Italian Association of Aeronautics and Astronautics
XXII Conference
Napoli, 9-12 September 2013

ETRUSCO-2: AN ASI-INFN PROJECT OF TECHNOLOGICAL DEVELOPMENT AND "SCF-TEST" OF GNSS LASER RETROREFLECTOR ARRAYS

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ABSTRACT
The **S**atellite/Lunar/GNSS laser ranging and altimetry **C**haracterization **F**acility (SCF) and SCF-Test are respectively a new test facility and test procedure to characterize and model the detailed thermal behaviour and optical performance of Cube Corner laser Retroreflectors (CCRs) for the Global Navigation Satellite System (GNSS) in laboratory-simulated space conditions, developed by INFN-LNF and in use by NASA, ESA, ASI and ISRO. Our key experimental innovation is the concurrent measurement and modelling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of retroreflector payloads under thermal conditions produced with a close-match solar simulator. The apparatus includes infrared cameras for non-invasive thermometry, thermal control and real-time payload movement to simulate satellite orientation on orbit with respect to solar illumination and laser interrogation beams. These capabilities provide: unique pre-launch performance validation of the space segment of Lunar/Satellite Laser Ranging (LLR/SLR); retroreflector design optimization to maximize ranging efficiency and signal-to-noise conditions in daylight. Extra Terrestrial Ranging to Unified Satellite COnstellations-2 (ETRUSCO-2) project goals will be achieved using the innovative test procedure described in [1].

Keywords: satellite laser ranging, cube corner retroreflectors, Galileo, SCF-Test.

1. INTRODUCTION TO THE SCF_LAB

This paper describes select activities and results on the design, construction and characterization of LRAs presented at the Italian Association of Aeronautics and Astronautics XXII Conference.
The SCF_Lab is dedicated to the characterization and modeling of the space segment of SLR [1][2], LLR [3] and PLRA [3] for industrial and scientific applications (info on different applications can be found at http://www.lnf.infn.it/conference/laser2012/). The two OGSEs of the SCF_Lab are called "SCF" (Satellite/lunar laser ranging Characterization Facility, of INFN property) and "SCF-G" (property of INFN and of the Italian Space Agency, ASI, which doubles the metrology capabilities for GNSS applications). Views of the SCF are shown in Fig. 1, 2 and 3; The SCF is very versatile for its large number of measurement ports (side and back), very long horizontal translations and capabilities for LLR and PLRA CCR payloads. A view of the SCF-G is shown in Fig. 4.

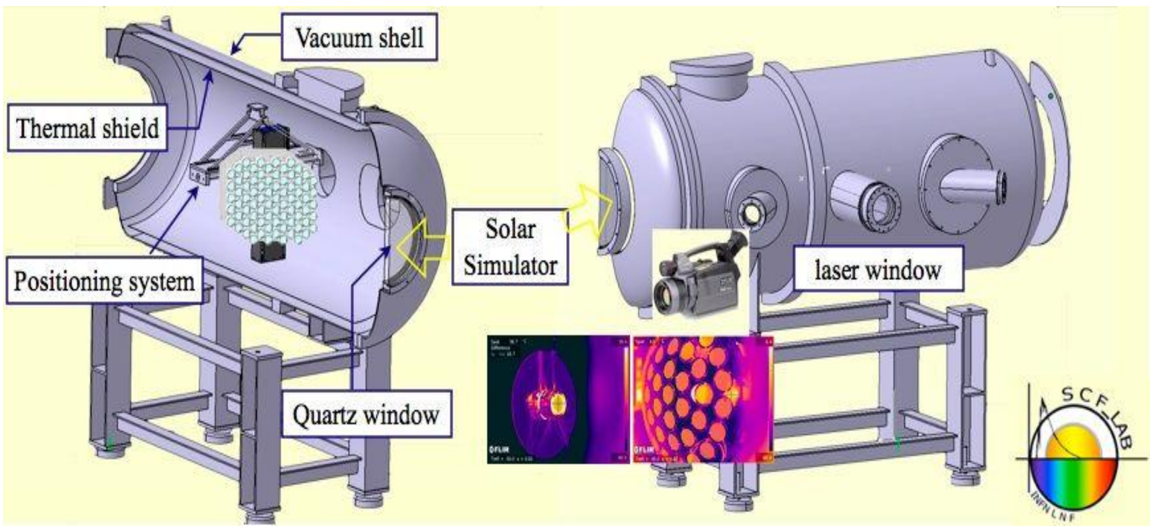

Figure 1. Schematic view of SCF cryostat with: IR pictures of the LAGEOS Sector LRA and of a Galileo IOV CCR under test, IR camera and SCF_Lab logo

