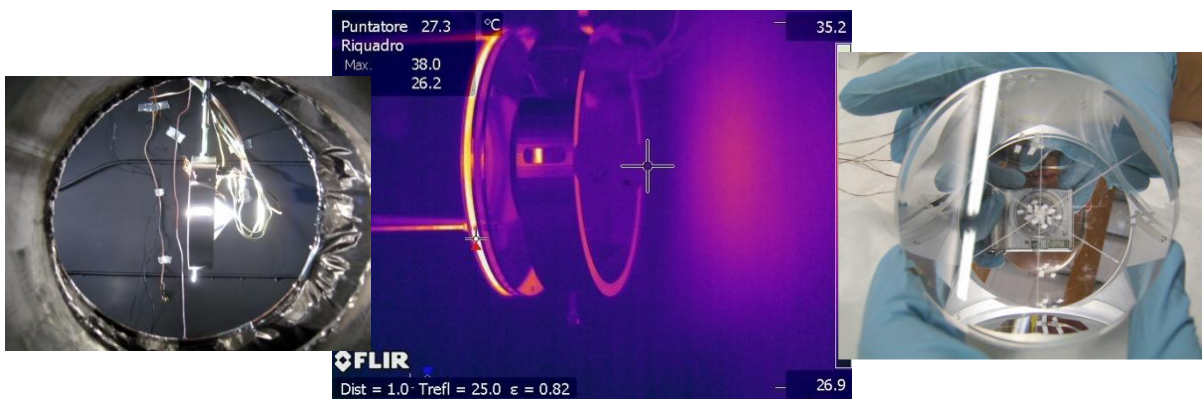

Figure 3. LSSO CCR (top left). Thermal test in SCF: bottom left photo and right (IR photo).

A new theory that can be tested with 2nd generation LLR is the braneworld theory of [2]. 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 by about 1mm/orbit. The GR geodetic precession is about 3m/orbit and is currently well measured with a precision of 2 cm. This braneworld theory cannot be tested with 1st generation LLR but it will be weill in the domain of an LLRA21/MoonLIGHT array.

The International Lunar Network (ILN)

On July 24, 2008 space agencies (including ASI) met for the 2nd time at NASA-AMES and signed a Statement of Intent (SoI) to establish a network of 6 to 8 nodes of agreed core instruments deployed with robotic missions [3]. Agency representatives are called the ILN Steering Group, chaired by J. L. Green, Director of NASA SMD/Planetary Science Division. 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; Site Selection, to be formed in spring 2009.

NASA is preparing a mission, now in Phase A, to establish four initial "Anchor Nodes" with a single ATLAS V launch no earlier than 2016. The US science definition team (SDT) completed a final report, which foresees a "baseline mission" with four core instruments per node (in priority order: seismometer, heat-flow probe, E&M sounding, CCR) and a "floor" mission only one instrument (the seismometer). 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.* It is not clear which country will lay the 1st ILN node.

The SDT specs for the CCR are: ~10cm diameter, ~1Kg reflector weight (with ~1Kg extra weight for the CCR deployment). The CCR developed for LSSO and studied for ASI meets these specs, and it 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 as described below and shown in fig. 5 and 6. 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 UMCP on Dec. 19, 2008, in response to the Request for Information (RFI) issued by NASA for its Anchor Nodes. Other responses to this RFI have been submitted by the Italian scientific community.

Additional missions, which could contribute to the ILN are MoonLITE by the BNSC and Selene-2 by JAXA, both now in Phase A. MoonLITE includes a relay satellite and 5 penetrator payloads for geophysics studies. Selene-2 includes one orbiter and two landers.

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/instrument:
- 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 unsampled 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 [2] 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 next ILN meeting (the 4th).

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.

