SCF-Test of a Galileo-IOV retroreflector and thermal-optical simulation of a novel GNSS retroreflector array on a critical orbit

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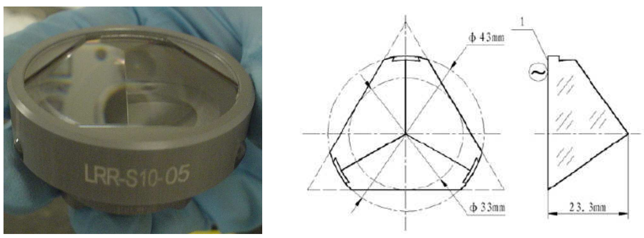
***Abstract*—Thorough laboratory measurements performed at INFN-LNF (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati), in the framework of the ETRUSCO (Extra Terrestrial Ranging to Unified Constellations) experiment, proved fundamental to characterize retroreflectors for GNSS (Global Navigation Satellite System) satellites. The standard test developed, SCF-Test, was important to outline the weaknesses of past retroreflectors payloads (in use on GPS, GLONASS and GIOVE A/B satellites). For the upcoming deployment of the Galileo constellation ESA requested, in 2010, a full SCF-Test campaign, to characterize a prototype retroreflector of the first IOV satellites of the constellations. We report the results of a standard SCF-Test, important to characterize some basic performance of these retroreflectors. For this occasion it has been introduced an improvement in the test campaign: the test of a simulated orbit, called GCO (Galileo Critical half-Orbit). With the experience gathered with the ETRUSCO experiment, INFN, in 2010, started a R&D project, co-funded by ASI, called ETRUSCO-2, whose aim is to develop and measure, in a newly built facility, a full size array of retroreflectors to be deployed on GNSS constellations. Here we report preliminary concurrent thermal and optical simulations of the array. A simplified structure of the array was subject to a simulated space environment in a GCO; the resulting temperature distribution inside each retroreflector, was the input of the optical software to determine the variation of the intensity, throughout the orbit, coming back at a ranging station. The goal is to limit as much as possible signal fluctuations.**

I. Introduction

INFN-LNF, in the framework of the experiment ETRUSCO, thoroughly tested single retroreflectors, arrays and prototypes in use on current GNSS constellations, at the SCF (Satellite/lunar laser ranging Characterization Facility). The SCF-Test developed at the LNF proved fundamental to assess thermal properties and optical performance of such payloads [1]. In particular, measurements performed on old generation GNSS Laser Retroreflector Arrays (LRAs), GPS/GLONASS/GIOVE, explained the experience of ILRS (International Laser Ranging Service) ground stations all over the world: difficulty to track GNSS payloads due to a severe decrease of laser return from such payloads and impossibility for the majority of stations to perform daylight ranging. The SCF-Test showed a significant degradation of CCR (Corner Cube Retroreflector) performance due to illumination by our Solar Simulator (SS), of $\sim 87\%$. Two were the causes identified for such degradation: the coating used on the three reflecting faces of the CCR, and a non-optimized thermal isolation between the housing and the CCR. Uncoated CCRs with proper mounting scheme minimize thermal degradation and significantly increase optical performance [2], and as such, are the design recommended for modern GNSS. In fact, most of the upcoming GNSS constellations, global and regional, are equipped with uncoated retroreflectors. In particular the first two IOV (In Orbit Validation) satellites of the Galileo constellation are equipped with 84 uncoated retroreflector arrays. The enhanced ranging accuracy obtainable with SLR (Satellite Laser Ranging), along with its independence from Microwave tracking technique, gives an important validation and calibration of GNSS orbit quality [3]. In this way the effects of atomic clock modeling, for example, can be separated from orbit modeling, leading to a better understanding of current modeling errors in GNSS orbit predictions and to a check of clock performance. SLR is moreover of great importance in assisting the tracking networks in the early phases of constellation deployments. A laser tracking of a whole constellation will give great benefits to the determination and long-term stability of the ITRF (International Terrestrial Reference Frame) [4]. For such an improvement is fundamental the co-location of different techniques, such as GNSS (traditional tracking) and SLR, on either the ground and the space segments. GNSS is fundamental in the process of the development and maintenance of the International Atomic Time (TAI), providing a time standard used worldwide by ground systems and telecommunication satellites. The T2L2 experiment [5], using the LRA on Jason2 satellite, proved the feasibility of a Time Transfer using laser tracking, increasing the synchronization accuracy achieved by microwave tracking. Greater benefits would however come from a combination of Microwave and SLR data in orbit determination, in terms of improved satellites orbits accuracy and improved ITRF determination. Combined GNSS+SLR orbits have been recently implemented using the Bernese software [6].

