ETRUSCO-GMES (Activity Report 2012)

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1 Introduction

The SCF_Lab is a specialized infrastructure operational at INFN-LNF . It consists of two innovative OGSE (Optical Ground Support Equipment) facilities: SCF and SCF-G, for the SCF-Test. They were developed by INFN-LNF and are in use by NASA, ESA, ASI, ISRO (Indian Space Research Organization) and the Italian Ministry of Defence. They characterize an innovative industrial thermal-optical-vacuum 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 (Global Navigation Satellite System), i.e. it is composed of specialized instruments capable of measuring and modeling optical Far Field Diffraction Pattern (FFDP), Wavefront Fizeau Interferogram (WFI) and temperature distribution of Laser Retroreflector Arrays (LRAs) of CCRs under space conditions accurately simulated in the laboratory and also produced with close-match solar simulators. LRAs/CCRs are passive, maintenance-free instruments, which provide absolute positioning in space with respect to the Earth center of mass (geocenter), which is metrologically defined with SLR to LAGEOS I and II and to other ILRS reference satellites. SLR, with almost uniquely VLBI (and other geodesy techniques), also defines the absolute scale of length in space because the improvement of GNSS orbits will increase the accuracy, stability, and distribution of the ITRF (International Terrestrial Reference Frame), to provide a better definition of the geocenter (origin) and the scale (length unit). We will describe the SCF_Lab capabilities to design, construct and characterize LRAs for earth observation (EO) satellites and GNSS constellations paying particular attention to the project ETRUSCO G-MES (Global Monitoring for Environment & Security) whose main goal is the development and characterization of GNSS Retroreflector Arrays (GRA), targeted to Galileo and GPS-3, but open to other GNSS satellite constellations.

ETRUSCO-GMES (Extra Terrestrial Ranging to Unified Satellite Constellation-Global Monitoring for Environment & Security) is one of the two European Union flagship programmes in space that will provide data to help deal with a range of disparate issues including climate change and border surveillance. Land, sea and atmosphere - each will be observed through GMES, helping to make our lives safer. The project acronym underlines the importance of the integration (unification) between GNSS (Global Navigation Satellite System) and SLR positioning techniques. This project is aimed at optimizing the space segment and integrating GNSS with SLR geodesy techniques. Furthermore, 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-GMES project are:

1. general relativity tests performance
2. space geodesy studies
3. improvement of GNSS orbits accuracy
4. enhancement of stability and distribution of ITFR to provide a more precise definition of its origin and scale.
5. geology

It is important for the development of LRAs with Formation Flying Functionality (LRA-3F) capabilities which is possible thanks to the framework of the R&D activities of the INFN National Scientific Committee n. 5 (INFN-CSN5) and the national contracts with public Entities which even encouraged the development an orbit-realistic SCF-Test for GNSS that we applied to Galileo IOV (In- Orbit Validation).
ETRUSCO-GMES is composed of:

- ETRUSCO-IOV: SCF-Test for Galileo IOV
- ETRUSCO-IRNSS : SCF-Test for 'Indian Galileo' (GNSS)
- G-CALIMES: Unification of Galileo and Italian constellations for radar mapping of Earth surface

In view of the HORIZON 2020 program, GMES has been renamed "Copernicus".

2 SCF_LAB

SCF_LAB (Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility LABoratory) is a new ISO 7 Clean Room of about 85 m2 located inside the Frascati National Laboratories of the INFN. Unique worldwide, it is dedicated to design, characterization and modeling of the space segment of Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and Planetary Laser Ranging and Altimetry (PLRA) for industrial and scientific applications and endorsed by the International Laser Ranging Service (ILRS). Built to develop and characterize laser retroreflector arrays for GNSS, EGNOS-V2 and inter-satellite laser links, by means of specialized thermal-optical-vacuum test procedures and specialized instrumentation, it was originally constructed for the existing SCF (INFN property, Fig. 1, 2 and 3) which is very versatile for its large number of measurement ports (side and back), capability of long LRA horizontal translations and customization for LLR, PLRA and CubeSatsand. Afterwards, on the basis of the experience matured with it, in 2012 we developed a new version of this facility, optimized for Galileo and GPS-3: the SCF-G (Satellite/lunar laser ranging Characterization Facility optimized for Galileo and the GPS-3,property of INFN and of the Italian Space Agency, ASI, Fig. 4), a new cryostat which doubles and optimizes our metrology capabilities for GNSS LRAs. Its structure is innovative respect to SCF because of a back gate and an amplified diameter aperture. The SCF . SCF and SCF-G complement each other.

