World first SCF-Test of the NASA-GSFC LAGEOS Sector and Hollow Retroreflector

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ABSTRACT

With the INFN experiment "ETRUSCO (Extra Terrestrial Ranging to Unified Satellite COnstellations)" we used the "Satellite/lunar laser ranging Characterization Facility" (SCF) [3] located at INFN-LNF in Frascati, Italy, to characterise and model the detailed thermal behavior and the optical performance ("SCF-Test") of LAGEOS[1] and of a prototype hollow cube corner retroreflector. Our key experimental innovation is the concurrent measurement and modeling of the optical far field diffraction pattern (FFDP) and the temperature distribution of the retroreflector payload under thermal conditions produced with a close-match solar simulator. These unique capabilities provide experimental validation of the space segment for Satellite and lunar laser ranging (SLR/LLR). Uncoated retroreflector with properly insulated mounting can minimize thermal degradation and significantly increase the optical performance, and as such, are emerging as the recommended design for modern GNSS[2] satellites. We report some results of an extensive, first-ever SCF-Test program performed on a LAGEOS engineering model retroreflector array provided by NASA (the "LAGEOS Sector"), which showed a good performance. The LAGEOS sector measurements demonstrated the effectiveness of the SCF-Test as an SLR/LLR diagnostic, optimization and validation tool in use by NASA, ESA and ASI. We also report the first-ever SCF-Test of a prototype hollow retroreflector provided by NASA, which showed an acceptable performance in the limited tested temperature range. These unprecedented results are the starting point for the development and validation of compact and (potentially) lightweight arrays of hollow laser retroreflectors with the size and the optical specifications to be selectively chosen depending on the specific space mission (that is satellite velocity aberration).

1. Introduction

An improvement of positioning accuracy, stability and precision with respect to the ITRF[3] of modern GNSS constellations is highly recommended by ILRS in order to strengthen determination and stability of the ITRF [1].Space and ground colocation of SLR and MW techniques would make possible to align a GNSS reference frame to the ITRF, whose origin and scale are mostly determined with the SLR technique. In order to achieve these results, Laser Retroreflector Arrays (LRAs) deployed on these satellites, should guarantee an adequate level of effective cross section coming back at the stations, as defined by ILRS [1,2].Hence LRAs performance must be improved. The INFN, with experiment ETRUSCO (Extra Terrestrial Ranging to Unified Satellite COnstellation), started to build, in 2005 a facility (SCF) and developed a standard test (SCF-Test) in order to characterize and validate the optical performance of GNSS LRAs, with particular attention on Galileo [3]. During the years we tested prototypes and flight models of first generation retroreflectors (coated) and LRAs for GNSS [3]. Those types of retroreflectors, both from actual SLR measurements and our SCF tests, proved to have problems that cause a low return rate to SLR stations and signal strength drop in certain parts of the orbit. New generation GNSS constellations are moving to uncoated retroreflectors, which with a proper mounting design can minimize thermal degradation of optical performance. Uncoated reflectors are deployed on one of the standard SLR target: the LAGEOS satellite. So in order to show a *calibration* of our SCF-Test, we tested in 2009 an engineering model of the LAGEOS satellite, lent by NASA-GSFC. In section 2 we report the results of these tests. Looking further in the future, new retroreflector

[1] Laser Geodynamic Satellite

[2] Global Navigation Satellite System

[3] International Terrestrial Reference Frame

designs are under study for SLR or LLR application, which consider the use of hollow retroreflectors. Again in collaboration with NASA-GSFC, in 2010, we received a prototype of an hollow retroreflector to be tested in a realistic space environment. In section 3 we report tests performed on this prototype.

2. SCF-Test of the LAGEOS engineering model

The LAGEOS engineering model, LAGEOS Sector, is an aluminum spherical sector of the whole satellite which includes the CCR[4] on the pole and three successive rings, 37 CCRs in total (as in Fig. 1).