II. SCF-Test of a GALILEO-IOV prototype retroreflector

At the end of June 2010 we proceeded with a series of tests requested by ESA on a prototype retroreflector of the upcoming (at that time) IOV satellites of the Galileo constellation. The measurements aimed to analyze in detail the thermal and optical properties of this CCR. The retroreflector is an uncoated prism made of Suprasil 311 with a height of 23.3 mm. The front face has an inscribed circle of 33 mm diameter



(a) (b)

Fig. 1. (a) Galileo-IOV CCR tested at LNF. (b) drawing of the CCR.

(see Fig. 1 b). To compensate for the velocity aberration (VA), effect of satellite-station relative velocity, three Dihedral Angle Offsets (DAO) (small increment to the $90°$ angle) of 0.8 arcsec are introduced in the angles between the faces. The CCR is then placed in an Aluminum housing which holds it through three tabs on the cylindrical surface (see Fig. 1 a). The array mounted on board of Galileo-101 and Galileo-102 (Fig. 2) has 84 retroreflectors. The retroreflector tested at the SCF, inside

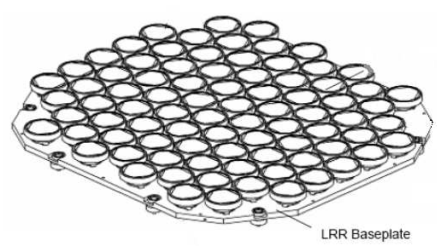


Fig. 2. GALILEO complete LRA drawing.

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. The Al housing was suspended with a G10 screw to the payload support/positioning system rotating around the vertical direction. One of the physical edges of the retroreflector was positioned horizontally. The Al housing was then controlled in temperature with heating tapes in order to test the effect of different temperatures of the housing on CCR performance. The first test performed on this CCR was the measurement of its characteristic heating/cooling time, τ_{CCR}, with the standard SCF-Test (SS beam orthogonal to CCR's front face), at the temperatures of 310 K and 370 K of the external Al housing. Data taken with an InfraRed (IR) camera (front face temperature) were fitted exponentially to extract the information of the τ_{CCR}, using the following formula:

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

The results are presented in Tab. I. These data represent a sur-

TABLE I
Thermal relaxation times of Galileo CCR at two different external housing temperatures

	$\mathbf{T_{Al} = 310K}$	$\mathbf{T_{Al} = 370K}$
$\tau_{\mathbf{heating}}$ (sec)	245	341
$\mathbf{\Delta T}\,(^\circ\mathbf{C})$	3.0	2.6
$\mathbf{T_0}\,(^\circ\mathbf{C})$	25.8	75.5

prisingly short time constant compared with the previous measurements performed at the SCF on solid cubes of similar volume [1]. For the Al-coated CCRs of GPS/GLONASS/GIOVE satellites the relaxation time was of the order of $\sim\ 1000$ sec while for the engineering prototype of LAGEOS [2] were measured τ of thousand of seconds. Moreover τ_{CCR} increases from $310K$ to $370K$ by $\sim\ 30\%$, while simulations indicate a decrease $\sim\ 1/T^3$, in case of a dominant radiative heating exchange between the CCR and its housing cavity. A different behaviour could be caused by a non perfect isolation of the CCR with its housing, with subsequent conductive heating exchange.