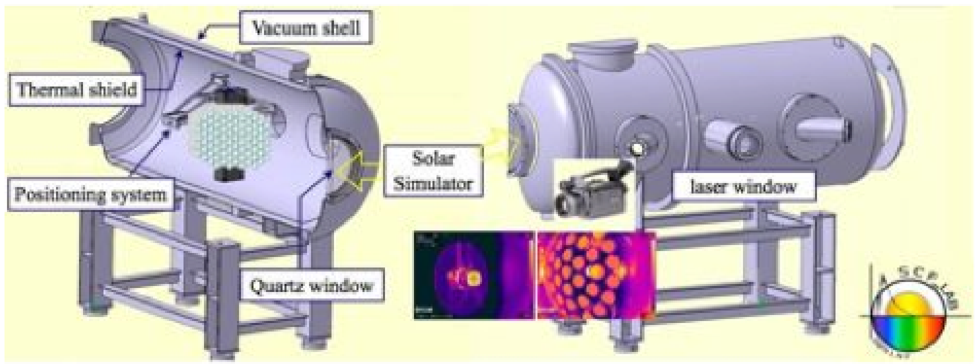


Fig. 2.1: Schematic view of SCF cryostat with: IR pictures of the LAGEOS Sector LRA and of a Galileo IOV CCR under test, IR camera and SCF_Lab logo

The success of doubling the metrology capabilities has been achieved also thanks to the optical instrumentation mounted on the three optical tables (in order to acquire Far Field Diffraction Patterns) and the new Solar Simulator (SS), installed to simulates the solar flux, both the intensity and the spectrum, outside the atmosphere according with the standard AM0 (Air Mass zero). 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. In effect, 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. Hence, there is a close correspondence at long wavelengths between the spectrum of the new SS and the standard AM0 spectrum.
In the SCF_LAB we have SCF-Tested CCR of the following satellites: GNSS (GPS, GLONASS, GIOVE, Galileo IOV), LAGEOS, Apollo, new generation lunar and hollow CCRs. We are now testing an LRA of IRNSS (Indian Regional Navigation Satellite System).

3 WORK ACCOMPLISHED WITH ASI- INFN R&D FOR GALILEO AND GPS-3

We describe some key products of the INFN project of technological development ETRUSCO-GMES

- Definition of an improved and enhanced test procedure SCF-Test/Revision-ETRUSCO-GMES: implementation of advanced and innovative operational procedures for the test of the what we call the “GNSS Critical Orbit” (GCO), developed for Galileo IOV

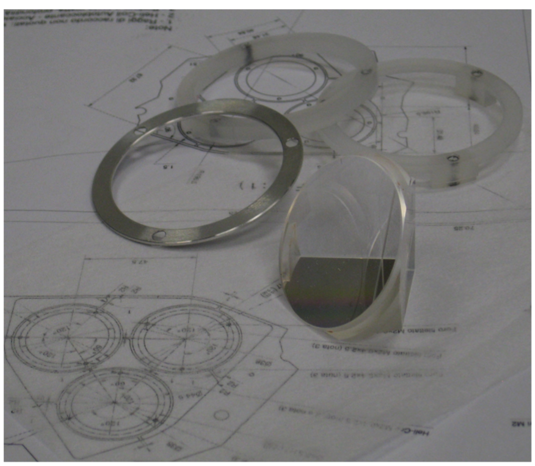
- Full-size prototype GNSS Retroreflector Array (GRA) for Galileo & GPS-3: inherited from LAGEOS, it is composed of 55 CCRs of solid uncoated CCRs. GRA SCF-Test and modeling has been very successful.

