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Optical FFDP and interferometry measurement and modeling of GNSS retroreflector payloads at SCF_Lab

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Abstract.*INFN (IstitutoNazionale di FisicaNucleare), in the framework of the R&D project ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite Constellations-2), designed and tested a full scale retroreflector array for GNSS applications, the GRA. This payload was designed in order to optimize optical performance in orbit. The standard test procedure we developed and optimized for other retroreflectors we tested before this project, is conceived of three steps. First we measured each retroreflector of the array in air, to check compliance with design specifications. Second we performed a standard SCF-Test on representative CCRs (Corner Cube Reflectors) of the array, checking for the variation of FFDP intensity at the correct velocity aberration due to thermal stresses. Third we measured some CCRs on a simulated Galileo orbit in order to check the variation of performance, in terms of FFDP and wavefront interferogram, in a more realistic environment. We repeated the latter test for a simulated thermal/optical model of the GRA. A fine tune between simulations and measurements would allow us to simulate the array in conditions which are difficult to replicate in laboratory. We will apply tests here described to other GNSS retroreflector payloads such as a few other retroreflectors of the Galileo IOV satellites and an array of the IRNSS constellation.*

1. Introduction

ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite COnstellations-2), was a 3-year ASI-INFN project of technological development, natural continuation and evolution of an INFN R&D experiment, ETRUSCO (Dell'Agnello 2010), whose main purpose was to design, characterize and model the performance of a GRA (GNSS Retroreflector Array), with application on Galileo and GPS3 constellations. The characterization of retroreflectors in a realistic space environment has been addressed by INFN as a missing topic to better design LRAs (Laser Retroreflector Arrays) for GNSS constellations, whose past experience proved itself being fundamental to highlight difficulties on past constellations tracking (Dell'Agnello 2010) and gave important informations on the current ones (Dell'Agnello 2011). Thanks to the ETRUSCO-2 project, we matured the experience to design a payload that could improve LRAs performance, for GNSS, in orbit.
In this work we describe design, simulation and experimental activity carried on for the project during the last three years at the SCF_Lab (Satellite/Lunar/GNSS laser ranging and altimetry Characterization Facilities Laboratory), focusing on the optical performance of the GRA as it was designed and realized by the INFN-LNF group. In section 1 there will be a brief description of the

payload and the concept that brought to its final design. In section 2 we will illustrate the measurements performed at the SCF_Lab on a simulated Galileo orbit, while in section 3 we will show some of the optical results on a simulated model of the GRA.

2. GNSS Retroreflector Array: GRA

The GRA is a planar array made of an aluminum base onto which CCRs are mounted. On the array there are 55 CCRs; each one 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 tolerance of ±0.5 arcsec. This choice followed a simulation process optimized to meet ILRS (International Laser Ranging Service) specifications for GNSS LRAs tracking (Pearlman 2009). In order to respect ILRS standards for the Galileo constellation, the number of CCRs necessary would be in principle 88. However, for budget and weight reasons the number was limited to 55.To control target signature effects caused by the variation of the relative inclination between the satellite and a laser ranging station, we decided to design a quasi-circular shaped array. **Figure 1** shows the payload as it was realized (with all CCRs mounted).

