PROBING GRAVITY WITH SATELLITE AND LUNAR LASER RANGING IN THE SOLAR SYSTEM

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Abstract

We describe the experimental tests of gravity carried out with the techniques of satellite and lunar laser ranging in the solar system, the prospects for new measurements and for the developement of new laser retro-reflector payloads. We also report the technological application of SLR to the satellite navigation[1].

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[1] Presented by S. Dell'Agnello

1 Introduction

Satellite laser ranging (SLR) and lunar laser ranging (LLR) are two consolidated time-of-flight techniques which provide the most precise AND, at the same time, the most cost-effective method to track in space the position of satellites or test-masses equipped with cube corner laser retro-reflectors (CCRs). The first and most important experiments were Apollo on the Moon surface (missions 11, 14, 15) and LAGEOS-I (1976) at 6000 Km Earth altitude. These are still operational and actively analyzed today. SLR and LLR missions produced a host of precise tests of General Relativity (GR) and unique measurements in Space Geodesy and Geo-dynamics.

A new "Satellite/lunar laser ranging Characterization Facility (SCF)", has been built in the context of the ETRUSCO experiment (see section 6) and is operational at INFN-LNF to perform the detailed calibration of the thermal properties and the laser-ranging performance of CCRs in a realistic space environment. Such a qualification has never been performed before and this INFN facility is defining the standard for SLR and LLR space characterization 1).

2 Physics with Second Generation Lunar Laser Ranging

The Apollo Lunar Laser Langing gives the most accurate measurement of the De Sitter effect in GR (PPN parameter β) nd of Yukawa-like deviations from the $1/r^2$ law. Together with laboratory tests at very small distances, LLR gives the most accurate test of the Weak Equivalence Principle. It also allows for a unique, 10^{-4}-level test of the Strong Equivalence Principle which is at the heart of GR. Current limits are shown in Table 1, together with the tighter constraints that can be done with a 2^{nd} generation CCR array like the one that we are developing for NASA and ASI.

In 2006 An R&D for a 2^{nd} generation LLR experiment (MoonLIGHT[2]) has been proposed to NASA by a US-ITALY team led by the University of Maryland (UMCP) and co-led by INFN-LNF. At the same time a robotic deployment version of this project was the subject of an ASI study. MoonLIGHT was approved by NASA in the context of the Lunar Sortie Scientific Opportunity (LSSO) program, which is targeted to the manned landings of the late next decade. We have developed an LLR payload capable of improving the space segment contribution to positioning on the Moon by a factor 100 or more. This will be achieved by replacing the small (38mm diameter), tightly spaced Apollo CCRs with a sparse array of single, large (100 mm diameter) CCRs separated by few tens of meters in order that their laser returns yeald separate return signals on the Earth detectors. Such an array will not suffer from the time

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[2] Moon Laser Instrumentation for General reletivity High-accuracy Tests.

Table 1: *Limits on gravity tests based on LLR data and expected physics reach for second generation LLR.*

Phenomenon	Current LLR	1mm LRR	0.1mm LLR	Measurem. timescale
Weak Equivalence Principle (Δa/a)	10^{-13}	$\sim 10^{-14}$	$\sim 10^{-15}$	2 yr
Strong Equivalence (Nordtvedt param.)	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 parameter β)	3×10^{-3}	$\sim 10^{-4}$	$\sim 10^{-5}$	6-10 yr
Deviations from $1/r^2$ (Yukawa)	10^{-10} ×gravity	$\sim 10^{-11}$ ×gravity	$\sim 10^{-12}$ ×gravity	6-10 yr

broadening of the return pulse from the Apollo arrays due to the Moon geometric librations. These librations currently limits the LLR accuracy to 1-2 cm. Testing of the new 100-mm CCR at the SCF has started in September 2008 with the measurement of the solar absorptivity of the CCR, which is an important engineering number driving the thermal distortions of the CCR far field diffraction pattern back to the Earth.