This SCF-Test was performed maintaining the SS beam orthogonal to the CCR front face; however it is crucial to test different incidence angles. Depending on 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 $17°$. During its movement around the orbit, the CCR experiences different Sun rays inclination angles. For this reason we refined the SCF-Test introducing the test of a critical orbit of a satellite; for this particular case we tested an orbit of Galileo, calling it Galileo Critical half-Orbit (GCO). The GCO is the orbit whose angular momentum is orthogonal to Sun-Earth direction. For this particular orbit the inclination vector of Sun rays lays on a plane, and the orientation 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 $\sim$ 29600 Km, which corresponds to an orbital period of ~ 14 hrs. We simulated half of the orbit, from the moment in which sun rays rise above CCR's front face till they fall on the other side, corresponding to a period of $\sim$ 7 hrs. A conceptual drawing of this simulated orbit is in Fig. 3. In the SCF the GCO is the horizontal plane, so starting with the SS beam parallel to the CCR's front face we rotated the CCR, at regular angle steps, with respect to the SS, therefore

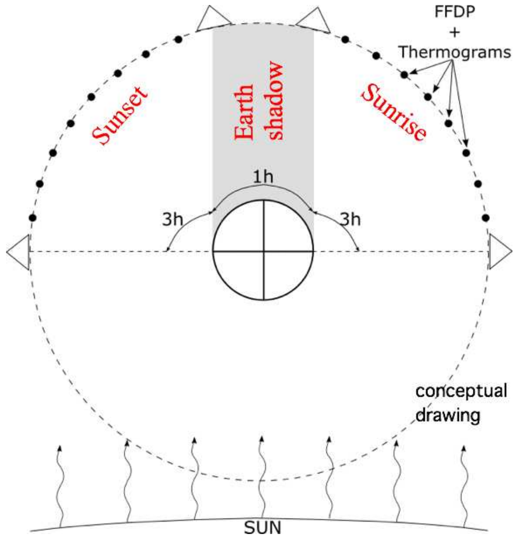


Fig. 3. Galileo GCO conceptual drawing

simulating the *sunrise* phase, the passage through the Earth shadow and afterwards the *sunset*, as schematically shown in Fig. 3. The CCR was oriented with an edge horizontal in a direction such that optical BT could occur only during the sunset. Fig. 4 shows the arrangement used for this test. We

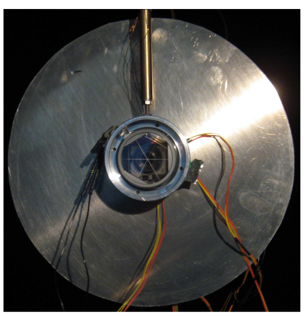


Fig. 4. Galileo CCR set up for GCO measurement.

positioned a circular aluminum plate, behind the assembly used for the SCF-Test, in order to simulate the presence of the satellite. 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 started simulating the GCO. Fig. 5 shows the temperatures measured during the GCO. "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. A large temperature excursion occurred during the simulated orbit. The Far Field Diffraction Patterns (FFDPs) acquired by CCD cameras were post-processed with a MATLAB script which provides the picture and the average intensity over the VA of each FFDP and a summary plot of the intensity, in Optical

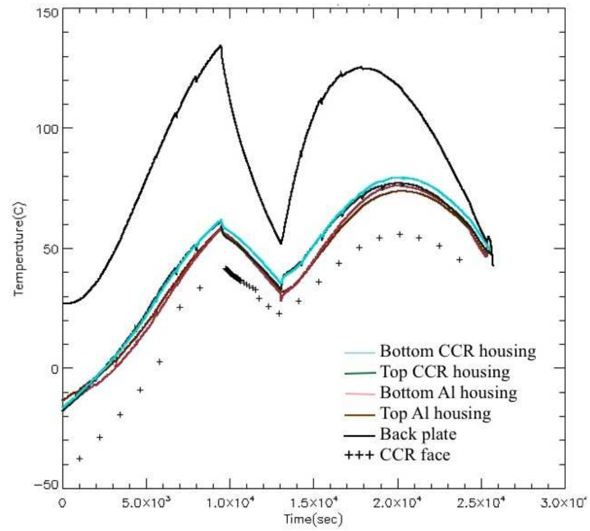


Fig. 5. Temperatures of the IOV CCR assembly during the GCO. The horizontal scale is $0 - 3 \times 10^4$ sec