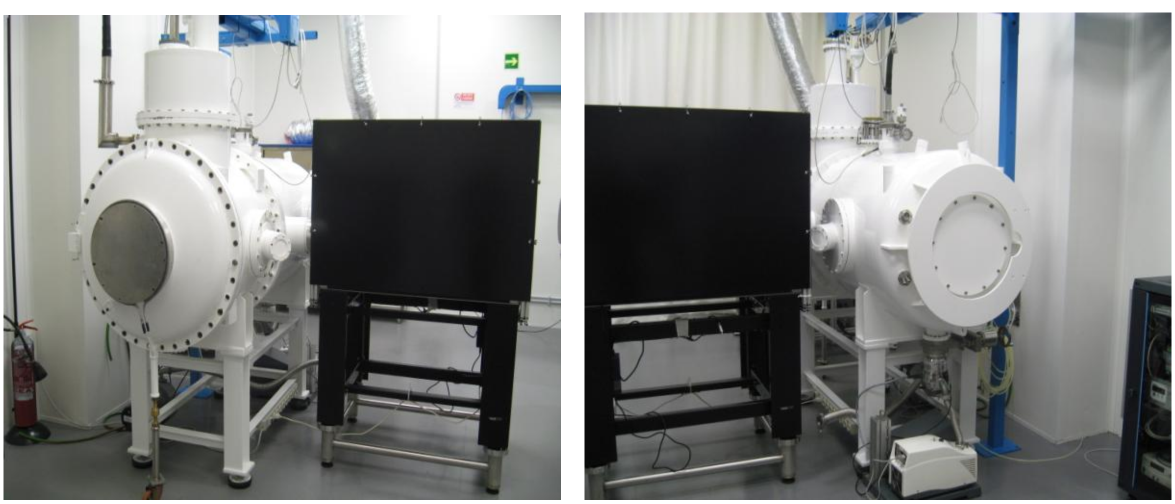

Figure 2. Front and rear view of SCF cryostat. Optical instrumentation is in the black enclosure

The new industry-standard thermal-optical-vacuum test to characterize and model the detailed optical performance and thermal behavior in representative space conditions is called "SCF-Test", and is background intellectual property of INFN [1].

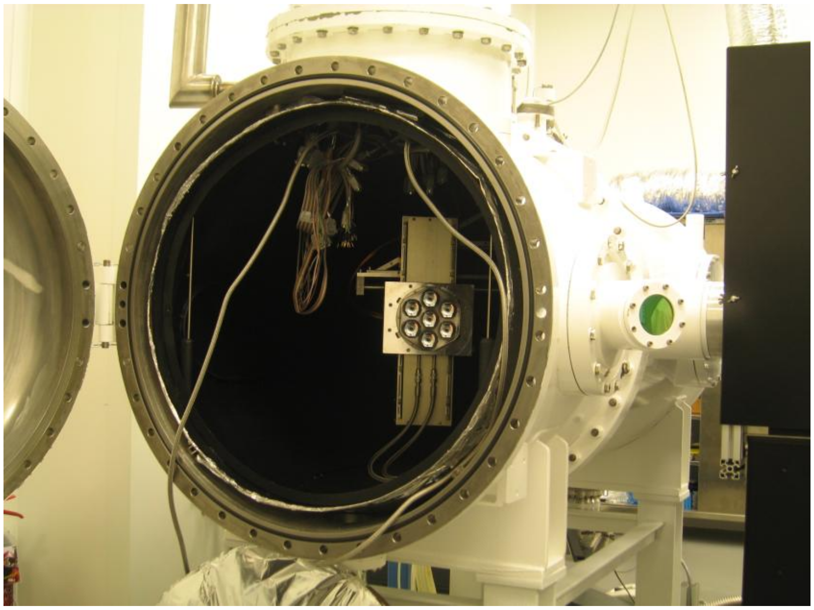

Figure 3. SCF cryostat with hollow-CCR LRA (GRA-H) installed prior to testing. The IR measurement port is shown on the right, with its Ge window visible

Figure 4. SCF-G cryostat with GNSS LRA installed prior to testing. The IR measurement port is shown on the right (Ge window hidden by a black cover)

The WFI on the optical table next to the SCF-G is shown in Fig. 5. This is a dedicated, built-to-order vibration-insensitive and air-turbulence insensitive device to characterize the WFI of CCR kept under representative space conditions during SCF-Tests. This can be done with different laser polarizations (linear and circular). The WFI is used to characterize the optical performance of LRA during SCF-Testing, in addition to separate, independent and redundant FFDP measurements of the CCRs.