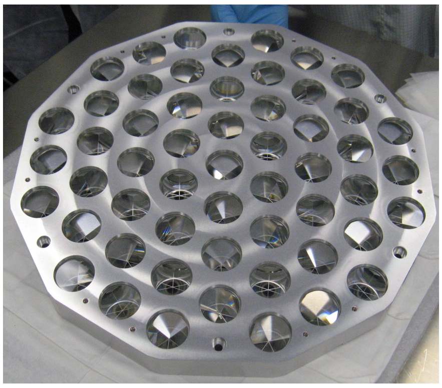

Figure 1 GRA with all CCRs mounted

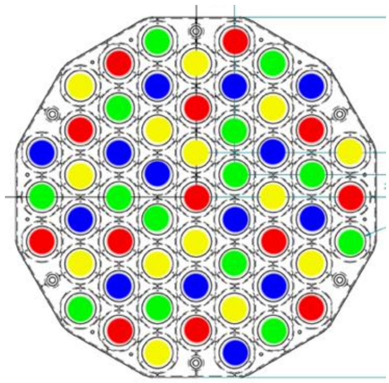

Figure 2 Azimuth rotation of CCRs on the GRA

Optical simulations with CODEV were essential to determine the basic characteristics of the GRA to be realized for the project. These CCRs were then arranged on the array in four groups of orientation, as shown in Figure 2,in order to obtain an axial-symmetric FFDP. These four orientations were evenly distributed on the array to avoid accumulation of the same family of CCRs

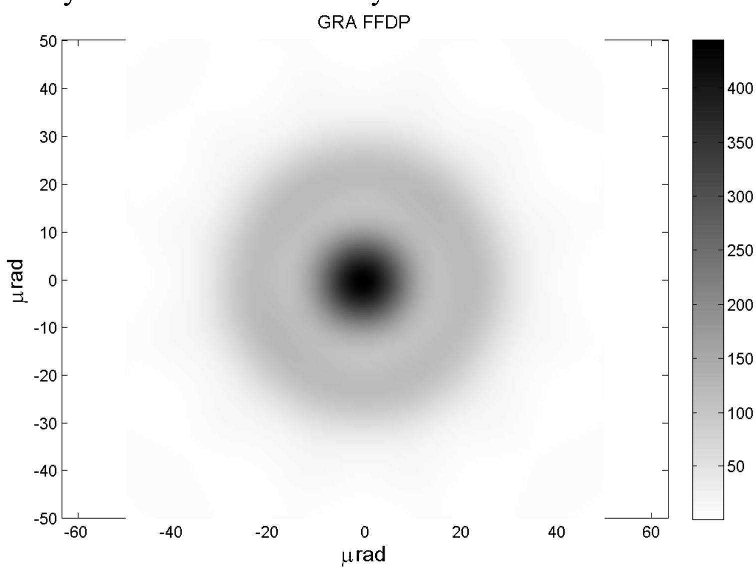

Figure 3 Simulated FFDP of the GRA

as much as possible and to have the barycenter of each orientation group coincident with the center of the array. The resulting simulated FFDP is shown in Figure 3: the intensity of the array at the VA (Velocity Aberration) of a Galileo satellite, ~24 μrad, is $113 \bullet 10^6$ m^2 (in Optical Cross Section units).

3. SCF-Test of the GRA at the SCF_Lab

The SCF-Test is a standard procedure we applied in the course of time on many retroreflector payloads (Dell'Agnello 2010) and revised for the ETRUSCO-2 project in order to introduce the measurement of an LRA on a simulated orbit, called GCO (Galileo half-Critical Orbit), whose distinctive features are described in detail in (Dell'Agnello 2011). We applied this standard procedure to the GRA, following three steps:

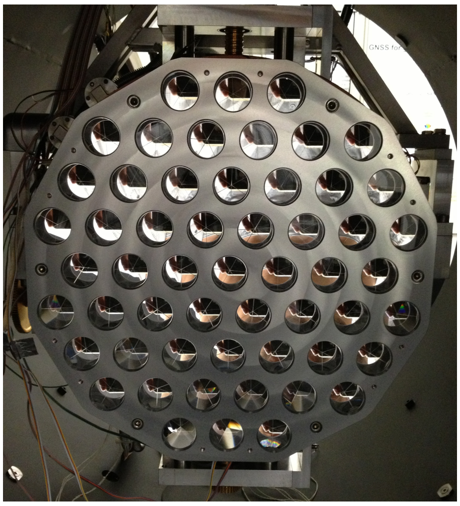

Figure 5 GRA inside the SCF-G facility

1. FFDP measurement of all 55 CCRs in air and isothermal conditions (with the GRA installed inside the cryostat)
2. SCF-Test of some CCRs at three different metal support structure temperatures
3. GCO measurement

Figure 5 shows the GRA installed into the SCF-G facility ready to start the tests. Along with usual thermal and FFDP measurements done so far, we introduced interferometric measurements with a commercial fizeau interferometer during the measurement of the GRA. In this paper we are going to describe the procedures and some results obtained during the GCO test.

