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Probing gravity in the Earth-Moon system with ETRUSCO, MoonLIGHT and LAGEOS*

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Abstract

We describe the experimental tests of gravity carried out with the techniques of lunar and satellite laser ranging in the Earth-Moon system, the prospects of searches for new physics, the developement of a new laser retro-reflector payload for the "Lunar Sortie Scientific Oppoertunities" program of NASA (manned landings), for the ASI lunar studies and for the "International Lunar Network" (robotic landings). We also report the technological application of SLR to satellite navigation.

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1 Introduction

Lunar laser ranging (LLR) and satellite laser ranging (SLR) are two consolidated time-of-flight techniques which provide the most precise and, at the same time, the most cost-effective method to track the position of satellites or test-masses equipped with cube corner laser retro-reflectors (CCRs) in space. This is made possible by about 40 laser stations spread across the globe, forming the International Laser Ranging Service (ILRS). One of the best performing stations is the Matera Laser Ranging Observatory (MLRO), operated by ASI in Matera, which is both LLR and SLR capable.

The first and most important laser ranging experiments were Apollo 11, 14, 15 on the Moon surface and LAGEOS-I (1976) at 6000 Km Earth altitude. These are still tracked and actively analyzed today. LLR and SLR missions produced a host of precise tests of General Relativity (GR) and unique measurements of 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. The SCF is defining the standard for SLR and LLR space characterization. This "SCF-Test" is an effective and innovative tool for precision experimental tests of gravity (Bosco, Cantone, Dell'Agnello et al 2006).

2 Second-generation Lunar Laser Ranging

Apollo LLR gives the most accurate measurements of the De Sitter effect in GR (PPN parameter β) and 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 reached with a 2^{nd} generation CCR array like the one that we are developing for NASA and ASI.

In 2006 a research project for a 2^{nd} generation LLR experiment (LLRRA21/MoonLIGHT[1]) has been proposed to NASA by a US-ITALY team led by the University of Maryland (UMCP; PI is D. G. Currie) and co-led

[1]Lunar Laser Ranging Retro-reflector Array for the 21^{st} Century (US name) / Moon Laser Instrumentation for General relativity High-accuracy Tests (Italian name).

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

Phenomenon	Current LLR	1mm LLR	0.1mm LLR	Measur. 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} $\times$gravity	$\sim 10^{-11}$ $\times$gravity	$\sim 10^{-12}$ $\times$gravity	6-10 yr

by INFN-LNF. The italian team participates at zero cost for NASA. 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 of 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 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 geometric librations. These librations currently limit the LLR accuracy to 1-2 cm. Testing of the new 100-mm CCR at the SCF 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 its optical far field diffraction pattern back to the Earth. The LSSO CCR has been manufactured with requirements on the dihedral angle offsets tighter than normal ($\pm$0.2 arcsec) and its FFDP preliminarly tested in air.

Particular care has been devoted to the thermal design of this payload and to the choice of the materials used for the CCR mounting cavity. 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 by 2m thermal blanket will be deployed around the CCR to stabilize locally the environment.

Note that the replacement of the Apollo CCRs 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 (see discussion). 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. 1.

An example of new theory that can be tested with 2^{st} generation LLR is the brane-world theory of (Dvali, Gruzinov, Zaldarriaga, 2003). This is a new quantum theory of "weak" gravity at horizon scales, which 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.

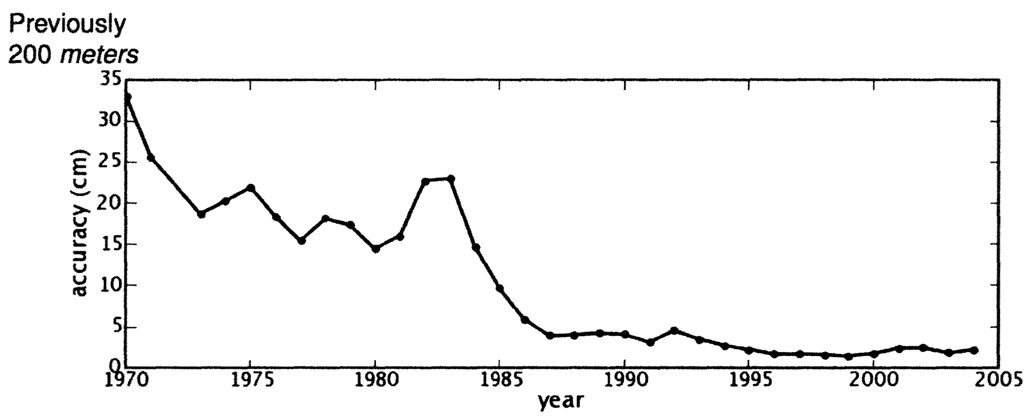

Figure 1: Historical accuracy of the 1^{st} generation LLR.