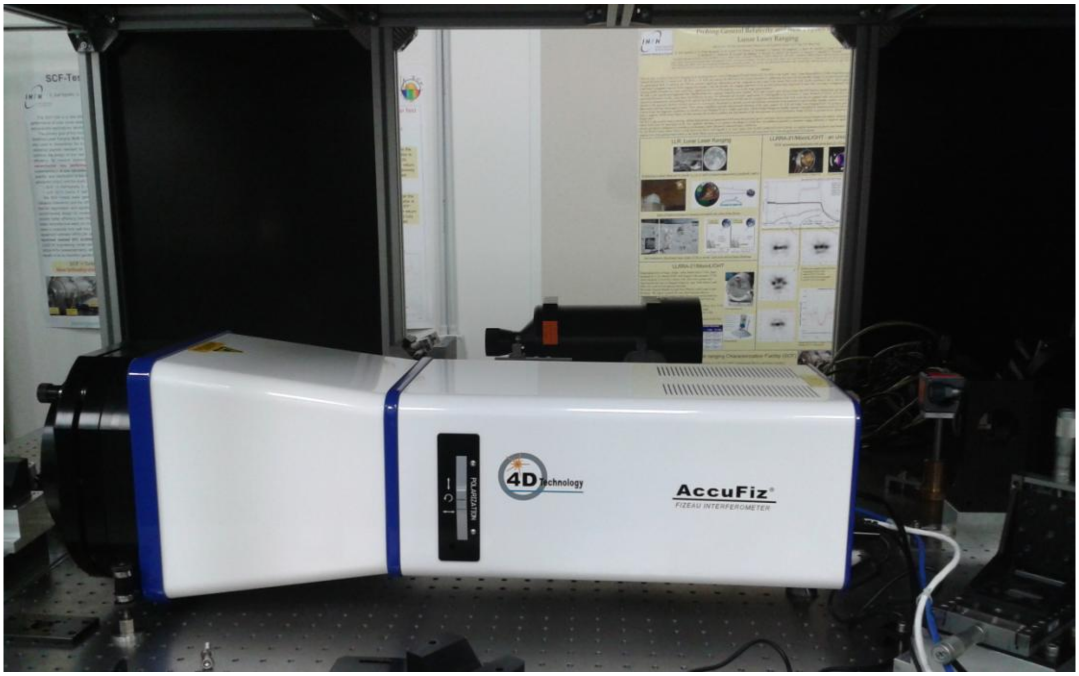

Figure 5. SCF_Lab laser Wavefront Fizeau Interferometer (WFI)

The SCF_Lab banner, with its logo and the INFN-LNF logo is shown in Fig. 6.

Figure 6. SCF_Lab banner

The OGSEs are operated in a clean room of Class 10000 or better shown in Fig. 7.

Figure 7. Left: SCF_Lab ISO 7 Clean Room (SCF cryostat and optical circuit black enclosure on the left; SCF-G optical circuit black enclosure on the right).
Right photo: some young people of the SCF_Lab Team

The primary goal of these OGSEs is to provide critical design and diagnostic capabilities for SLR to Galileo and other GNSS constellations [2], as well as EO missions equipped with LRAs. The capability allows us to optimize LRA designs to maximize ranging efficiency, to improve signal-to-noise conditions in daylight, to provide pre-launch validation of retroreflector performance, as well as to characterize ‘as-built’ LRA payloads. We have SCF-Tested CCR of the following satellites: GPS, GLONASS, GIOVE, Galileo IOV, LAGEOS, LLR, hollow CCRs.

2. WORK PROGRAM OF ASI-INFN R&D ON GALILEO AND GPS-3

We describe some key activities of the ASI-INFN project of technological development ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite Constellations – 2):

- Definition of an improved and enhanced “**SCF-Test/Revision-ETRUSCO-2**”
  - Implementation of advanced and innovative operational procedures for the test of the “*GNSS Critical Orbit*” (**GCO**) developed for Galileo IOV [2]
  - Integration of the Wavefront Fizeau Interferometer (**WFI**)
- Design and construction of a 2nd OGSE optimized for GNSS constellations: **SCF-G**
  - Inherits from SCF, built in part by INFN and in part by SME (G&A Engineering) with INFN supervision and collaboration according to INFN Guidelines.
  - INFN part includes: state-of-art WFI insensitive to vibrations and air turbulence; 2nd, new solar simulator.
- Integration of SCF-G with SCF_Lab infrastructure.
- Reduced-size prototype GNSS Retroreflector Array built with Hollow technology (**GRA-H**) according to INFN Guidelines
  - Inherits from R&D done with GSFC, built by SME (Kayser Italia) with INFN supervision and collaboration
  - 7 hollow CCRs, 6 on a ring and one in the center
  - Characterized with SCF and thermo-structural modeling

- Full-size prototype GNSS Retroreflector Array (**GRA**) for Galileo & GPS-3 built according to INFN Guidelines.
  - Inherits from LAGEOS, built by SME (Kayser Italia) with INFN supervision and collaboration
  - 55 CCRs of solid retroreflector technology
  - To be characterized with the SCF-G according to the new SCF-Test/Revision-ETRUSCO-2