- We studied the improved test of the gravitational redshift (GRS) predicted by General Relativity combining Galileo H-maser clocks with SLR stations equipped with H-maser clocks & collocated with respect to the ITRF through SLR & GNSS: the contribution of typical SLR positioning accuracy (cm level) on the GRS error budget is negligible compared to clock instrumental and calibration errors. The latter are the limiting contributions. The capability of performing the absolute calibration of the clock frequency of Galileo satellites is unique to SLR . Thanks to SLR data we evaluated the gravitational potential difference between Galileo and Earth. Supposing fixed the Earth gravitational potential, the GRS variation depends from the Galileo potential variation. Studying the perigee-apogee periodic Galileo potential variation along its orbit, we found that the GRS measurement must be done on orbit segments of about 1 hour. These data are also used for the validation of orbits fit with GNSS data.

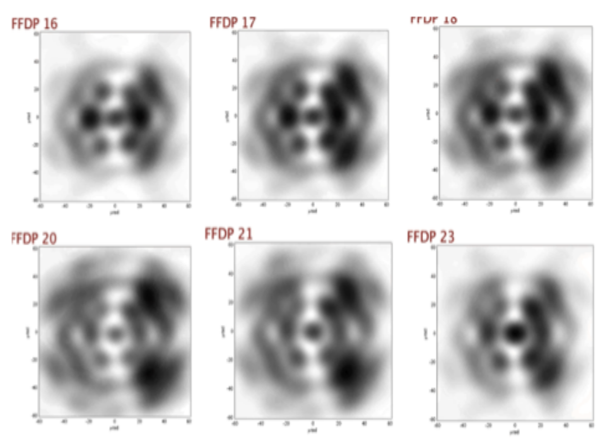
4 SCF-TEST OF GALILEO IOV RETROREFLECTORS

The GRA has been characterized with the SCF-G, with the procedures which include

1. GCO SCF-Test under exposure to the new solar simulator
2. Measurement of CCR optical performance (FFDPs and WFIs)
3. Thermal behavior (IR thermometry and contact probes)



(a) Bare CCR with the Al ring and two KEL-F rings



(b) IOV CCR: FFDP relative intensity during the GCO. FFDP scales are [-60,+60] µrad(right)

We performed an extensive SCF-Test on a prototype Galileo IOV retroreflector which is a fused silica uncoated CCR, deployed in planar arrays of 84 units on Galileo IOV satellites. This is very important for further SCF-Testing to expand the characterization of IOV LRAs, which have a better performance compared to old generation Al-coated GNSS CCRs (GPS, GLONASS, GIOVE). 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, TM, starting from the expected average temperature, TAVG, of the payload in space. In Earth orbits the default LRA temperature is TAVG = 300 K. TAVG, the expected variation range of

TM 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 τCCR 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 TM from TAVG to different temperatures inside the expected range of variation. This overall procedure is also performed for different SS illumination conditions. The Test evolved adding new items such as the thermal-optical conditions experienced by retroreflectors during a GNSS Critical half-Orbit and the retroreflector Wavefront Interferogram (WI) in space conditions. The GCO test has been developed with ETRUSCO for the IOVs.

4.1 GNSS Critical Orbit (GCO) SCF-TEST

The GNSS Critical Orbit is the orbit with its nodal line parallel to the Sun-Earth joining line. The test protocol, with the aim to reproduce an half GCO, has contemplated a three-hour period during which the payload has been rotated with 5 minute steps from the shroud towards the solar window (through which the emitted beam has been irradiated from the solar simulator) followed by a one hour period of shadow (during which the solar simulator was overshadowed by a shutter and the payload has been rotated towards the optical window to acquire FFDP, interferograms and ir photos) to finish with a three-hour period during which the payload has been rotated with 5 minute steps from the solar window towards the optical window.

