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Probing gravity with the proposed MAGIA and ILN lunar missions

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Abstract. MAGIA (Missione Altimetrica Gravimetrica GeochImica Lunare) is a mission approved by the Italian Space Agency (ASI) for Phase A study. Using a single large-diameter laser retroreflector, a large laser retroreflector array and an atomic clock onboard MAGIA, we propose to perform several fundamental physics and absolute positioning metrology experiments: VESPUCCI, an improved test of the gravitational redshift in the EarthMoon system predicted by General Relativity; MoonLIGHT-P, a precursor test of a second generation Lunar Laser Ranging (LLR) payload for precision gravity Network (ILN). Future ILN geodetic nodes equipped with MoonLIGHT and the Apollo/Lunokhod retroreflectors will become the first realization of the International Moon Reference Frame (IMRF), the lunar analog of the ITRF (International Terrestrial Reference Frame).

Key words. LLR – SLR – Gravitational redshift – Lunar science – ILN – Tests of general relativity

1. Introduction

In 2008 ASI approved for Phase A Study five proposals presented in response to the call for

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"Small Missions" issued in 2007. One of these is MAGIA (Missione Altimetrica Gravimetrica GeochImica Lunare), whose Principal Investigator is A. Coradini (INAF-IFSI Rome) and Prime Contractor is Rheinmetall Italia spa. MAGIA is an altimetry, gravimetric and geochemical mission consisting of a main Orbiter in polar orbit, which will release a Subsatellite at the end of the mission. One of the LNF-INFN contributions in MAGIA will be the VESPUCCI (VEga or Soyuz Payload for Unified Clock vs. Ccr Investigation) payload, with the aim to measure the gravitational redshift in the Earth-Moon system.

The ILN (International Lunar Network) initiative comes at an opportune time when international space agencies are focusing unprecedented resources on lunar exploration. This will allow the network as a whole to monitor geophysical activity over the entire Moon. Each of the lander nodes will carry a core set of ILN defined instruments. One of the instrument categories that are being considered for the ILN, is a new generation of LRRs (Lunar Laser ranging). We propose to test on MAGIA spacecraft a new LLR payload, MoonLIGHT-P (Moon Laser Instrumentation for General relativity Highaccuracy Test-Precursor), integrating with thermal and optical characterization at SCF (Space/lunar laser ranging Characterization Facility) at LNF-INFN.

2. The ASI lunar mission MAGIA

The MAGIA's scientific goals have been identified in order to avoid overlaps with currently planned, ongoing, or just concluded orbiter or impactor missions: (1) study of the mineralogical composition of the Moon by means of a VIS/NIR imaging spectrometer; (2) characterization of the Moon polar regions by means of concurrent observations with different instruments, (imaging experiment, altimeter and thermal); (3) characterization of the lunar Gravity field with a two-satellite tracking similar to GRACE, with a main Orbiter and a small Sub-satellite; (4) characterization of the lunar radiation environment by means of a particle radiation monitor; (5) characterization of the lunar exosphere; (6) fundamental physics test of gravity; (7) absolute positioning metrology measurements; (8) precursor technological test for second generation LLR (Coradini et al. 2010).

This work will exploit passive, maintenance-free laser retroreflectors and an atomic clock on the Orbiter. With MAGIA we propose to perform the following experiments in the Earth-Moon system: (1) VESPUCCI: a significant improvement of the measurement of the gravitational redshift in the trans-lunar flight and in Moon orbits. This will be illustrated in Section 2.1; (2) MoonLIGHT-P: a technological test of the payload for second generation LLR. The importance of a precursor test will be explained in Section 2.2. The retroreflectors will be tracked by the ILRS (Pearlman et al. 2002). If MAGIA will be approved, the performance of the two retroreflector payloads will be characterized at the dedicated "Satellite/lunar laser ranging Characterization Facility (SCF)" of INFN-LNF (Dell'Agnello et al. 2008). For the atomic clock analysis we consider a clock stability in the range between 10^{-13} and 2×10^{-14} (Section 2.1).