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 standard payloads 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.

NASA is preparing two lunar missions to establish initial anchor nodes around the mid of next decade. Their science definition team (SDT) has foreseen a payload of four core instruments: 1) seismometer, 2) EM sounding, 3) heat flow probe, 4) CCR. The SDT specs for the CCR are: $\sim$ 10cm diameter, $\sim$ 1Kg reflector weight (with some extra weight for the CCR deployment cavity). The MoonLIGHT CCR that we are developing meets these specs and it was proposed as a natural candidate for the ILN.

4 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 the observation of the Lense-Thirring effect (LT, or "frame-dragging"), a truly rotational, non-static effect predicted by GR in 1918. Current LT measurement with LAGEOS agrees with GR with a relative accuracy of 10% (Ciufolini, Pavlis, 2004).

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, 2007) to constrain torision with the data of the Gravity Probe B mission (GPB). Our work was suggested by I. Ciufolini after the work by Mao et al was published; the theoretical calculations have been performed by March, Bellettini and Tauraso. The limit was obtained by S. Dell'Agnello.

This model of GR with torsion 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 (see Mao et al, 2007). Using the average LAGEOS nodal rate of (Ciufolini, Pavlis, 2004) 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 (Mao et al. 2007) we report our preliminary limit graphically in Fig. 2, together with other current constraints on the PPN parameters γ and α_1.

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 (GPB) and orbital (LAGEOS) Lense-Thirring experiments are effective probes to search for its experimental signatures, even if these analyses 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.

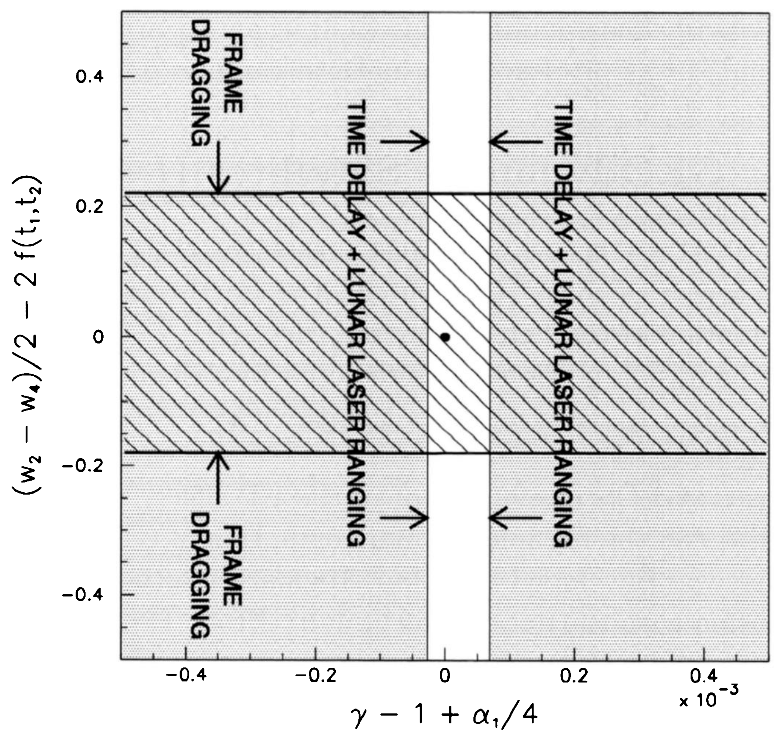

Figure 2: Constraints on PPN parameters (γ, α_1) and on torsion parameters (t_1, t_2, w_2, w_4) from solar system tests. The grey area is the region excluded by lunar laser ranging, Cassini tracking and VLBI. The LAGEOS measurement of the Lense-Thirring effect excludes values of $(w_2 - w_4)/2 - 2f(t_1,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

5 Satellite laser ranging in deep space

INFN-LNF is also desiging a prototype laser-ranged test mass for the Deep Space Gravity Probe (DSGP) mission, led by JPL (PI is S. Turyshev), proposed to NASA and ESA. 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)", coordinated 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 micro-waves from the Earth) used as bridge to determine the motion of the laser-ranged test masses in the field of the Sun (Fig. 3).

