Exp Astron
DOI 10.1007/s10686-010-9195-0

ORIGINAL ARTICLE

Fundamental physics and absolute positioning metrology with the MAGIA lunar orbiter

Simone Dell'Agnello · Caterina Lops · Giovanni O. Delle Monache · Douglas G. Currie · Manuele Martini · Roberto Vittori · Angioletta Coradini · Cesare Dionisio · Marco Garattini · Alessandro Boni · Claudio Cantone · Riccardo March · Giovanni Bellettini · Roberto Tauraso · Mauro Maiello · Luca Porcelli · Simone Berardi · Nicola Intaglietta

Received: 5 March 2010 / Accepted: 29 July 2010

Abstract MAGIA 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 Earth–Moon system predicted by General Relativity; *MoonLIGHT-P*, a

S. Dell'Agnello · C. Lops (✉) · G. O. Delle Monache · M. Martini · M. Garattini · A. Boni · C. Cantone · M. Maiello · L. Porcelli · S. Berardi · N. Intaglietta
INFN—Laboratori Nazionali di Frascati (LNF), via E. Fermi 40, 00044, Frascati RM, Italy
e-mail: Caterina.Lops@lnf.infn.it

D. G. Currie
Department of Physics, University of Maryland (UMD), College Park, MD 20742 USA

R. Vittori
Aeronautica Militare Italiana, Rome, Italy

A. Coradini
INAF—Istituto di Fisica dello Spazio Interplanetario (IFSI), via Fosso del Cavaliere 100, 00133, Rome, Italy

C. Dionisio
Rheinmetall Italia S.p.A., via Affile 102, 00131 Rome, Italy

R. March
INFN—LNF and CNR-Istituto per le Applicazioni del Calcolo (IAC), viale del Policlinico 137, 00161, Rome, Italy

G. Bellettini · R. Tauraso
INFN—LNF and Department of Mathematics, University of Rome "Tor Vergata", via della Ricerca Scientifica, 00133, Rome, Italy

Published online: 27 August 2010

precursor test of a second generation Lunar Laser Ranging (LLR) payload for precision gravity and lunar science measurements under development for NASA, ASI and robotic missions of the proposed International Lunar Network (ILN); *Selenocenter* (the center of mass of the Moon), the determination of the position of the Moon center of mass with respect to the International Terrestrial Reference Frame/System (ITRF/ITRS); this will be compared to the one from Apollo and Lunokhod retroreflectors on the surface; *MapRef*, the absolute referencing of MAGIA's lunar altimetry, gravity and geochemical maps with respect to the ITRF/ITRS. The absolute positioning of MAGIA will be achieved thanks to: (1) the laboratory characterization of the retroreflector performance at INFN-LNF; (2) the precision tracking by the International Laser Ranging Service (ILRS), which gives two fundamental contributions to the ITRF/ITRS, i.e. the metrological definition of the *geocenter* (the Earth center of mass) and of the *scale* of length; (3) the radio science and accelerometer payloads; (4) support by the ASI Space Geodesy Center in Matera, Italy. 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.

Keywords 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 "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 Sub-satellite at the end of the mission. The scientific goals have been identified in order to avoid overlaps with currently planned, ongoing, or just concluded orbiter or impactor missions:

- study of the mineralogical composition of the Moon by means of a VIS/NIR imaging spectrometer;
- characterization of the Moon polar regions by means of concurrent observations with different instruments, (imaging experiment, altimeter and thermal);
- characterization of the lunar Gravity field with a two-satellite tracking similar to GRACE, with a main Orbiter and a small Sub-satellite;
- characterization of the lunar radiation environment by means of a particle radiation monitor;
- characterization of the lunar exosphere;
- fundamental physics test of gravity;

- absolute positioning metrology measurements;
- precursor technological test for second generation LLR.

MAGIA is designed to reach its goals by exploiting for the Orbiter a new satellite concept, under development by Rheinmetall (derived from the MIOSAT platform). The payload module will use instruments in an advanced development phase for other important planetary missions (BepiColombo, JUNO, Chandrayaan-1), like the Italian Spring Accelerometer (ISA, to be deployed on BepiColombo). This approach will make available innovative instruments of high technological content and a relatively moderate cost. The detailed science program, mission timeline and orbit evolution is described in detail elsewhere [4]. 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:

- VESPUCCI (VEga or Soyuz Payload for Unified Clock vs. Ccr Investigation): 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.
- MoonLIGHT-P (Moon Laser Instrumentation for General relativity High-accuracy Test-Precursor): a technological test of the payload for second generation LLR. The importance of a precursor test will be explained in Section 3.
- Selenocenter: independent measurement of the position of the Moon center of mass with respect to the ITRF (see http://itrf.ensg.ign.fr/; [2, 14]), until now performed using the Apollo and Lunokhod retroreflectors. MapRef: grid of absolute ITRF positions of MAGIA's lunar altimetry, gravity and geochemical maps, to be taken wherever the Orbiter can be tracked by LLR. Some prospects for Selenocenter and MapRef will be briefly discussed in the conclusive Section 4.

The retroreflectors will be tracked by the ILRS (Pearlman [22]; see also http://ilrs.gsfc.nasa.gov/) with Satellite and Lunar Laser Ranging (SLR and LLR). These time-of-flight measurements are widely recognized as the most accurate and, at the same time, the most cost-effective techniques to determine the position of satellites and of the Moon in the Earth–Moon system with respect to the ITRF. The latter is established with a variety of space metrology techniques by the International Earth rotation and Reference systems Service (IERS; see http://www.iers.org/; [10]). 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 [3, 8, 9].

For the atomic clock analysis we consider a clock stability in the range between 10^{-13} and 2×10^{-14} (see Section 2).

In this paper we summarize the results of the Phase A study of these experiments.