2.1. VESPUCCI: improved measurement of the gravitational redshift

The measurement of the gravitational redshift (GRS) is an important test of the Local Position Invariance (LPI) of General Relativity (GR) and of any metric theory of gravity (Will 2006). The most accurate GRS measurement in space, $|\alpha| < 2 \times 10^{-4}$, was performed in 1976 by the satellite Gravity ProbeA (GP-A) (Vessot et al. 1980), which employed a space-borne hydrogen-maser clock, reached a maximum orbital height of 10,000 km and took data for about 2 h. The trans-lunar flight of MAGIA and the period the orbiter will spend around the Moon (~7 months) offer the possibility to perform an experimental test of the gravitational redshift in the Earth-Moon system based on Corner Cube Retroreflector-Array (CCR-A), Corner Cube Retroreflector-Moon (CCR-M) and an onboard atomic clock with relative frequency stability of 10^{-13} or less. Positions on the ground and space clocks will be referenced to the ITRF (Fermi, M., et al. 2010). MAGIA is suited to improve significantly the GP-A measurement for the following reasons: (1) the high-precision ISA (Italian Spring Accelerometer) (Iafolla, V., Peron, R. 2010) and radio science (RS) payloads which ensure that the systematic error due to the Doppler shift background will be kept under control; (2) lots of data will be acquired in a region between the Earth and the Moon where the two gravity fields can be considered simple point-like potentials, thus greatly simplifying the physics analysis; (3) MAGIA will navigate two gravity potential wells experiencing the highest possible variation of GRS in the EarthMoon system; (4) MAGIA positioning with respect to the ITRF is achieved with two complementary techniques: SLR/LLR tracking by the ILRS, which includes the Space Geodesy Center of ASI in Matera, Italy (ASI-CGS), providing very accurate and absolute distance determination with respect to the ITRF, and mission radio telemetry from the ASI-CGS (and possibly, other stations). Our goal is to improve the best direct limit by GP-A, $|\alpha| < 2 \times 10^{-4}$. As shown in fig.1, GRS will increase away from the Earth and slightly decrease near the Moon, up to the nominal MAGIA altitude of 100 Km over the Moon surface.

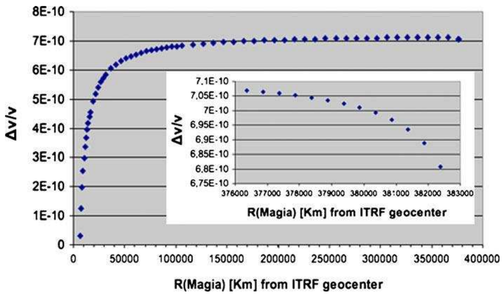

Fig. 1. GRS variation vs. MAGIA distance from the geocenter, assuming point-like potentials. The inset shows a blow-out of the end point of the curve very near the Moon.

The expected statistical error on α for a POD (Precise Orbit Determination) accuracy of 10 m and for three different clock accuracies: (1) $|\alpha| < 8 \times 10^{-5}$ for a clock accuracy of 3.3×10^{-13}, a factor 2.5 improvement over GP-A; (2) $|\alpha| < 2 \times 10^{-5}$ for a clock accuracy of 10^{-13}, a factor 10 improvement over GP-A; (3) $|\alpha| < 1 \times 10^{-5}$ for a clock accuracy of 5×10^{-14}, a factor 20 improvement over GP-A.

The current baseline design of CCR-A is shown in fig.2. The arrays will be made of solid, fused silica CCRs, with a diameter identical to the Apollo mission lunar reflectors. Other optical and mechanical array parameters will be optimized and finalized in later phases of the mission, if approved. The mounting scheme and the choice materials will inherit from the Apollo/LAGEOS(LAser GEodinamics Satellite) payloads and will be characterized at INFN-LNF.

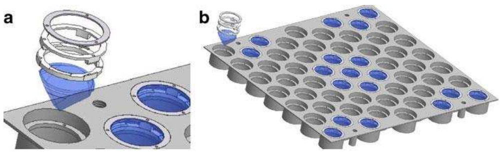

Fig. 2. Sketches of CCR-A: (a) exploded view of the CCR showing the aluminum and Poly-ChloroTriFluoroEthylene (KEL-F) assembly rings; (b) full array.

2.2. MoonLIGHT-P: a precursor for second generation lunar laser ranging

MoonLIGHT-P is developed by the University of Maryland and INFN-LNF for NASA's Lunar Science Sortie Opportunities (LSSO) program (Currie et al. 2006, 2009), for two ASI studies and, currently, for the ILN. The Primary Investigator (PI) of LSSO was D. G. Currie and Co-PI was S. DellAgnello; Italian collaborators participated at no cost for NASA. This project is known to NASA as Lunar Laser Ranging Retroreflector Array for the 21st Century (LLRRA21).