Thermal Design and Emplacement of the Payload for NASA's LSSO and the ASI Study

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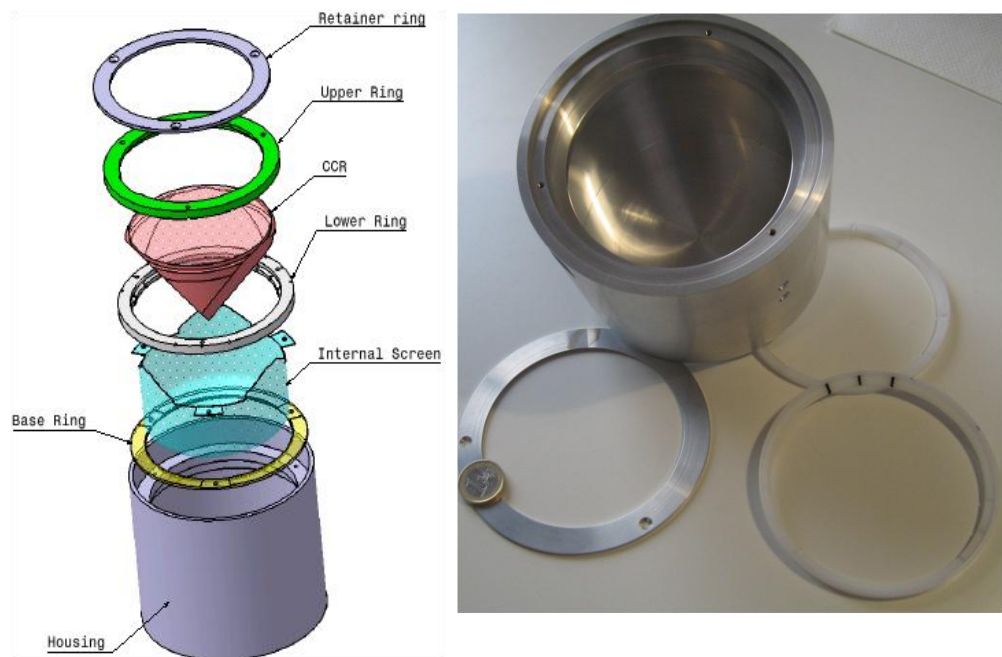

Figure 4. Illustration (photo) of 2nd (1st) CCR housing built at LNF show at left (right). The lower ring (to be made of KEL-F plastic) has line inserts (in black) to reduce heat flow from the cavity to the tabs of the CCR. This is an improvement of the Apollo and LAGEOS design.

The emplacement of the latter into the lunar soil will be done with an Invar or ULE foot, 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.
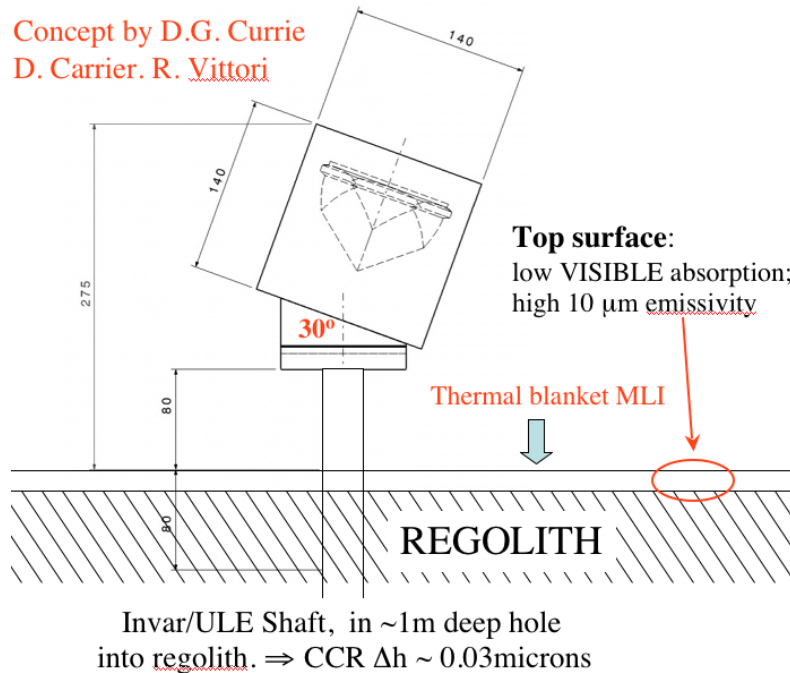

Figure 5. Emplacement concept developed for NASA's LSSO and the ASI Study.

The concept of fig. 5 is to be completed by an outer shield (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.

Figure 6. Inner housing, outer Bubbola

The ASI Lunar Orbiter Mission MAGIA

In February 2008 ASI approved for Phase A five proposals presented in response to its 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, Prime Contractor is Rheinmetall Italia S.p.A.
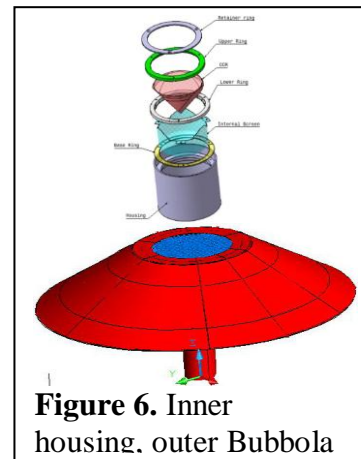
Using two retroreflector, atomic clock, acceleratometer and radio science payloads, INFN and UMCP proposed for MAGIA the improved measurement of the gravitational redshift, a precursor test of the functionality of the MoonLIGHT CCR and a direct measurement of the position of the selenocenter with respect 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 the Moon altimetry model will be needed to select landing sites, while the gravity model 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. MAGIA is now awaiting the ASI decision.

Acknowledgments

References

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