Cross Section (OCS) units, over time at the VA of $24\,\mu rad$ (design VA for Galileo IOV CCRs, according to info from ESA). Fig. 6 shows the variation of the average intensity at $24\,\mu rad$ 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. 7 shows some of the key FFDPs of the GCO

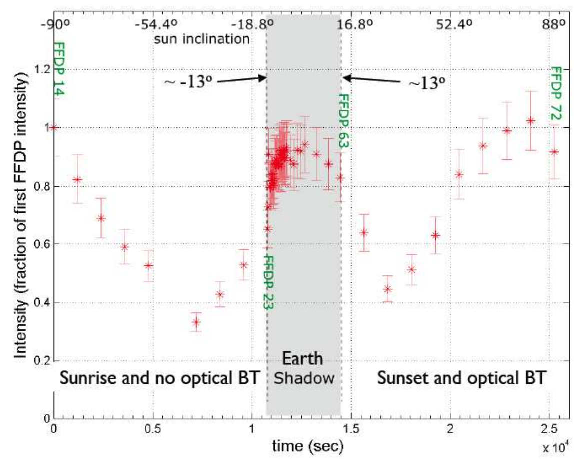


Fig. 6. FFDP average intensity, relative to the first FFDP, of the IOV CCR during the GCO at $24\,\mu rad$

simulated orbit. The basic SCF-Test showed a degradation of $\sim$ 25% on optical performance, compared to the much larger one ($\sim$ 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 μrad VA had a degradation of $\sim$ 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

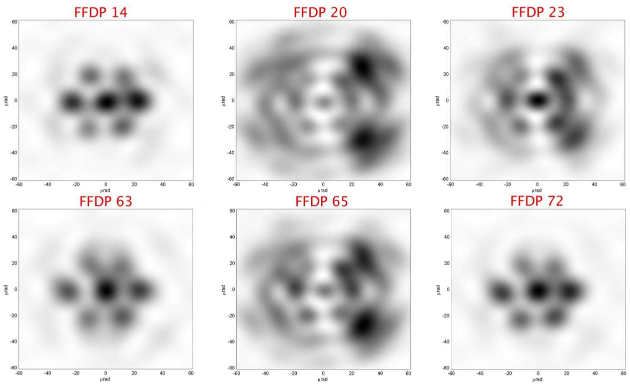


Fig. 7. Galileo IOV measured FFDP during the GCO. Grid dimensions are $[-60; 60]\mu rad$. Intensity colors are scaled to 100.

with relatively large thermal conductance, as the standard SCF-Test described earlier seemed to point out.

III. Thermal-Optical simulation of a novel GNSS LRA

The SCF-Test performed at INFN proved fundamental to thoroughly characterize thermal and optical response of LRAs in a realistic space environment. Measurements here presented, along with others described in [1], [2], represented a crucial background for the subsequent project in which INFN has been involved, and still is, ETRUSCO-2 [7]. The project, started in 2010, is the natural continuation and evolution of ETRUSCO. It is a project of technological development, co-funded by ASI-INFN, with INFN as Prime Contractor. The goal is to optimize the design of a GNSS Retroreflector Array (GRA) to maximize ranging efficiency, to improve signal intensity in daylight, to provide pre-launch characterization of retroreflectors performance under accurate laboratory-simulated space conditions (in a newly realized test facility, SCF-G), as well as characterize "as-built" payloads.

A. Optical design of the GRA retroreflector array

Measurements on the Galileo IOV retroreflector prototype have demonstrated that the choice of uncoated retroreflectors have improved the optical response of GNSS LRAs, but some further improvement could be done. The design of the LRA was targeted at minimize as much as possible thermal exchange between the CCR and the rest of the satellite; thus we inherited the CCR mounting rationale from that of the LAGEOS satellite and Lunar CCRs, shown in Fig. 8. The CCR

