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

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The SCF and SCF-Test are a new test facility and test procedure to characterize and model the detailed thermal behaviour and optical performance of cube corner laser retroreflectors for the GNSS (Global Navigation Satellite System) in laboratory-simulated space conditions, developed by INFN-LNF and in use by NASA, ESA, ASI and ISRO. Under ASI-INFN contract n. I/077/09/0 ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite COnstellations-2) we have built and we are operating a new experimental apparatus (our second), the Satellite laser ranging (SLR) Characterization Facility optimized for Galileo and the GPS-3 (SCF-G) to characterize and model the detailed thermal behaviour and the optical performance of cube corner GNSS Retroreflector Arrays (GRAs). 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. Integrated thermal and optical modelling of retroreflectors on GNSS orbits, tuned to SCF-Test data, also performed. These capabilities provide: unique pre-launch performance validation of the space segment of LLR/SLR (Lunar/Satellite Laser Ranging); retrorereflector design optimization to maximize ranging efficiency and signal-to-noise conditions in daylight. Results of the SCF-Test of our CCR payload will be presented. We will describe the addition of a vibration-insensitive CCR optical Wave front Fizeau Interferogram (WFI) to be used concurrently to CCR FFDP/temperature measurements in the framework of ETRUSCO-2. The SCF-G, is optimized for GNSS and we have built and tested a standard GNSS Retroreflector Array (GRA) of uncoated solid CCRs and an innovative prototype GRA of Hollow CCRs (GRA-H). We have worked on the SCF-Test of the first four Galileo In-Orbit Validation (IOV) satellites directly for ESA [2]; while for the GPS-3, a collaborative effort with the US GNSS community is in preparation. We will also SCF-Test the retroreflector array of the Indian Regional Navigation Satellite System. ETRUSCO-2 goals will be achieved using the innovative test procedure described in [1], the SCF-Test, and its evolution and refinement outlined here, the SCF-Test/Revision-ETRUSCO-2. The existing SCF facility and the new SCF-G are operated in an infrastructure owned by INFN-LNF, the SCFLAB; which includes a dedicated cleanroom of class 10000 or better.

I. ETRUSCO-2

This project is the continuation and evolution of an INFN R&D experiment, ETRUSCO carried out in 2006-2010, which concluded with a comprehensive, refereed publication ([1], the published proceedings of the 2nd Int. Colloquium on Galileo Science held in Padua, Italy, in 2009), where the SCF-Test is fully described and the main experimental results are reported. While ETRUSCO-2 is a full-blown, co-funded ASI-INFN project of technological development, for which INFN is the Prime Contractor, the SCF-Test is background intellectual property of INFN.

The project acronym affirms the importance of the tight integration ('unification') of GNSS and Satellite/Lunar Laser Ranging (SLR/LLR) geodesy techniques, which must start from an optimized, integrated space segment. SLR and LLR are unambiguous time of flight (and distance) measurements with short laser pulses to arrays of cube corner laser retroreflectors (CCRs). They provide ground-to-space normal points with mm-level precision, and orbits with cm-level precision. SLR/LLR provides absolute positioning accuracy, because they give the metrological definition of the Earth center of mass (geocenter) and, with other space geodesy techniques, define the absolute scale of length in Earth orbits [1].

In 2011 INFN-LNF has completed the construction of a new Clean Room of class 10,000 (class ISO 7) or better of about 85 m2, now operational, for the existing SCF (Satellite/lunar laser ranging Characterization Facility, described in detail in [1] and in the Appendix to this paper). Based on the experience made with the SCF, the "Satellite laser ranging Characterization Facility optimized for Galileo and the GPS-3", SCF-G, has been built and has been commisioned in the first half of 2012 in the same Clean Room infrastructure. Additional laboratory space is also in use. The SCF is being further optimized for LLR [3] and for (inter)planetary applications through a dedicated INFN R&D experiment, MoonLIGHT-ILN (Moon Laser Instrumentation for General relativity High-accuracy Tests-International Lunar Network). The ILN is a scientific concept (see http://iln.arc.nasa.gov/) developed for the realization of a Lunar Geophysical Network (LGN).

The primary goal of these unique, doubled and extended retroreflector metrology capabilities (SCF plus SCF-G) is to provide critical diagnostic, optimization and validation tools for SLR to all flagship GNSS programmes (not only Galileo and GPS-3) and for LLR. The capability will allow us to optimize GRA (GNSS laser Retroreflector Arrays) designs to maximize ranging efficiency, to improve signal-to-noise conditions in daylight, to provide pre-launch validation of retroreflector performance under accurately laboratory-simulated space conditions, as well as to characterize 'as-built' payloads. Implementation of optimized GRA designs will help to improve GNSS orbits, which will then increase the accuracy, stability, and distribution of the International Terrestrial Reference Frame (ITRF) [4], to provide better definition of the geocenter (ITRF origin) and the scale (ITRF unit of length).

