SCF_Lab

G. Bellettini (Ass.), G. Bianco (Ass.), E. Ciocci (AR), S. Contessa (AR)
S. Dell'Agnello , G.O. Delle Monache, N. Intaglietta (Tec.), M. Maiello (Ass.),
R. March (Ass.), M. Martini (AR), C. Mondaini (Art. 15), L. Porcelli (AR),
L. Salvatori (Art. 15), R. Tauraso (Ass.), M. Tibuzzi (Art. 15), R. Vittori (Ass.)

1 SCF-Test

The SCF_Lab (Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory)[1] is a specialized infrastructure, unique worldwide, dedicated to design, characterization and modeling of the space segment of Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and Planetary Laser Ranging and Altimetry (PLRA) for industrial and scientific applications. I developed advanced laser retroreflectors for solar system exploration, geodesy and for precision tests of General Relativity (GR) and new gravitational physics. Our key experimental innovation is the concurrent measurement and modeling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of the SLR/LLR payload of retroreflectors under thermal conditions produced with a closematch solar simulator. The primary goal of these innovative tools is to provide critical design and diagnostic capabilities for SLR to Galileo and other GNSS (Global Navigation Satellite System) constellations. The implementation of new retroreflectors designs being studied will be helpful to improve GNSS orbits, increasing, this way, accuracy, stability, and distribution of the International Terrestrial Reference Frame (ITRF), in order to provide a better definition of the geocenter (origin) and the scale (length unit). The SCF is also actively used to develop, validate and optimize 2nd generation LLR arrays for precision tests of GR with the MoonLIGHT-2 (Moon Laser Instrumentation for General relativity High-accuracy Tests Phase 2) project. Laser ranging and laser reflectors throughout the solar system are also used to develop new fundamental gravity physics models and study the experimental constraints to these models. Starting from 2004 INFN invested resources and manpower to build and operate the SCF Lab in Frascati, near Rome, dedicated to the characterization of the thermal properties and the laser ranging response of laser retroreflector arrays (LRAs) of CCRs (Cube Corner Retroreflectors) in space conditions accurately simulated in the laboratory (SCF-Test). The SCF Lab consists of two OGSE (Optical Ground Support Equipment) called SCF (property of INFN) and SCF-G (which doubles our metrology capabilities for applications to GNSS, property of INFN and ASI). A schematic view of the cryostats is shown in Fig.:3. We have tested a large variety of CCRs, from LAGEOS (Laser GEOdynamics Satellite) to Apollo and GNSS LRAs.

[1] http://www.lnf.infn.it/esperimenti/etrusco/

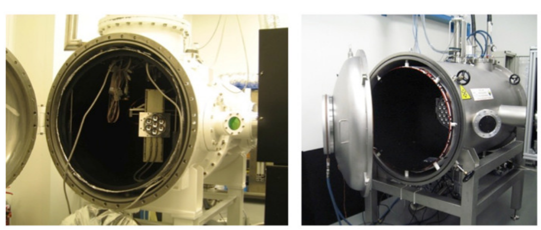

Figure 1: *SCF and SCF-G cryostats with GNSS LRAs inside.*

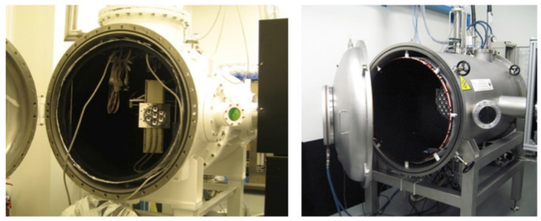

Figure 2: *SCF and SCF-G cryostats with GNSS LRAs inside.*

2 Experimental Test

2.1 LRG2

2.1.1 Introduction

We shall present the activities that are being performed in the framework of the joint ASI-INFN 'Premiale' Project 'Laser Ranging to Galileo (LR2G)', which is funded by the Italian Ministry of Research. Thanks to LR2G, ASI-CGS and INFN-LNF are implementing important upgrades of their respective equipments and infrastructures, and, subsequently, they will carry on their peculiar tasks for the completion of the project. Namely, ASI-CGS will laser range to LRAs (Laser Retroreflector Arrays) on board Galileo IOV (In-Orbit Validation) vehicles and to LAGEOS satellites; whereas, INFN- LNFs SCF_{Lab} will complete full laboratory thermo-vacuum-optical characterisations of the 5th spare flight Galileo IOV LRA (on loan to LNF from ESA) and of the LAGEOS Engineering Model (also known as LAGEOS Sector, on loan to LNF from NASA). Besides the technical challenges related to equipment/infrastructure upgrades (which will be commented), the objective of the present project is to compare Galileo IOV retroreflectors against LAGEOS retroreflectors, both in the laser ranging station and on the laboratory optical bench. Following results will help optimizing GRA (GNSS Retroreflector Array) design and manufacturing. The project has started in 2016 and, during its first year, has envisaged tests on LAGEOS only; we shall then present the rationale of the activities and some already obtained results.