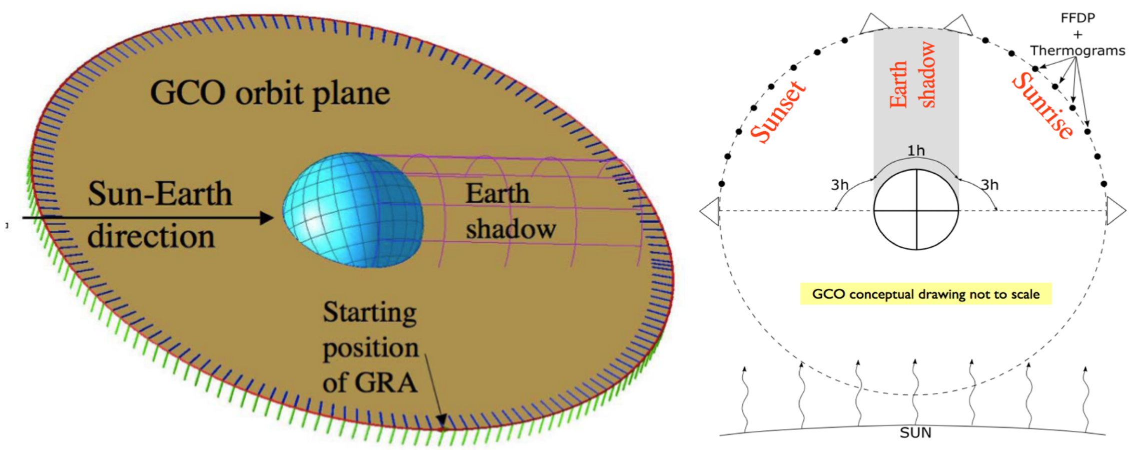


Fig. 4.1: GCO in space(left); GCO SCF-Test concept(right)

In order to evaluate the CCRs optical response, an optical circuit , outside of the cryostat, has been set up to reveal the horizontal and vertical Far Field Diffraction Patterns, subsequently integrated together in the analysis phase in order to obtain the total response of the retroreflector in exam. In addition to FFDP obtained by a 532 nm laser beam, the interferograms with a 633nm laser beam have been also made through the AccuFiz interferometer. Regarding the thermal response of all CCRs, it was possible to plot the thermal trend of the CCRs themselves thanks to an Infrared Camera.

5 THERMAL-OPTICAL SIMULATION OF THE GRA

Another considerable activity of the project is 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 just to the simple GCO case.
The procedure of the simulation is divides into:

1. Definition of a finite element model of the GRA using the simulation software ANSYS® to then simulate it on a GCO orbit with the program Thermal Desktop considering no perturbations from high harmonics of the gravity field to simplify the problem. The program calculated the temperature distribution inside each CCR of the arrays for every step .

2. Development of an optical model of the GRA with the software CODEV to simulate the effects of a temperature distribution inside the CCRs which must be converted into an index of refraction distribution because we are dealing with optical characteristics.

3. Final analysis of the results using 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.

4. 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 not typical . For the simulations we used the measured intensity profile of the SCF-G laser.