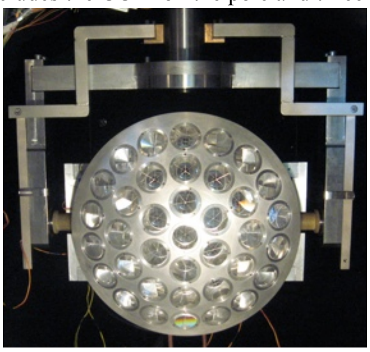

Figure 1. LAGEOS Sector inside the SCF on the positioning system

Prior to the beginning of the SCF-Test we deeply optically tested all of the CCRs in air and at room temperature. FFDP were taken in three different orientations of the CCRs (each physical edge vertical). A first analysis is presented in [4].After this analysis, we implemented a refined one in order to overcome some of the weaknesses of the former one. The attempt to find characteristic structures from the FFDP, made the analysis subject to the particular settings of the measurements (orientations of CCRs with respect to polarization vector). We'll show some of the results obtained with such an analysis on FFDP tests performed in air, at λ=532nm on the Sector. What we did was,first, derive average intensity plots from both measured and simulated FFDPs. Measurements plotted came from each CCR orientation; simulations plotted were those with on spec DAOs (1.25" on the three edges) and the extremes of the ±0.5" error band. Fig. 2 shows the results.

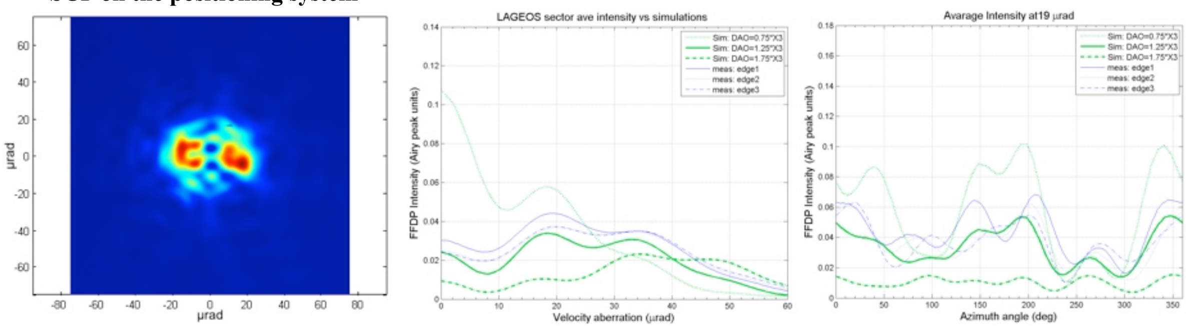

Figure 2. Left: edge 1 FFDPs . Center: average intensity vs distance from FFDP center. Right: Intensity along a circle at 19 µrad. Comparison between simulated patterns (CODEV) and measured patterns. Measured intensity has ±25% relative error not shown

The one above is a CCR with DAOs close to its specifications, as the measured average intensity is close to the bold green line. The average intensity gives however just part of the information we can extract from these measurements. After we analyzed the intensity fluctuations at a certain velocity aberration, to see how the intensity level changes along that ring (one never knows were the station will be in the FFDP domain). For now we identified positions of peaks in simulated average intensity plots and checked the intensity fluctuations there. Again, we compared measurements with simulations. Fig. 2 is the result at 19 µrad. Measurements, as expected, cannot respect exactly the symmetry of the simulations, so do their peaks, but, within errors, we can arrive at the same conclusions given for the average intensity.

For the SCF-Test we installed the Sector inside the SCF on the rotation+tilt positioning system, controlled in temperature by an interface copper plate. Temperature sensors recorded its temperature, while an IR (InfraRed) camera measured CCRs' front face temperatures. Measurements were performed in several conditions:

1. With the Sector held at 300K we placed the polar CCR inside its housing with two different torque screws of the aluminum retainer rings: *0.135 Nm* (LAGEOS nominal value) and *0.2 Nm*.
2. With a screw torque of the polar CCR, as defined above, set at 0.2 Nm we maintained the Sector at three different temperatures: *280K*, *300K* and *320K*.

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[4] Corner Cube Retroreflector

Concurrent optical and thermal measurements were performed only on the polar CCR, while full thermal analysis has been performed also on the first and second CCR rings of the Sector.