2 VESPUCCI: improved measurement of the gravitational redshift

The acronym of the VESPUCCI experiment is due to the indication given by ASI during the 2007 lunar studies, that the launch vehicle of the robotic lunar missions could be a modified VEGA or a SOYUZ rocket.

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.

Current experimental status is shown in Fig. 1. The most accurate GRS measurement in space, $|\alpha| < 2 \times 10^{-4}$, was performed in 1976 by the satellite Gravity Probe A (GP-A, [23]), 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. MAGIA is suited to improve significantly the GP-A measurement for the following reasons:

- the high-precision ISA and radio science (RS) payloads which ensure that the systematic error due to the Doppler shift background will be kept under control;

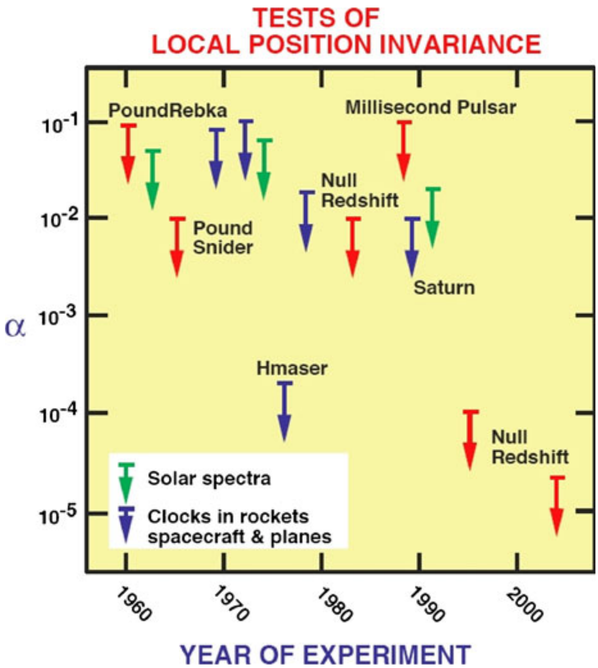

Fig. 1 From Will [24]: "selected test of local position invariance via gravitational redshift experiments, showing bounds on α, which measures degree of deviation of redshift from the formula $\Delta\nu/\nu = (1+\alpha)\Delta U(r)/c^2$. In null redshift experiments, the bound is on the difference between different kinds of clocks"

- 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;
- MAGIA will navigate two gravity potential wells experiencing the highest possible variation of GRS in the Earth–Moon system;
- MAGIA positioning with respect to the ITRF is achieved with two complementary techniques:

  1. 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.
  2. Mission radio telemetry from the ASI-CGS (and possibly, other stations).

Our goal is to improve the best direct limit by GP-A, $|\alpha| < 2 \times 10^{-4}$, with a clock of relative frequency stability of 10^{-13} or less and precise orbit determination (POD) with an absolute accuracy with the respect to ITRF of 10 m or less by means of radio tracking and SLR/LLR tracking of CCR-A and CCR-M. For the clock analysis we will consider a clock stability in the range between 10^{-13} and 2×10^{-14}. Currently, our baseline clock is the RAFS (Rubidium Atomic clock Frequency Standard) and the target stability that we want to reach is 5×10^{-14} (but 2×10^{-14} seems achievable with the characterization described below). These clocks are manufactured for example by PerkinElmer (US), are deployed on GPS-II and will be deployed on GALILEO. Choice of a beyond-the-baseline clock may be possible depending on the level of funding and decisions to be taken at later mission phases.

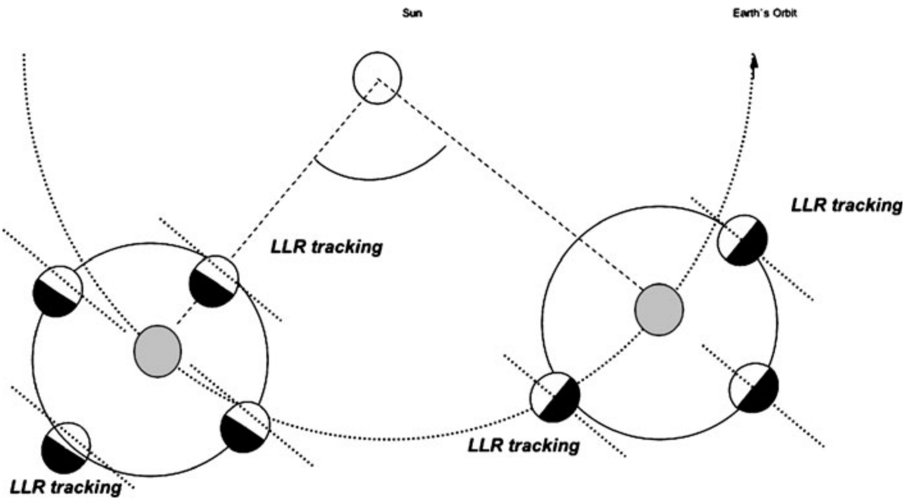

Fig. 2 LLR tracking of MAGIA with two different orbital configurations of the Moon, the Earth, the spacecraft and the sun illumination. CCR-A and CCR-M will be located on the different sides of the Orbiter in order to separate their laser returns to ground

SLR provides station-to-satellite distance (single range) measurements with cm accuracy or less. For well-established orbits (like for LAGEOS, the two LAser GEOdynamics Satellites) this amounts to a slightly larger accuracy on the absolute orbital trajectory (1–2 cm); but the less the SLR coverage of the orbit, the worse the absolute ITRF positioning. For a trans-lunar flight of about 1 week we assume very conservatively a degradation of POD SLR accuracy of a factor 100 (up to a few meters), which is still good enough for our goal. Around the Moon MAGIA orbits will be fully visible from ILRS stations for extended periods twice per month (once for CCR-A and once for CCR-M), as shown by Fig. 2; however, with respect to the trans-lunar flight the laser return will decrease as $1/(\text{distance})^4$.