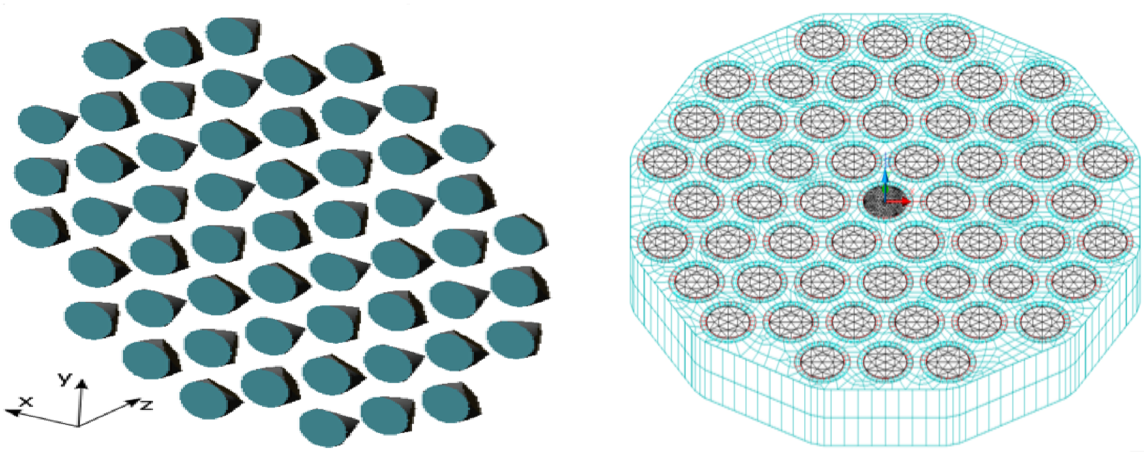


Fig. 5.1: GRA optical model (left); GRA finite element model (right)

6 RESULTS

These tests in the SCF_LAB will allow us to provide pre-launch validation of retroreflector performance under space conditions accurately simulated in the laboratory (in terms of pressure and temperature), as well as to characterize 'as-built' payloads, in order to optimize payload designs, to maximize ranging efficiency, to improve signal-to-noise conditions in daylight.
The GRA is an array made of 55 solid uncoated retroreflector, made of Suprasil 1. Five of these CCRs 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.
Figures 6.1 shows the temperature variation of two of the CCRs tested, as results of the GCO measurement:

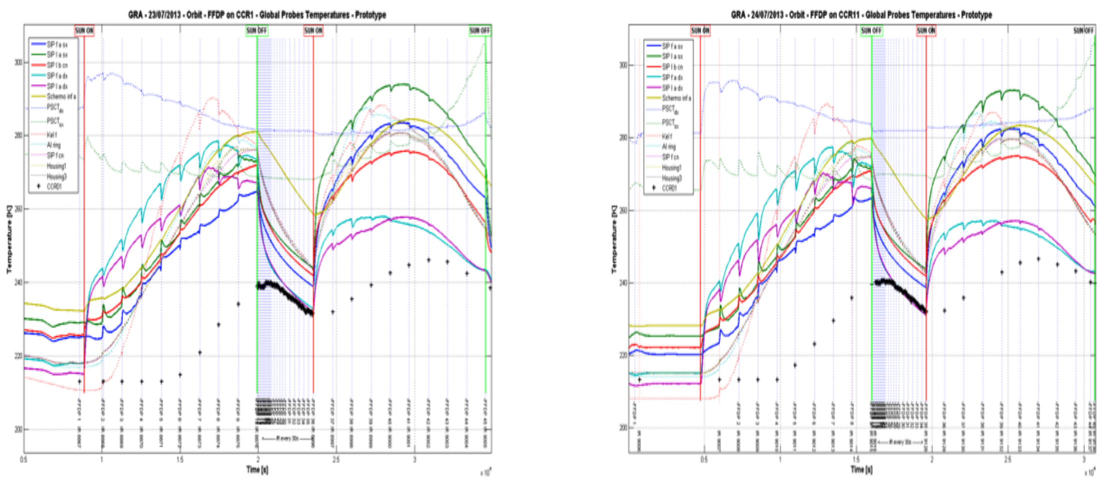
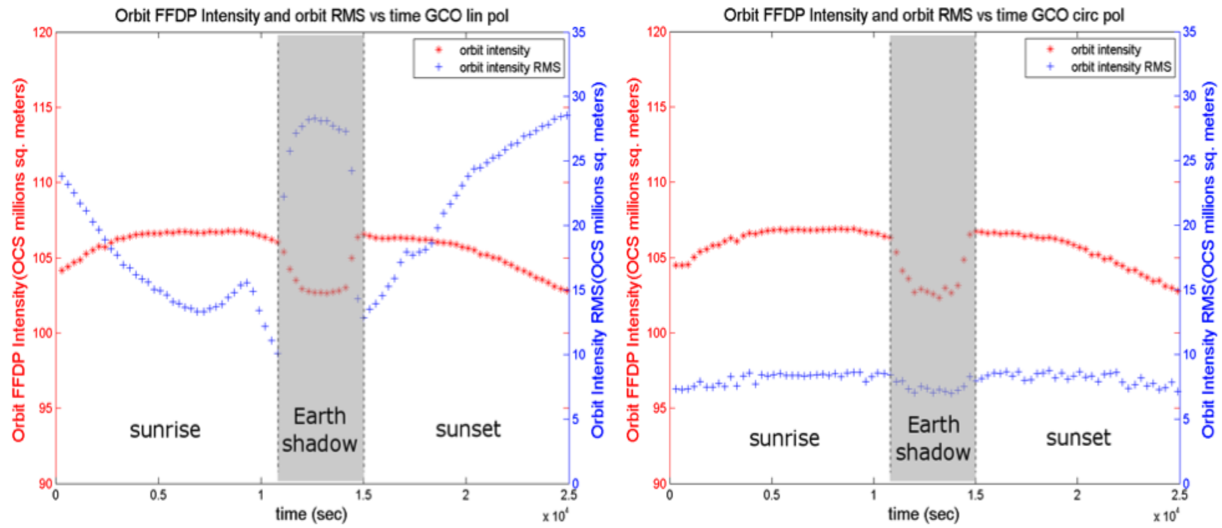