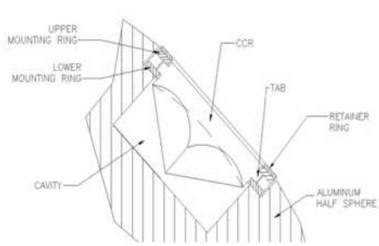


Fig. 8. Mounting scheme of a LAGEOS retroreflectors.

is held in place by two rings of KEL-F, a plastic material with low thermal conductivity and low hygroscopic potential, and an aluminum retainer ring that tightens the whole mounting system with three screws. Optical simulations determined the basic design characteristics of each CCR and of the final array arrangement. Each CCR is a solid uncoated retroreflector, made of Suprasil 1, with a circular front face of 33 mm diameter. Angles between the reflecting faces are $90°$, with a manufacturing error of $\pm$ 0.5 arcsec. Its design FFDP, made with the optical software CODE V [8] is the following in Fig. 9. In order to respect ILRS standards [9] the number

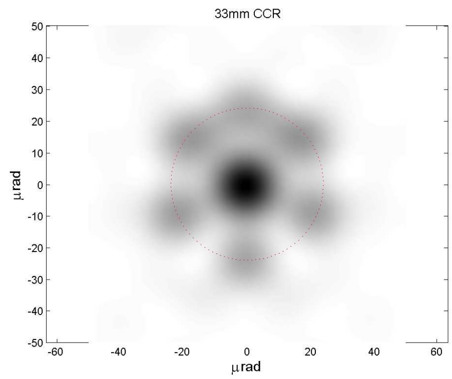


Fig. 9. GRA CCR FFDP. $\lambda = 532\,nm$, Horizontal polarization. Grid limits $\pm\,50\,\mu rad$. Red dotted circle represents the VA of Galileo.

of CCRs necessary on the array would be 88. To control target signature effects caused by the variation of the relative inclination between the satellite and laser ranging station [10], we decided to design a circular shaped array. To meet this requirement it would be possible to design an array of 84 CCRs, but, following the decision made by ESA to design LRAs of reduced dimensions for budget and weight reasons, we designed an array of 55 retroreflectors. Fig. 10 shows a sketch of the arrangement chosen for the GRA. A single

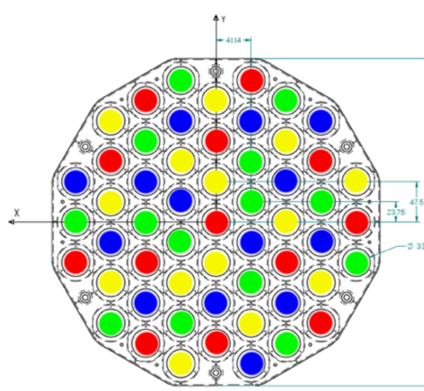
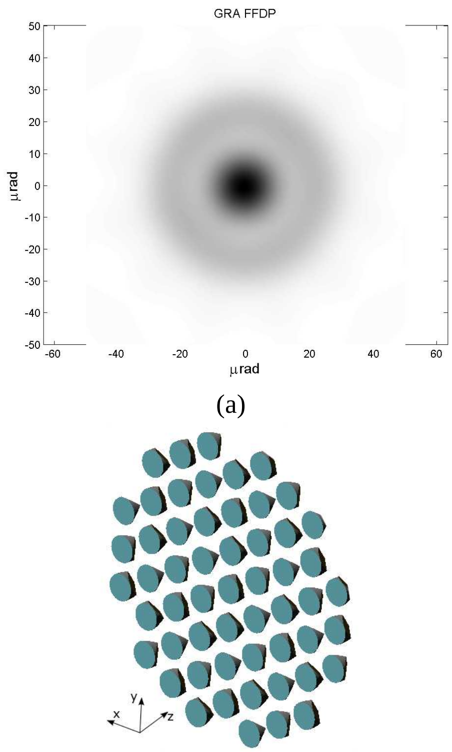


Fig. 10. GRA preliminary drawing. CCRs are oriented around their symmetry axis according to the following color convention. red=0°, green=30°, blue=60°, yellow=90°.