At the beginning of the GCO test, the chamber environment was in space conditions, in terms of pressure and temperature; The GRA is controlled at a certain T_{low}. As soon as all the parts of the prototype reached the equilibrium with the external environment, the test started. The

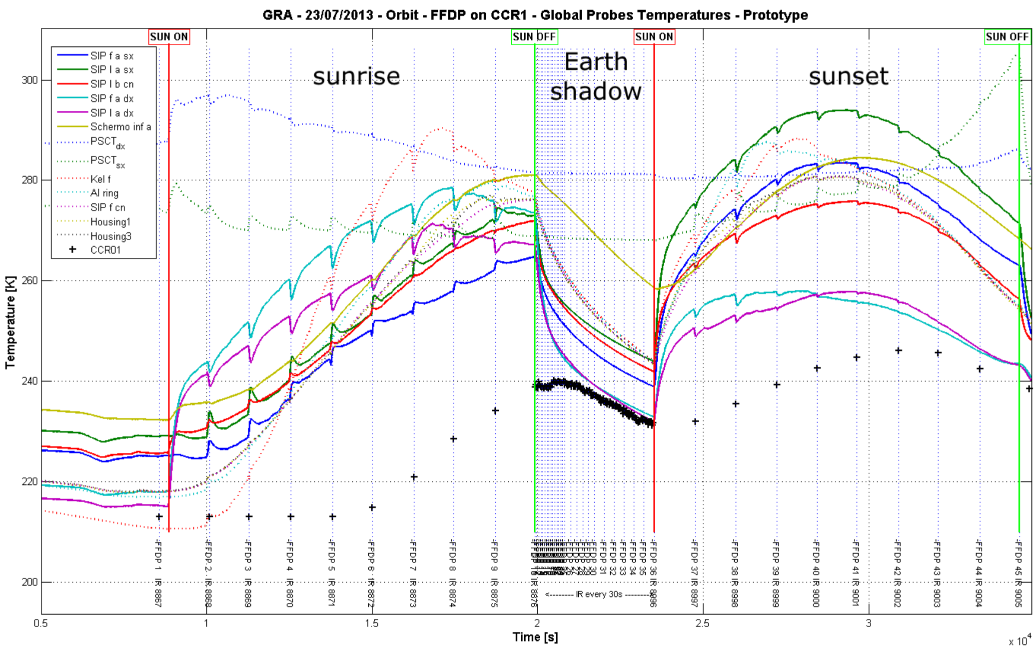

Figure 4 Temperature variation of GRA parts during GCO measurement. Black crosses are the temperatures of the CCR front face taken with InfraRed camera.

temperature control of the array was switched off and we let the SS (Sun Simulator) beam enter the chamber with the front face of the array parallel to it. The array was automatically rotated at discrete steps, with the same angular velocity of a Galileo satellite, lasting almost seven hours. Figure 4 shows the temperature variation of different parts of the payload during the GCO test. The test was repeated on 8 of the GRA retroreflectors, one for each orientation and, for each orientation, one inside and one on the edge of the array. Five CCRs of the GRA were realized with a different material, Suprasil 311, and two of the eight tested CCRs were made of this material; however, any particular difference between the two materials did not come out from the measurements. Thermal and optical results show a good performance of the array in this realistic condition, representing a significant improvement from previous measured retroreflectors (Dell'Agnello 2011).

