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Completion of ETRUSCO-2, thermal test results and thermal optical simulation of the standard GNSS Retroreflector Array (GRA)

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Abstract. *The SCF (Satellite/Lunar/GNSS laser ranging/altimetry Characterization Facility) and SCF-Test are an innovative OGSE (Optical Ground Support Equipment) and innovative industrial test procedure to characterize and model the detailed thermal behavior and optical performance of cube corner laser retroreflectors (CCRs) for the Satellite Laser Ranging (SLR) to GNSS in accurately laboratory-simulated space conditions. They were developed by INFN-LNF and are in use by NASA, ESA, ASI, ISRO and the Italian Ministry of Defence. This is done with specialized instruments measuring and modeling optical Far Field Diffraction Pattern (FFDP), Wavefront Fizeau Interferogram (WFI) and temperature distribution of Laser Retroreflector Arrays (LRAs) of /CCRs under representative and/or critical space conditions accurately produced also with close-match solar simulators.*

Under ASI-INFN contract n. I/077/09/0 ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite COnstellations-2) we: built a second SCF optimized for GNSS and in particular for Galileo and GPS-III (SCF-G) and a GNSS Retroreflector Array (GRA) based on standards of the ILRS (International Lase Ranging Service); developed an orbit-realistic SCF-Test for GNSS and applied it to Galileo IOV. The new SCF-G will be described and results of the GRA characterization and of its integrated thermal and optical modeling will be reported.

1. Introduction

ETRUSCO-2 is a co-founded ASI-INFN project of technological development, with INFN as the Prime Contractor. The project acronym underlines the importance of the integration (unification) between GNSS (Global Navigation Satellite System) and SLR positioning techniques. This project started in 2010 as the evolution and obvious continuation of ETRUSCO experiment, conducted in 2006-2010 (Dell'Agnello 2010). The main aim of ETRUSCO project was to improve the satellite navigation capabilities thanks to the integration of SLR with the MWR (Micro-Wave Ranging) standard. In order to enhance the satellite navigation capabilities, the retro-reflectors and LRAs are very carefully characterized inside an environment with realistic space conditions. ETRUSCO-2 project aim is to optimize the space segment and to integrate GNSS with SLR geodesy techniques. Moreover its primary goal was to design an optimized GRA to propose for the deploying on Galileo and GPS-3 constellations, able to maximize ranging efficiency and improve signal intensity. Other purposes of ETRUSCO-2 project are: (1) to perform general relativity tests, included the test of gravitational red-shift, (2) space geodesy studies, (3) to improve GNSS orbits accuracy, (4) to improve stability and distribution of ITFR (International Terrestrial Reference Frame) to provide a better definition of its origin and scale. Based on the experience matured with the SCF, in 2012 INFN developed another apparatus, SCF-G (Satellite/lunar laser ranging Characterization Facility optimized for Galileo and the GPS-3) similar to the SCF but optimized for GNSS arrays. SCF and SCF-G are located in the same Clean Room, known as SCF_Lab, completed in 2011 by INFN-LNF. These unique and extended retro-reflector metrology capabilities (SCF plus SCF-G) provide critical diagnostic, optimization and validation tools for SLR to all GNSS programs.

2. New Solar Simulator

With the ETRUSCO-2 Project, the SCF_Lab has been placed inside a ~85 m^2 clean room; the testing capabilities of the Laboratory have been doubled with the construction of a new cryostat (the SCF-G) but also with the setup of a second optical table. A second Solar Simulator (SS) has also been installed; this simulator reproduces the solar flux, both the intensity and the spectrum, outside the atmosphere according with the standard AM0 (Air Mass zero). Both Suprasil 1 and Suprasil 311, which are the grades of fused silica used for the laser retroreflector of the GRA, have low solar absorptivity but high infrared emissivity: it means that even though the main part of the solar spectrum is made by high energy photons (with short wavelengths), it is the final part of the spectrum (at long wavelengths) that mostly warms up the reflectors when they are exposed to the sun in space or to the simulated solar beam inside the Laboratory. The following Figure 1 shows the comparison between the spectrum of the new SS and the standard AM0 spectrum. The overall match is good and there is a close correspondence at long wavelengths. Many solar simulators are usually implied in solar panel testing, it means that the part of the spectrum at short wavelength is the most important, while this solar simulator is customized right for the SCF-Test.