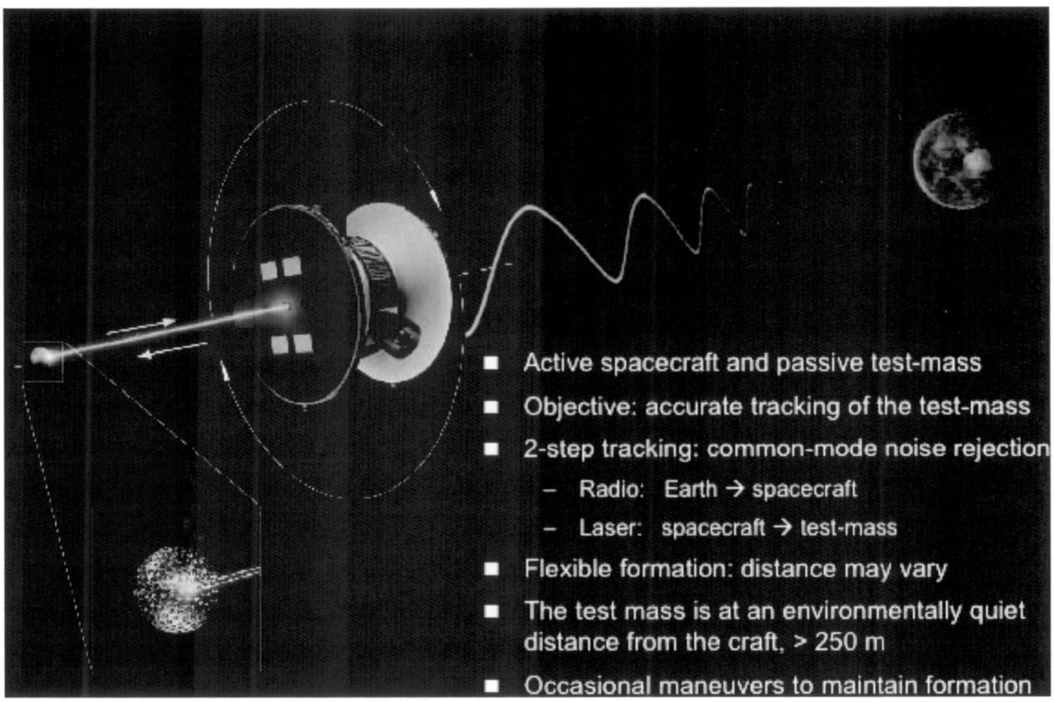

Figure 3: The concept of the satellite formation of the Deep Space Gravity Probe missione to test the Pioneer Anomaly (courtesy of S. Turyshev, NASA-JPL).

The so-called "Pioneer Anomaly" (PA) is a deceleration of magnitude $\sim 10^{-9} m/sec^2$, 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 (Bosco, Cantone, Dell'Agnello et al, 2006). This implies that with the SCF we can characterize NGPs which are 1/100th of the PA and reach the goal of designing and accurately modeling 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 CCR