An innovative prototype GRA of Hollow retroreflectors (GRA-H), made of 7 hollow cubes, one in the center and six in circle around it, has been built and tested at the SCF. Results are beeing processed and will be published shortly. This work inherits from a previous collaborative effort between INFN-LNF, GSFC and CfA. In fact, with ETRUSCO a hollow reflector prototype by NASA-GSFC was tested in 2010 and results recently reported in [2]. Comparisons between these test measurements and thermo-structural simulations are in [5] and [6]. Another hollow reflector development that could benefit from an SCF-Test is in [7]. Depending on the behaviour of the GRA-H, a full-size GRA will be built with hollow or with the solid, uncoated fused silica retroreflector technology. This GRA will be characterized with the SCF-G in the INFN-LNF Clean Room, using the new SCF-Test/Revision-ETRUSCO-2 described in this paper.

ETRUSCO-2 hardware construction and dissemination activities are carried out with Italian sub-contracting Small-Medium Enterprises. Scientific studies of space geodesy and general relativity are performed in collaboration with ASI-CGS and the University of Bologna and will be reported in the future.

II. ETRUSCO RESULTS ON GPS/GLONASS/GIOVE AND LAGEOS

We SCF-Tested older generation, Al back-coated fused silica retroreflectors of the satellites GIOVE-A and -B and the satellites GPS-35 and -36 designs (see Fig. 1).

Fig. 1: GPS-2 flight array property of the University of Maryland SCF-Tested in Frascati (Rome), Italy

The test of the GPS array of Fig. 1 was done exposing it to heating with a Sun Simulator (SS) for 1 hour, with the array bulk temperature, TB, controlled at 300 K. we report results for one CCR of the flight array. The temperature increase of this CCR is in Fig. 2: from an exponential fit to the curve we get: a CCR thermal relaxation time $\tau CCR = (700 \pm 90)$ sec and a temperature change $\Delta TCCR = (21.5 \pm 0.6)$ K. The plot inset in Fig.2 shows the optical Far Field Diffraction Pattern (FFDP) intensity after ~1 hour: the optical response is low, completely degraded. Fig. 3 reports the CCR FFDP intensity vs. time, AFTER 1 hour of SS heating: in this plot time = 0 is when the SS is turned off and the FFDP is maximally degraded as in the inset of Fig. 2. For t > 0 the CCR cools down and the FFDP degradation (~87%) is recovered. This effect has been measured in the SCF laboratory at INFN-LNF for the very first time.

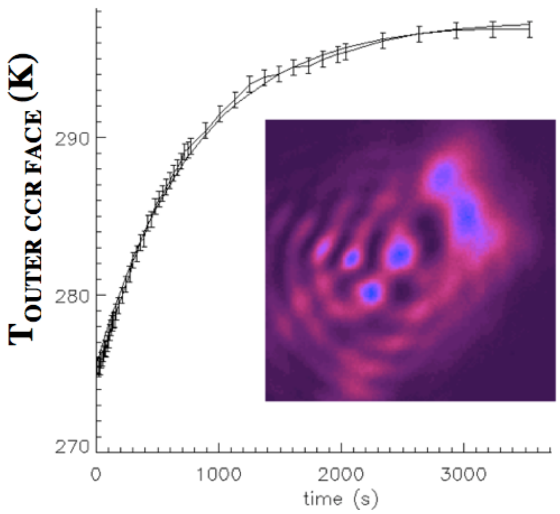

Fig. 2: GPS-2 flight CCR: heating during exposure to the SS. Inset: FFDP at t~3000

The FFDP thermal degradation is due to the CCR Al-coating and non-insulated mounting scheme in the array [1]. This behaviour follows τ_{CCR}. Fig. 4 shows the CCR cooldown: the exponential fit to the curve gives the same τ_{CCR} and ΔT_{CCR} of Fig. 2.