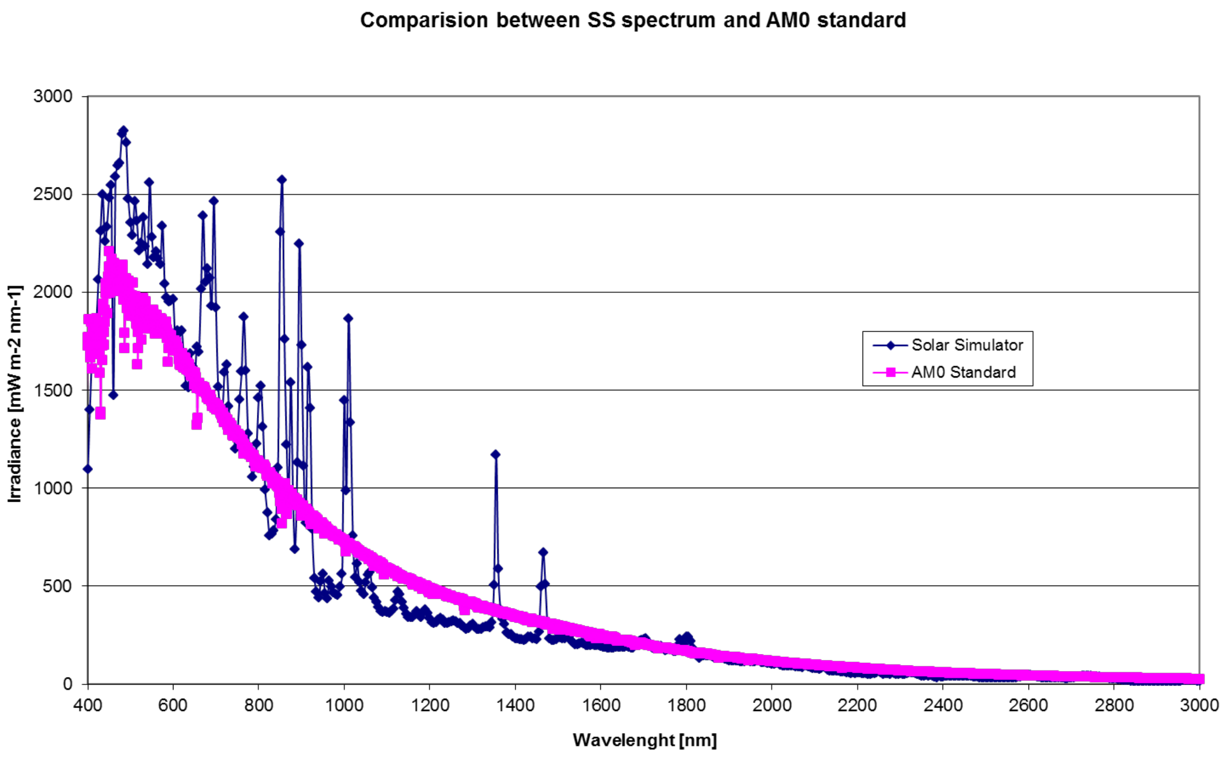


Figure 1: comparison between the spectrum of the solar simulator, blue diamonds with several spikes, and the AM0 standard spectrum, pink squares and regular shape. There is an overall good agreement in particular at long wavelength.

Even though the ETRUSCO-2 Project has significantly enhanced the testing capabilities of the SCF_Lab, the idea of the SCF-Test is a background intellectual property of INFN. The SCF-Test consists in integrated and concurrent thermal and optical measurements performed either on single CCRs or on LRA breadboards, prototypes or flight payloads. The CCR/LRA is held at a fixed temperature, T_M, starting from the expected average temperature, T_{AVG}, of the payload in space. In Earth orbits the default LRA temperature is T_{AVG} = 300 K. T_{AVG}, the expected variation range of T_M and the conditions of the LRA to spacecraft interface are inputs of the test. With SCF data and analysis we evaluate the CCR FFDPs under simulated space conditions and we compare them with the FFDPs measured in air conditions; the laser beam has a default linear polarization and an adjustable incidence angle with respect to the normal to the CCR face (the default laser angle is 0°). CCR surface temperature and its thermal relaxation time τ_{CCR} are measured during the test; we also measure the temperature and evaluate the thermal relaxation times of the other components of the LRA. The above procedure is repeated several times changing T_M from T_{AVG} to different temperatures inside the expected range of variation. This overall procedure is also performed for different SS illumination conditions.