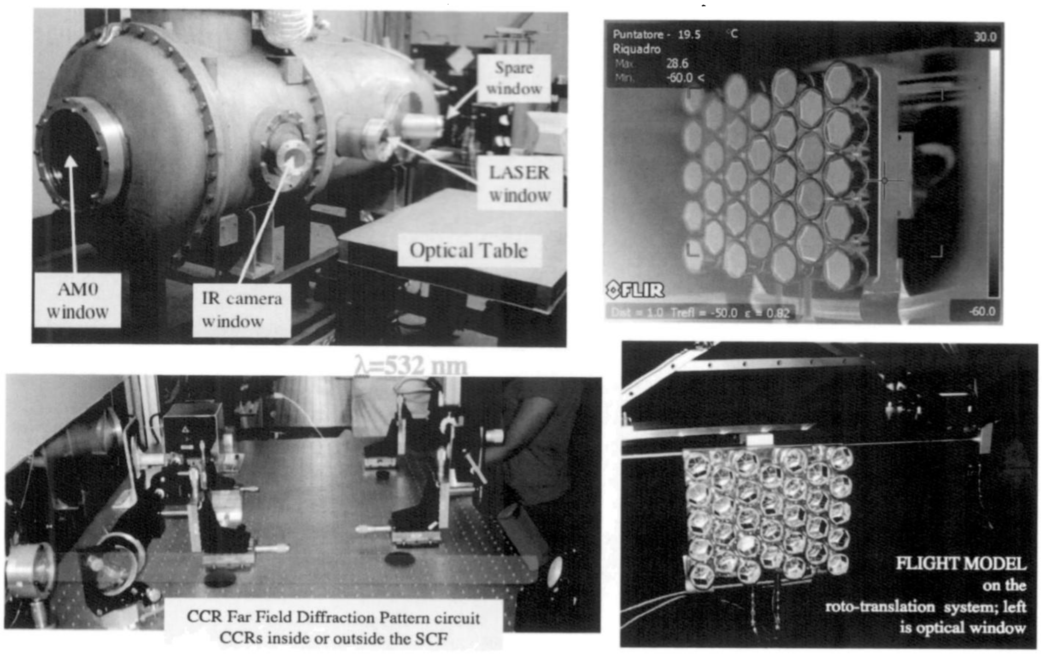

Figure 4: SCF-Test of the GPS-2 flight-model CCR array. Top left: the SCF with the three windows used for the Sun simulator (AMO), non-invasive IR thermometry (IR camera) and for FFDP testing (LASER). Bottom left: FFDP otical circuit. Top right: IR photo of the array. Bottom right: 'visible' photo of the array.

arrays on all 30 satellites of the European constellation, GALILEO. Only two GPS-2 satellites are equipped with CCRs and a third GPS-2 CCR array is under SCF-Testing at LNF. COMPASS, the new Chinese GNSS, will also carry CCRs. The first COMPASS satellite was launched in 2007 and successfully laser-ranged since then.

SLR will give the GALILEO satellites absolute positioning and long-term stability with respect to the Geocenter, which is uniquely defined by SLR and dominated by the LAGEOS data. The addition of SLR to the standard microwave ranging will improve the (absolute) positioning accuracy of GNSS satellites by one order of magnitude, down to cm level. With the this absolute positioning accuracy, which is unprecedented for GNSS, GALILEO could contribute to (and improve) the definition of the Geocenter and of the Scale of Length of the International Terrestrial Reference Frame (ITRF). Note that at the moment to build the ITRF only LLR/SLR and VLBI[2] data are used; GNSS data are not used.

SLR, coupled to the precise time measurement with H-maser clocks aboard GALILEO, could allow for the improvement of the measurement of

[2]Very Long Baseline Interferometry

the gravitational redshift with the first satellites of the constellation (when not in its "industrial" operational mode, which, by design, cancels the redshift to make the time onboard equal to the ground time). An multidisciplinary INFN experiment was approved in summer 2006, ETRUSCO (Extra Terrestrial Ranging to Unified Satellite COnstellations), to build a new facility, the SCF, dedicated to the space characterization of the optical performance of GNSS CCR payloads. With ETRUSCO we SCF-Tested the 3^{rd} GPS-2 flight-model CCR array on loan from UMCP (see Fig. 4). This array should then fly on one of the next satellites. The basic CCR unit of this flight payload is the same used on the Russian GLONASS constellation and on GIOVE-A/B, the two satellite prototypes of GALILEO.

7 Conclusions

In summary, for the first time ever the Frascati SCF groupo has performed the integrated thermal and optical characterization of laser-ranged payloads in a realistic space environment to test GR and new gravitational theories and for applications of Space Geodesy and Satellite Navigation in Earth Orbits and on the Moon. So far we have tested prototypes of LAGEOS, 1^{st} generation Apollo, Glonass, GIOVE and GPS-2 CCRs.

In the near future we will SCF-Test an innovative hollow retro-reflector in collaboration with NASA-GSFC, which is proposing it for the GPS-3 constellation (first satellite to be launched by 2014). Hollow CCRs are lighter than the traditional, solid, fused-silica CCRs and can be made more compact thus saving weight and space onboard the satellites. However, since they are now made of three separate pieces glued and bolted together, a thorough check of the their structural stability and optical performance in space must be performed with the SCF prior to their deployment.

8 Acknowledgements

This work was partially supported by NASA through its LSSO program, and by ASI through its 2007 lunar studies. Therefore, we wish to thank Kelly Snook of NASA and Sylvie Espinasse and Elisabetta Cavazzuti of ASI.

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Discussion

G. Chincarini: I seem to recall that the Apollo LLR experiment (the early one from the McDonald Observatory in the early 70s) had a problem in testing General Relativity because of imperfections in the knowledge of mass distribution of the Earth and the Moon. Now with the much better accuracy you will reach (a factor 100 or more) I assume new smaller irregularities or perturbations must be even more critical in the model.