2.1.2 Project

LR2G is a joint ASI-INFN project performed in the framework of the ASI-INFN Agreement N. 2015-048-R.0 for 'Adeguamento SCF_{Lab}'. The project as a whole was granted through Italian Ministry of Research Decree 25 November 2013 Nr. 973.
LR2G is building on previous experiences and direct involvement of ASI-INFN in cutting-edge laser ranging activities; namely:

- ASI, through MLRO (Matera Laser Ranging Observatory), is one of the core stations of the ILRS (International Laser Ranging Service) [3] and is deeply involved in the daily generation of geodetic products thanks to laser ranging measurements.
- INFN-LNFs SCF_{Lab} (Satellite/lunar/GNSS laser ranging/altimetry and cube/microsat Characterization Facilities Laboratory) is a space infrastructure, devoted to space RD and located inside an ISO 7 clean room; the experimental innovation of the SCF_{Lab} is the concurrent measurement and modelling of the optical FFDP (Far Field Diffraction Pattern) and the temperature distribution of SLR (Satellite Laser Ranging) payloads under realistically simulated space conditions, with respect to temperature, pressure and solar constant load. Recently,

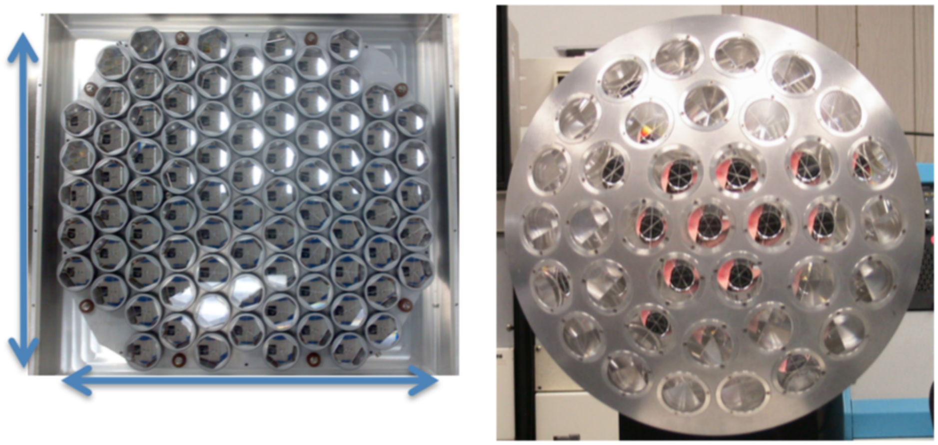

Figure 3: *Left:* 5^{th} *spare flight Galileo IOV LRA (ESA courtesy); dimensions are approximately 430 mm x 470 mm. Right: LAGEOS Engineering Model (NASA courtesy).*

the SCF_{Lab} has already been involved in thermo-vacuum-optical tests of spare and loose Galileo CCRs (Cube Corner Retroreflectors).

LR2G foresees equipment and infrastructure upgrades both at ASI-MLRO and SCF_{Lab}. ASI-MLRO will then laser range to LRAs on board Galileo IOV vehicles and to LAGEOS satellites; whereas, SCF_{Lab} will complete full laboratory thermo-vacuum- optical characterisations of the 5^{th} spare flight Galileo IOV LRA and of the LAGEOS Engineering Model.

2.2 MoonLIGHT-2 and SCF-G

The SCF-Test key experimental innovation is the concurrent measurement and modeling of the optical FFDP and the temperature distribution of the SLR/LLR retroreflector payload under thermal conditions produced with a closematch solar simulator. The tests apparatus includes infrared cameras for non invasive thermometry, PT100 probes for invasive thermometry, thermal control electronics and systems for real time movement of the payload to experimentally simulate payload orientation with respect to both solar illumination and laser interrogation beams. For the detail of Moonlight-2 orientation respect to the three window in the SCF-G and the convention used to define the angle value respect to payload orientation see figure 4.

With our experimetal tests we want evaluate:

1. CCR FFDPs under simulated space conditions in order to study the intensity of the returning optical pattern at the MoonLIGHT-2 velocity aberration before and after the SUN exposure;

2. CCR surface temperature and its thermal constant τ_{CCR} using the infrared camera FLIR SC 640;

3. temperature on the otherMoonLIGHT-2 structural component with PT100 contact probes. See following part of the section for the probes configuration used.

During the test the payload assembly inside the SCF-G is thermally decoupled from the environment then we take the SCF-G in cryogenic and vacuum condition (pressure about $\times 10^{-6} mbar$ and an temperature chamber about 90K). Then we hold the average temperature of theMoonLIGHT-2

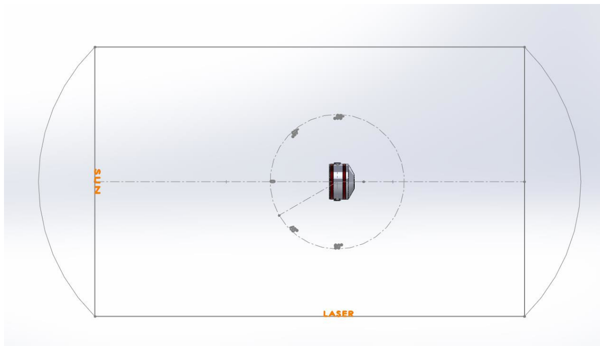

Figure 4: CAD sketching from an above viewpoint the position of MoonLIGHT inside the cryostat, with respect to the solar window (left) and the laser window (down).

mechanical support structure to the expected test average value, waiting plateau condition for MoonLIGHT-2 and SCF-G. In this phaseMoonLIGHT-2 faces the optical window for at least 12h. After the reach of the steady condition (plateau condition for 30-60 minutes) the test can start, this phase can be schematized in the following tree main steps:

- **Steady state conditioning**: we take 1 FFDP and 1 IR simultaneously in order to acquire the payload initial conditions before the test starts.
- **SUN ON heating phase**:MoonLIGHT-2 faces the solar window with a fixed angle (0 degree*and* 30 degree). Here we take only IR pictures with a fixed cadence. This phase lasts for 14h.
- **SUN OFF cooling phase**: the solar illumination is closed and the payload feces the optical window. Here we take IR pictures with a fixed cadence and simultaneously FFDP with a different fixed cadence. This phase lasts for 14h.