MAGIA gives the unique opportunity to measure a varying GRS across the two potential wells of the Earth–Moon system. As shown in Fig. 3, 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. Past experiments on airplanes [1] and spacecrafts [23] showed that variations of the GRS frequency shift ($\Delta\nu$) with position, r, in the potential field ($\Delta U(r)$) increase the statistical significance of test, as opposed to measuring a single GRS value at a single value of position r. They also showed that a detailed analysis is required to subtract Doppler shifts due to plane or spacecraft motion, and that tracking data are needed to determine the payload's location and the velocity (to evaluate the potential difference ΔU and the special relativistic time dilation) [23, 24]. Therefore, for MAGIA, the variation of $\Delta\nu$ with distance (basically the maximum possible in the Earth–Moon system) will make our GRS measurement largely insensitive to systematic errors on the

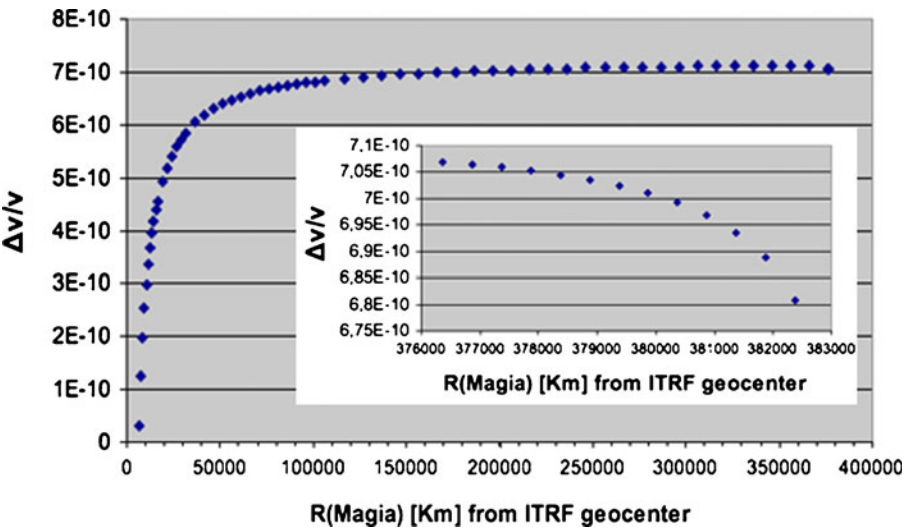

Fig. 3 GRS variation vs. MAGIA distance from the geocenter, assuming point-like potentials. The inset shows a blow-out of the end point of the curve very near the Moon

absolute frequency accuracy of the clock. For GR ($\alpha = 0$) the $\Delta\nu$ of MAGIA will be:

$$\Delta\nu = \nu_{\text{MAGIA}} - \nu_{\text{Earth}} = \nu_{\text{offset}} + \Delta U(r)/c^2 - \nu_{\text{Earth}}$$

where:

- ν_{offset} is the systematic error on the value of the RAFS absolute frequency. We will measure the absolute frequency accuracy with respect to a H-maser, to determine the residual sensitivity to ν_{offset} which we think it will have a negligible effect for our goals.
- ν_{Earth} is the frequency of the reference H-maser(s) on Earth;
- $\Delta U(r_{\text{MAGIA}}) = GM(1/r_{\text{MAGIA}} - 1/r_{\text{Earth}})$ for point-like potentials. Our measurement will be sensitive only to this frequency variation with distance. Therefore, from the clock operation point of view, we only need to control its stability, that is, drift vs. time and its Allan variance vs time with the measured drift removed. This is an advantage that MAGIA has with respect to any GRS measurement attempted with nearly circular orbits, for which a single number, ν_{offset}, has to be measured, instead of a frequency smoothly varying with distance (at least for GR).

GRS will be measured during the trans-lunar flight, with the satellite altitude controlled to make CCR-A array visible form the Earth, and in Moon orbits. Measuring the GRS in the Earth potential allows for a faster data analysis because the geo-potential is known much better than its lunar counterpart. Measuring the GRS around the Moon will require the completion of MAGIA gravimetric measurements.

The GRS measurement will be organized as follows:

1. Take N statistically independent measurements of clock frequency and position compared to Earth H-maser(s). The maser located at ASI-CGS is the privileged choice. POD will give the position. The clock plus on-board electronics will give the frequency (# of clock cycles divided by the time window, measured with an accuracy of tens of ns) and download it to the ground telemetry stations (one of which will be ASI-CGS).
2. The synchronization of the start and stop of the measurements with ground will be at ms level.
3. The duration of each measurement will be the shortest between the two time intervals for which: (a) the clock stability is below the target stability (this depends on the type of clock; the RAFS can reach 5×10^{-14} in less than 1,000 s, as shown in Fig. 4); (b) the variation of $\Delta\nu$ due to $\Delta U(r_{\text{MAGIA}})$ (MAGIA is moving away) is less than the target clock stability. In any case, clock data will be logged to ground with the system-wide rate of 10 s.
4. The Doppler frequency shift (and the special relativistic time dilation) will be measured concurrently to the GRS using the data from the RS and ISA experiments and subtracted from $\Delta\nu$. The latter two experiments are described in detail in [12] and [15], respectively. In particular, ISA will flag and measure non-gravitational perturbations (NGPs) on the orbit