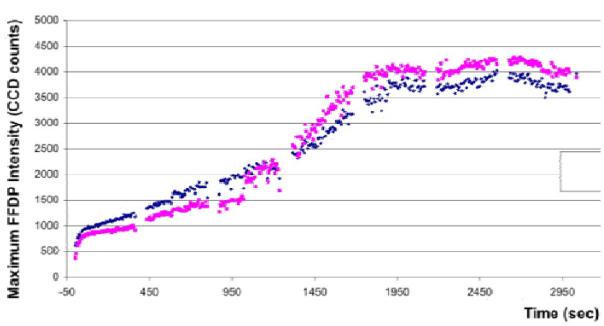

Fig. 3: GPS-2 flight CCR: FFDP intensity recovery when SS heating is turned off at t = 0

Fig. 5 describes how the distance between the FFDP laser return peaks recovers back to the nominal GNSS velocity aberration (45-50 µrad). Fig. 3, 4 and 5 are taken concurrently during the CCR cooldown, with the SS turned off. Fig. 2, instead, is taken during the previous 1 hour with the SS heating the CCR. SCF-Test of a GLONASS/GIOVE prototype built in 2007 is reported in [1] and gives similar results.

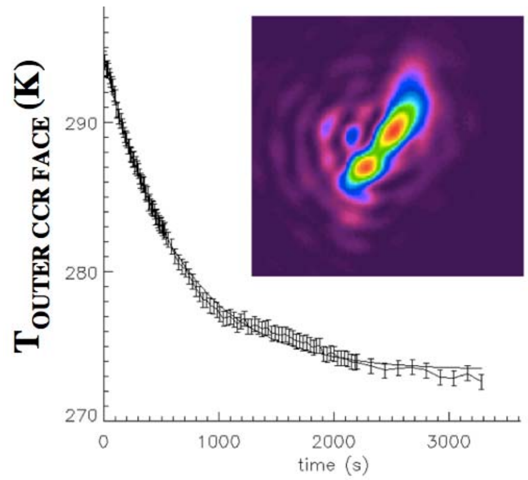

Fig. 4: GPS-2 flight CCR: thermal relaxation after degradation due to SS heating. Inset: FFDP at t~3000, with peaks at the nominal 45-50 µrad distance

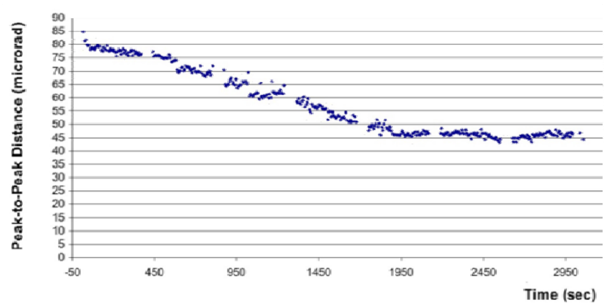

Fig. 5: GPS-2 flight CCR: recovery of FFDP peak-to-peak distance up to the nominal velocity aberration of 45-50µrad, after degradation due to SS heating

The SLR reference payload standard, LAGEOS (LAser GEOdynamics Satellite), was SCF-Tested for the first time ever [1] [2], using the “Sector” engineering model (see Fig. 6), with its bulk Al mass thermally controlled at T_B = 300 K. LAGEOS inherits the solid, uncoated CCR technology of Apollo [2]. Similarly to Fig. 3, Fig. 7 shows the LAGEOS CCR FFDP intensity vs. time, after 3 hours of SS heating: the thermal degradation of LAGEOS is minimal compared to the ~87% measured for the GPS/GLONASS/GIOVE CCRs in the SCF-Test at T_B=300 K.

Uncoated retroreflectors with proper mounting can minimize thermal degradation and significantly increase the optical performance, and as such, are emerging as the design recommended in [1] by the International Laser Ranging Service (ILRS [8]) for modern GNSS satellites: COMPASS, Galileo IOV, QZSS, IRNSS.

Uncoated CCRs provide better efficiency than those on GPS and GIOVE, including better daylight ranging performance. However, except for the IOV prototype CCR reported in the following, these new uncoated retroreflectors were not characterized in the laboratory under space conditions prior to launch, so we have no basis to evaluate how well they were optimized for future GNSS satellites. Al-coated reflectors have been retired also from GLONASS (GLONASS-115 and above), where they were first introduced in the 1980s.

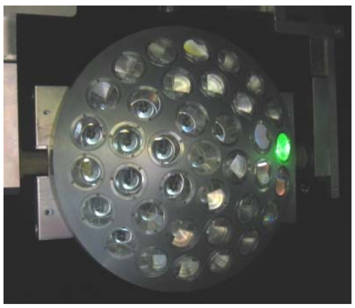

Fig. 6: LAGEOS Sector engineering model property of NASA-GSFC SCF-Tested in Frascati