Note that the replacement of the CCR must be followed by a similar improvement 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-user commnunities made very significant progress in their fields, which allowed for the major success of the 1^{st} generation LLR shown in Fig. 2.

An example of new theory that can be tested with 2^{st} generation LLR is the brane-world theory of ref. 3). This is a new quantum theory in a weaker gravity at horizon scales explains the apparent acceleration of the universe without Dark Energy and, at the same time, predicts a correction to the Moon geodetic precession by about 1mm/orbit. This is not detectable with 1^{st} generation LLR (as opposed to the GR geodetic precession of about 3m/orbit, which is measurend with the accuracy of 1-2 cm), but it will be well in the domain of a MoonLIGHT array.

3 The International Lunar Network (ILN)

On July 24, 2008, space agencies (including ASI), met at NASA-AMES and signed a Statement of Intent (SoI) to establish a network of standardized pay-

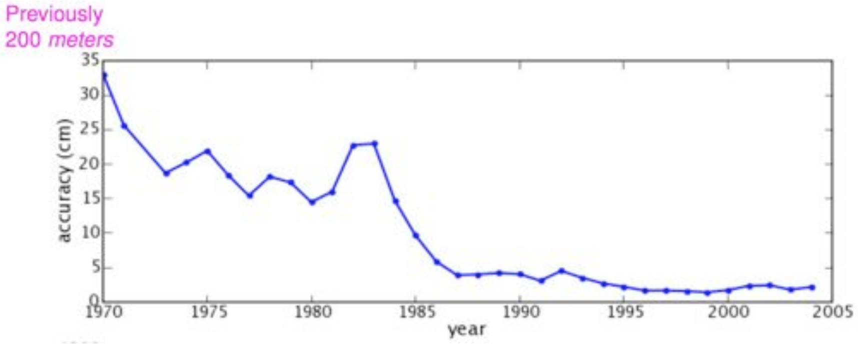

Figure 1: Historical accuracy of the 1^{st} generation LLR.

loads composed by a set of common core instruments to be deployed with robotic missions. In order to advise the agencies, two working groups were formed: 1) the Core Instrument Working Group (CIWG), in which INFN-LNF participates; 2) the Communications Working Group. A third group on Enabling Technologies, particularly dedicated to the generation of power on the surface is being formed, while a fourth one on the choice of the landing sites will be created in 2009. The text of the SoI is reported in the Appendix.

NASA is preparing two lunar missions to establish initial anchor nodes in 2013-14 and 2015-16. Their science definition team (SDT) has foreseen a core payload of four basic instruments: 1) seismometer, 2) EM sounding, 3) heat flow probe, 4) CCR. The SDT specs for the CCR are: 10 cm diameter, weight of 1Kg for the payload, plus additional weight for the CCR deployment hinge. The MoonLIGHT CCR meets these specs and it was proposed as a natural candidate for the anchor nodes at the July ILN meeting.

4 Phsycs with the LAser GEOdynamics Satellites (LAGEOS)

LAGEOS I and II are laser-ranged test masses used to define the position of the Earth center of mass (Geocenter), the Earth global scale of length and observation of the Lense-Thirring effect (LT, or "frame-dragging"), a truly rotational, non-static effect predicted with GR in 1918. Current LT measurement with LAGEOS agrees with GR with a relative accuracy of 10% 2).

Using this LAGEOS measurement of the LT effect, we present the preliminary limit on an the parameters of an extention of GR with the addition of Torsion that was developed by Mao, Tegmark, Guth and Cabi 4) to constrain torision with the data of the Gravity Probe B mission (GP-B). This work on the limit on torsion with LAGEOS data was suggested by I. Ciufolini, the theoretical calculations have been performed by March, Bellettini and Tauraso.

This GR with torsion model is determined by a set $t_1, t_2, w_1, \ldots, w_5$ of seven parameters describing torsion and three further parameters describing the metric $^{4)}$. Using the average LAGES nodal rate of $^{2)}$ we can only constrain a linear combination of a function $f(t_1, t_2)$ of t_1, t_2, and of w_2, w_4. The function f depends linearly on t_1 and t_2. Similarly to $^{4)}$ we report this preliminary limit graphically in fig. 4, together with the other current constraints on the PPN parameters γ and α_1.