3. SCF-Test Revision ETRUSCO-2

This evolution of the test inherits from the previous version the measure of FFDPs and the measurement of thermal relaxation times of the CCR, τ_{CCR}, and of the other mounting elements. New items in this revision are the thermal-optical conditions experienced by retroreflectors during a GNSS Critical half-Orbit (GCO, see Figure 2) and the retroreflector Wavefront Interferogram (WI) in space conditions. The GCO test has been developed with ETRUSCO for the IOVs. The GCO is the orbit with its nodal line parallel to the Sun-Earth joining line. Orbit conditions are reproduced in laboratory rotating the GRA inside the cryostat, in quasi-real time, for the proper GCO duration: 7 hrs for Galileo, 6 hrs for GPS.

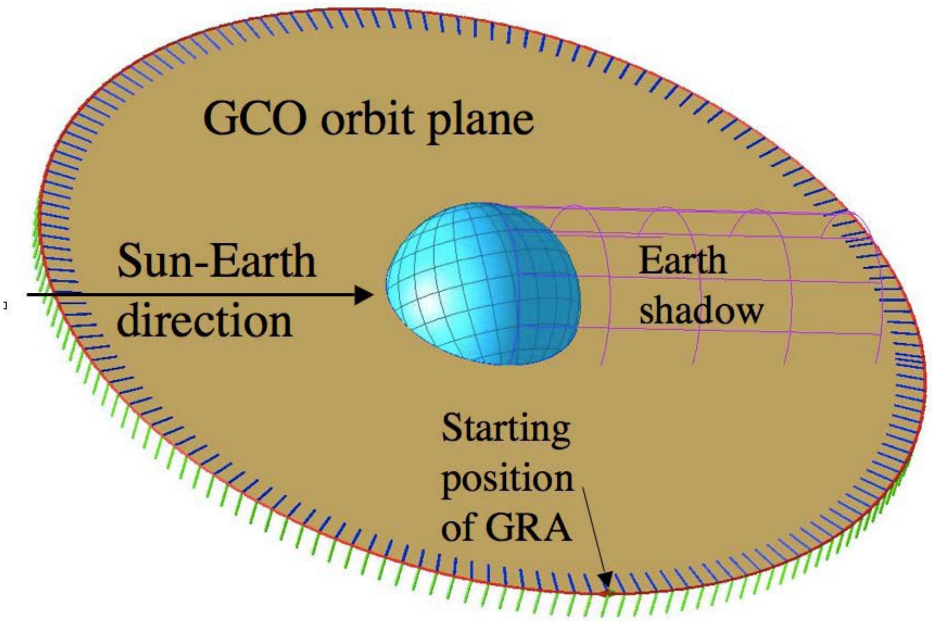
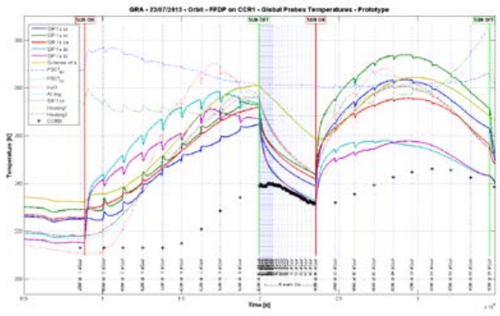
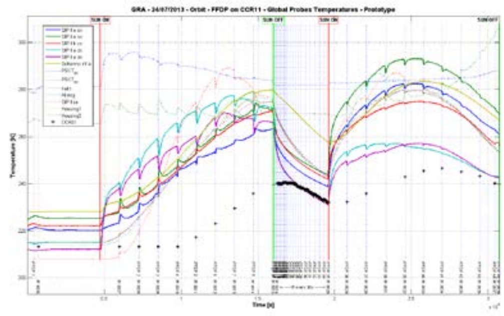
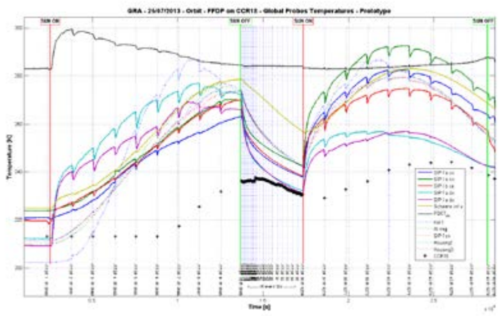
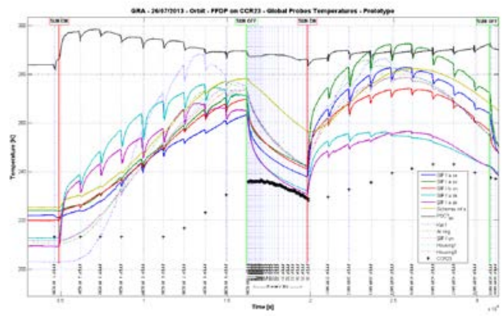
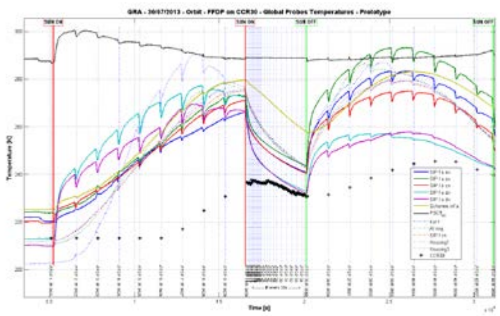
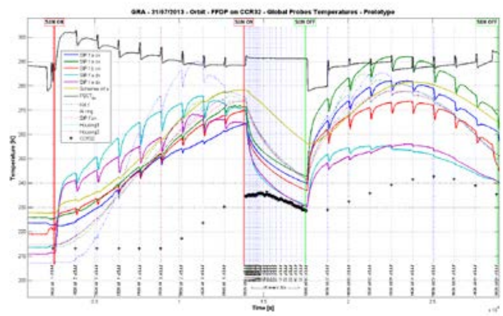
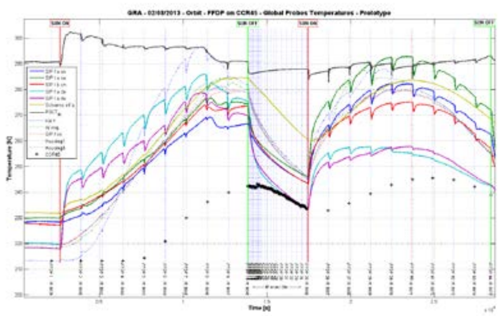
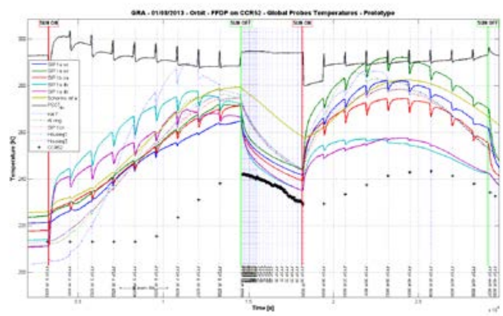