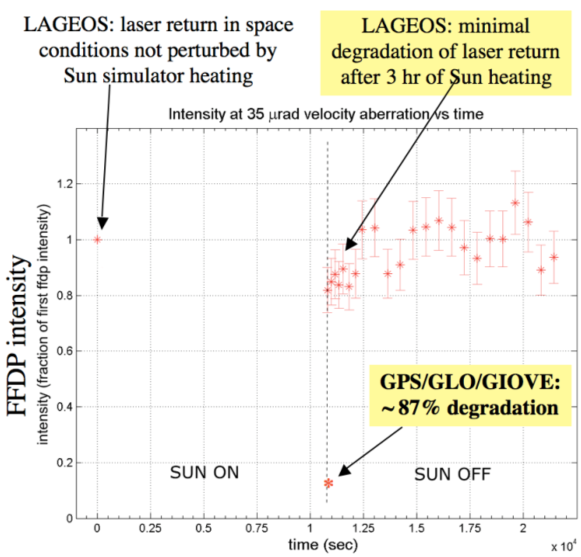

Fig. 7: LAGEOS CCR: FFDP relative intensity after degradation due to SS heating. Shown is also the 87% GPS FFDP degradation reported at t~3000 in Fig. 2

The thermal heating and cooling curves of the LAGEOS CCR are shown in Fig. 8. Note that the vertical scale in Fig. 8 is not shown because the full τ_{CCR} data are not published yet. However, we find the LAGEOS τ_{CCR} is significantly longer than for GPS even after properly scaling the measured τ_{CCR} for the different volumes of GPS and LAGEOS CCRs. We also find the LAGEOS ΔT_{CCR} comparatively lower than for GPS.

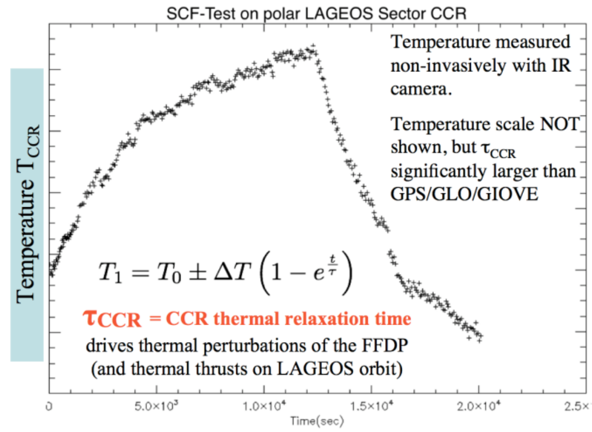

Fig. 8: LAGEOS CCR heating and cooling curves. Horizontal scale is 0-2.5×10^4 sec

Varying the Sector bulk temperature control in the range T_B = (280-320) K we measured that τ_{CCR} varies proportionally to $1/T_B^3$ [2]. This indicates that the heat exchange of the LAGEOS CCR with its mounting elements inside the bulk Al is mainly radiative, with an optimized mount conductance. This is confirmed by detailed thermal/orbital simulations, tuned to LAGEOS SCF-Test data and to thermal calibrations of the SCF facility. The above measurements indicate that the GPS/GLONASS/GIOVE CCR mounting scheme is less thermally optimized than for LAGEOS/Apollo.

More LAGEOS SCF-Test results are described in [2].

III SCF-TEST/REVISION-ETRUSCO-2

This evolution of the test inherits from [1] the following SLR/LLR Key Performance Indicators (KPIs): (1) τ_{CCR} and the thermal relaxations of CCR mounting elements; (2) FFDP. We can also measure the in-air, isothermal optical cross section of a full array, like we did for the GPS-2 flight array (see Appendix). The novel KPIs are: (3) the thermal-optical conditions experienced by reflectors during a GNSS Critical half-Orbit (GCO, see Fig. 9 and Fig. 10); (4) the reflector Wavefront Interferogram (WI) in space conditions. Optionally, we provide software modelling of the KPIs. The GCO test has been developed with ETRUSCO for the IOVs; the WI for GNSS is under development with ETRUSCO-2. 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. 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 reversed by 180 degrees. During the GCO, the GRA is also periodically rotated towards the infrared and optical windows of the cryostat (see Appendix) 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 behaviour of the GRA along the GCO.