The test will be repeated for different control temperature and different inclinations between CCR and solar radiation during the SUN ON phase, in this way we want to see how much the thermal and optical behavior changes in different experimental conditions. The above description is a general presentation of the SCF-Test, but we conduct three different test campaigns, with different probes MoonLIGHT-2 structures.

In the first test campagin we use the structures in figure 5 realize two SCF test, with sun angle at 0degree respect to the solar window and another one with 30degree inclination. In both we kept the housing temperature at 300K.

In the second test campaign we add a copper tape on the CCR tab (see figure 6) in order to reduce the thermal conductivity between the CCR and its housing. I realize three test, with the housing kept at 250K-300K-330K and always with 0 degree inclination respect to SUN in the SUN ON phase.

Finally in the last test campaign we remove the CAN in figure 5 and kept the copper tape. Here we realize two test just as in the first campaign: housing at 300K and with sun angle at 0degree respect to the solar window and another one with 30degree inclination.

In figure 7 are summarized all the results for the thermal analysis, while in in figures 8 and 9 are summarized the optical intensity results for the last test campaign.

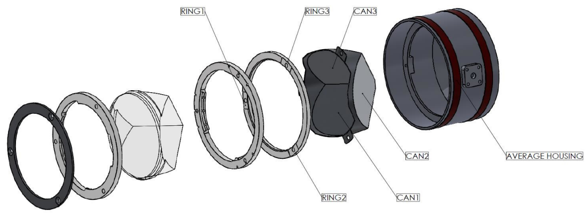

Figure 5: MoonLIGHT-2 structure.

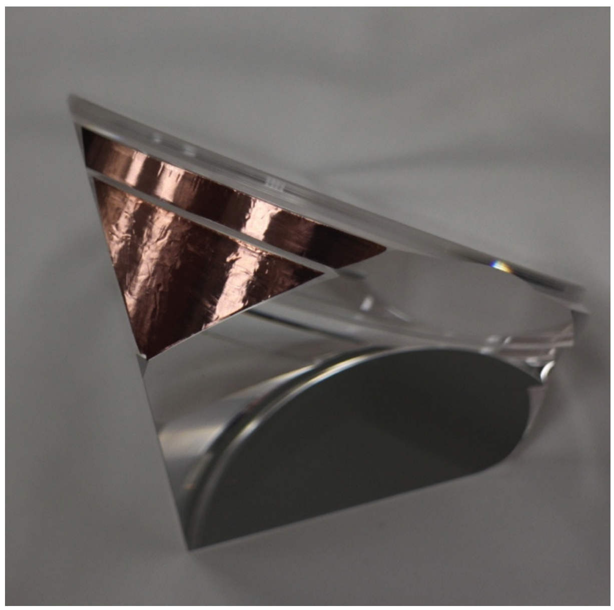

Figure 6: MoonLIGHT-2 structure.

2.2.1 Simulation

We have performed a number of numerical simulations in order to develop and optimize the design of MoonLIGHT type CCR in time for their deployment on the lunar surface. For these simulations we have used every LLR data available until 2014 plus dummy observations on MoonLIGHT-2 CCR.

All the dummy observations were computed by PEP after defining CCRs positions on the lunar surface (Fig.:10). We have used three different sets of parameters for the dummy observations. For the simulated observations, the round trip timing uncertainties are:

- 16 ps for APOLLO and 33 ps for other sites on existing reflectors, and 3 ps for APOLLO and 7 ps for other sites on the proposed reflectors (This is called STD accuracy)

- 32 ps for APOLLO and 66 ps for other sites on existing reflectors, and 6 ps for APOLLO and 14 ps for other sites on the proposed reflectors (This is called 2-STD accuracy)

- 8 ps for APOLLO and 16.5 ps for other sites on existing reflectors, and 1.5 ps for APOLLO