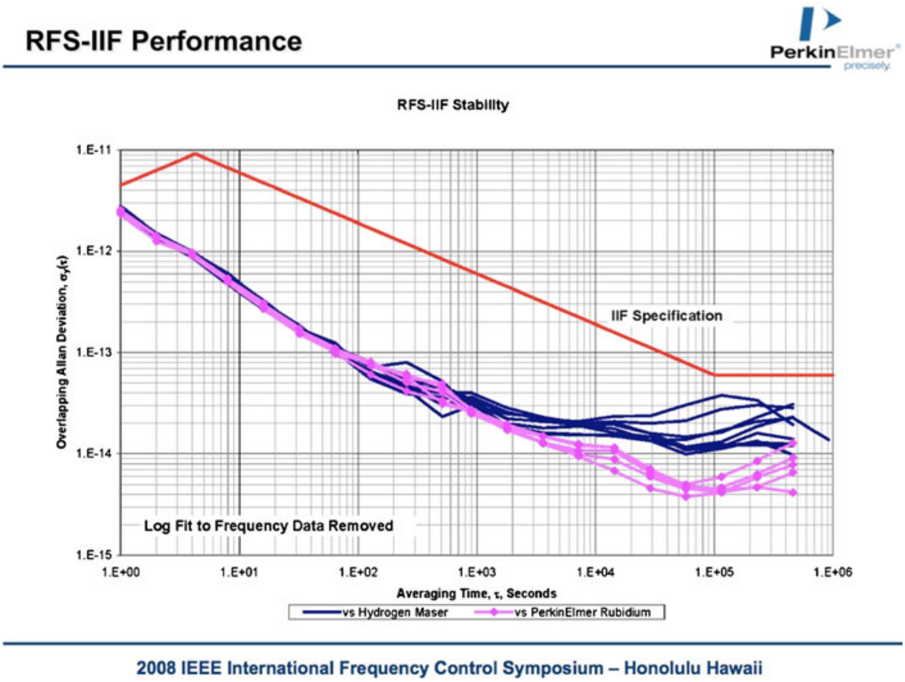

Fig. 4 Courtesy of PerkinElmer: RAFS Allan variance measured with respect to a H-maser, with the measured drift removed, for a period of about 6 days

due to thermal effects (time-varying radiation pressure by the Sun, asymmetric thermal emission by the spacecraft, planetary infrared emission near the Earth and Moon) and to occasional spacecraft maneuvering. This advanced instrumentation was not available to GPA, and it is one of the strongest features of MAGIA.

5. ν_{offset}, frequency drift vs. time and Allan Variance (with/without the measured drift removed) will be calibrated on the ground using the H-maser reference of ASI-CGS, which is a tri-located site capable of ITRF positioning measurements with three geodesy techniques: SLR/LLR, Global Navigation Satellite System (GNSS) and Very Long Baseline Interferometer (VLBI). Figure 4 shows the Allan variance measured by PerkinElmer after the calibration and removal of the drift of their clock, compared to a H-maser. In order to obtain the same stability result during the MAGIA trans-lunar flight, prior to launch we will install and operate the clock in a vacuum case for more than 180 days. In this period the clock will be kept as close as possible to the nominal and optimal operating conditions in space and monitored with the H-maser. We will also measure the sensitivity of the clock to changes in: temperature, voltage and vibrations simulating the effect of the launch. When its performance will be stabilized and characterized, the clock will be launched while still kept in vacuum and

nominal conditions. The RAFS has been chosen as baseline clock because of its relatively moderate cost and because its drift can be modeled and subtracted providing an excellent final stability.

6. During the flight, the clock stability will be checked "online" at r_{MAGIA} ~350,000 Km, where $\Delta\nu$ will be flat, the error on $\Delta\nu$ will be lower than 10^{-13} and where both the Earth and Moon potential can be considered as point-like potentials (see Fig. 3). The exact region will be decided on the basis of the final MAGIA ephemeris.

Finally, Fig. 5 shows the expected statistical error on α for single GRS measurements as a function of r_{MAGIA}, for a POD accuracy of 10 m and for three different clock accuracies of 3.3×10^{-13}, 10^{-13} and 5×10^{-14}. Assuming that the future measurement will agree with GR (e.g., it will yield a central value $\alpha = 0$) we can take a weighted average of all measurement errors plotted in Fig. 5, to get the following one standard deviation limits (at 68% CL, statistical uncertainty only):

1. $|\alpha| < 8 \times 10^{-5}$ for a clock accuracy of 3.3×10^{-13}, a factor 2.5 improvement over GP-A.

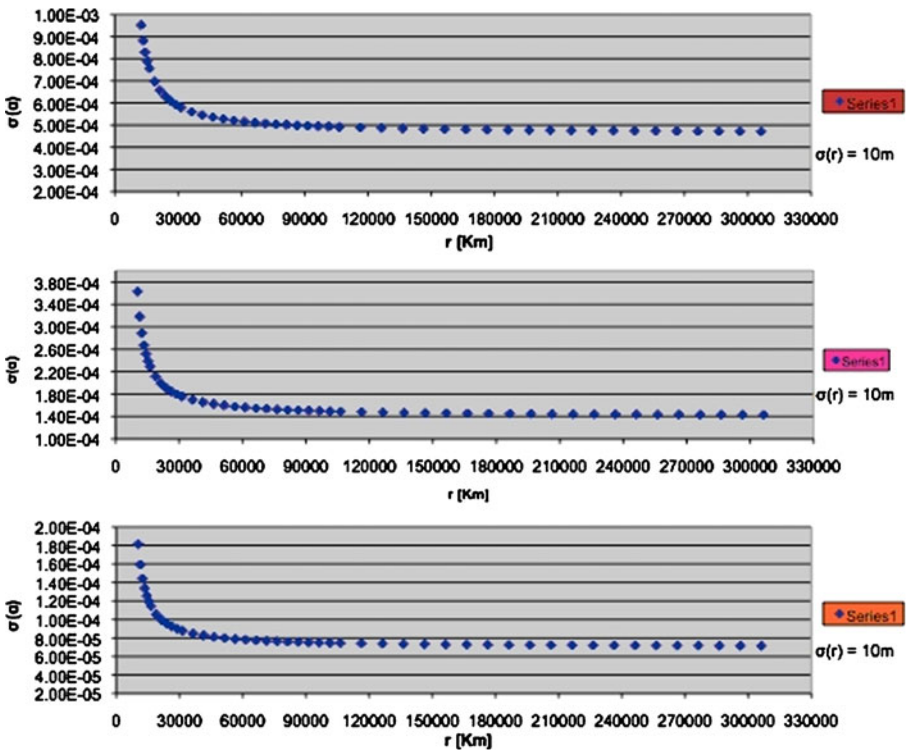

Fig. 5 Expected statistical error on the GRS test vs. distance from the ITRS geocenter