orientation of the CCRs in the array must be avoided because, being impossible to predict the relative motion of a ground station in the FFDP domain, a laser ranging station could experience a significant fluctuation in the signal strength. At the VA of Galileo, see Fig. 9, intensity has non-negligible fluctuations. Four orientation groups are though sufficient to guarantee a constant level of intensity at the right VA. The four groups were arranged carefully in order to have each group of rotations equally spaced around the center, radially and azimuthally, and with a centroid position of each group as close as possible to the center (see Fig. 10); $0°$ is a CCR with a physical edge vertical. The final array FFDP is that in Fig. 11, with an intensity at Galileo VA of $113 \cdot 10^6\, m^2$. This



(a)

(b)

Fig. 11. (a) GRA FFDP for a $\lambda = 532\, nm$ laser beam.(b) GRA model in CODE V used for optical simulations. CCRs are oriented around their symmetry axis according to Fig. 12 arrangement.

design is still under development and after the construction of the GRA, full tests will be performed at the new built SCF-G, as those described in section II. In parallel with measurements, using an optical model of the array, realized in CODE V, and integrated with a thermal/structural analysis software, we are proceeding to simulate the behaviour of a single CCR and of a whole array in the GCO orbit described earlier and in other critical orbits.

B. Thermal-optical simulations of GRA performance in orbit

Thermal and optical simulation analyses are fundamental to test the designed prototype in conditions impossible to realize in laboratory. We realized a finite element model of the CCR based on the characteristics of the GRA retroreflector. This CCR is placed in an Aluminum housing, like that designed for the GRA. The model is then introduced in the simulated space environment of a Galileo orbit, simulated as a simple keplerian orbit. During the orbit, as for usual GNSS payloads, the CCR face was always nadir pointing and the orientation of the CCR was such that one physical edge laid in the orbital plane. The orbit tested was the GCO described earlier. the x axis of Fig. **??**, in red, lays in the orbital plain, while the z axis points toward the Earth. The GCO in the local system of the CCR is shown in Fig. 12. The black lines represent two

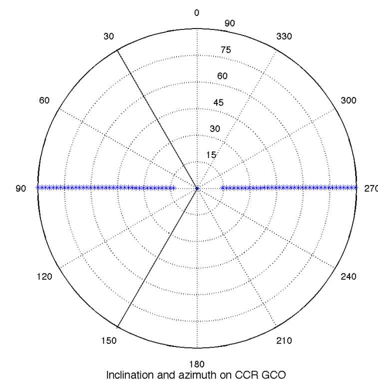


Fig. 12. Variation of Sun rays incidence vector in the CCR local frame.

edges of the CCR, while the third is horizontal on the right. The radial coordinate represents the increasing inclination of the Sun rays, starting from $0°$ in the center, while the angular coordinate the orientation of Sun rays, with $0°$ on the top and counting positive angles counter clockwise. Blue points are the trace of the GCO in the CCR local frame, which remains on the x/y plane. The result of the orbital simulation is the temperature distribution inside the CCR at each time step. Fig. 13 shows variation of the temperature at the center of the front face and at the tip. This temperature distribution

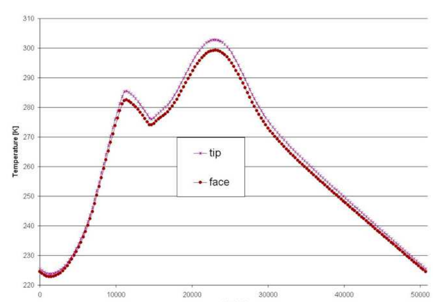


Fig. 13. Temperatures of CCR front face and tip along the orbit.

is then exported to the optical software as gradient of the index of refraction, modeled for simplicity as an axial gradient along the CCR symmetry axis. At each time step a FFDP is calculated and the variation intensity at $24\, \mu rad$ is plotted for the entire orbit.