Test campaign	SCF TEST		τ_{CCR} [10^3 sec]			Maximum ΔT [K]		
	Housing Temp [K]	SUN inclination	Heating phase	Cooling phase	Average	Heating phase	Cooling phase	Average
1st With Can No tape (11-12/2014)	300	0°	11.9 ± 0.8	13.3 ± 0.9	12.6 ± 1.0	3.6 ± 1.0	3.6 ± 1.0	3.6 ± 1.4
	300	30°	11.5 ± 0.7	14.4 ± 0.9	13.2 ± 2.1	5.8 ± 1.0	5.4 ± 1.0	5.6 ± 1.4
2nd With Can With tape (05-09/2015)	300	0°	15.1 ± 1.0	16.5 ± 1.1	15.8 ± 1.0	3.1 ± 1.0	2.9 ± 1.0	3.0 ± 1.4
	250	0°	10.4 ± 0.7	10.7 ± 0.7	10.5 ± 0.2	4.7 ± 1.0	4.1 ± 1.0	4.4 ± 1.4
	330	0°	15.6 ± 1.1	16.1 ± 1.1	15.9 ± 1.5	3.1 ± 1.0	3.4 ± 1.0	3.3 ± 1.4
3rd No Can With tape (12/2015)	300	0°	12.2 ± 0.8	13.6 ± 0.9	13.0 ± 1.2	2.9 ± 1.0	2.8 ± 1.0	2.9 ± 1.4
	300	30°	11.1 ± 0.7	13.2 ± 0.8	12.1 ± 1.1	3.3 ± 1.0	2.7 ± 1.0	3.0 ± 1.4

Figure 7: MoonLIGHT-2 SCF-Test all thermal results.

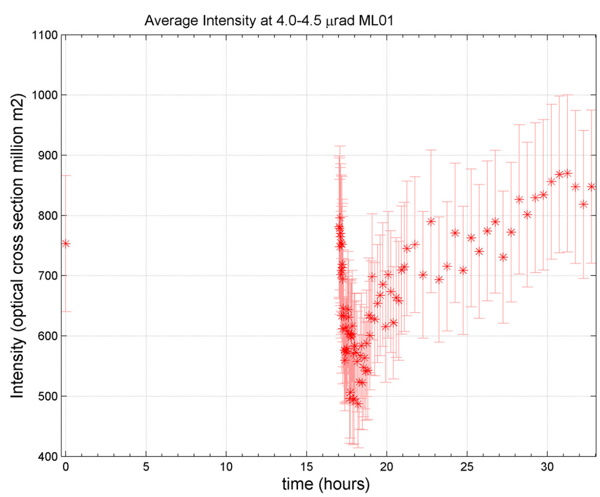

Figure 8: Laser return intensity for the third test campaign: 0 degree SUN inclination.

and 3.5 ps for other sites on the proposed reflectors (This is called HALF-STD accuracy)

The assumed accumulation of future data is calculated with a cadence of 30 days for APOLLO, 20 days for MLRS, 14 days for CERGA, and 8 days for MLRO. The results obtained with the simulations are shown in figg. 11 - 15

The σ reported in the results is the purely statistical uncertainty in the estimation of parameters, assuming no systematic errors in the data or imperfections in the model. It is better to talk about the PEP solution values as "estimates", rather than "measurements", and therefore it is

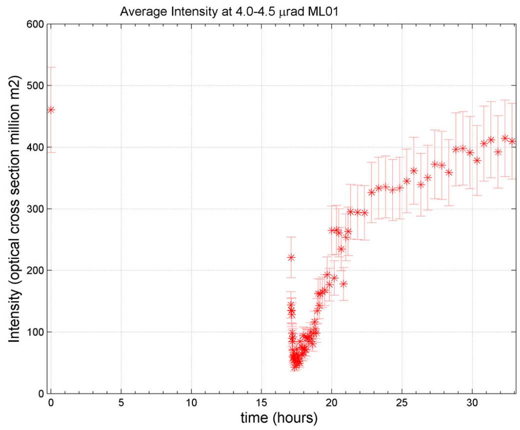

Figure 9: Laser return intensity for the third test campaign: 30 degree SUN inclination.

better to talk about of the "uncertainty" of the values, rather than their "accuracy". However, the main point is that the sigma put out by PEP is a formal uncertainty and not always a realistic uncertainty.
The results show the pessimistic case of not-upgraded laser station hardware and, most of all, with current version of the orbit software which only supports a total LLR error budget on the order of a cm. Most of all, figures 11 - 15 do not include the updates, optimizations and improvements of any current orbit software that will have to be implemented, and that will be possible to implement, as the LLR instrumental accuracy will improve thanks to the progressive deployment of MoonLIGHT CCRs on the Moon and thanks to the progressive upgrades of the LLR ground stations and/or additions of new LLR ground stations.

3 Conclusions and Future Prospects

Although Apollo retroreflectors will continue to operate and provide new science results, their geometry is now limiting the precision of the single photoelectron returns. The next generation retroreflector, MoonLIGHT-2, will support improvements in ranging precision, by one order of magnitude, depending on the method of deployment. Speaking about the experimental test done on MoonLIGHT-2 CCR we can conclude that the results shows that MoonLIGHT-2 can provide a mm-accuracy during lunar night. This is because the SUN-ON phase FFDPs are in good agreement with the simulations as shown by the longer τ_{CCR} and the reduced thermal gradient. Further analysis will be done in order to ensure the operatively phase not only during lunar night but also during lunar day time. However from the simulations we can see that we can obtain good GR results improvement using the payload even during the lunar night alone.
For the analysis part we can conclude that the simulations described in this work show that:

- The GR tests with MoonLIGHT-2 will be not dependent from the MoonLIGHT- 2 deployment site with the exceptions of the poles (because of the lunar libra- tion, the array is not always visible from Earth).
- There are not great differences in the GR tests using a MoonLIGHT-2 design with or without Sunshade. So we choose the design without the sunshade that will provide an important weight optimization (about 1kg) with similar results in GR tests.