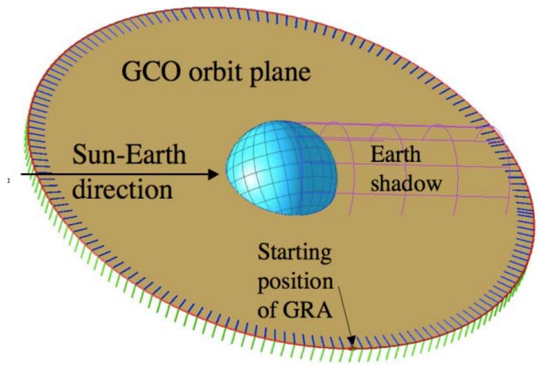

Fig. 9: Drawing of the GNSS Critical half-Orbit (GCO) test of the SCF-Test/Revision-ETRUSCO-2

With sunrise-eclipse-sunset (Fig. 10) the GCO probes the most critical features of the CCR thermal and optical behaviour. In particular, in the SCF an uncoated retroreflector can be set with one physical edge oriented along the GCO plane such that, for example, at sunset there is loss of total internal reflection. This occurs if sunrays hit the CCR at angles >17^{o} with respect to the normal to its face (**"optical breakthrough (BT)"**; Fig. 11): the sun heats directly CCR cavity and mounting elements, causing large FFDP thermal degradation.
The GCO test is more realistic and sensitive than the original SCF-Test with SS illumination of the CCR at normal incidence. The latter probes thermal conditions qualitatively similar to those occurring before/after the entrance of the satellite into the Earth shadow.

IV PROTOTYPE GALILEO IOV CCR: SCF-TEST OF THE GALILEO CRITICAL HALF-ORBIT

The GCO test has been successfully applied to a prototype Galileo IOV reflector, which INFN-LNF was provided with by ESA. These preliminary results are intellectual property of INFN, presented with ESA's authorization. The IOV reflector is uncoated and it has 33mm diameter (see Fig. 11). It is mounted in a separate cavity screwed on an Al support structure just like the CCRs of GPS/GLONASS/GIOVE, and unlike LAGEOS and Apollo CCRs, which are embedded in unibody Al arrays. Fig. 12 shows a qualitative picture of Galileo CCR arrays taken from the 2008 ESA specification document available publicly on the ILRS web site at: http://ilrs.gsfc.nasa.gov/docs/ESA-EUING-TN-10206_Issue_3.2.pdf.

In the SCF-Test the GCO is the horizontal plane; the laser polarization for FFDP measurements is also horizontal. Therefore, during the GCO, the IOV CCR is rotated around the vertical in 7 hours. One CCR physical edge is oriented horizontally such the optical BT occurs only during sunset (and not during sunrise).

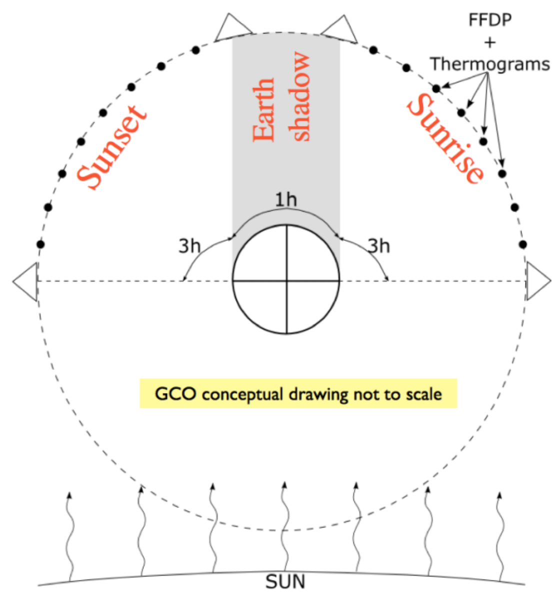

Fig. 10: Galileo GCO: Sunrise (3 hr)–eclipse (1 hr)–sunset (3 hr) sequence and concurrent measurements

Fig. 11: Uncoated IOV CCR. Left: camera taking photo at angle ~17o is still barely visible. Right: at angle >17o camera is not visible due to optical BT

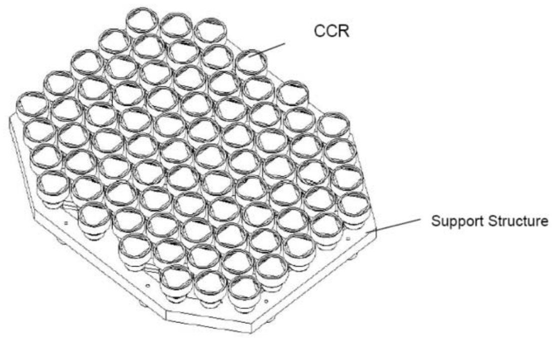

Fig. 12: Picture of Galileo CCR arrays from the ILRS web site, shown for qualitative purposes only. The actual IOV and FOC arrays can be different

Fig. 13 shows the CCR package used for the SCF-Test, to simulate the CCR thermal excursion on-board the IOV indicated by ESA. The package consists of:

- CCR unit in its mounting cavity, as in Fig. 11
- External, auxiliary Al housing cavity, in which the CCR is kept to simulate its conditions in the IOV array, surrounded by other CCRs. This housing can be thermally controlled and was suspend from the positioning system with a G10 screw.
- Al back-plate to simulate the array plate and to perform thermal control of the package.