The first generation LLR based on the retroreflector payloads deployed with Apollo and Lunokhod missions has provided numerous precision tests of gravity (Williams et al. 2004) and unique measurements of lunar planetary science (Williams et al. 2006). In particular, LLR currently gives the best overall test of General Relativity with a single experiment, as shown by tab.3, included also the major improvements expected from second generation LLR with a total range accuracy of 1 mm and 0.1 mm:

Science Measurement	First Gen. Limit cm accuracy	Second Gen. Limit 1 mm	Second Gen. Limit 0.1 mm	Timescale
Parameterized Post-Newtonian (PPN) β	$\|\beta-1\| < 1.1 \times 10^{-4}$	10^{-5}	10^{-6}	Few years
Weak Equivalence Principle (WEP)	$\|\Delta a/a\| < 1.4 \times 10^{-13}$	10^{-14}	10^{-15}	Few years
Strong Equivalence Principle (SEP), Nordtvedt Parameter η	$\|\eta\| < 4.4 \times 10^{-4}$	3×10^{-5}	3×10^{-6}	Few years
Geodetic Precession, K_{GP} Parameter	$\|K_{GP}\| < 6.4 \times 10^{-3}$	$\sim 5 \times 10^{-4}$	$\sim 5 \times 10^{-5}$	5–10 years
Time Variation of the Gravitational Constant	$\|\dot{G}/G\| < 9 \times 10^{-13} yr^{-1}$	5×10^{-14}	5×10^{-15}	$\sim$ 5 years
Inverse Square Law, Yukawa parameter α	$\|\alpha\| < 3 \times 10^{-11}$	10^{-12}	10^{-13}	$\sim$ 10 years

Fig. 3. Expected physics reach of first Gen. LLR and with Second Gen. LLR (with MoonLIGHT/LLRRA21).

The deployment of our large, single retroreflector on MAGIA will allow for testing two critical instrumental effects: the thermal perturbation of the optical performance due to the Sun and the laser ranging return at lunar distances for an orbiting target, which is more difficult than for a payload on the surface.

Finally, MoonLIGHT-P, a precursor test of CCR-M on MAGIA, will strengthen the Italian contribution to the International Lunar Network (ILN, see also http://iln.arc.nasa.gov/) in the areas of fundamental physics and lunar science. The ILN was formed by space agencies from nine countries (including ASI) to establish a network of standardized payloads composed by a set of common core instruments to be deployed with robotic missions. The ILN selected the following core instruments: (1) seismometer, (2) electromagnetic sounding, (3) heat flow probe, (4) CCR (Morgan, Dell'Agnello et al. 2009). The preliminary specs for the ILN CCR are fully compatible with our MoonLIGHT/LLRRA21 payload.

3. New generation of lunar laser ranging

In 2007 a new station capable of mm-class range accuracy started operations: APOLLO, the Apache Point Apache Point Observatory Lunar Laser-ranging Operation, funded jointly by National Science Foundation (NSF) and NASA (Murphy et al. 2008). Following this, the largest source of error is now closely linked to the retroreflector arrays on the lunar surface, which are particularly affected by the lunar librations.

The motivation for a sparse, distributed arrays of single, very large CCRs (10 cm diameter) on the lunar surface is to remove the perturbation of the geometric librations of the Moon from LLR. Currently the librations of the Apollo and Lunokhod retroreflectors are the dominant contribution to the LLR error. Our goal is to improve by a factor at least 100 this contribution, from cm level down to 0.1 mm. This new approach has been developed by UMD and INFN-LNF with thermal, optical and orbital simulations and is now being validated at INFN-LNF with the SCF-Test (Section 4) of a 100 mm diameter CCR funded by NASA for LSSO. The general concept of the second generation of LLR is to consider a number (notionally eight) large single Cube Corner Retroreflectors spread over tens of meters, unaffected by the libration and, consequently, by increased spread of the return laser pulse. The return from each of the CCRs will be registered separately and can be identified by comparison with the nominal lunar orbit and earth rotational parameters. This is shown schematically in fig.4.

We currently envision the use of 100 mm CCRs composed of T19 SupraSil I. This is the same material used in LLRA 20^{th} and both LAGEOS satellites. This will be mounted in an aluminum holder that is thermally shielded from the Moon surface, in order to maintain a relatively constant temperature through the lunar day and night. It is also isolated from the CCR, by two coassial "gold cans", so the CCR receives relatively little thermal input due to the high temperature of the lunar day and the low temperature of the lu-

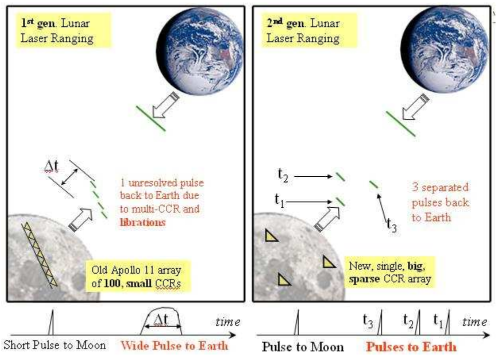

Fig. 4. Concept of the 2nd generation of Lunar Laser Ranging.

nar night. Actual hardware prototype and the mounting of the CCR inside the housing are shown in fig.5. KEL-F rings could be used for this mounting (its used in LAGEOS) due to its good insulating, low out-gassing and non-hygroscopic properties. The CCR and the thermal shield have been provided by LSSO funds. Mechanical design and construction of the housing, rings and SCF-testing has been provided by INFN-LNF.