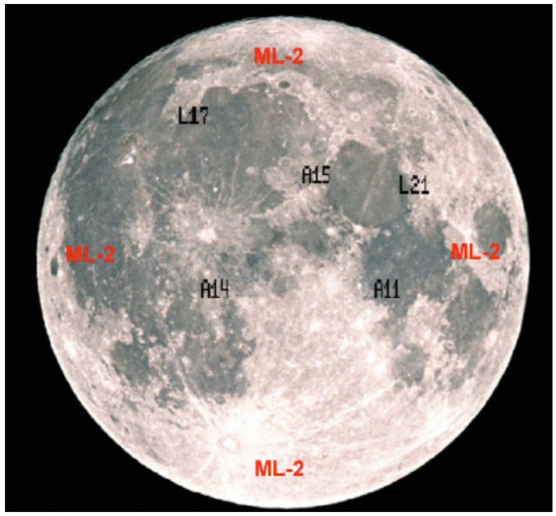

Figure 10: *CCRs position on the lunar surface.*

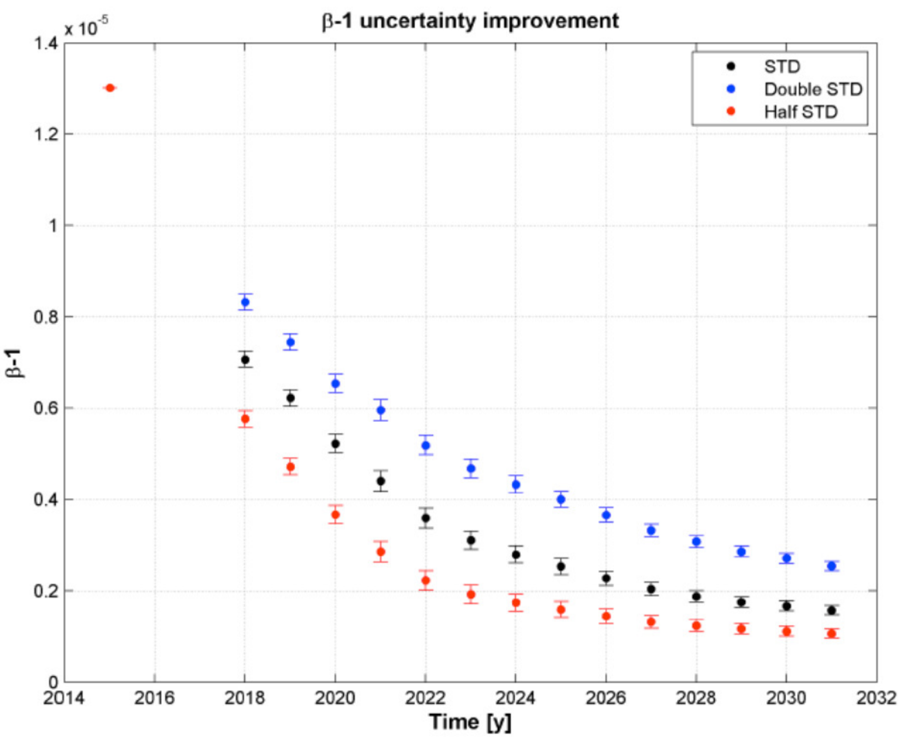

Figure 11: *β uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

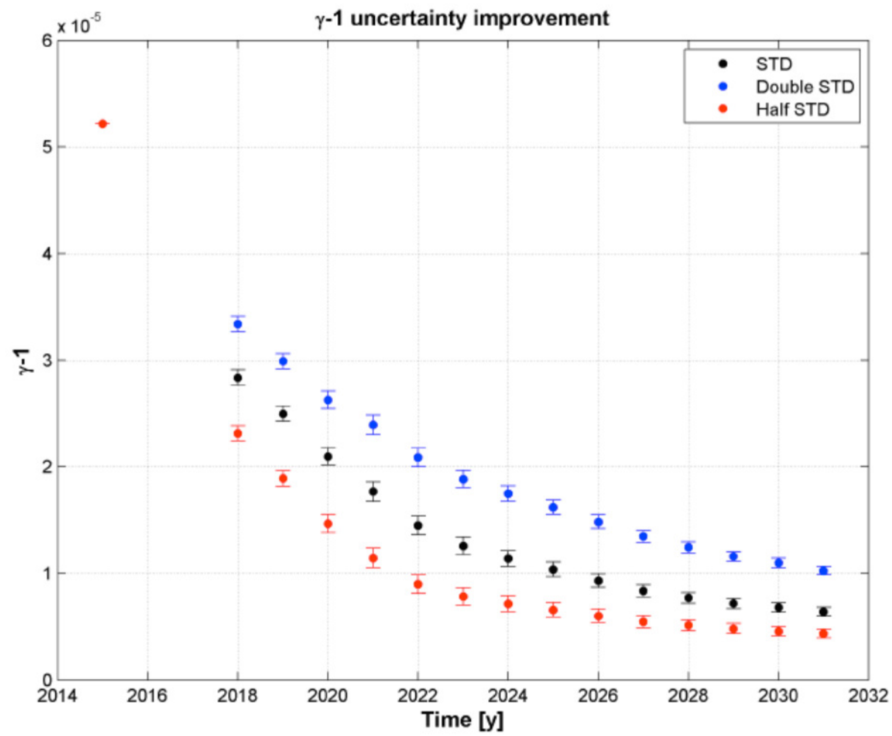

