SCF_Lab

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1 Introduction

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.:1. 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/

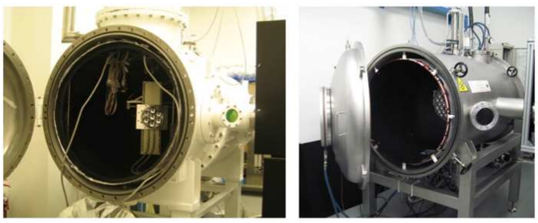

Figure 1: *SCF and SCF-G cryostats with GNSS LRAs inside.*

2 Experimental Test

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 2.

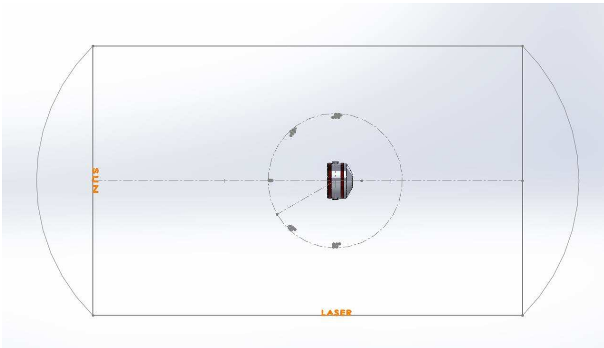

Figure 2: CAD sketching from an above viewpoint the position of MoonLIGHT inside the cryostat, with respect to the solar window (left) and the laser window (down).

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 mechanical support structure to the expected test average value, waiting plateau condition forMoonLIGHT-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 3 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.

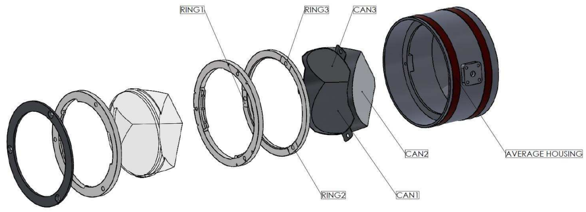

Figure 3: MoonLIGHT-2 structure.

In the second test campaign we add a copper tape on the CCR tab (see figure 4) 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 3 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 5 are summarized all the results for the thermal analysis, while in in figures 6 and 7 are summarized the optical intensity results for the last test campaign.

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

Figure 4: MoonLIGHT-2 structure.

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^o	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^o	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^o	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^o	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^o	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^o	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^o	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 5: MoonLIGHT-2 SCF-Test all thermal results.

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. 9 - 13

The σ reported in the results is the purely statistical uncertainty in the estimation of parameters,

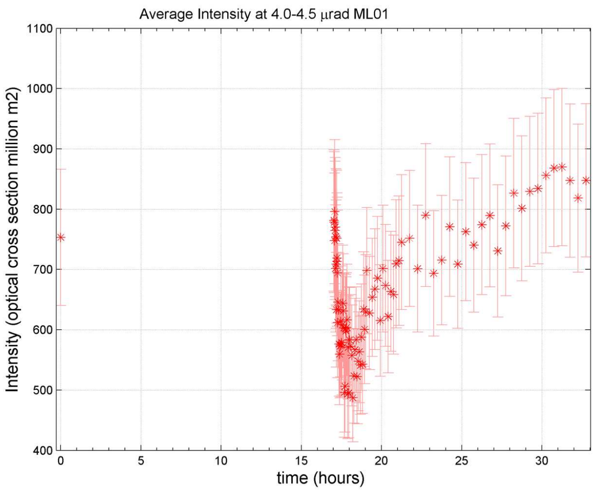

Figure 6: Laser return intensity for the third test campaign: 0 degree SUN inclination.

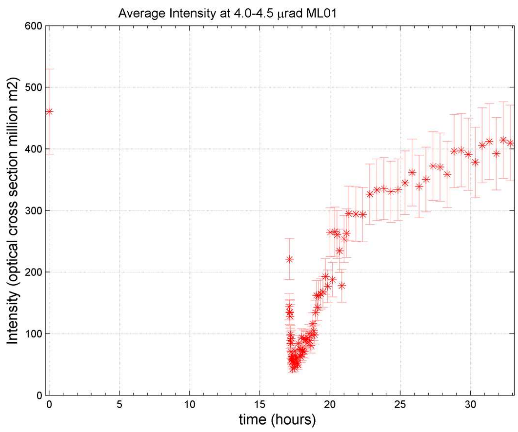

Figure 7: Laser return intensity for the third test campaign: 30 degree SUN inclination.