S. Dell'Agnello: You are raising the complex issue of the overall error budget of LLR. The goal of our project, MoonLIGHT, is to improve the accuracy of the LLR space segment, that is, the retro-reflectors located on the Moon surafce. We will reduce drastically, by a factor at least 100, the main source of LLR error, which is the geometric libration of the Moon coupled to the structure of the Apollo reflectors (large array, composed by 100 CCRs for Apollo 11 and about 400 for Apollo 15). Current LLR accuracy, 1-2 cm, is limited mainly by these geometric librations. Our new CCR concept removes this effect and will leave the smaller, residual error sources: physical librations (due to the inner structure and dynamics of the Moon), atmospheric corrections (laser pulse delay), geodynamic effects (like ocean loading), finite laser pulse length and the resolution of laser return detector/electronics. I will address the last two in the answer to the second question. Let me briefly address these other, smaller error sources.

Physical librations: these will have to be measured and subtracted to study gravity. The large planetology community is interested in using LLR to study them and it cannot do that with the Apollo reflectors.

Atmospheric corrections: these are being determined with the two-color laser ranging technique, measuring the relative delay of green (Nd:Yg) and red (He-Ne) wavelengths. This is one of the major goals of modern SLR space geodesy, in particular for the benefit of having an ITRF with an ultimate precision of better than 1 mm per epoch and stability better than 1 mm/yr. Geodesy and geodynamics effects are, so-to-say, “background” effects for studing GR, and, fortunately, the synergetic work of the geodesy and gravity communities has so far been very successfull. Let me also add that in order to study gravity, the Earth-Moon system is the most conveniently and accessible laboratory that we have. The new frontier is building a gravitational model of the Moon at a level of accuracy better that what Clementine and Prospector did. Several orbiter missions will do that in the next years (Selene, Change’, Chandrayaan, LRO, GRAIL). So far we only know the motion of the Selenocenter thanks to the Apollo arrays at the cm level. This is not enough, and MoonLIGHT will start improving over Apollo in a significant way.

Improving the space segment of LLR (ie, removing the effect of geometric librations) opens the way to the work which will improve the other smaller error components, on which it would not make sense to work on now. In other words, like for 1^{st} generation LLR, we will put innovative reflectors on the Moon ... “and they will come”. One of us, D. G. Currie, was there 40 years ago and saw this happen the first time. In fact, Doug was the very first leader of the McDonald LLR Observatory, and you might have met him there at that time.

K. Wu: You have mentioned the measurement of Earth-Moon distance, 384.000 Km, with an accuracy of 100 μm. This implies that the timing accuracy is about 1 part in 10^{-12}. How can you control the timing accuracy in space given this requirement?

S. Dell’Agnello: The time taken by a laser pulse to reach the Moon from the Earth is about 1.25 sec. An accuracy of 100 μm is equivalent to about 330 fsec. To make an LLR measurent with the target 10^{-12} relative accuracy it takes at least: a short laser pulse ($<$ 1 psec), fast and accurate (($<$ 1 psec) electronics, high repetition rates and large signal return from a single retro-reflector.

Once again, ILRS stations do not have at present this type of performance, because this is not required given current limitation imposed by the geometric librations of 1-2 cm! For instance, typical ILRS pulse lengths are now 10 psec. However, laser technologies allow already now sub-psecond values (at INFN-LNF there is one such laser, SPARC/X). Typical accuracies of the laser ranging electronics is 1 to a few psec, and it is well-known that ILRS timing electronics is by far superior to the one used in astro/particle physics applications. Note, however, that an ILRS station needs a few channels, while prticle physics experiments needs up to hudrewds of thousands of channels. ILRS stations used H-maser clocks, while particle physics experiments do not use ordinarily atomic clocks. The ILRS detectors are strak cameras (which do have sub-psecond accuracy) or high-performance (and expensive) microchannel-plate PMTs. The requirements that our MoonLIGHT retro-reflector will poses on ILRS laser technologies do not seem problematic for the normal and quick evolution of lasers and their industrial applications. Suffice to say that during the 40 years of 1^{-st} genration LLR, laser technolgies improved by a factor 10^4.

It is interesting to note that, in general, CCR arrays on satellites in Near Earth Orbits give multiple laser returns (ie, from more than one CCR). This broadens the final SLR accuracy. This is another, tough source of error intrinsic to the space segment (called the satellite "signature"). Instead, our MoonLIGHT CCR is designed in such a way that each single unit will produce a clean, large return on ILRS detectors. MoonLIGHT CCRs will also be deployed at a relative distance large enough no to overlap returns form separate CCRs.

In summary, ILRS ground segment technologies will have to evolve in order to meet the requirements of 2^{nd} generation LLR and follow the factor 100 improvement of the space segment provided by MoonLIGHT. But probably this will take less time and will be less difficult than for the effects pointed out by Guido Chincarini.