Fig. 6.1: Results of the ETRUSCO-GMES SCF-Test of 2 different CCRs

The CCR front face temperature measurements taken with InfraRed camera 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.
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).
GRA SCF-Test and modeling has been very successful.
Regarding Thermal-Optical simulations, we used the measured intensity profile of the SCF-G laser. Results are in the following figures.



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

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

The intensity distribution of a CCR is however deeply influenced by the polarization of the laser. In Figure 6.2 a 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 (Figure 6.2 b), in order to make a comparison to check for changes in performance. Comparing red 'stars' plots of the two Figures, 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 the two Figures. 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.

7 APPLICATIONS TO LRA-3F (CURRENT WORK AND FUTURE PROSPECTS)

With a shared 50%-50% collaboration between INFN and the Italian Ministry of Defense we are developing LRA-3F payloads for EO and GNSS missions of national and European interest, as well as customized, ad-hoc SCF-Test procedures for these missions. This effort includes design, construction, as well as characterization and study activities. We will apply all capabilities and instrumentations of the SCF_Lab to LRA-3F, including the SCF-Test/Revision-IR at 1064 nm laser wavelength is being developed for PLRA missions and for Satellite Formation Flying Missions and Technologies (SFFMT, including EO and GNSS). This is performed with a third movable table for optical FFDP measurements. The SCF-Test/Revision-IR capability is in addition to the SCF-Testing capabilities at 532 nm and 633 nm previously described. The 532 nm and 633 nm wavelengths have been used over the years by ILRS for SLR and LLR missions. The 1064 nm one is typically used for PLRA missions (including Mars Global Surveyor, Lunar Reconnaissance Orbiter and MESSENGER). Results from the current (first) Phase of the Defense-INFN contract must be consigned by 2014, with the publication of non-confidential content at the end of Phase 1 after the unanimous approval.

8 CONCLUSIONS

Inside the SCF_Lab we have developed unique procedures for the characterization of the performance of LRAs for several GNSS and lunar laser ranging missions and for LAGEOS, that is a reference of the standard ILRS payload. These are based on specialized instrumentation , on the measurement of the optical and temperature standard ILRS observable LRAs and on reference and/or representative orbit configurations (Default 'Earth-eclipse' SCF-Test, GCO SCF-Test, lunar day tests). Results in Figures 6.2 (a,b) show really good performance of the array in orbit with a contained average intensity variation. Experimental thermal results of the GRA test campaign have been shown and they underline the very good optical performance of the GRA. 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. The work is proceeding to apply the SCF_Lab work program to LRA-3F for EO and GNSS missions. Current preliminary results and specifications are not released for publication. This work is the continuation and evolution of INFN and ASI work on laser ranging of GNSS, Moon and LAGEOS, in the framework of ILRS activities (see http://ilrs.gsfc.nasa.gov and http://www.lnf.infn.it/conference/laser2012/).