As described in [3] the SCF-Test consists of a first phase in which prototypes, reached a stationary state, are heated under the Sun Simulator beam and then cooled down. From the thermal analysis point of view, the output is the thermal relaxation time, τ_{CCR}, of the CCR, based on IR measurements of the variation of the CCR's front face temperature. τ_{CCR} is taken from the following formula:

$$T_1 = T_0 \pm \Delta T\left(1 - \exp\left(t/\tau\right)\right)$$

In Fig. 3 is shown a typical plot of the front face temperature variation and the results of the analysis for the case in which we changed the Sector's temperature. Actual values of the relaxation times will be subject of a future publication, but at this stage we can observe few outcomes from these measurements. The right plot in Fig. 3 shows the average relaxation times, between heating and cooling phases, of each of the thermally analyzed CCRs. The first important outcome of the measurements is that τ_{CCR} decreases as the temperature of the aluminum increases. The ratio between the average values of all the relaxation times, at each temperature, is close to the following: $\tau_{T1}/\tau_{T2} \approx (T_2/T_2)^3$.This behaviour is clearer for the first seven CCR in the plot (the polar one and the first ring) than for the rest; this could be due to two reasons: effect of the breakthrough on CCRs or difficulty of the IR camera to focus properly the CCRs of the second ring.

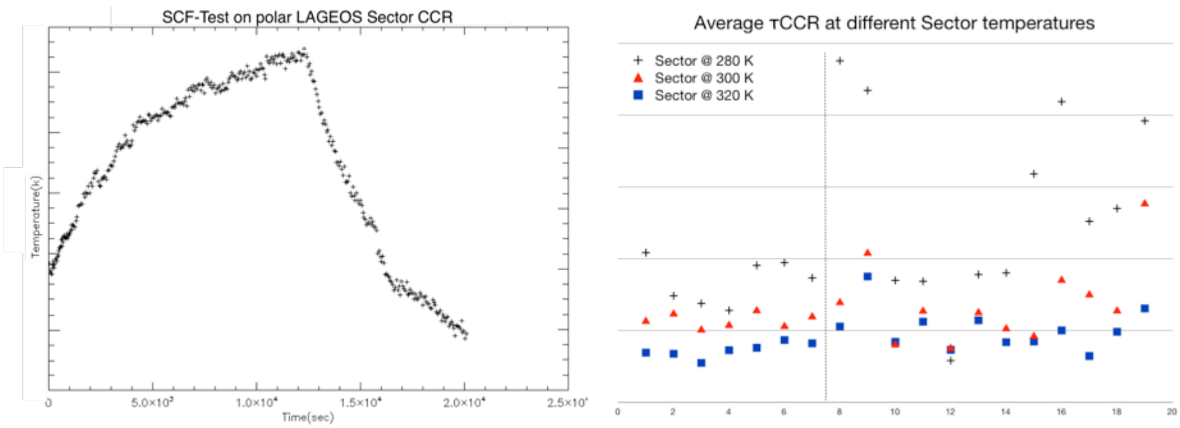


Figure 3. Left: SCF-Test performed on polar CCR with Sector held at 300K. Right: average τ_{CCR} for all of the CCR at various Sector temperatures.

Concurrent FFDP measurements were performed during the test, in order to check the variation of the intensity at a defined velocity aberration. We analyzed the variation of the intensity at 35 µrad (~ the velocity aberration of LAGEOS). Fig. 4 shows the outcome of the measurements for case 1 and 2. An increase in the screw torque from the nominal value decreases the intensity of the FFDP, after the CCR is illuminated by the Solar Simulator (SUN OFF phase). An increase in the temperature of the aluminum decreases the intensity of the FFDP in the SUN OFF phase.