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 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 9 - 13 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

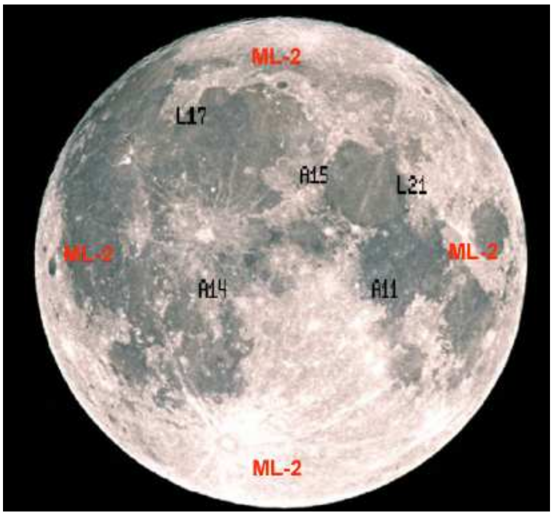

Figure 8: *CCRs position on the lunar surface.*

additions of new LLR ground stations.

4 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.
- 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

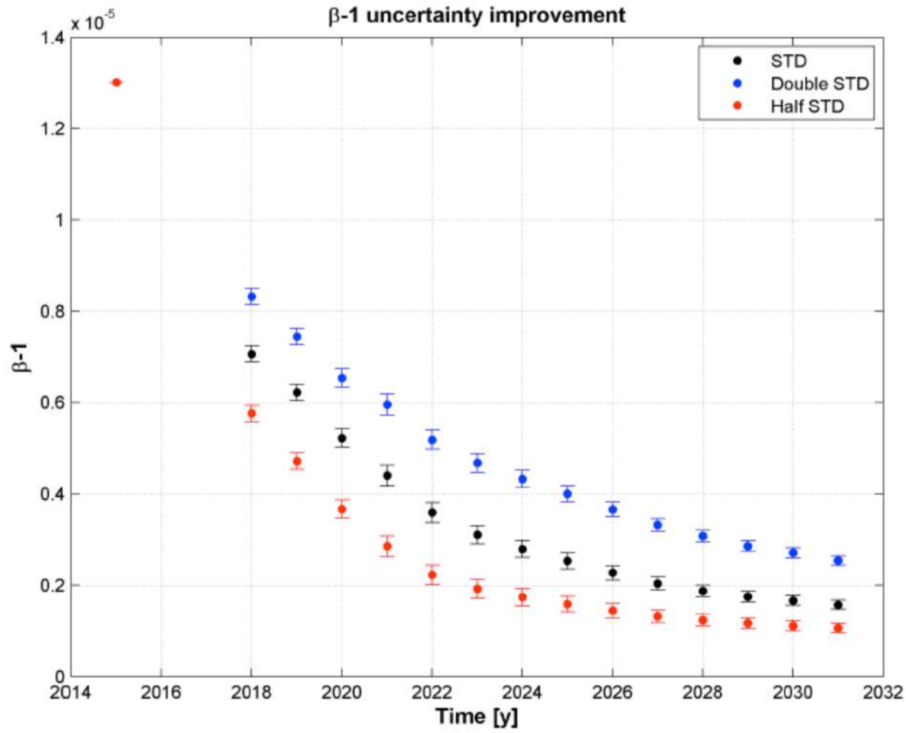