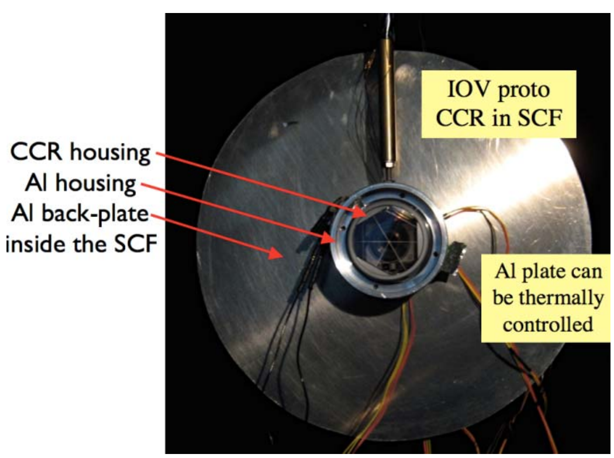

Fig. 13: IOV CCR inside the SCF for the GCO test

The redundant thermal control on the Al housing and the Al back-plate were used as safety to prevent CCR from getting too cold, below the lowest operating temperature indicated by ESA. In the GCO SCF-Test, however, the temperature of the CCR package was not controlled, as it is not in orbit. When the CCR temperature reached 244 K, we started simulation the GCO. Fig. 14 shows the temperatures measured during the GCO: "Bottom/Top CCR housing" are temperatures taken with probes on two outside points of the CCR unit; "Bottom/Top Al housing" and "Back plate" are taken on two points of the auxiliary Al cavity an on the plate, respectively. "CCR face" is measured with the IR camera. Note the large temperature excursion, >100K.

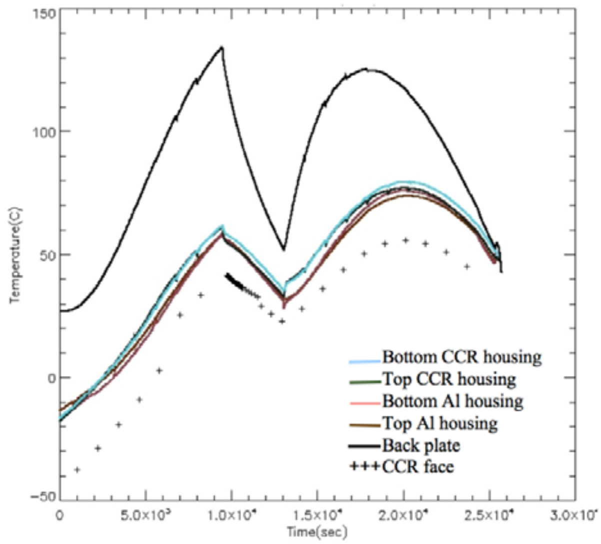

Fig. 14: Temperatures of the IOV CCR package during the GCO. The horizontal scale is 0-$3x10^4$ sec

FFDP intensities are presented as relative fractions of the FFDP acquired in approximately stationary conditions at the beginning of the test, taken as a reference. FFDP relative intensities are averaged around 24 μrad (design velocity aberration for Galileo IOV CCRs, according to info from ESA) and in the 22÷26 μrad range of velocity aberration. We estimated a 10% error on average relative FFDP intensities, due to instruments, statistics and residual systematic fluctuations of the SCF environment. Fig. 15 shows the variation of FFDP average intensity at 24 μrad (top plot) and in the (22-26) μrad range (bottom plot). Fig. 16 shows a selection of FFDPs at 24 μrad, during sunrise.

The IOV FFDP degradation for 0o sun inclination (also from other specific SCF-Tests not reported here) is ~25%. The GPS/GLON/GIOVE FFDP degradation for 0o sun inclination is ~ 87%, much larger than for IOV.

Averaging over the whole GCO, which is a half-orbit, the measured IOV CCR prototype FFDP degradation of is ~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.

