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Galileo, the European GNSS program, and LAGEOS

S. Berardi(1), S. Dell'Agnello(1), G. Delle Monache(1), A. Boni(1), C. Cantone(1), M. Garattini(1), C. Lops(1), M. Martini(1), G. Patrizi(1), M. Tibuzzi(1), R. Vittori(2), G. Bianco(3), S. Zerbini(4), N. Intaglietta(1) and E. Ciocci(1)

(1) *Laboratori Nazionali di Frascati (LNF) of INFN - Via E.Fermi 40, 00040 Frascati (RM) Italy*
(2) *Aeronautica Militare Italiana (AMI) - Viale dell'Università 4, 00185 Rome, Italy and ESA-HSO-U*
(3) *Centro di Geodesia Spaziale G. Colombo (CGS) of ASI - Località Terlecchia P.O. Box ADP, 75100 Matera, Italy*
(4) *Department of Physics Sector of Geophysics, University of Bologna Viale Berti Pichat 8 40127 Bologna, Italy*

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Summary. — With the ASI-INFN project "ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite COnstellations-2)" we have the opportunity to continue and enhance the work already done with the former ETRUSCO INFN experiment. With ETRUSCO (2005-2010) the SCF_LAB (Satellite/lunar laser ranging Characterization Facility LABoratory) team developed a new industry-standard test for laser retroreflectors characterization (the SCF-Test). This test is an integrated and concurrent thermal and optical measurement in accurately laboratory-simulated space environment. In the same period we had the opportunity to test several flight models of retroreflectors from NASA, ESA and ASI. Doing this we examined the detailed thermal behavior and the optical performance of LAGEOS (Laser GEOdynamics Satellites) cube corner retroreflectors and many others being used on the Global Navigation Satellite System (GNSS) constellations currently in orbit, mainly GPS, GLONASS and GIOVE-A/GIOVE-B (Galileo In Orbit Validation Element) satellites, which deploy old-generation aluminium back-coated reflectors; we also SCF-Tested for ESA prototype new-generation uncoated reflectors for the Galileo IOV (In-Orbit Validation) satellites, which is the most important result presented here. ETRUSCO-2 inherits all this work and a new lab with doubled instrumentation (cryostat, sun simulator, optical bench) inside a new, dedicated 85 m^2 class 10000 (or better) clean room. This new project aims at a new revision of the SCF-Test expressly conceived to dynamically simulate the actual GNSS typical orbital environment, a new, reliable Key Performance Indicator for the future GNSS retroreflectors payload. Following up on this and using LAGEOS as a reference standard target in terms of optical performances, the SCF_LAB research team led by S. Dell'Agnello is designing, building and testing a new generation of GNSS retroreflectors array (GRA) for the new European GNSS constellation Galileo.

PACS 42.30.-d – Imaging and optical processing.
PACS 95.10.Eg – Orbit determination and improvement.
PACS 95.30.sf – Relativity and gravitation.

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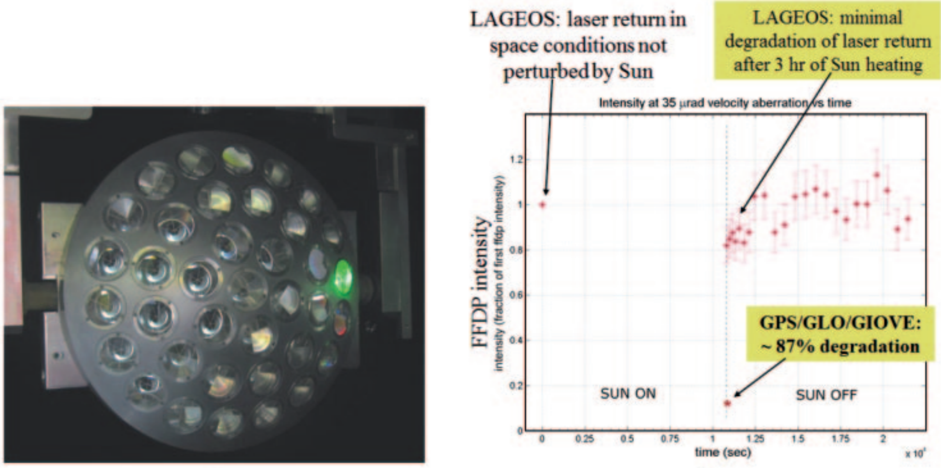
1. – Introduction