As CCRs in the GRA are grouped in four orientation, simulations for just four CCRs are sufficient to thermally model the whole array. Optical simulations were instead made on a model of the whole array, as in Fig. 11. The final plot is in Fig. 14. The result of the simulation shows some similarities

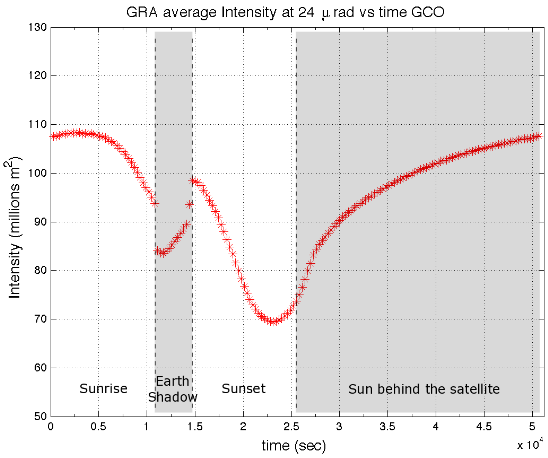


Fig. 14. GRA average intensity variation at $24\,\mu rad$ during the simulated GCO.

with the GCO test of Fig. 6, but a fundamental distinctive difference. During the sunrise there is not the thermal BT. The average decrease of the intensity is contained, if compared to the Galileo IOV retroreflector prototype measurements, both because of the different housing and of four oriented groups of CCRs. Looking at the FFDPs in some key points of the simulation it is possible to notice that the reduction of the intensity at the satellite VA corresponds also to a loss of symmetry of the FFDP; in those situations the intensity is no longer constant as in the design conditions (Fig. 11 (a)).

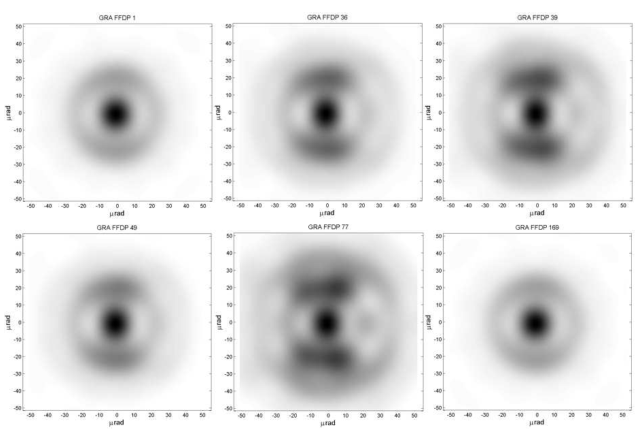


Fig. 15. FFDPs of the GRA at key points of the orbit. (1) Beginning of the orbit. (36) Beginning of Earth shadow. (39) Lowest intensity point of Earth shadow. (49) End of the Earth shadow. (77) Point of lowest intensity during the orbit. (169) End of the orbit.

IV. Conclusions

All of the improvements that the GNSS could benefit from the independent laser ranging technique need a full orbital coverage of tracked satellites. This is now difficult due to two main reasons: space segment performance and ground station capabilities. The first issue can be approached with both a careful design and full tests in a realistic space environment, as was the INFN intention building the SCF laboratory. The SCF-Test on a Galileo prototype CCR demonstrated such improvements, but, INFN-LNF thought that some further efforts could be undertaken. The design of the GRA has the purpose to enhance the LRA performance, with respect to current operative payloads, in three crucial aspects:

- Improved thermal isolation between CCRs and the array metal structure.
- Uniform pulse spreading of the return signal for every laser beam orientation.
- Uniform FFDP intensity with azimuth, at the right VA.

Optical simulations have shown that the choice of DAO and arrangement of the CCRs on the array produce an array FFDP that is axial symmetric, see Fig. 11. Orbital thermal and optical simulations, even if under some simplified hypotheses, have furthermore shown that intensity losses due to solar radiation, for the solo CCR case, not shown in this work, and for the array, are contained, if compared to the measurements performed on the single Galileo CCR; there is not any longer a "thermal BT" and, in the worst thermal conditions of the BT, the performance degradation is reduced.

The model will be in future improved to test orbital conditions other than the GCO, introduce a gravitational potential with terms higher than the first, test more general temperature distribution in the optical software and varying laser incidence onto the LRA (possibly simulating a laser ranging station tracking). This will eventually be compared to measurements of the GRA in the new SCF-G measurement facility.

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