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 above estimates are for r_{MAGIA} <310,000 Km. Using data up to 370,000 km, the improvement will be larger. Note that Fig. 4 shows that after 1 h the stability of a calibrated RAFS is $<2 \times 10^{-14}$, which corresponds to a GRS test improvement of a factor 50. The GRS measurement in Moon orbits will be done once the MAGIA lunar gravity potential will be ready. Then it will be combined with the Earth/trans-lunar flight GRS and it will give a further improvement of the test, up to an overall factor 100 of improvement over GP-A. Note that, if the MAGIA flight will be longer than 1 week (as it is foreseen in some alternative, beyond-the-baseline mission scenarios, where solar electric propulsion could be used for the transfer to the Moon), then the improvement will be significantly larger.

Finally, assuming GR is valid ($\alpha = 0$), the measurement of the Moon GRS will also be an a posteriori high-level validation of the MAGIA gravity model.

2.1 The CCR array

MAGIA is designed to fully exploit SLR and LLR, inheriting significantly from the consolidated Apollo and LAGEOS experience and from the R&D work done by INFN-LNF and the University of Maryland in 2006–2009.

The current baseline design of CCR-A is shown in Fig. 6. The arrays will be made of solid, fused silica CCRs, with a diameter identical to the Apollo 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 payloads and will be characterized at INFN-LNF.

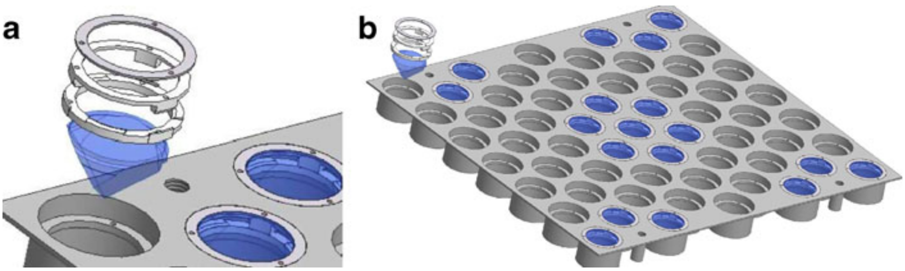

Fig. 6 Sketches of CCR-A: **a** exploded view of the CCR showing the aluminum and PolyChloroTriFluoroEthylene (KEL-F) assembly rings; **b** full array

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

MoonLIGHT-P developed by the University of Maryland and INFN-LNF for NASA's Lunar Science Sortie Opportunities (LSSO) program [5, 6], for two ASI studies and, currently, for the ILN. The Primary Investigator (PI) of LSSO was D. G. Currie and Co-PI was S. Dell'Agnello; 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 two ASI studies were "Observation of the Universe from the Moon" [7] and MAGIA, completed respectively in 2007 and in 2008. The former was concluded in May 2007 by a national workshop at INFN-LNF and organized by ASI, INFN and INAF (http://www.lnf.infn.it/conference/moon07/).

The first generation LLR based on the retroreflector payloads deployed with Apollo and Lunokhod missions has provided numerous precision tests of gravity [25] and unique measurements of lunar planetary science [26]. In particular, LLR currently gives the best overall test of General Relativity with a single experiment, as shown by Table 1.

The LLR measurement principle is shown in Fig. 7.

The selenocenter position with respect to the ITRF is determined at the few-cm level using the first generation LLR arrays (shown in Fig. 8) of Apollo 11, 14, 15 and of the Russian Lunokhod 1 and 2 (one of the latter two was not giving laser returns, until). These arrays are laser ranged by ILRS ground stations, like McDonald in the US and the recently upgraded one in France (OCA). Other stations are expected to become Moon-capable in the near future. ASI-MLRO in Italy has recently re-started LLR operations. The historical improvement of range precision is shown in Fig. 9. However, in 2007 a new station capable of mm-class range accuracy started operations: APOLLO, the Apache Point Apache Point Observatory Lunar Laser-ranging

Table 1 Expected physics reach of first Gen. LLR [25] and with Second Gen. LLR (with MoonLIGHT/LLRRA21)

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

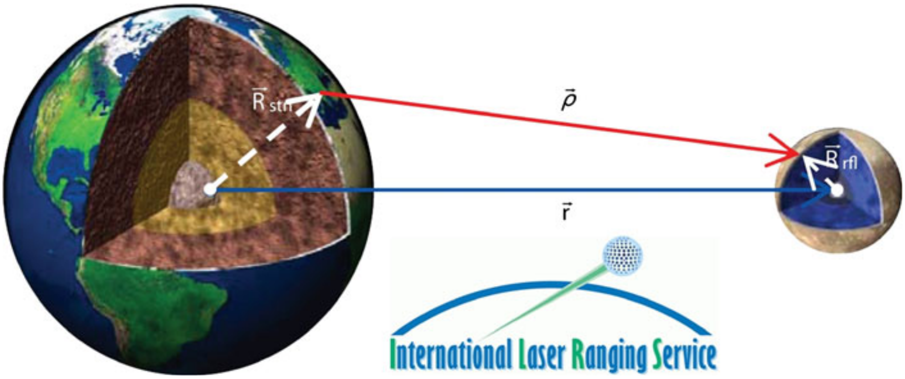

Fig. 7 Ground stations at positions R_{STN} with respect to the geocenter of the ITRS measure the range (ρ) of retroreflectors located on the surface of the Moon at positions R_{RFL} with respect to the selenocenter (the origin of the future IMRF, the lunar analog of the ITRF; see [19])

Operation, funded jointly by National Science Foundation (NSF) and NASA [20].