Figure 12: γ *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

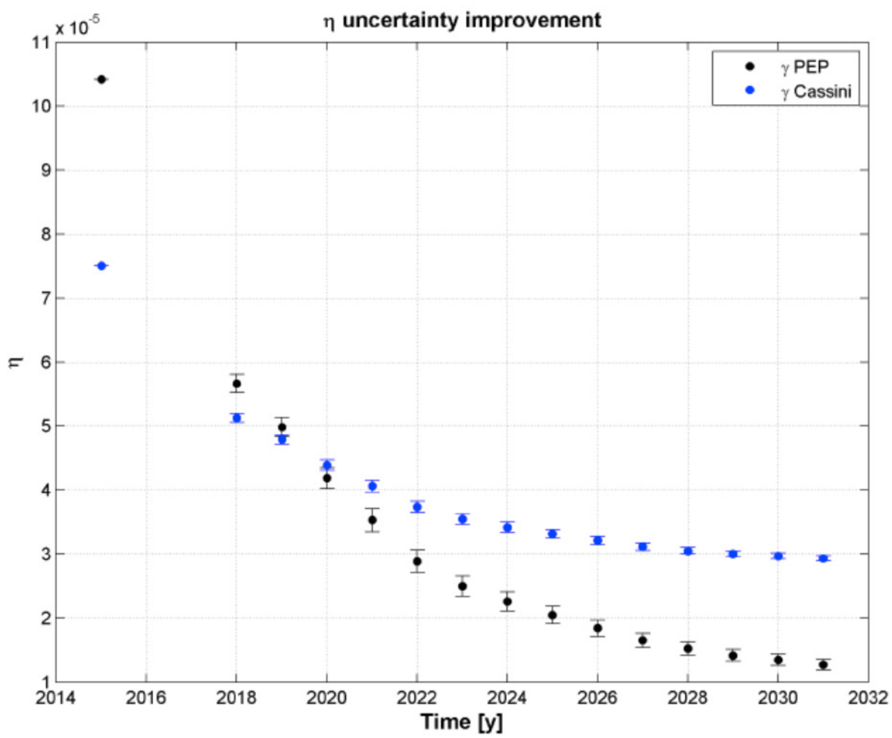

Figure 13: *η uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

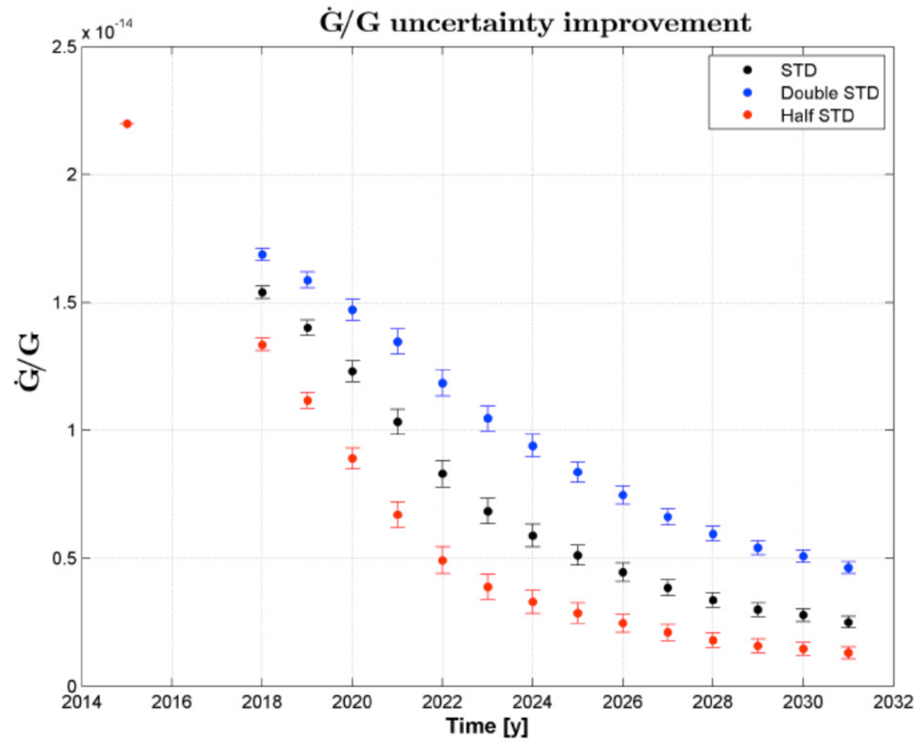

Figure 14: $\frac{\dot{G}}{G}$ *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