3. LAGEOS

Uncoated retroreflectors are deployed on the SLR reference payload standard of the ILRS: LAGEOS (LAser GEOdynamics Satellite). Similarly, the uncoated Apollo CCRs are the reference standard for LLR. Uncoated retroreflectors with properly insulated mounting (like Apollo and LAGEOS) can minimize thermal degradation and significantly increase optical performance and, as such, are emerging as the recommended design for GNSS satellites. LAGEOS is a satellite designed by NASA and launched in 1976. It is a passive sphere with a diameter of 60 cm, mainly made of Aluminum, covered by 426 uncoated CCRs. Since its launch the satellite provided important information on Earth's shape, gravitational field and tectonic plate movements, but, most important, due to its high mass-to-area ratio and orbit stability, it gives a reference for the Earth's center of mass (geocenter), along with other cannonball SLR targets.
Therefore, in order to "calibrate" our SCF-Test, in 2009 we tested an engineering model of the LAGEOS satellite (the "Sector"), lent by NASA-GSFC. The Sector is shown in Fig. 8: photo taken at GSFC (left); Sector in the SCF, controlled in temperature by an interface Cu plate, with laser illuminating one CCR (right).

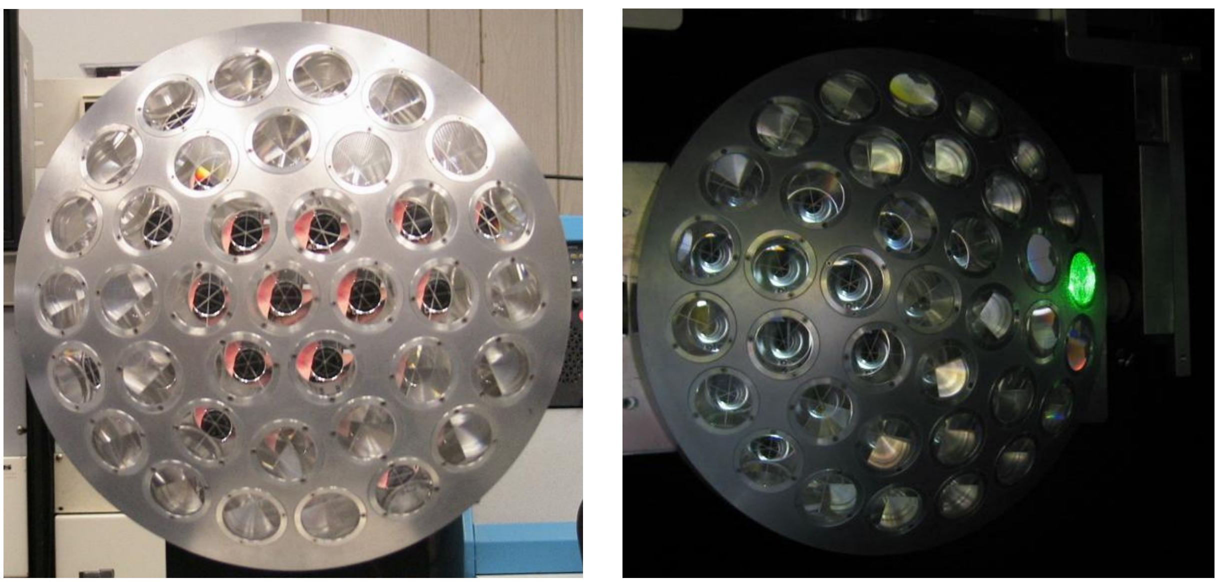

Figure 8. LAGEOS Sector at NASA-GSFC and at the SCF_Lab

Two thermal and optical measurements of the Sector are shown in Fig. 9: IR thermogram (bottom left); CCR FFDP in velocity aberration plane in microrad units (bottom right).