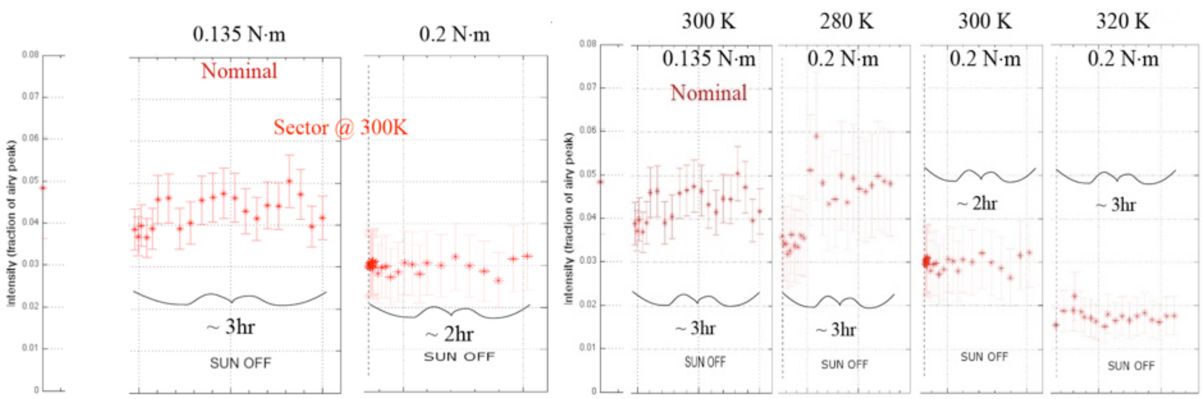


Figure 4. Effect of polar CCR screw torque (left) and on Aluminum temperature (right) on FFDP intensity after SUN ON phase. Relative error is ±10%

3. SCF-Test of the Hollow retroreflector prototype

The Hollow corner cube we tested at the SCF is a prototype made by three pyrex faces, with a metallic reflecting surface coating of optical quality. Joints between the surfaces are made with stycast glue for space applications. The whole unit is supported, at the bottom, by an Invar foot, screwed to just one of the faces. Fig. 5 shows the CCR.

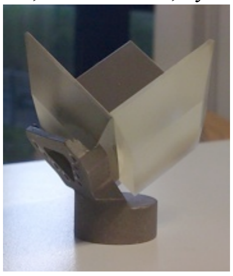
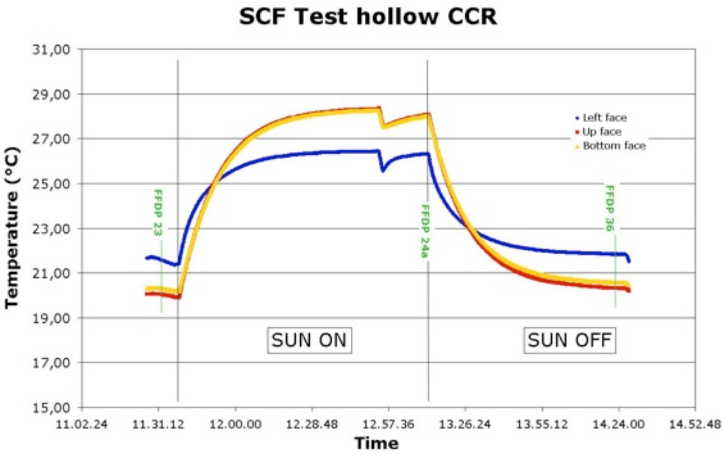


Figure 5. NASA-GSFC Hollow retroreflector tested at INFN-LNF

The CCR was held inside the SCF with an aluminum housing, with the Invar foot in thermal contact with the aluminum. The housing was built in order to simulate the presence of other CCRs around the one under test. With respect to the cryostat the CCR was positioned with one physical edge (the one opposite to the face linked with the Invar foot) horizontal. Three Platinum RTD probes measured the temperature of each of the three reflecting surface, giving us only the information of the overall temperature of the reflecting surfaces, not gradients throughout them. The housing was controlled in temperature at 300K with a Peltier cell on the back of aluminum base. The Solar Simulator illuminated the CCR orthogonally.

The procedure used for its test was the same, described earlier in this paper, for the LAGEOS Sector test, and the variation of faces' temperatures is the one in Fig. 6. As we can see from this figure the SCF-Test started in a condition in which the three reflecting faces were not at the same temperature, as at the beginning in air; the one in contact with the Invar foot ("left face") was at an higher temperature. This face also experienced, during the whole test, a temperature variation smaller than the other two.



	$\tau_{heating}$ (sec)	$\tau_{cooling}$ (sec)
left face	617	671
up face	871	879
bottom face	889	897

Figure 6. Left: SCF-Test of the hollow CCR. Right: Table 1. Thermal relaxation times of the three hollow retroreflector's faces for heating (SUN ON) and cooling (SUN OFF) phases. $\sigma(\tau)$= 80s

This behaviour is caused by the thermal contact we induced between the Invar foot and the aluminum housing. Analyzing these data we came out with the thermal relaxation times of Tab. 1. The effect of the thermal link is clear also looking at τ_{CCR} values. The "left face" has a smaller relaxation time than the other two. The other two faces have the same relaxation time. Between the heating and cooling phase we can say that, considering the quoted errors on τ, relaxation times are equal.