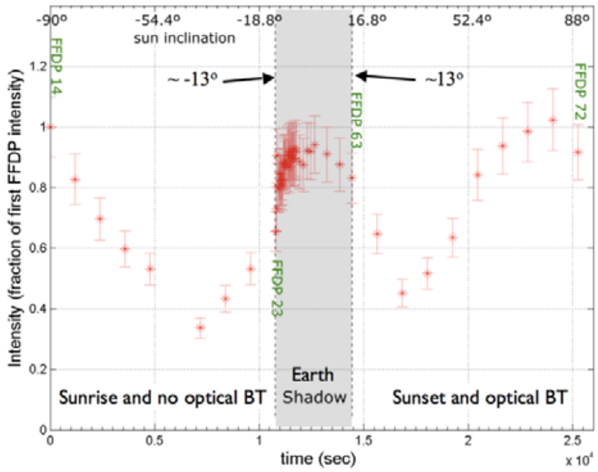

Fig. 15: FFDP relative intensity of the IOV CCR during the GCO at 24μrad (top plot) and in the (22-26) μrad range (bottom plot) of the velocity aberration. The horizontal scales are 0-2.7x10^4 sec

We call this effect "thermal breakthrough". Thermal BT could be due to an IOV CCR mounting scheme with relatively large thermal conductance. This hypothesis has been studied with the τCCR measurements reported in the following subsection.

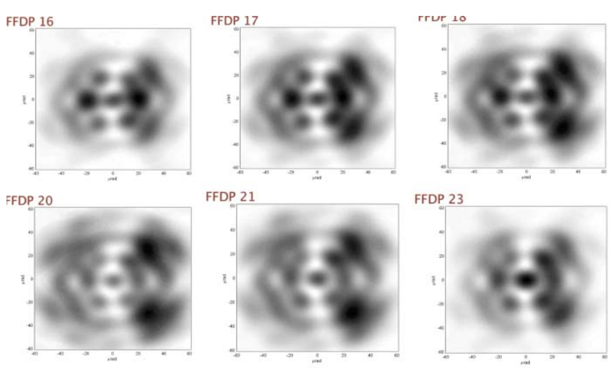

Fig. 16: IOV CCR: FFDP relative intensity during the GCO. FFDP scales are [-60,+60] μrad

4.1. Prototype Galileo IOV CCR: measurement of the thermal relaxation time

The auxiliary Al housing was controlled in temperature at TB = 370 K and then at TB = 310 K. The Al back-plate was not used, because not needed, since Al housing was held at fixed temperatures. The CCR was sunlit by the SS at 0o inclination (orthogonally to its front face). Fig. 17 shows the IOV τCCR at 310 K (top plot) and at 370 K (bottom plot).

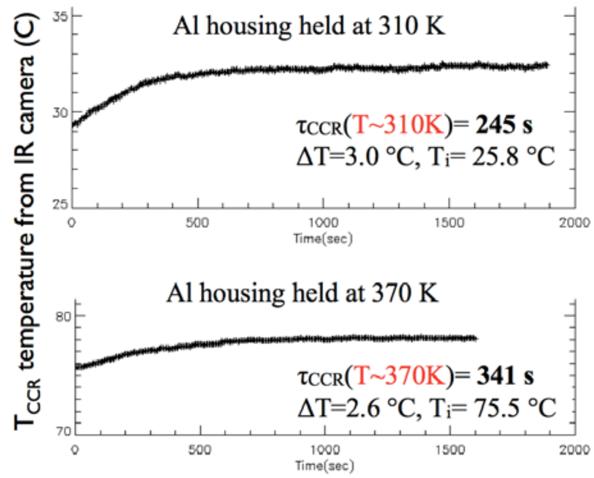

Fig. 17: IOV CCR: measurement of the thermal relaxation time at TB = 310 K and 370 K

We note that τCCR~250 sec at 310 K for the 33 mm diameter IOV CCR is shorter than previous SCF-Test measurements (and simulations):

- Al-coated GPS/GLONASS/GIOVE CCRs, whose active diameter is 28 mm have τCCR~(700-1100) sec
- LAGEOS has τCCR ~ thousands of seconds.

We also note that τCCR increases from 310 K to 370 K by ~30%. If radiative heat exchange between CCR and its mounting elements inside the CCR housing cavity would dominate, τCCR should decrease with TB as ~1/TB3. Since this is not the case, τCCR measurements indicate that in the prototype IOV CCR cavity the thermal mount conduction dominates over radiative exchange.

V CONCLUSIONS AND PROSPECTS

After feedback form SCF-Tests and from the long-time operational experience of the ILRS, modern GNSS satellites (including GLONASS) have finally abandoned Al back-coated retroreflectors after almost 30 years of use (since their first introduction on GLONASS). Some constellations are still keeping the design of separate CCR units screwed to metal back-plates as support structures, similar to the GPS/GLONASS/GIOVECCR array configuration. In addition, each constellation has its own mechanical/thermal scheme for mounting the fused silica element inside its metal cavity. Except for the prototype IOV CCR provided by ESA and reported in this paper for the first time, these new uncoated retroreflectors were not characterized in the laboratory under space conditions, so we have no basis to evaluate how well they were optimized for current and future GNSS satellites.