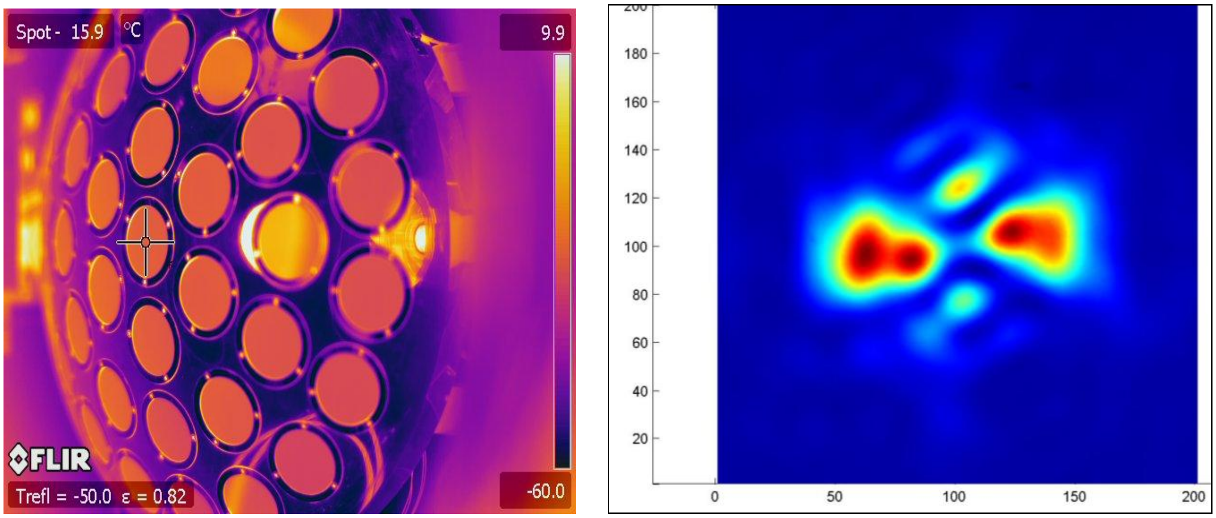

Figure 9. LAGEOS Sector measurement at the SCF_Lab

4. GPS-2 FLIGHT LRA PAYLOAD

A flight model LRA of the GPS-2 constellation was lent by the University of Maryland to INFN-LNF for SCF-Testing and to measure its nominal optical ('lidar') cross section [1]. It is a rectangular array of 32 CCRs positioned on an aluminum tray of 239 mm length, 194 mm width and 1.27 kg weight, shown in Fig. 10.

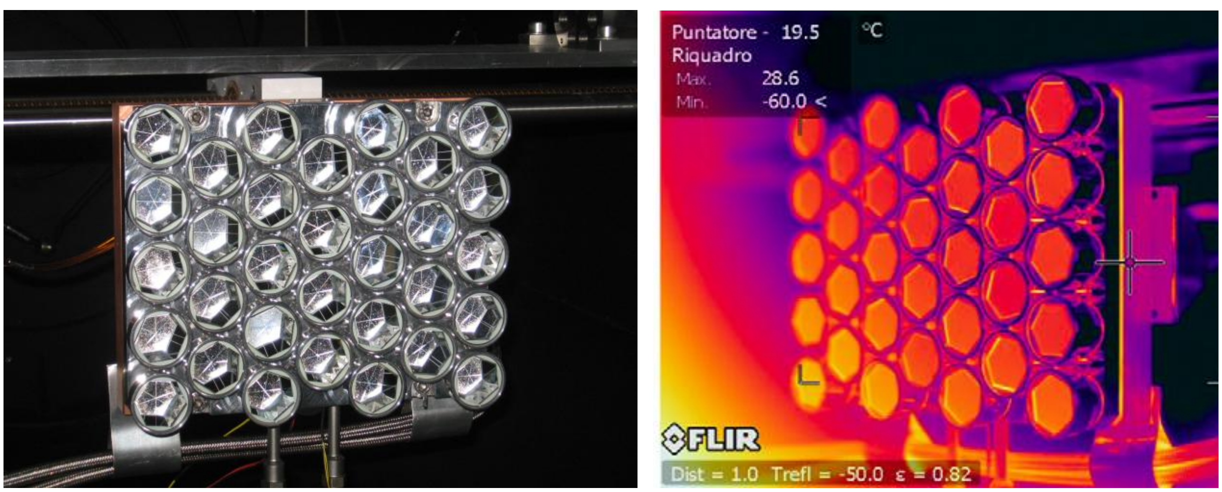

Figure 10. Third GPS flight array inside the SCF (left) and an IR thermogram taken during Sun Simulator illumination (right).

5. GALILEO IN-ORBIT VALIDATION (IOV) RETROREFLECTOR

In 2010 INFN performed an extensive SCF-Test campaign requested by ESA on a prototype Galileo IOV retroreflector. This is a fused silica uncoated CCRs, deployed in planar arrays of 84 units on the four Galileo IOV. This is shown in Fig. 10: front view (bottom left); setup inside SCF for GCO test (top left); IR thermogram (top left). IOV engineering model LRA being built by LNF for further SCF-Testing (bottom right).