An improvement of positioning accuracy, stability and precision with respect to the ITRF [1](1) of modern GNSS constellations is highly recommended by ILRS(2) in order to strengthen determination and stability of the ITRF [2]. Space and ground colocation of SLR and MW(3) 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 [2, 3]. Hence LRAs performance must be improved. The INFN, with experiment ETRUSCO, 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 [1]. During the years we tested prototypes and flight models of first generation retroreflectors (coated) and LRAs for GNSS [1]. 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(4). In sect. **2** we report the results of these tests. Moreover with Galileo's atomic clocks and LRAs the measurement of the gravitational redshift will be improved and LAGEOS is being used to measure the $\mathrm{G} \cdot M_{\oplus}$ (gravitational constant times Earth mass), to test the inverse-square force law [4], to investigate the Lense-Thirring effect [5] and to costrain spacetime torsion [6, 7].

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 37 CCRs (Cube Corner Retroreflectors) [8] in total, one on the pole and 36 on three successive rings (as in fig. 1a). The test we performed on this prototype pointed out the excellent mounting design of the CCR inside the cylindrical cavities of the aluminium body. This mounting allows a good thermal insulation of the CCR fused silica body from the bulk aluminium body of the satellite. A good insulation leads to minimal degradation of laser return intensity when the body is exposed to sun heat and, consequently the CCR are subject to strong thermal gradients that can change the refractive index along the light path inside the CCR volume. The intensity of the light return in the transition from sunlight exposition to shadow showed a decrease of less than 20% compared to the unperturbed CCR (fig. 1b). The light return stability is particularly remarkable when compared to that offered by the main competing technology for CCR uncoated arrays, the coated ones. This kind of CCR are currently installed on several orbiting bodies (GPS/GLONASS/GIOVE-A/B) and we had the opportunity to test some of them. Coated CCR showed a light return degradation of about 87%. This

(1) International Terrestrial Reference Frame.
(2) International Laser Ranging Service.
(3) Satellite Laser ranging and MicroWave.
(4) NASA-Goddard Space Flight Center.



a b

Fig. 1. – LAGEOS sector inside the SCF cryostat (a) and the SCF-Test plot of LAGEOS sector uncoated CCR compared to coated CCR (b).

data has been included in the plot of fig. 1b in order to have an immediate comparison between the different levels of performance.

Concerning the LAGEOS sector SCF-Test, as described in [1], it consists of a first phase in which prototypes, reached a stationary state, are heated under the sun simulator (SS) 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 CCRs front face temperature. τ_{CCR} is taken from the following formula:

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

We decided to SCF-Test all the retroreflectors of the prototype. Numbering them from the polar one to the outers we plotted the τ_{CCR} of each CCR for three different temperature setpoints of the bulk aluminium body. This plot is reported in fig. 2, showing the average relaxation times, between heating and cooling phases, of the first nineteen 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:

$$\frac{\tau_{T_1}}{\tau_{T_2}} \simeq \left(\frac{T_2}{T_1}\right)^3.$$

For the left part of the plot (polar CCR and first ring) the time constant of the retroreflectors shows a typical behavior that is consistent with computer simulations and, thus, with the formula mentioned above. In the right part of the plot (from CCR 8 to 19) the behaviour is not so clear since the outer retroreflectors (second and third ring) have an inclination that exceeds the capacity of the CCR to avoid the sun radiation to enter the cavity. This phenomenon, conventionally called breakthrough, leads to a behaviour that is unpredictable for mathematical models and computer simulations.