The motivation for a *sparse, distributed* arrays of single, very large CCRs (10 cm diameter) on the lunar surface to remove the perturbation of the geometric librations of the Moon from LLR is described in detail in [5–7]. The MoonLIGHT concept is also synthetically shown in Fig. 10. 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

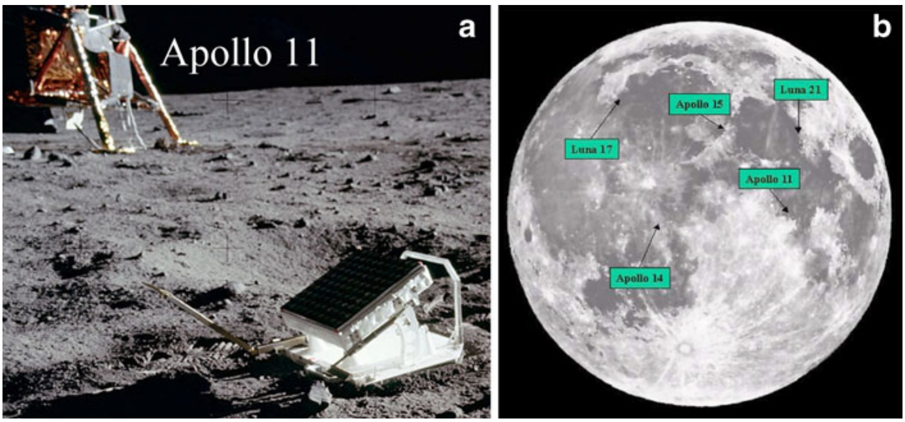

Fig. 8 Apollo 11 retroreflector payload (**a**). Locations of all First Generation retroreflectors (**b**)

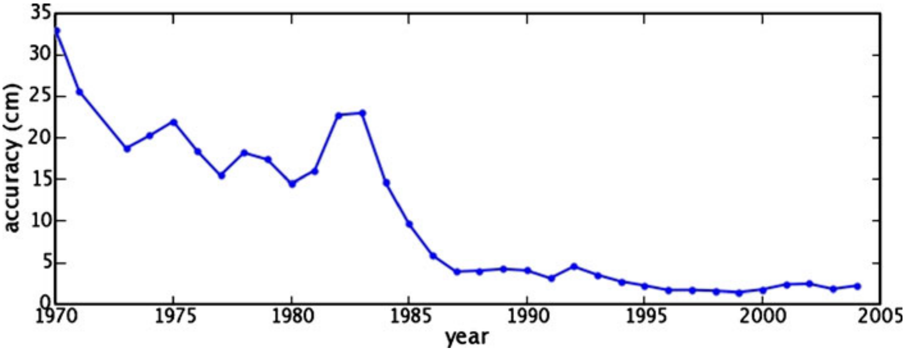

Fig. 9 Historical range accuracy of First Gen. LLR. Previously it was hundreds of meters

SCF-Test [6, 8, 9] of a 100-mm diameter CCR funded by NASA for LSSO. The CCR fused silica satisfies NASA traceability criteria for flight. Table 1 shows the major improvements expected from second generation LLR with a *total* range accuracy of 1 mm and 0.1 mm. The latter improvement will allow for a conclusive test unified braneworld theories which may explain the apparent acceleration of the universe by correcting the General Relativity at large, horizon/super-horizon scales and yet have an effect on the Earth–Moon distance measurable by second generation LLR [11]. A new gravitational theory of spacetime torsion beyond GR can be constrained by a variety of

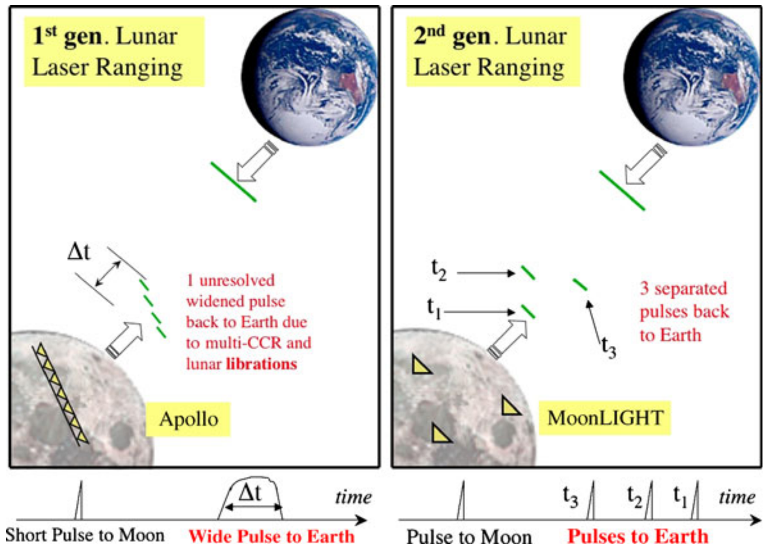

Fig. 10 The MoonLIGHT/LLRRA21 concept for second Gen. LLR, proposed to NASA, ASI and ILN

solar system data [13, 16], including first generation LLR data [17]. Such a theory will be more tightly limited by MoonLIGHT payloads.

The deployment of our large, single retroreflector on MAGIA will allow for testing two critical instrumental effects: (1) the thermal perturbation of the optical performance due to the Sun and (2) the laser ranging return at lunar distances for an orbiting target, which is more difficult than for a payload on the surface.

Current hardware prototype is shown in Fig. 11. The CCR and the thermal shield have been provided by LSSO funds. Construction of the housing, rings and SCF-testing has been provided by INFN-LNF. These hardware components will be used as bread-board models for MoonLIGHT-P on MAGIA, if approved. The main components of the current design are shown in Fig. 12. The Mechanical design is by INFN-LNF.