4. Thermal-optical simulation of the GRA

Another major activity of the project was the development of a software procedure to integrate thermal and optical simulations of LRAs performance. ThermaOptiSim was an ETRUSCO-2 work package developed to realize this integration and better analyze CCRs behavior in a simulated orbit. The SCF-Test is fundamental to thoroughly investigate retroreflectors performance, but limited to just the simple GCO case; a simulation suite, properly tuned to laboratory measurements, is necessary to analyze their behavior in conditions not replicable in the SCF_Lab. In this section we describe the procedure concept and some results of simulations applied to the GCO case.

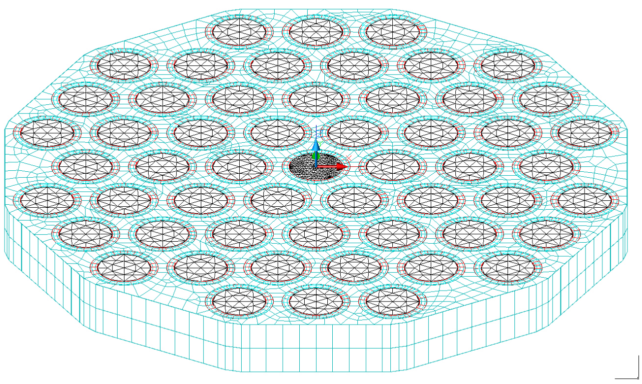

Figure 6 Complete GRA finite element model

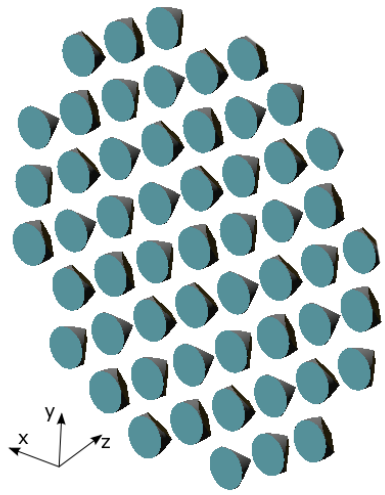

Figure 7 Complete GRA optical model

Using ANSYS® we developed a finite element model of the GRA, see Figure 6, and simulated it, with Thermal Desktop, on a GCO orbit, simplifying the motion to a one body problem with no perturbations form high harmonics of the gravity field. On each time step of the orbit the software calculated the temperature distribution inside each CCR of the array. Separately, we developed an optical model of the GRA with the software CODEV, see Figure 7. This software can simulate effects of a temperature distribution inside CCRs, but, since we are dealing with optical characteristics, a temperature distribution must be converted into an index of refraction distribution. Using the output of the thermal software we first converted the 3D temperature distribution in a thermal gradient and second we converted it into an index of refraction gradient that could be used inside CODEV. We finally analyzed the results separately in MATLAB, producing the FFDP of the whole array at each time step and the variation of the average intensity at the VA of Galileo, ~24μrad, during the GCO half orbit. To make things simpler the laser beam was considered orthogonal to the front face of the CCRs, even if in real laser ranging measurements this condition is quite rare. For the simulations we used the measured intensity profile of the SCF-G laser. Results are in the following figures.

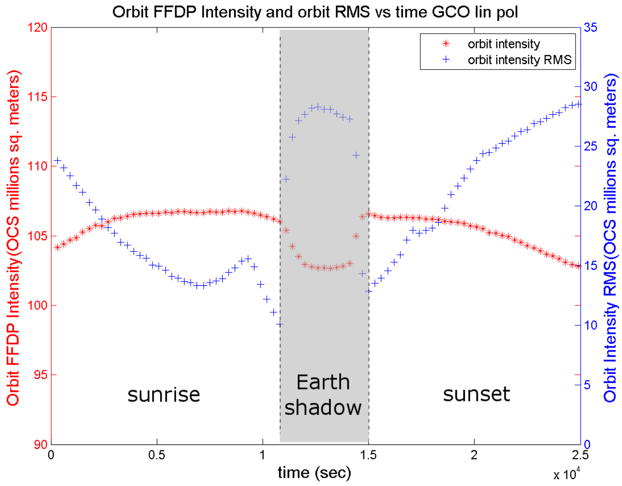

Figure 8 Simulated GRA FFDP average intensity (red) and FFDP intensity RMS (blue), laser linearly polarized