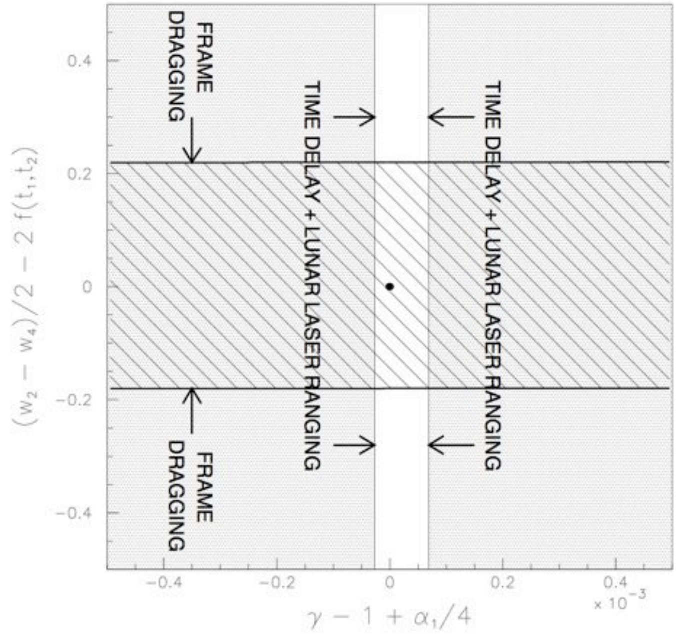

Figure 2: constraints on PPN parameters (γ, α_1) and on torsion parameters (t_1, t_2, w_2, w_4) from solar system tests. The grey area is the region excluded by lunar laser ranging, Cassini tracking and VLBI. The LAGEOS measurement of the Lense-Thirring effect excludes values of $(w_2 - w_4)/2 - 2f(t_1, t_2)$ outside the hatched region. General Relativity corresponds to $\gamma = 1$, $\alpha_1 = 0$ and all torsion parameters $= 0$ (black dot).

It is not known whether torsion is an intrinsic feature of the ultimate, quantum theory of gravity. If torsion exists, it is also not known what its nature is: whether it is spacetime torsion (as considered in this case) or whether it is related to the spin of elementary particles yet to be discovered, hopefully finding hints of new physics at the Large Hadron Collider of CERN. If torsion does exist, however, the combined constraints from gyroscope (GP-B) and orbital Lense-Thirring experiments (LAGEOS) are effective probes to search for its experimental signatures, even if the analyses reported in 4) and here fall within the framework of classic (i.e., non-quantum), non-standard torsion theories which extend General Relativity. In this sense, LAGEOS and GPB are to be considered complementary frame-dragging and, at the same time, torsion experiments.

5 Satellite Laser Ranging in Deep Space

INFN-LNF is also developing a prototype laser-ranged test mass for the Deep Space Gravity Probe (DSGP) mission, led by JPL (PI is S. Turyshev), proposed to the ESA "Cosmic Visions" Program. DSGP is conceived to study the Pioneer 10/11 effect in the outer reaches of the Solar System. This R&D work is being financed by ASI in the context of the three-year study on "Cosmology and Fundamental Physics (COFIS)", led by P. de Bernardis. DSGP is a satellite formation made by a main, active spacecraft, which will release a few CCR-equipped test-masses in deep space and laser-range them. The ultimate test of the PA will be performed by using the active spacecraft (tracked with microwaves from the Earth) as bridge to determine the motion of the laser-ranged test masses in the field of the Sun.

The magnitude of the "so-called" Pioneer Anomaly (PA) is $\sim 10^{-9}$ m/sec^2, which is a factor 10 larger than the highest non-gravitational perturbations (NGPs) that act on LAGEOS. These NGPs, in turn, can be characterized with the SCF at the 10% level. This implies that the SCF-testing is capable of characterizing NGPs which are 1/100th of the PA. Therefore, we can reach the goal of designing and calibrating a laser-ranged test mass for DSGP.