INFN-LNF has developed an evolution and refinement of the SCF-Test, based on a new powerful Key Performance Indicator, the GNSS Critical half-Orbit, which is capable of probing the critical optical and thermal features of GNSS retroreflectors. Thanks to the availability of the prototype IOV CCR, we cleanly demonstrated in realistic space conditions the effect of optical breakthrough for uncoated retroreflectors, and we measured and defined experimentally the effect of "thermal breakthrough". The GCO test showed that this specific prototype IOV CCR has a better performance compared to the GPS/GLONASS/GIOVE CCRs that have been SCF-Tested.

Given the amount of useful information coming from [1] and the IOV GCO test we believe that it is:

- Important to SCF-Test more IOV retroreflectors, more extensively, to confirm our preliminary conclusion that the IOV GRA performs better than old generation GPS/GLONASS/GIOVE arrays
- Mandatory to SCF-Test retroreflectors of the 14 satellites of the FOC-1 part of the Galileo Constellation, which are different from the IOV retroreflectors (different maker of a different country)
- Important to develop and SCF-Test the best possible GRA for the 12 satellites of FOC-2, with a pan-European effort in order to reduce dependence of Europe's flagship programme from non-European retroreflector technologies
- Important to SCF-Test different CCRs of all GNSS constellations, to ensure the highest possible SLR efficiency; this is because when the GNSS will be complete and operational, the ILRS will have to track 100+ satellites, compared to the ~30 satellites that is tracking now (and not without difficulties, especially for daylight ranging, for some of the stations).

The ETRUSCO-2 ASI-INFN is targeted to Galileo and the GPS-3, but is open to the other GNSS constellations: IRNSS, COMPASS, QZSS. In fact, discussions are underway with all GNSS communities.

VI ACKNOWLEDGMENTS

We wish to warmly thank ASI, and its President Enrico Saggese in particular, for the support and encouragement given to the ETRUSCO R&D and to the ETRUSCO-2 project. We also thank NASA for making the LAGEOS Sector available for testing. We deeply thank Daniel Navarro-Reyes, Rafael Garcia Prieto (with whom technical discussions have been very constructive and fruitful for more than two years), and Giuliano Gatti of ESA for authorizing the publication of the preliminary SCF-Test results of one prototype Galileo IOV laser retroreflector, in time for the "3rd International Colloquium on the Scientific and Fundamental Aspects of the Galileo Programme", held in Copenhagen, Denmark, on August 31 – September 2, 2011, where this paper was first presented.

In the framework of the ETRUSCO-2 ASI-INFN project, we keep working to make the SCF-Test service given to ESA as useful as possible for Galileo, and also for any other GNSS constellation. This is a service that Italy, with the endorsement of the ILRS, makes available to international space agencies, industries and research institutes, through INFN-LNF.

VII REFERENCES

1. Dell'Agnello, S., et al. (2011). Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS. Adv. Space Res. 47, 822-842.
2. Boni, A., et al. (2011). World-first SCF-Test of the NASA-GSFC LAGEOS Sector and Hollow Retroreflector. In Proc. 17th Intern, Workshop on Laser Ranging, Bad Kötzting, Germany.
3. D. Currie, S. Dell'Agnello, G. Delle Monache (2011). A Lunar Laser Ranging Retroreflector Array for the 21st Century. Acta Astron. 68, 667–680.
4. Altamimi, Z., Collilieux, X., Legrand, J., et al. (2007) ITRF2005, a new release of the International Terrestrial Reference Frame based on time series of station positions and Earth orientation parameters. J. Geophys. Res. 112(B9), B09401.
5. Cantone, C., et al. (2010). Structural analysis and preliminary space characterization of a prototype hollow laser retroreflector. In Proc. 61st Intern, Astronautical Congress, Prague, Czech Republic.
6. Dell'Agnello, S., G. Delle Monache, G., Cantone, C., et al. (2011). ETRUSCO-2: an ASI-INFN Project of Development and SCF-Test of GNSS Retroreflector Arrays (GRA) for Galileo and GPS-3. In Proc. 17th International Workshop on Laser Ranging, Bad Kötzting, Germany.
7. Neubert et al. (2011). Single Open Reflector for MEO/GNSS Type Satellites. A Status Report. In Proc. 17th International Workshop on Laser Ranging, Bad Kötzting, Germany.
8. Pearlman, M.R., Degnan, J.J., Bosworth, J.M. (2002). The international laser ranging service. Adv. Space Res. 30(2), 135–143.