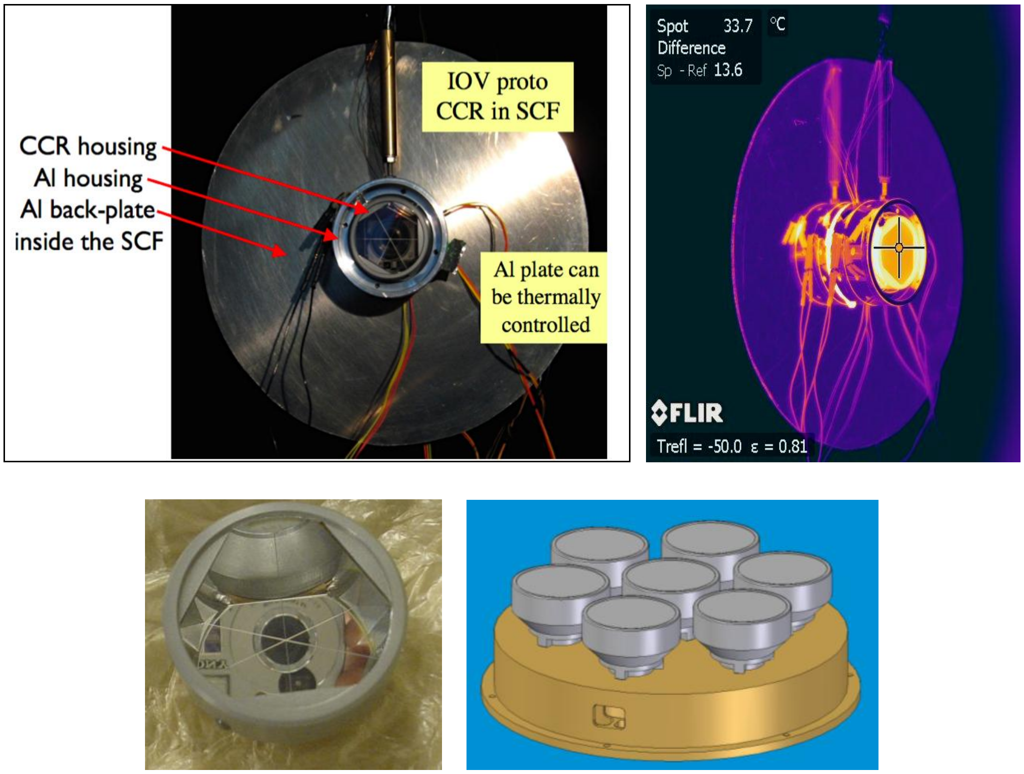

Figure 10. Galileo IOV CCR characterized at the SCF_Lab

INFN signed a contract with ESA called *Thermo-optical vacuum testing of Galileo IOV laser retro-reflectors* (kick-off meeting 15th October 2013). The contract will be one year long and during this period INFN will test the 7 IOV CCRs, showen in Figure 10, and will build the mounting structure of array. Then ESA provides us with the flight model laser retroreflector array of 4 Galileo IOV satellites.

Moreover we refined the SCF-Test introducing the GCO (GNSS Critical Orbit). Galileo satellites have a quasi-circular orbit with orbital period of about 14 hrs. We simulated half of the orbit, from the moment in which sunrays rise above the CCR front face till they fall on the other side for about 7 hrs. SCF-Test results are in [2]. This is shown in Fig. 11.

In 2007 and 2008 we SCF-Tested retroreflectors originally adopted by GLONASS. They are Al back-coated CCRs, with hexagonal front face of ~26mm of inscribed circle diameter. The CCR is inserted into a polished Aluminum housing screwed into the Aluminum baseplate of the LRA. LRAs of 32 GLONASS-type CCRs (identical to the flight LRA characterized at the SCF_LAB) were deployed on the GPS-35 and GPS-36 satellites. GLONASS LRAs were deployed also on GIOVE-A and GIOVE-B.

SCF-Test results reported in [1] have shown that the GLONASS suffers from sever degradation of the optical performance when operated in space conditions. Form GLONASS-115 this Al back-coated CCR has been abandoned by modern GNSS (including Galileo IOV) in favor of uncoated CCRs.

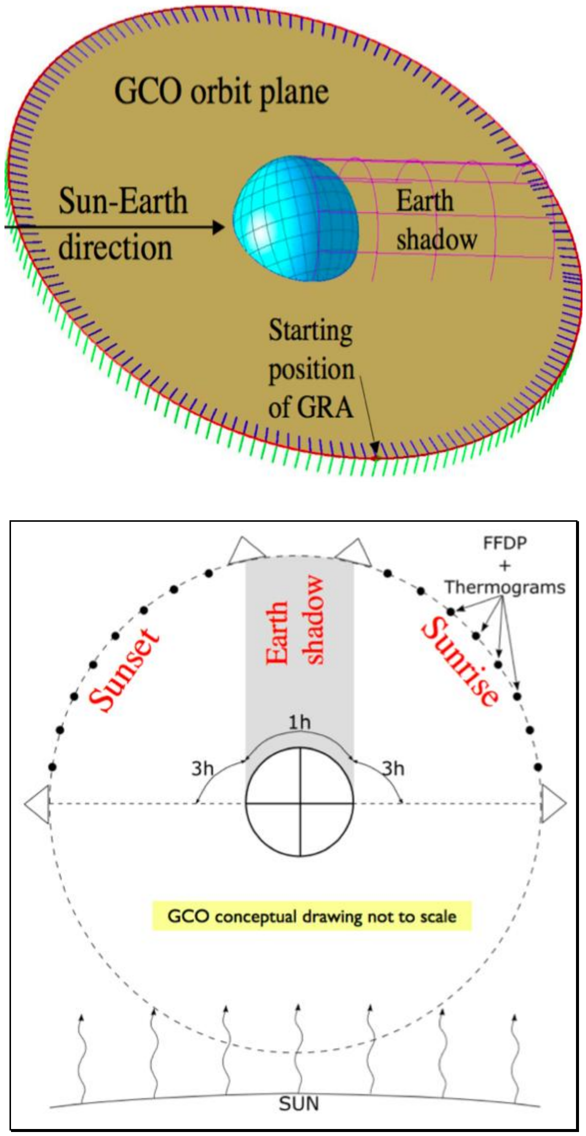

Figure 11. GNSS Critical Orbit (GCO) in space (top); GCO SCF-Test concept with measurement sequence & solar simulator illumination (bottom)