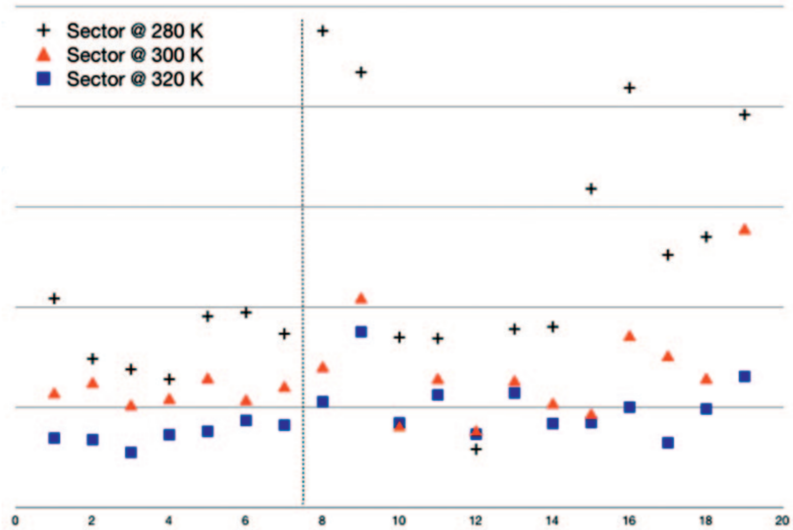


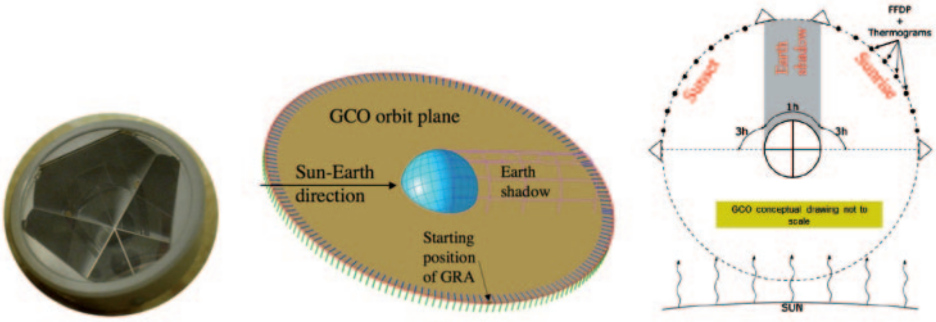
Fig. 2. – Average τ_{CCR} at different temperatures setpoints for the LAGEOS Sector aluminium bulk body.

3. – First GCO SCF-Test of a prototype uncoated CCR for Galileo-IOV satellites provided by ESA

Galileo is the European GNSS constellation named after Galileo Galilei, the famous Italian astronomer. The main goal of Galileo is to provide a non-military navigation system to rely on even during political disagreements with other countries that already owns a GNSS system. The entire system is being built by the European Union (EU) and European Space Agency (ESA) and will ensure better coverage at high latitudes and with high buildings with interoperability with GPS and GLONASS. The first two satellites were launched in October 2011 and the estimated end of phase 2 (30 satellites and ground segment operational) is 2020.

Galileo represents a great opportunity for the scientific community too, since each satellite of the constellation will be equipped with a retroreflector array, allowing the SLR network to remarkably increase the amount of measurements and, thus, the orbit determination precision. This is the starting point to improve several fundamental physics measurements such as gravitational redshift or the determination of the terrestrial reference system. This opportunity has been underlined by an issue published on Advances in Space Research [9].

In summer 2010 we had the opportunity to test an uncoated CCR prototype designed for Galileo-IOV satellites and provided by ESA (fig. 3a). We decided to study a new test procedure in order to simulate the most stressing conditions for an optical payload onboard a typical GNSS satellite. This happens when the nodal line is parallel to the sun-earth direction as shown in fig. 3b. We call this particular orbit and the related test the "GNSS Critical half-Orbit" (GCO). This is only a half of the complete orbit since in the symmetrical part the incidence angle of the sun rays on the retroreflectors front face is more than 90°. Shifting from sunlight to shadow and back, critical aspects of the thermal and optical behavior of the CCR occurs, including breakthrough: depending on