To analyze the optical performance we took first an FFDP in air at room temperature, which was our reference, then another FFDP prior to the beginning of the SCF-Test; passed the SUN ON phase with no measurements, we took a series of patterns during the SUN OFF phase at increasing time intervals. Results are in Fig. 7. The temperature difference between the faces of the CCR, at the beginning of the SCF-Test, influenced the intensity of the FFDP. The FFDP in air had a peak intensity of 1.00 which dropped to 0.31 at the beginning of the SCF-Test. During the SUN ON phase the FFDP almost recovered its "in air" shape, hence the intensity of the peak increased almost twice. The relaxation during the SUN OFF made the intensity come back to its first value (beginning of SCF-Test).

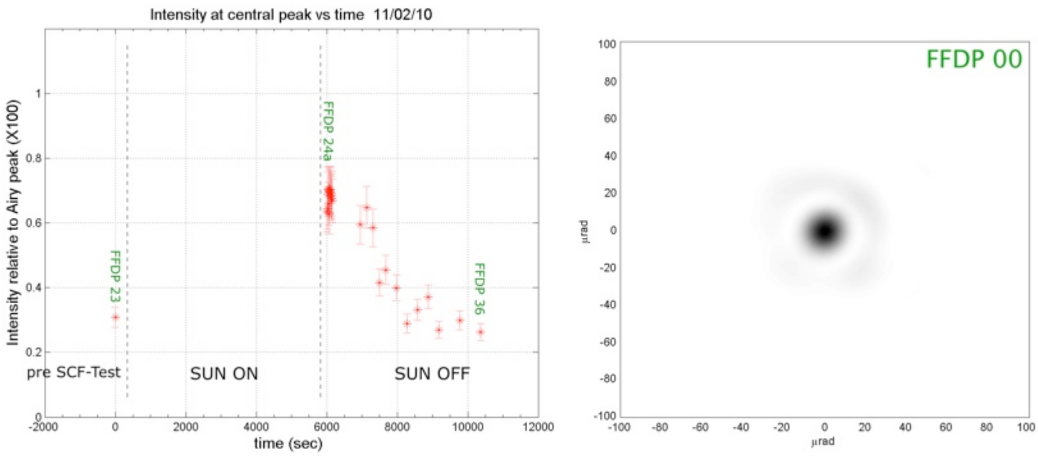


Figure 7. Intensity variation of FFDP at the central peak during the SCF-Test(left). FFDP in air-room temp (right)

4. Conclusions

The SCF has proven to be the right facility for the first-ever test of LAGEOS and hollow CCRs in an accurate laboratory-simulated space environment. The fruitful collaboration with NASA-GSFC, CfA and ASI-CGS is one of our best achievements. LAGEOS SCF-Test has shown the good space performance of what is now the reference ILRS payload standard. This paper extends the LAGEOS results reported in [3]. In particular the SCF-Test showed that:1) increasing the retroreflector mount conductance, by increasing the screw torque, with respect to nominal, degrades the FFDP intensity , 2) increasing temperature of the satellite degrades the FFDP intensity affecting the retroreflector thermal behaviour. A future publication will report the full FFDP analysis of the whole dataset of the LAGEOS measurement campaign. We demonstrated the hollow CCR prototype performance in our laboratory-simulated space conditions in a limited temperature range near 300K. We found an effect of the mounting foot arrangement on the performance of the CCR. Moreover we measured a significantly shorter hating/cooling retroreflector relaxation time, compared to LAGEOS.

References

1. http://lrs.gsfc.nasa.gov/docs/retroreflector_specification_070416.pdf

2. Pearlman, M.R., *International Technical Laser Workshop on SLR Tracking of GNSS Constellations*, Metsovo, Greece, 2009: Technological challenges of SLR tracking of GNSS constellations

3. 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 (2011), 822-842

4. Boni A., et al., *Optical Far Field Diffraction Pattern test of laser retroreflectors for space applications in air and isothermal conditions at INFN-LNF*, INFN-LNF Report LNF-08/26(IR), 2008.

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