6. GRA-H AND GRA

To verify the readiness of hollow retroreflectors for LRAs, we deigned and built the GRA-H as a prototype of reduced size, made of 7 hollow CCRs of 38.1 mm (1.5") optical clear aperture, purchased from PLX, Inc. Due to ITAR restrictions, only CCRs with zero values of the dihedral angle offsets were available for the ETRUSCO-2 project. All CCRs have reflecting faces made of a Pyrex substrate coated with a high reflectivity film. Two sets of retroreflectors were procured, with Aluminum and Silver coatings. An Invar foot mount holds one of the reflecting faces onto which the others are glued. The GRA-H has been extensively characterized with the SCF (see Fig. 12) and the results reported at http://www.lnf.infn.it/conference/laser2012/).

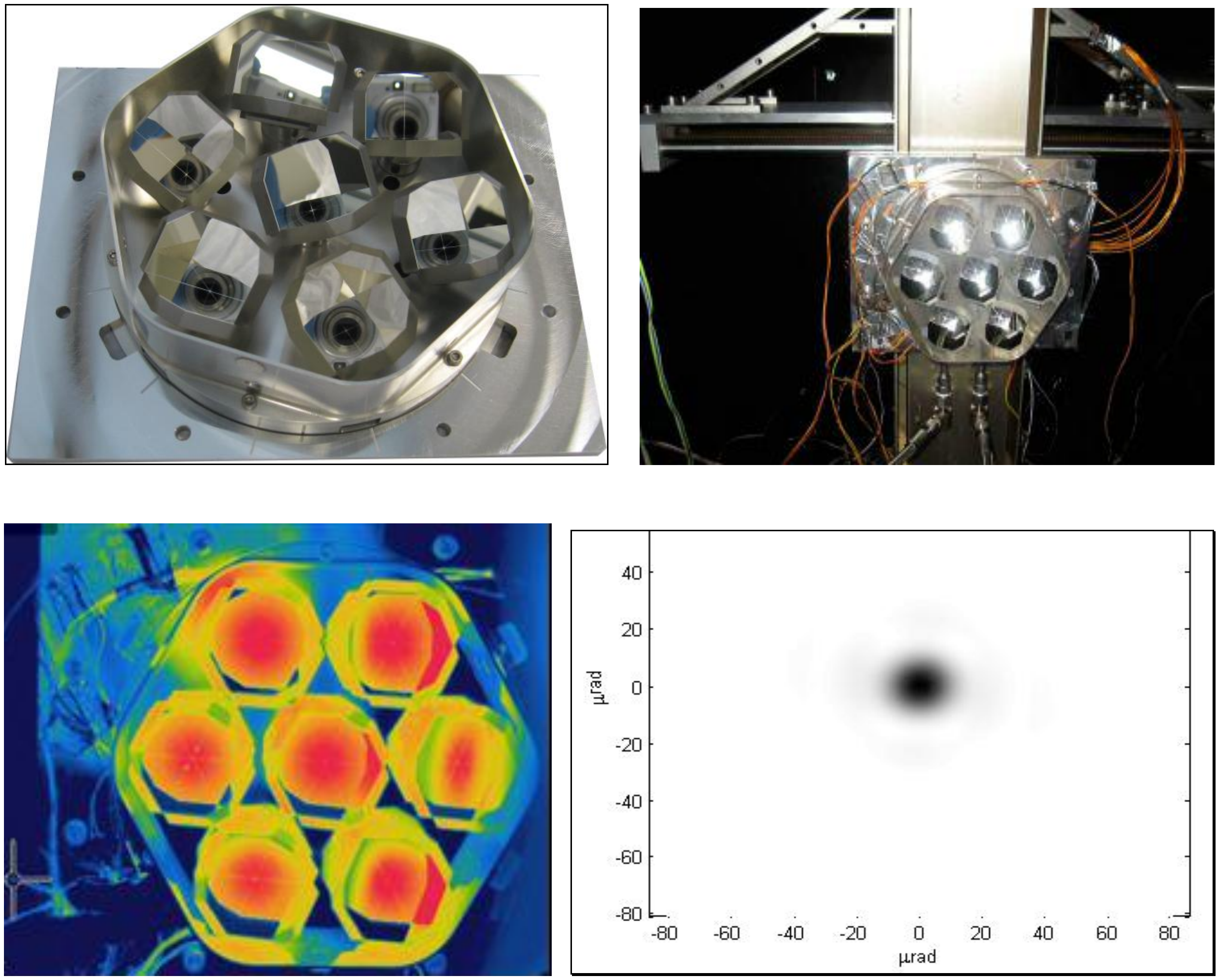

Figure 12. GRA-H fully assembled (top left), inside the SCF with PT100 temperature probe on each retroreflector (top right); IR picture during SS illumination (bottom left); FFDP of one of its CCRs