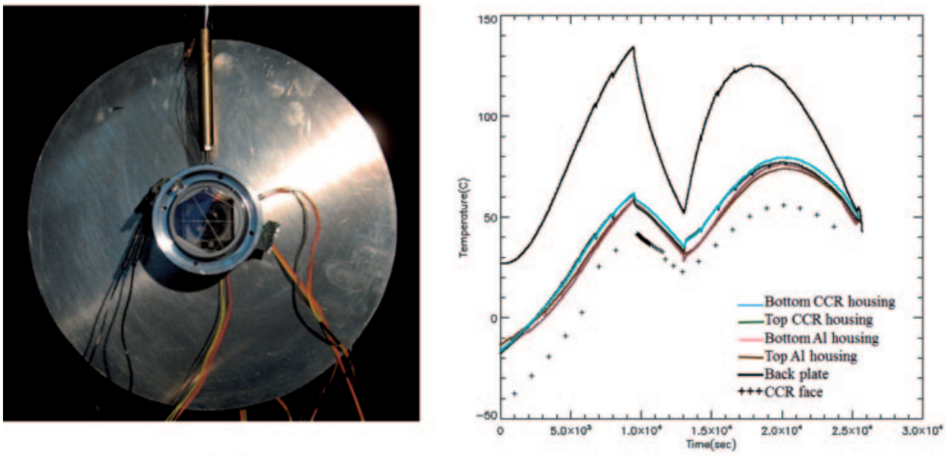


a b c

Fig. 3. – The Galileo-IOV uncoated retroreflector (a), a GNSS Critical half-Orbit conceptual drawing (b) and a scheme of the GCO test sequence (c).

the orientation of the CCR with respect to the SS beam, there are cases in which total internal reflection is broken and rays pass through the CCR heating the internal surfaces of the housing (breakthrough (BT)). For uncoated CCRs this occurs when a light ray is tilted with respect to the symmetry axis above 17°.

The retroreflector tested at the SCF, inside its housing, was installed inside an Al enclosure built at LNF, to replicate the condition of a CCR inside the array surrounded by other CCR housings (fig. 4a). The Al housing was suspended with a G10 screw to the payload support/positioning system rotating around the vertical direction. We positioned a circular aluminum plate behind the CCR housing in order to simulate the presence of the satellite body. This aluminum plate was thermally controlled, but just to bring the CCR to the right starting temperature, indicated by ESA; afterwards the object was left floating, as it is in orbit. When the CCR temperature reached 244 K, we



a b

Fig. 4. – Galileo-IOV CCR mounted inside the SCF for the GCO (a) and the temperatures of the IOV CCR assembly during the GCO (b).

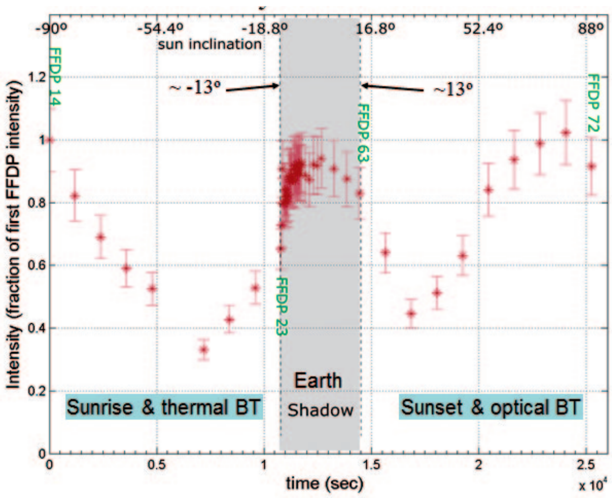


Fig. 5. – Average relative FFDP intensity at 24 μrad.

started simulating the GCO. One of the physical edges of the retroreflector was positioned horizontally. Along the GCO the inclination of the sun rays with respect to the CCR front face changes from $-90°$ to $+90°$. These conditions are reproduced in laboratory by rotating the LRA inside the cryostat, at discrete angle steps, for the proper GCO period. Galileo satellites have a quasi-circular orbit with a semi-major axis of about 29600 Km, which corresponds to an orbital period of about 14 hs.

We simulated half of the orbit, from the moment in which sun rays rise above CCRs front face till they fall on the other side, corresponding to a period of about 7 hrs. A conceptual drawing of this simulated orbit is in fig. 3c. In the SCF the GCO is the horizontal plane, so starting with the SS beam parallel to the CCRs front face we rotated the CCR, at regular angle steps, with respect to the SS, therefore simulating the sunrise phase, the passage through the Earth shadow and afterwards the sunset. The CCR was oriented with an edge horizontal in a direction such that optical BT could occur only during the sunset. The temperatures trend during the GCO is shown in fig. 4b. Bottom/Top CCR housing are temperatures taken with temperature probes on two points of the CCR housing. Bottom/Top Al housing are taken on two points of the auxiliary Al cavity. Back plate is the temperature of the plate. CCR face is the temperature of the CCR front face measured with the IR camera. Note the large temperature excursion of more than 100 K and the asymmetrical behavior due to the BT phenomena. After the completion of the orbital simulation the data acquired in the lab were post-processed with a MATLAB® script in order to obtain several analysis on the light return behavior. The main output of this analysis is fig. 5, a summary plot of the intensity, in optical cross section (OCS) units, over time at the velocity aberration (VA) of 24 μrad (design VA for Galileo-IOV CCRs, according to info from ESA). In this plot is shown the fluctuation of the OCS during the GCO. Plotted data have an estimated error of 10% on the average relative intensity, due to instrument, statistics, and residual systematic fluctuations of the SCF environment.