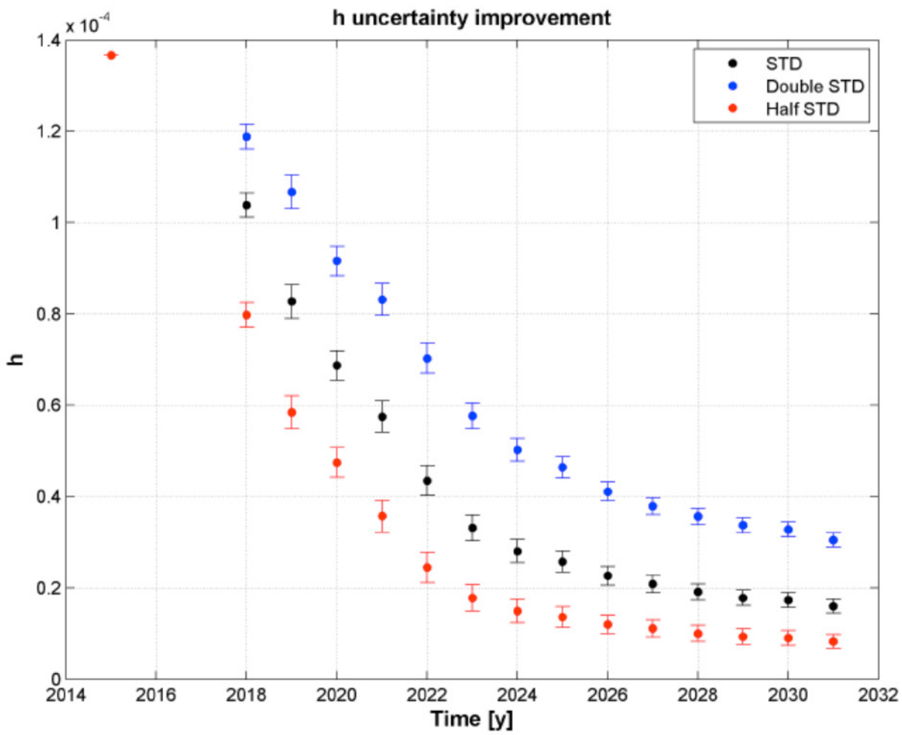

Figure 15: *Geodetic precession uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

- The improvements shown in the simulations represent the most pessimist case where we do not considerate the LLR station upgrade or any software update and only few MoonLIGHT deployed in non optimal locations.

The ultimate scientific objective of MoonLIGHT-2 is to provide constraints on the theories that are proposed to determine the properties of Dark Matter and Dark Energy, and other gravitational theories. This improved precision will be useful to identify the theoretical directions that will further the development of an understanding of these mysterious phenomena that lie beyond our current understanding. Summarizing we can say that the simulations showed are a good starting point in order to achieve better tests of GR using the Earth-Moon system and MoonLIGHT-2 CCRs. Nevertheless if we want to better investigate GR we have to include in our analysis data not only from the Moon but also from other rocky solar system bodies. By this end is possible to study not only Moon-related parameters but also other GR parameters.
For the near future we are moving forward to have main areas:

- Test: By the end of 2015, it is scheduled another MoonLIGHT test campaign. In particular we are going to change the MoonLIGHT design (see 4.3.3) in order to reduce the thermal conductivity between the CCR and the housing. The first test will be carried out removing the conformal can to reduce the thermal radiative load on the object. Using this new configuration we are going to study also the change in the optical performance of the CCR under space conditions.

- Structural design: At the same time, other MoonLIGHT configuration will be simulated at the SCF Lab. These structural simulations concerns about the conformal can, the bracket and the tabs.
  The presence of the braces decreases the displacement on each cornercubic surface of the can, especially at the intersection point of each braces couple (where the displacement is maximized). On the other hand, the use of the braces increases the weight of the entire can and therefore increases the stress in the critical zones; The braces increase the value of the first resonance frequency, so decreasing the problems due to shock and vibration loads; The use of large tabs, instead of small tabs, decreases significantly the stress in the area closer to the tabs. The structural simulations and the experimental tests must provide the best match between low thermal conductivity and a proper structure design avoiding stress during the launch.

- Vibration tests: After the items above and before the end of 2016, the validation tests for the launch will be carried out.

- PEP improvements on GR tests: we have already planned possible improvements in the PEP software in collaboration with the Center for Astrophysics. The first update concern about the computation of PPN parameter η in order to estimate the violation of the Equivalence Principle. Second, we also want to estimate the position of the Center of Mass of the Earth and Mars.

Most of all, after the MoonLIGHT deployment on the lunar surface, we will acquire the first new LLR data to begin the second generation of LLR measurements and GR tests.

4 CORA

Regarding CORA we did free different SCF-tests and one Orbital Test in order to reproduce a critical COSMO second generation satellite orbit. The orbital parameter using for orbit tests was computed with a specific studies carried out with a Matlab code, in this way we were able to obtain the the solar rays inclination on the ccr front face during the orbit. Regarding the SCF test the plate temperature was 280 K 300 K e 320 K.

5 Publications

1. C. Mondaini, Roma, Thermal-vacuum optical characterization of next-generation lunar laser retroreflectors, Conference: 18th Italian National Conference on Photonic Technologies (Fotonica 2016)
2. S. Dell'agnello, WEB, Thermo-optical vacuum testing of Galileo In-Orbit Validation laser retroreflectors, Advances in Space Research 57(11)
3. S. Dell'agnello, WEB, INRRI-EDM/2016: the first laser retroreflector on the surface of Mars, Advances in Space Research