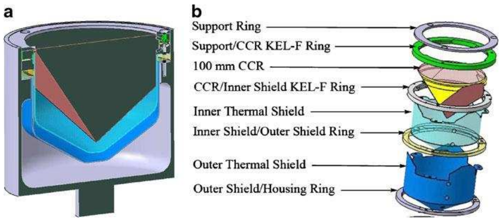

Fig. 5. Views of current design of the MoonLIGHT/LLRRA21 CCR: (a) fully assembled; (b) exploded view with its internal mounting elements and outer aluminum housing.

4. Thermal and optical tests in Frascati

SCF (Satellite/lunar laser ranging Characterization Facility), at LNF/INFN in Frascati, Italy, is a cryostat where we are able to reproduce the space environment: cold (77 K with Liquid Nitrogen), vacuum, and the Sun spectra. The SCF includes a Sun simulator (www.ts-space.co.uk), that provides a 40 cm diameter beam with close spectral match to the AM0 standard of 1 Sun in space (1366.1 W/m^2), with a uniformity better than ±5% over an area of 35 cm diameter. Next to the cryostat we have an optical table, where we can reproduce the laser path from Earth to the Moon, and back, studying the Far Field Diffraction Pattern (FFDP) coming back from the CCR to the laser station, useful to understand how good is the optical behavior of the CCR.

The SCF-Test (Dell'Agnello et al. 2011) is a new test procedure to characterize and model the detailed thermal behavior and the optical performance of laser retroreflectors in space for industrial and scientific application, never before been performed. We perform an SCF-Test on the MoonLIGHT CCR to evaluate the thermal and optical performance in space environment. About thermal measurements we use both an infrared (IR) camera and temperature probes, which give a real time measurements of all the components of the CCR and its housing. In particular we look at the temperature difference from the front face to the tip, studying how the FFDP changes during the different thermal phases. This is the best representative of the thermal distortion of the return beam to the Earth. Various configurations and designs of the CCR and the housing have been and are being tested in the SCF Facility, with the solar simulator, the temperature data recording, the infrared camera and the measurement of the Far Field Diffraction Pattern (FFDP).

In fig.6 is shown the MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2V/c) during key points of the SCF-Test: (1) in air, (2) in vacuum, (3) during chamber's shields cooling, (4) Sun on orthogonal to the CCR's face with the housing temperature controlled at T=310 K, (5) Sun on at 30° of inclination (no break-thru), (6) Sun on at −30° of inclination (break-thru), (7) Sun on orthogonal with the housing temperature left floating. From this graph we can deduce that the intensity decreases during no orthogonal lighting of the CCR, in particular when the

Sun enters in the housing cavity during the break-thru phase. This effect is due to a strong increase of the "Tip-Face" thermal gradient during this two phase of the test. When the housing temperature is left floating, the intensity slightly increases because the "Tip-Face" gradient is reducing.

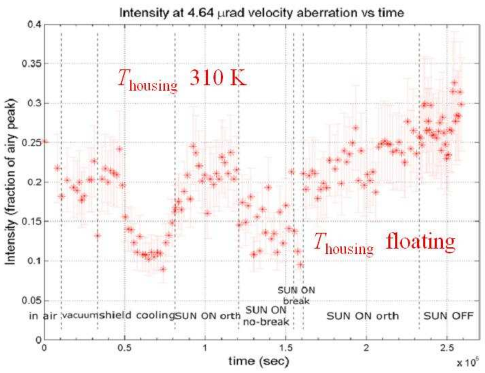

Fig. 6. MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2V/c) during tests.

5. Conclusions

The Phase A study was concluded in December 2008 with the final review and the full MAGIA Proposal was submitted to ASI. The MAGIA collaboration is now awaiting the decision of the new ASI management and the new National Space Plan. In the meantime, the work of the INFN-LNF group on the development of the MoonLIGHT-P prototype continued in 2010-2011 in the framework of the ILN and with an R&D experiment approved by INFN for the period 2010-2012, called MoonLIGHT-ILN.

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