Since the performance of the GRA-H hollow retroreflectors was not found satisfactory, as foreseen by the ETRUSCO-2 project guidelines, we designed and built the GRA using the consolidated fused silica retroreflector technology space-qualified first with Apollo LRAs and later with LAGEOS. Some of the criteria used in the GRA design are the ones endorsed by ILRS and reported in [1]. The GRA is shown inside the SCF-G in Fig. 13.

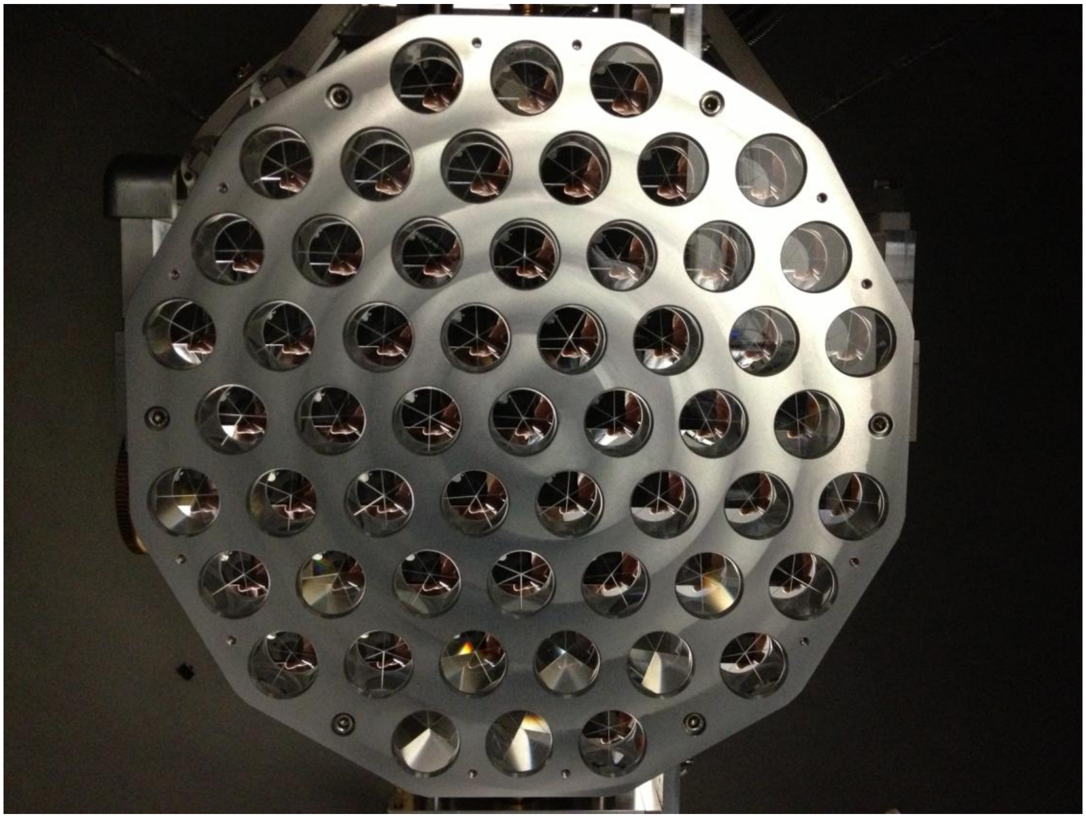

Figure 13. GRA with all its 55 uncoated CCRs mounted installed on the roto-translation positioning and thermal control system inside the SCF-G

The GRA will be characterized with the SCF-G, according to the procedures foreseen by the SCF-Test/Revision-ETRUSCO-2, which include investigation of the GRA optical performance and thermal behavior along the GNSS Critical Orbit, under exposure to the solar simulator illumination. The GRA optical performance will be assessed in terms of FFDPs and of the WFIs of its retroreflectors. The thermal behavior will determined with IR thermometry and contact probes.

6. **CONCLUDING REMARKS**

At the SCF_Lab we have developed unique procedures for the characterization of the performance of LRAs for a variety of GNSS and lunar laser ranging missions and for LAGEOS, that is a reference ILRS payload standard.

These are based on specialized instrumentation [1] [2] and on the measurement of ILRS-standard optical and temperature LRA observables and on reference and/or representative orbit configurations (Default 'Earth-eclipse' SCF-Test [1], GCO SCF-Test [2], lunar day tests [3]).

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/).

6. ACKNOWLEDGEMENTS AND REFERENCES

We thank the Italian INFN-CSN5, which is supporting the SCF_Lab since 2005 (with funding 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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