6 Applications to Satellite Navigation

SLR will play another very important role for the Global Navigation Satellite System (GNSS) with the mission-critical large-scale deployment of LRR arrays on all 30 satellites of the European GNSS constellation, GALILEO. SLR will provide 'absolute' positioning, as well as long-term staiblity to the orbits of GALILEO satellites with respect to the Geocenter, which is uniquely defined by the LAGEOS. The addition of SLR to the standard microwave ranging will improve the absolute positioning accuracy of GNSS by one order of magnitude, down to cm level. SLR, coupled to the precise time measurement with H-maser clocks aboard GALILEO, will allow for the improvement of the measurement of the gravitational redshift with the first satellites of the contellation. An approved multidisciplinary INFN experiment, ETRUSCO[3], is dedicated to the SCF calibration of the laser retro-reflector payloads of the GNSS. With ETRUSCO we performed the thermal and optical qualification of a flight model CCR array used for the American GPS-2 (whose basic CCR is also used on the Russian GLONASS constellation) on loan from UMCP and due to fly on the next satellites of the GPS-3 contellation (see Fig. 6).

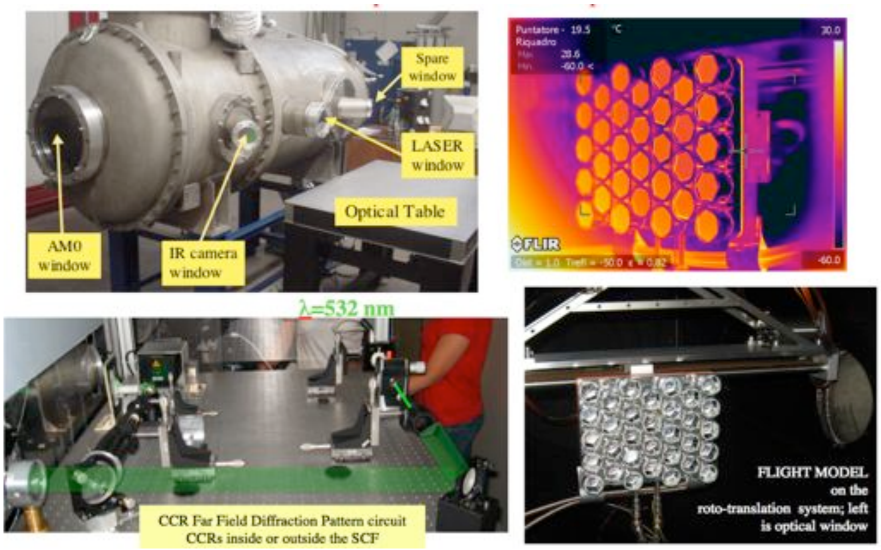

Figure 3: SCF-Test of the GPS-2 CCR array flight model.

7 Conclusions

In summary, the Frascati SCF is performing for the first time ever the integrated thermal and optical calibration of laser-ranged payloads in a realistic space environment for applications of GR, new gravitional theories, Space Geodesy and Satellite Navigation in Earth Orbits, on the Moon and in the outer solar system. So far we have tested CCR prototypes of LAGEOS, of

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[3] Extra Terrestrial Ranging to Unified Satellite COnstellations

the 1^{st} generation Apollo cubes, of Glonass and GPS-2. In the near future we will SCF-Test an innovative hollow retro-reflector in collaboration with NASA-GSFC, which is proposing the hollows for the GPS-3 constellation (first satellite launched ny 2014). Hollow cubes are lighter than the standard, solid, fused-silica CCRs and can be made more compact thus saving weight and space onboard the satellites. However, since they are usually made of three separate pieaces glued and bolted together, a thorough check of the their structural stability and of their optical performace in space must be performed with the SCF prior to their deployment on any expensive and critical mission.

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