Figure 2: illustration of the GNSS Critical Orbit (GCO)

Initially, the GRA and its reflectors are parallel to the SS beam; then the GRA is gradually rotated experiencing sunrise, eclipse (simulated by obscuring temporarily the SS) and sunset. At the end of the GCO, the GRA is 180 degrees reversed. During the GCO, the GRA is also periodically rotated towards the infrared and optical windows of the cryostat to take temperature (IR thermograms in the case of fused silica CCRs) and optical measurements of the reflectors, and rotated back to its progressing GCO orientation, all in a few seconds. This quick measurement rotation has a negligible influence on the thermal and optical behavior of the GRA along the GCO.

4. Results

The GRA is a planar array with CCRs mounted on an aluminum base. On the array there are 55 CCRs; each one of them is a solid uncoated retroreflector, made of Suprasil 1, with a circular front face of 33 mm diameter. In the following table the results of the ETRUSCO-2 SCF-Test of 8 different CCRs are shown:

The CCR temperature measurements are marked with black crosses; they are all in the range between 213 K and 246 K even though their trends show some differences due to the different position of the single tested CCR. The other elements of the assembly are in the range between 200 K and 300 K.

The overall GRA has been thermally simulated using a commercial software. The temperature distribution inside the CCR, calculated with the thermal simulation, becomes the input for a different simulation using an optics commercial software (Boni 2013). The optical simulation requires a fine mesh of the CCR, but the thermal software has the upper limit of 20000 per model. The problem has been overcame realizing 8 different thermal models of the GRA, one per every CCR orbit tested: the CCR tested is meshed with more than 1000 nodes while the remaining 54 CCRs are modeled with only 110 nodes each; all the remaining elements of the assembly are kept unvaried in all the models. A comparison between simulations and tests, only for the test of the central CCR of the GRA, is given in the following.