9 ACKNOWLEDGEMENTS

We thank the Italian INFN-CSN5, which is supporting the SCF_Lab since 2005 (with funds for the interdisciplinary experiments ETRUSCO, MoonLIGHT-ILN and ETRUSCO-GMES), and the Italian Ministry of Defense, which is co-funding SCF_Lab R&D activities under Defense-INFN Contract n. 10263. We also thank ASI for co-funding SCF_Lab R&D activities related to Galileo and GPS under ASI-INFN Contract n. I/077/09/0 (ETRUSCO-2 project).

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See also: http://ilrs.gsfc.nasa.gov/about/reports/other_publications.html.

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http://ilrs.gsfc.nasa.gov/reports/special_reports/index.html. Results reported here are world-first measurements on Al-coated CCRRs deployed on the first generation of GNSS (GLONASS, GPS, GIOVE) and on an uncoated CCRR of LAGEOS.

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http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/gali_reflector.html, 3 documents are reported: 1) ESA's request for laser tracking of Galileo IOV-1 and IOV-2 satellites that were launched on Oct. 21, 2011; 2) ESA's IOV retroreflector info; 3) INFN's world-first SCF-Test activity for the CCR of Galileo IOVs. IOVs, the first 4 satellites of Galileo, have uncoated CCRs like IRNSS, COMPASS and QZSS CCRs.

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LIST OF ACRONYMS

BIPR = Background Intellectual Property Right
CCR = Cube Corner Retroreflector
COSMO-SkyMed = COnstellation of small Satellites for the Mediterranean basin Observation
CSG = COSMO Second Generation
CSNV = Commissione Scientifica Nazionale V, INFN National Scientific Committee V
CSK = COSMO-SkyMed
DAO = Dihedral Angle Offset
ESA = European Space Agency
ETRUSCO = Extra Terrestrial Ranging to Unified Satellite COnstellations, an INFN-CSNV interdisciplinary program for GNSS and LAGEOS
ETRUSCO-2 = Extra Terrestrial Ranging to Unified Satellite COnstellations-2, an ASI-INFN co-funded project of technological development for GNSS
3F = Formation Flying Functionality
FFDP = Far Field Diffraction Pattern
G-CALIMES = Galileo-COSMO-SkyMed Absolute Laser Intercalibration with Measurements on Earth and in Space
GNSS = Global Navigation Satellite System
GMES = Global Monitoring for Environment and Security
GSEG = Ground SEGment
HW = HardWare
ILRS = International Laser Ranging Service (http://ilrs.gsfc.nasa.gov/)
INFN = Istituto Nazionale di Fisica Nucleare (http://www.infn.it/indexen.php)
IRNSS = Indian Regional Navigation Satellite System, the Indian GNSS
ISF = Internal Special Facility of the LNF
ITRF = International Terrestrial Reference Frame
LAGEOS = LAser GEOdynamics Satellites-I (by NASA, 1974) & II (by NASA/ASI, 1992)
LEO = Low Earth Orbits
LLR = Lunar Laser Ranging (to Apollo and Lunokhod LRAs)
LNF = Laboratori Nazionali di Frascati dell'INFN, Frascati (Rome), Italy (http://www.lnf.infn.it/user.html/)
LRA = Laser Retroreflector Array (of CCRRs)
MAIT = Manufacture Assembly Integration Testing
NASA-GSCF = National Aeronautics and Space Admin. − Goddard Space Flight Centre
OCS = Optical Cross Section
OGSE = Optical Ground Support Equipment
P_{STC} = Plate for Support and Thermal Control in the SCF
RD = Reference Document

SCF = Satellite/lunar laser ranging Characterization Facility, the OGSE built at LNF by INFN with ETRUSCO
SCF-Test = Set of test procedures to characterize the detailed thermal behavior and optical performance of LRAs with the SCF; BIPR of INFN
SAR = Synthetic Aperture Radar
SCF_LAB = SCF LABoratory, the LNF laboratory consisting of the SCF and of the Clean Room where the SCF is operated
SLR = Satellite Laser Ranging
SW = SoftWare
τ_{CCR} = CCR Thermal Relaxation Time
VA = Velocity Aberration