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 is aided by Core instrument Working Group (CIWG), which selected the following core instruments: (1) seismometer, (2) electromagnetic sounding, (3) heat flow probe, (4) CCR [19]. The preliminary specs for the ILN CCR are fully compatible with our MoonLIGHT/LLRRA21 payload. NASA is considering one (or two) lunar missions to establish four ILN *Anchor Nodes* in the second part of the 2010 decade. The space agencies which launched the last successful orbiter mission (Chinese, Japanese, Indian and NASA) are now considering soft-landing missions on the surface of the Moon for lunar science [21] and precision GR tests [18].

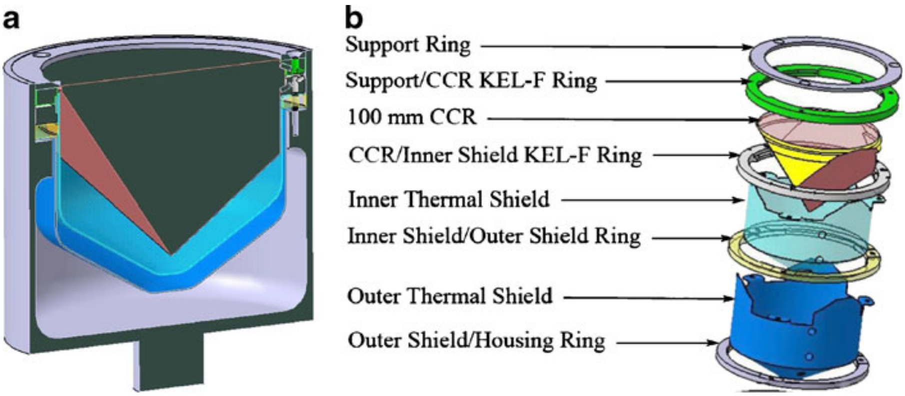

Fig. 11 Views of current design of the MoonLIGHT/LLRRA21 CCR: **a** fully assembled; **b** exploded view with its internal mounting elements and outer aluminum housing

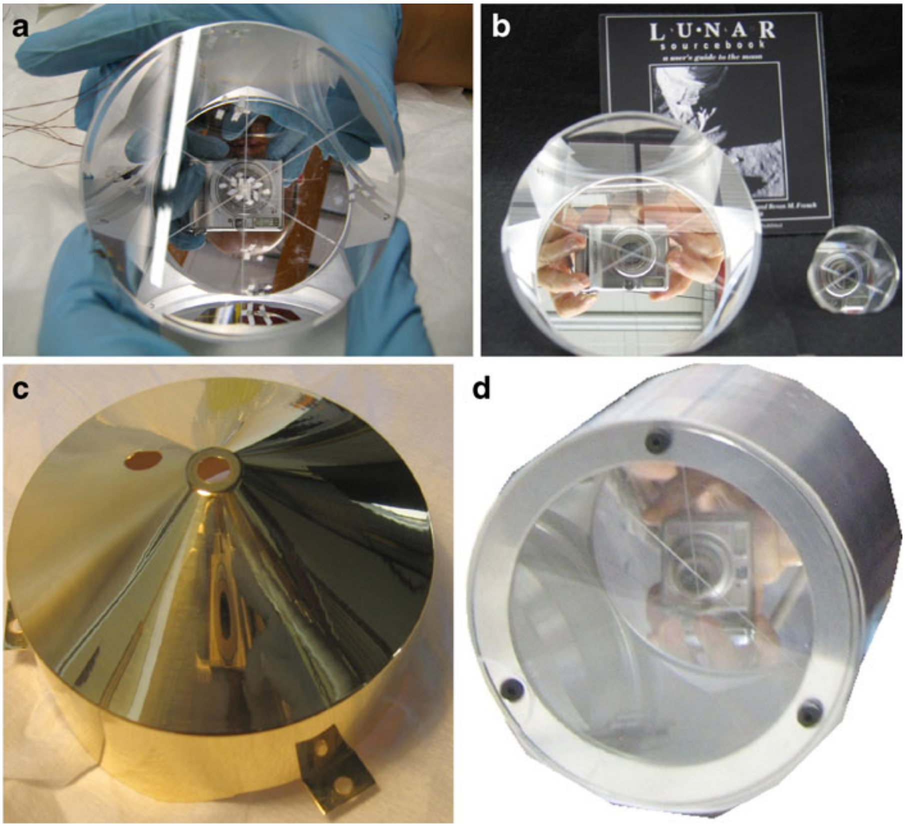

Fig. 12 Views of the LSSO 10-cm CCR alone (beginning from top left, in clockwise (**a**) and next to an old Apollo CCR (**b**). Photo of the inner thermal shield (**c**) and of the CCR mounted with plastic rings into its outer aluminum housing but without thermal shield (**d**)

4 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 2009 in the framework of the ILN CIWG and with an *R&D experiment* approved by INFN for the period 2010–2012, called MoonLIGHT-ILN.

Thanks to the absolute POD, granted by the cube corner retroreflectors and its capability to improve distance measurements, is possible to accurately tie the MAGIA lunar survey maps (altimetry, gravity, surface thermometry, geochemistry, etc) to the geocenter of the ITRS. This planned measurement in support of the lunar science goals of MAGIA is named MapRef. In addition, in principle the selenocenter position can be measured independently using orbiting satellites. For the selenocenter, we can do the same by LLR tracking of MAGIA, provided that NGPs on the orbiter can be controlled to an acceptable level. However, NGPs on MAGIA will be determined exploiting the data of the ISA and RS instruments.