Figure 9: β *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

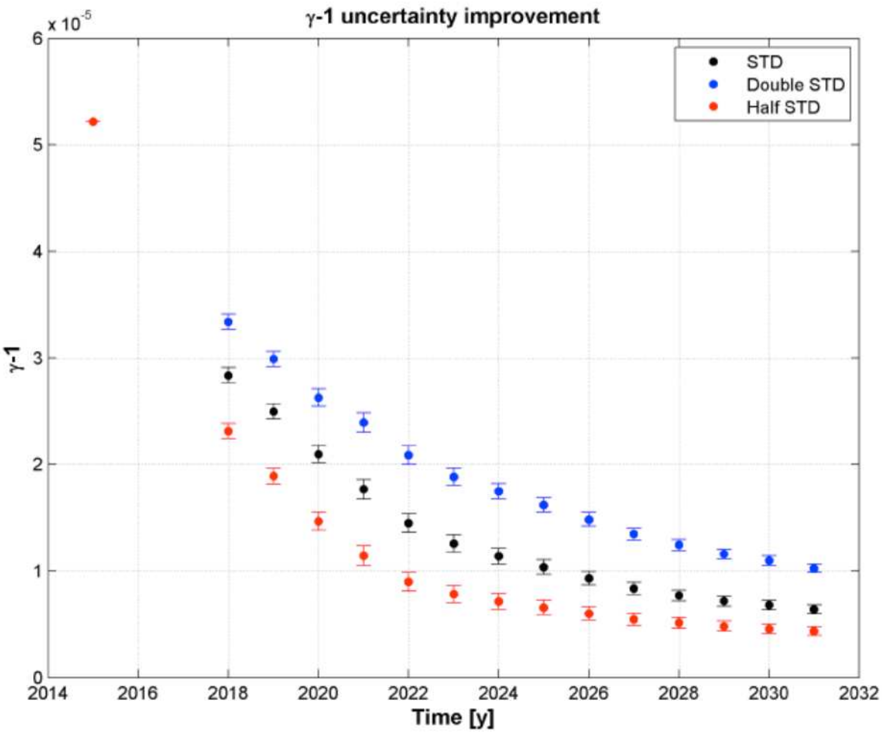

Figure 10: γ *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

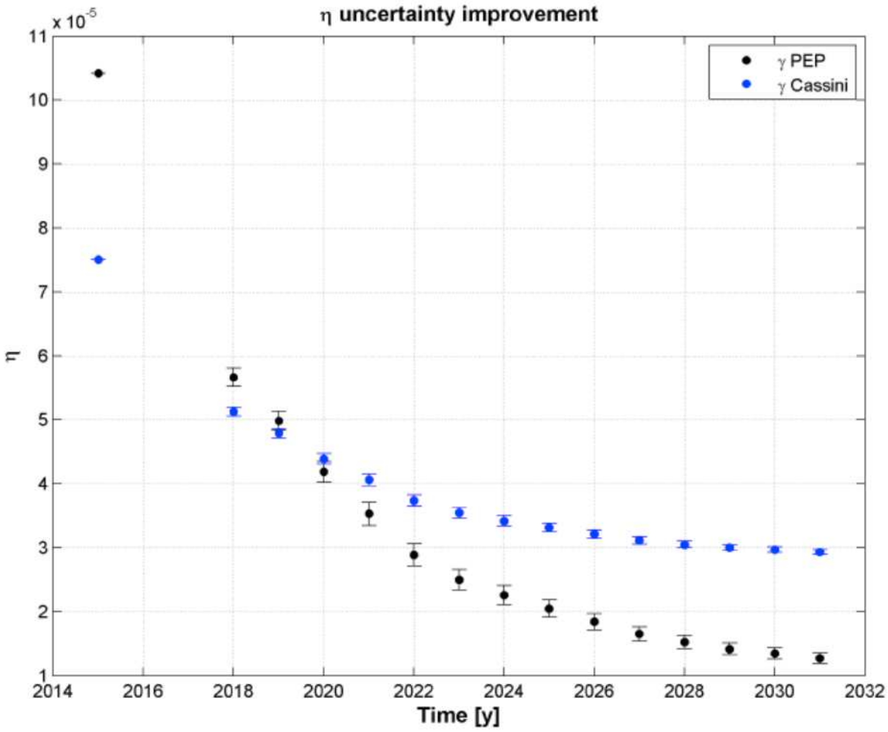

Figure 11: η *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

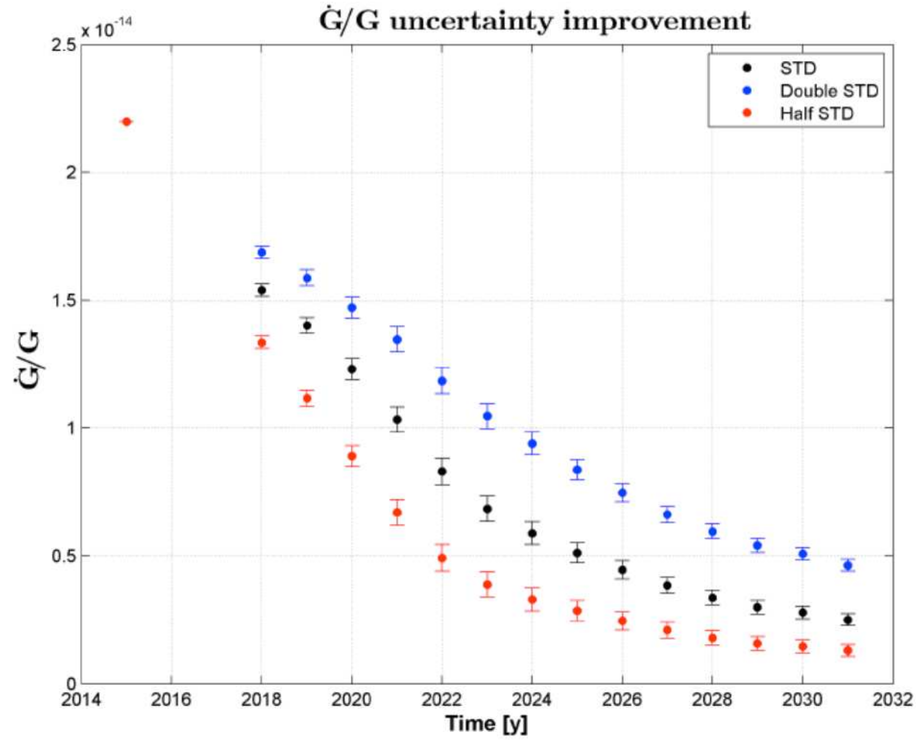

Figure 12: $\frac{\dot{G}}{G}$ *uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