References

1. Dell'Agnello, S., et al, *"Creation of the new industry standard space test of laser retroreflectors for the GNSS and LAGEOS"*, Adv. in Space Res. 47,822-842, http://dx.doi.org/10.1016/j.asr.2010.10.022.
2. Dell'Agnello, S., et al. (2011) ETRUSCO-2, an ASI-INFN Project for the Development and SCF-Test of GNSS *Laser Retroreflector Arrays. ESA Proc. of 3rd International Colloquium Scientific and Fundamental Aspects of the Galileo Programme, Copenhagen*, http://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/ga01_reflector.html.
3. Murphy T., Battat J., et al., *"The Apache Point Observatory Lunar Laser Ranging Operation (APOLLO): two years of Millimeter Precision Measurements of the Earth-Moon Range"*, PASP 121, 29 (2009).
4. D.G.Currie, S. Dell'Agnello, *"A Lunar Laser Ranging Retroreflector Array for the 21st Century"*, AMOS 2009.
5. J.G.Williams, S.G.Turyshev, D.H.Boggs, *"Progress in Lunar Laser Ranging Test of Relativistic Gravity"*, Phys.Rev.Lett.93:261101,2004.
6. Bender P. L., et al, *"The Lunar Laser Ranging Experiment"*, Science, Volume 182, Issue 4109, pp. 229-238, 1973.
7. Williams J. G., Turyshev S. G., Boggs D. H., Ratcliff J. T., *"Lunar Laser Ranging Science: Gravitational Physics and Lunar Interior and Geodesy"*, 35th COSPAR Scientific Assembly, July 18-24, 2004.
8. Williams J. G., Boggs D. H., Ratcliff J. T., *"A larger lunar core?"*, 40th Lunar and Planetary Science Conference, March 23-27, 2009.
9. Williams J. G., Turyshev S. G., Boggs D. H., *"Lunar Laser Ranging Test of the Equivalence Principle with the Earth and Moon"*, International Journal of Modern Physics D, Volume 18, 1129-1175, 2009.
10. Rambaux N., Williams J. G., Boggs D. H., *"A Dynamically Active Moon-Lunar Free Librations and Excitation Mechanisms"*, 39th Lunar and Planetary Science Conference, March 10-14, 2008.

11. Williams J. G., Boggs D. H., Ratcliff J. T., *"Lunar Tides, Fluid Core and Core/Mantle Boundary"*, 39th Lunar and Planetary Science Conference, March 10-14, 2008.

12. Nordtvedt K., *"Lunar Laser Ranging: a comprehensive probe of post Newtonian gravity"*, Gravitation: from the Hubble length to the Planck length, edited by Ciufolini I., Coccia E., Gorini V., Peron R., Vittorio N., ISBN 07503 0948, published by Institute of Physics Publishing, the Institute of Physics, London, 2005, p.97.

13. Murphy T. W., Adelberger E. G., Strasburg J. D., Stubbs C. W., Nordtvedt K., *"Testing Gravity via Next Generation Lunar Laser Ranging"*, Nuclear Physics B Proceedings Supplements, Volume 134, 155-162.

14. Nordtvedt K., *"Testing the Equivalence Principle with laser ranging to the Moon"*, Adv. in Space Research, Volume 32, Issue 7, 1311-1320.

15. Dvali G., Gruzinov A., Zaldarriaga M., *"The Accelerated Universe and the Moon"*, Physical Review D, Vol. 68, Issue 2, id. 024012.

16. Currie D. G., et al., *"A Lunar Laser Ranging Retro Reflector Array for NASA's Manned Landings, the International Lunar Network, and the Proposed ASI Lunar Mission MAGIA"*, 16th International Workshop on Laser Ranging Instrumentation, October 13-17, 2008.

17. Prete F., *"Contact structural analysis of the MoonLIGHT Laser Retro reflector Assembly with ANSYS"*, Bachelor thesis (unpublished), Dipartimento di Meccanica e Aeronautica, University of Rome "La Sapienza".

18. Minghiglioni A., *"Modal analysis of the MoonLIGHT Laser Retro reflector Assembly with ANSYS"*, Bachelor thesis (unpublished), Dipartimento di Meccanica e Aeronautica, University of Rome "La Sapienza".

19. `http://ilrs.nasa.gov/docs/retroreflectorspecification070416.pdf`

20. Pearlman M. R., Degnan J. J., Bosworth J. M., *"The International Laser Ranging Service"*, Adv. in Space Research, Vol. 30, No. 2, 135-143, 2002.

21. Urschl C., Beutler G., Gutner W., Hugentobler U., Schaer S., *"Contribution of SLR tracking data to GNSS orbit determination"*, Adv. in Space Research, 39(10), 1515-1523, 2007.

22. Urschl C., Beutler G., Gutner W., Hugentobler U., Ploner M., *"Orbit determination for GIOVE-A using SLR tracking data"*, ILRS Workshop, 2006.

23. `http://ilrs.nasa.gov/docs/ILRSRetroreflectorStandards200812.pdf`

24. Neubert R., Neubert J., Munder J., Grunwaldt L., *"Proposed Single Open Reflector for the GALILEO Mission"*, International Technical Laser Workshop on SLR Tracking of GNSS Constellations, 2009.

25. M.E. Ash, Determination of Earth Satellite Orbits, MIT libraries Techical Note 1972-5, 19 April 1972.

26. M.J. Tausner, General Relativity and its effect on planetary orbits and interplanetary observation, MIT libraries Techical Report 425, 07 October 1966.

27. M.A. Slade, The Orbit of the Moon, Partial fulfillment of the requirements for the degree of Doctor of Philosophy, September 1971.