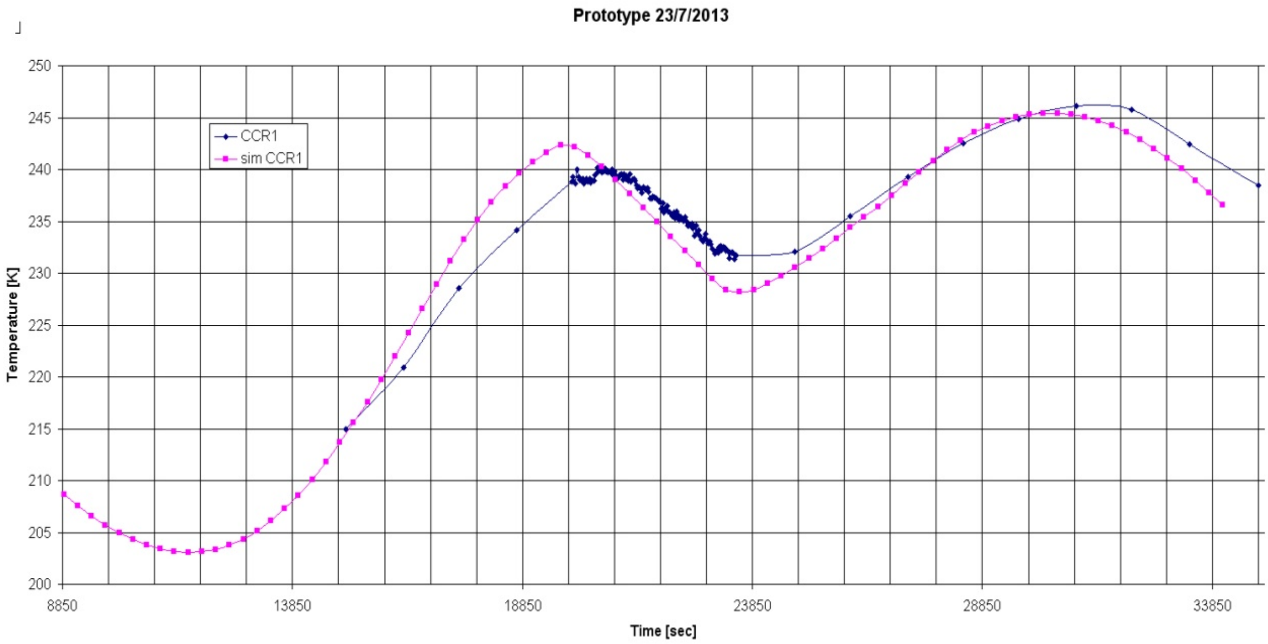


Figure 3: comparison between thermal simulation and temperature measurement of the central CCR of the GRA along the GCO.

From the simulation it is possible to evaluate the temperature difference between tip and face of the CCR which hardly influences the optical performance: this difference is always rather small, between 0.4 K and 1.2 K and the GRA optical performance was very good. This temperature gradient has its maximum when the CCR enters the Earth shadow, because the tip is still warmed up by the surroundings elements while the face is no longer enlightened by the Sun: measured FFDPs also showed a clear reduction of the optical performance in the passage from light to shadow.

5. Conclusions

The ETRUSCO-2 project enhanced the testing capabilities of the SCF_Lab; a new experimental apparatus has been completely setup: the cryostat, the SCF-G, the optical table and the SS (which spectrum and its comparison with the AM0 standard is given in Figure 1). A new array of laser retroreflector, the GRA, has been built and tested inside this project. Experimental thermal results of the GRA test campaign have been shown. With a simulated model, the temperature difference between the tip and the face of the CCR has been evaluated; the results of these simulations show that this difference is always rather small, between 0.4 K and 1.1 K and this matches the very good optical performance of the GRA. For a wider discussion about optical performance refer to (Boni 2013) also presented in this Congress. During the period of the ETRUSCO-2 Project the SCF_Lab team started new collaborations: with the European Space Agency for testing the retroreflectors of Galileo IOV; with the Indian Space Research Organization for testing the reflectors of their regional navigation system and with the Italian Ministry of Defense for a research activity focused on the Italian satellite COSMO-SkyMed. The work around the GRA is still in progress since, together with the GRA, a cover of cylindrical shading around every CCR to protect it from the Sun has been designed and built but this cover is rather heavy, 0.9 kg, and the GRA already performed very well without it. In the future tests we will evaluate the pros and cons of this additional structure.

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