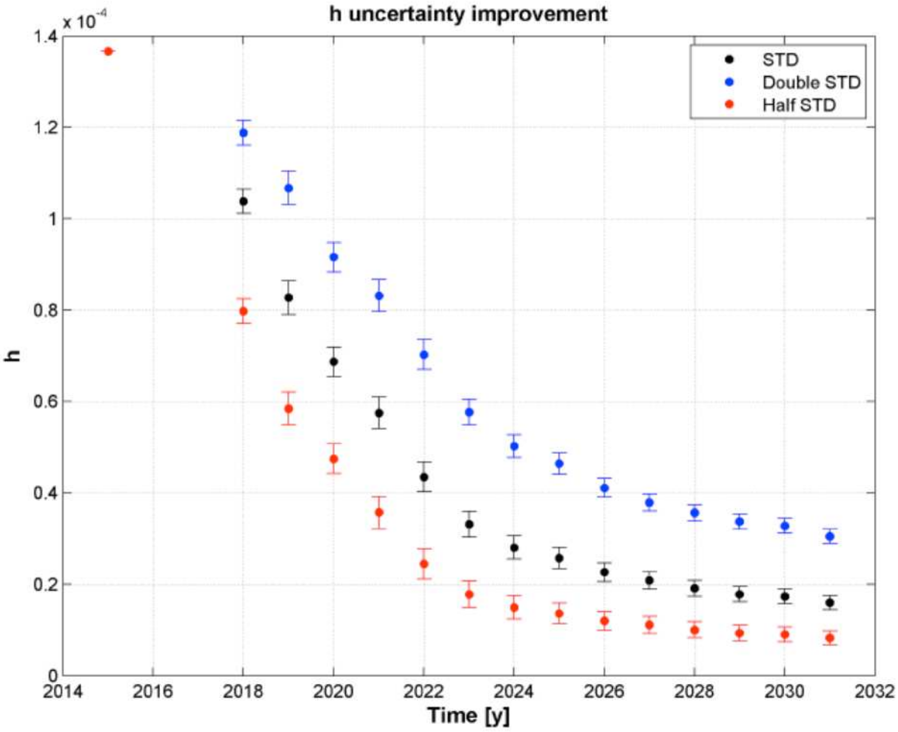

Figure 13: *Geodetic precession uncertainty improvement during a long time simulation using MoonLIGHT-2 CCRs.*

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.

5 List of Conference Talks by LNF Authors in Year 2015

1. L. Porcelli, Matera, Thermo-optical vacuum testing of Galileo IOV laser retro-reflectors of GALILEO IOV LRA, 2015 ILRS Technical Workshop

2. L. Porcelli, Matera, Thermo-optical vacuum testing of IRNSS LRA qualification model, 2015 ILRS Technical Workshop

3. G.O. Delle Monache, Matera, INRRI-EDM/2016: the First Laser Retroreflector Payload on Mars, 2015 ILRS Technical Workshop

4. M. Martini, Benevento, Laser Ranging Positioning Metrology for Galileo and the Moon, 2nd IEEE International Workshop on Metrology for Aerospace

5. E. Ciocci, Roma, Next generation Laser Retroreflectors for Precision Tests of General Relativity, Fourteenth Marcel Grossman Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation, and Relativistic Field Theories

6 Publications

1. S. Dell'Agnello et al, Advanced Laser Retroreflectors for Astrophysics and Space Science Journal of Applied Mathematics and Physics, 2015, 3, 218-227

2. M. Martini and S. Dell'Agnello, Probing Gravity with Next Generation Lunar Laser Ranging Gravity: Where do we stand?, Chapter 4, DOI 10.1007/978-3-319-20224-2.

3. Integrated Thermal-Optical simulations of a GNSS Retroreflector Array, Boni A., et al., Adv. Space Res. (2015).

4. Quantum effects on Lagrangian points and displaced periodic orbits in the Earth-Moon system, E. Battista, S. Dell'Agnello, G. Esposito, J. Simo, Phys. Rev. D 91, 084041 (2015)

5. Earth-moon Lagrangian points as a test bed for general relativity and effective field theories of gravity, E. Battista, S. Dell'Agnello, G. Esposito, L. Di Fiore, J. Simon, A. Grado, Phys. Rev. D 92, 064045 (2015).

6. Perturbation of the metric around a spherical body from a nonminimal coupling between matter and curvature, N. Castel-Branco, J. Paramos, R. March, Physics Letters B 735 (2014) 25?32.

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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.

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