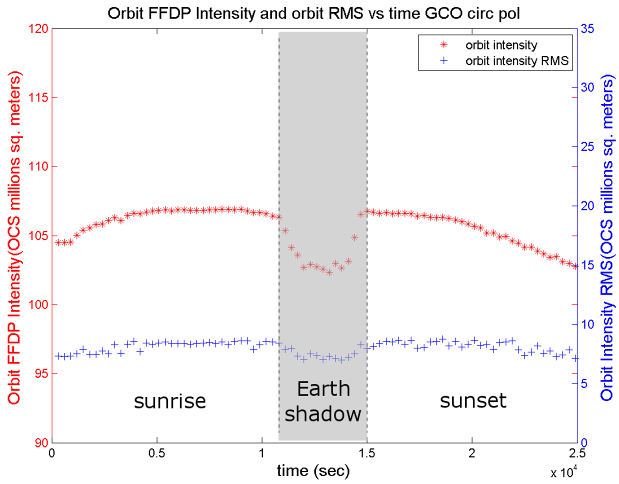

Figure 9 Simulated GRA FFDP average intensity (red) and FFDP intensity RMS (blue), laser circularly polarized

At first we simulated a linearly polarized beam, red 'stars' plot in Figure 8. At the beginning of the orbit, retroreflectors have a contained thermal gradient that does not change the intensity of the FFDP too much from its design value. As the portion of the front face of the CCRs hit by Sun rays becomes more consistent, they experience an intensity rise because the thermal gradient inside each one of them is actually decreasing. As the array enters the Earth shadow there is a non-negligible drop in intensity. This is due to the fact that while the front face of the CCRs is no longer experiencing the Sun radiation, the tip is still influenced by its internal housing structure. This behaviour, opposite in sign, is also observed at the end of the Earth shadow. In the second irradiated part, "sunset", the variation of intensity is symmetrical to the first for the same reasons described before.
The intensity distribution of a CCR is however deeply influenced by the polarization of the laser. In Figure 8 we simulated a linearly polarized beam, but, since recently there has been a wide discussion in the global laser ranging community regarding the use of a circular polarization (Kirchner 2012, Davis 2012), we analyzed the case of a circular polarization, in order to make a comparison to check for changes in performance. Comparing red 'stars' plots of Figures 8 and 9, displaying average intensity variations, there is not an appreciable difference, but it is looking at the intensity fluctuations at 24 μrad that the differences come out. We quantified those by calculating the RMS of the intensity at 24 μrad for each orbit position, blue 'plus' plots in Figure 8 and Figure 9. A circular polarized laser determines more contained fluctuations at the Galileo VA; this means that a ground SLR station moving in the FFDP plane would experience a much smaller fluctuation of intensity, using a circular polarized laser beam instead of a linear one.

5. Conclusions

The ETRUSCO-2 project brought to the design and the completion of the GRA as showed in **Figure 1**. We completed in 2013 a full SCF-Test campaign, which consisted of preliminary FFDP measurements in air and the standard SCF-Test, fundamental to determine thermal and optical basic characteristics of CCRs. Furthermore, we measured the array on a realistic half-orbit, GCO; the project is not over yet and the results cannot be fully disclosed. The other big part of the project was the set up of a software simulation procedure to integrate thermal and optical simulations of LRAs performance. We presented some preliminary results applied on a full scale GRA model and simulated it on the same GCO orbit used during the measurements. Results in Figure 8 show really good performance of the array in orbit with a contained average intensity variation. Moreover we showed that a shift from a linearly polarized laser beam to a circularly polarized one could bring a benefit in terms of intensity fluctuations, RMS, at the VA of the satellites.

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