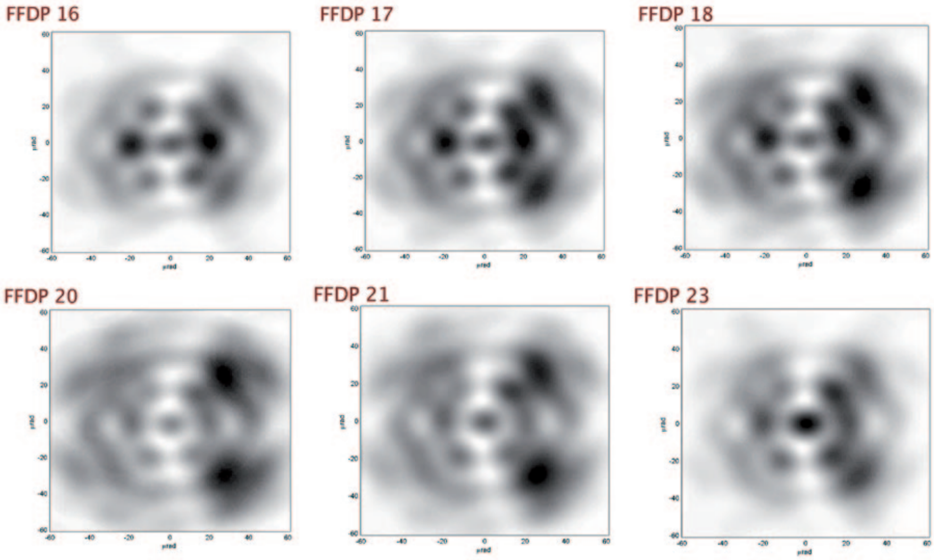


Fig. 6. – Galileo-IOV measured FFDP during the GCO. Grid dimensions are $[-60; 60]\,\mu$rad. Intensity grey-scale levels are scaled to 100.

Figure 6 shows some of the key FFDPs(5) of the GCO simulated orbit. The basic SCF-Test showed a degradation of about 25% on optical performance, compared to the much larger one (about 87%) of old GPS/GLONASS/GIOVE ones. Averaging over the entire GCO, which is a half orbit, the measured IOV CCR average intensity at $24\,\mu$rad VA had a degradation of about 35%. The prototype IOV CCR shows the expected FFDP degradation due to optical BT during sunset, but also for almost symmetric sun inclinations during sunrise, when there is no optical BT. We call this effect "thermal breakthrough". Thermal BT could be due to an IOV CCR mounting scheme with relatively large thermal conductance, as the standard SCF-Test described earlier seemed to point out.

4. – Conclusions

For the ETRUSCO-2 project the original SCF-Test has been improved and fine-tuned on the specific GNSS space environment and, furthermore, the SCF_LAB team had the chance to apply this new procedure to a first prototype of the Galileo-IOV CCRs.

This opportunity confirmed our former SCF-Test conclusions on the uncoated CCR good thermo-optical behaviour compared to the coated technology. The metallic coating on the back faces of the retroreflectors has been removed, finally, on modern GNSS, after 30 years, thanks to our SCF-Test results. Now it is very important to SCF-Test more IOV retroreflectors and, especially, reflectors of FOC (Full Orbit Capability) satellites, which are different from IOV (different makers).

In the next months in our test facility, during the next SCF-Tests, we will be able to perform concurrent wavefront interferograms of the retroreflectors inside the cryostat

(5) Far Field Diffraction Patterns.

and, as the ultimate goal, we will develop and SCF-Test a new Galileo-optimized GRA for FOC-2, with a pan-European effort, to reduce the dependence of Europes flagship programme from non-European laser retroreflector technologies. Moreover, discussions are underway for GPS-3 and other GNSS constellations like IRNSS([6]), COMPASS([7]) & QZSS([8]).

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([6]) Indian Regional Navigational Satellite System.

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([8]) Quasi-Zenith Satellite System.