Acknowledgements In support of the research at Frascati, we wish to acknowledge the support of the Italian INFN-LNF, granted since the LSSO project, MoonLIGHT-M(anned) (Currie 2006, Dell'Agnello 2007). We also wish to thank the support of ASI during the 2007 lunar studies and the 2008 Phase A study for MAGIA. We warmly thank Sylvie Espinasse, formerly at ASI, now at ESA, for encouraging the lunar science applications of our work within the ILN. D. G. Currie would also like to acknowledge helpful conversations with Jack Schmidt, Ken Nordtvedt and Ed Aaron. We wish to acknowledge the support of the University of Maryland via the NASA LSSO program (Contract NNX07AV62G) to investigate Lunar Science for the NASA Manned Lunar Surface Science and the LUNAR consortium (http://lunar.colorado.edu), headquartered at the University of Colorado, which is funded by the NASA Lunar Science Institute (via Cooperative Agreement NNA09DB30A) to investigate concepts for astrophysical observatories on the Moon.

References

1. Alley, C.O. et al.: In: Bertotti, B. (ed.) Experimental Gravitation, Proceedings of the Conference at Pavia, Italy (September 1976). Academic, New York (1977)
2. Altamimi, Z., Collilieux, X., Legrand, J., et al.: ITRF2005: a new release of the International Terrestrial Reference Frame based on time series of station positions and Earth orientation parameters. J. Geophys. Res. **112**(B9), B09401 (2007)
3. Bosco, A., et al.: Probing gravity in NEOs with high-accuracy laser-ranged test masses. Int. J. Mod. Phys. D. **16**(12A), 2271–2285 (2007)
4. Coradini, A., et al.: Missione Altimetrica Gravimetrica geochImica lunAre (MAGIA): an Italian mission for the geodesy, geophysics and geochemistry of the Moon. Earth, Moon and Planets (2010, submitted)
5. Currie, D.G., et al.: MoonLIGHT-M, NASA LSSO proposal (2006), INFN-LNF Report LNF-06-2 8(IR), http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=LNF-06-28(IR).pdf
6. Currie, D.G., et al.: AMOS Technical Conference (2009), Paper # 4132364
7. Dell'Agnello, S., et al.: MoonLIGHT-R, ASI Lunar Study (2007), INFN-LNF Report LNF-06-2 8(IR), http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=LNF-07-2(IR).pdf
8. Dell'Agnello, S., et al.: Creation of the industry-standard space test of laser retroreflectors for GNSS, fundamental physics and space geodesy: the "SCF-Test". In: Proceedings of the "16th International Workshop on Laser Ranging", Poznan, Poland (2008)
9. Dell'Agnello, S., et al.: A lunar laser ranging array for NASA's manned landings, the international lunar network and the proposed ASI lunar mission MAGIA. In: Proceedings of the "16th International Workshop on Laser Ranging", Poznan, Poland (2008)
10. Dick, W.R., Richter, B.: The international earth rotation and reference systems service (IERS). In: Heck, A. (ed.) Organizations and Strategies in Astronomy, 5, (Astrophysics and Space Science Library, 310), pp. 159–168. Kluwer, Dordrecht, Boston, London (2004)
11. Dvali, G., Gruzinov, A., Zaldarriaga, M.: The accelerated universe and the moon. Phys. Rev. D **68**, 024012 (2003)
12. Fermi, M., Gregnanin, M., Mazzolena, M., Chersich, M., Reguzzoni, M., Sansò, F.: The lunar gravity mission MAGIA: preliminary design and performances. Exp. Astron. doi:10.1007/s10686-010-9188-z
13. Flanagan, E.E., Rosenthal, E.: Can gravity probe b usefully constrain torsion gravity theories? Phys. Rev. D **75**, 124016 (2007)
14. Geodesist's Handbook: Bulletin Geodesique, 66. Springer, Berlin (1992)
15. Iafolla, V., Peron, R.: Italian Spring Accelerometer: accelerometric techniques and Moon geodesy and gravimetry. Experimental Astronomy (2010, submitted)

16. Mao, Y., Tegmark, M., Guth, A., Cabi, S.: Constraining torsion with gravity probe B. Phys. Rev. D **76**, 104029 (2007)
17. March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S.: Constraining spacetime torsion with the Moon and Mercury. Phys. Rev. D (2010, submitted)
18. Merkowitz, S.M., et al.: The Moon as a Test Body for General Relativity, A White Paper submitted to the Planetary Science Decadal Survey, September 2009, http://www8.nationalacademies.org/ssbsurvey/DetailFileDisplay.aspx?id=60
19. Morgan, T., Satoshi, T., Williamson, M., Bindsted, K., Hipkin, V., Spohn, T., Sreekumar, P., Dell'Agnello, S., Choi, Y., Choi, G., Min, K.W., Banerdt, B., Wieczorek, M., Garcia, R.: International Lunar Network Core Instruments Working Group: Final Report (2009)
20. Murphy, T.W., et al.: The Apache Point Observatory Lunar Laser-Ranging Operation (APOLLO): two-years of millimeter precision measurements of the earth–moon range. Publ. Astron. Soc. Pac. **120**, 20 (2008)
21. Neal, C.R.: The Rationale or Deploying a Long-Lived Geophysical Network on the Moon, A White Paper submitted to the Planetary Science Decadal Survey, September 2009, http://www8.nationalacademies.org/ssbsurvey/DetailFileDisplay.aspx?id=128
22. Pearlman, M.R., Degnan, J.J., Bosworth, J.M.: The international laser ranging service. Adv. Space Res. **30**(2), 135–143 (2002), doi:10.1016/S0273-1177(02)00277-6
23. Vessot, R.F.C., et al.: Test of relativistic gravitation with a space borne hydrogen maser. Phys. Rev. Lett. **45**, 2081–2084 (1980)
24. Will, C.M.: The confrontation between general relativity and experiment. Living Reviews of General Relativity **9**(3), 14 (2006); gr-qc/0510072
25. Williams, J.G., et al.: Progress in lunar laser ranging tests of relativistic gravity. Phys. Rev. Lett. **93**, 261101 (2004)
26. Williams, J.G., et al.: Lunar laser ranging science: gravitational physics and lunar interior and geodesy. Adv. Space Res. **37**, 67–71 (2006), http://arxiv.org/abs/gr-qc/0412049