Creation of the New Industry-standard Space Test of Laser Retroreflectors for GNSS, Fundamental Physics and Space Geodesy: the "SCF-Test"[1]

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Abstract

We created a new experimental apparatus (the SCF[2]) and a new test procedure (the SCF-Test) to characterize and model the detailed thermal behavior and the optical performance of laser retroreflectors in space for industrial and scientific applications. One of the primary goals of this innovative tool is to provide critical capabilities in a timely fashion for the advent of the European GNSS, GALILEO: (i) validation of the functionality of GNSS laser retroreflector payloads; (ii) optimization of their design in order to maximize the efficiency of satellite laser ranging (SLR) observations by the International Laser Ranging Service (ILRS). This will allow for a significant improvement of the positioning of GNSS satellites, both in terms of absolute accuracy and of long-term stability. Thanks to its superior H-maser clocks and SCF-Tested retro-reflectors GALILEO will also provide a large improvement in the measurement of the gravitational redshift. The SCF-Test was developed in the context of the ETRUSCO [1] experiment of INFN (approved in Summer 2006) at INFN-LNF, Frascati (Italy), a large-scale infrastructure of the European Research "Framework Programme" (FP). This research has been funded by INFN and carried out at two dedicated LNF facilities, in collaboration with Italian and American partners. Since a comprehensive and non-invasive space characterization like the SCF-Test has never been performed before, the results reported in this paper are important to understand the SLR performance on current and future GNSS, as well as the fundamental physics reach of 2nd generation lunar laser ranging (LLR). We identified the SCF-Test as a missing industry standard for space applications and as a missing critical service/functionality for GALILEO. We proposed its adoption as a tool for the simulation and testing of GALILEO SLR and of 2nd generation LLR for the "International Lunar Network" (ILN) and for NASA's manned landings.

SCF-Test of the "GPS3" Laser Retroreflector Array Flight Model

The full description of ETRUSCO, the SCF, the SCF-Test and the test results obtained on cube corner retroreflector (CCR) prototypes of GLONASS/GIOVE and of LAGEOS can be found in [1]. Here we report the results of the SCF-Test of the 3rd and last existing laser retroreflector array (LRA) flight model built in Russia for the GPS-2 GNSS constellation. We call this LRA the "GPS3". The GPS3, now loaned to LNF, is property of UMD.

[1] Presented by S. Dell'Agnello at the 16th ILRS Workshop, Poznan, Poland, October 13-17, 2008.
[2] Satellite/lunar laser ranging Characterization Facility, Frascati (Rome), Italy.

The New Industry-Standard Space Test of Laser Retroreflectors: the "SCF-Test"

The SCF-Test consists of the integrated thermal and optical measurements described below performed on LRA breadboards, prototypes or payloads. The SCF-Test is innovative. Its comprehensive and non-invasive set of measurements was never performed before. For example, it was not done on LAGEOS I and LAGEOS II. It was also never done for GNSS. The SCF-Test concept for an orbital configuration corresponding to the sunlit to earth shadow transition is shown in Fig. 1.

The new test that we developed and validated with GNSS and LAGEOS CCRs consists of several measurements and software simulations, which include:

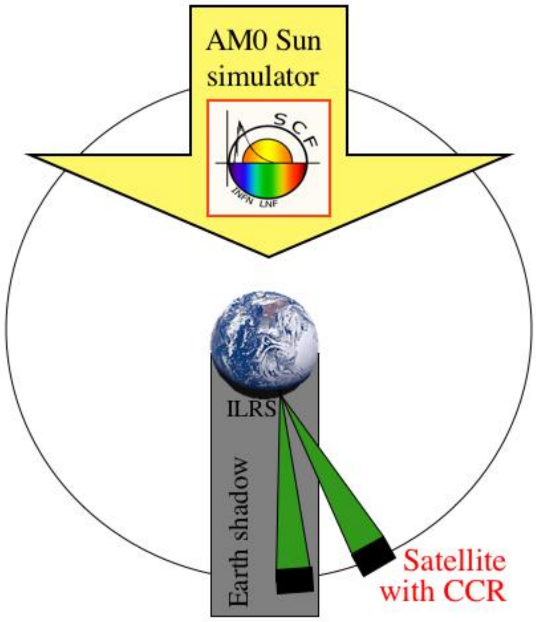

Figure 1. SCF-Test conceptual drawing.

- Hold the average temperature of the LRA mechanical support structure (Al for LAGEOS, GLONASS, GPS-2, GIOVE-A/B), T_M, to the expected value, T_{AVG}. T_{AVG} has been estimated with thermal simulations for LAGEOS. T_{AVG} is an input to the SCF-Test. Evaluate with SCF data and TRS models:
    1. CCR surface temperature and τ_{CCR}.
    2. CCR far field diffraction patterns (FFDPs) in representative space conditions (see Fig. 2, left) and in air/isothermal conditions (Fig. 2, right). FFDPs are measured with the external optical circuit [1][2].
    3. Surface temperature of non-CCR components of the LRA.
    4. Temperature difference between the CCR outer face and its corner inside the cavity. This evaluation is a combination of measurement plus modeling to assess the CCR optical functionality.
    5. Repeat the above for T_M different from T_{AVG}, in the appropriate range.

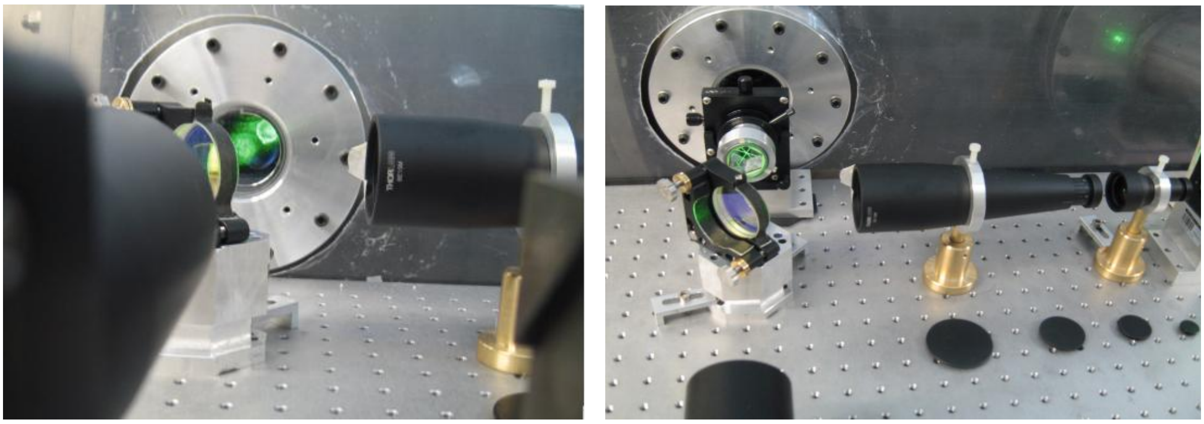

Figure 2. FFDP measurement of a Glonass CCR inside the SCF (left) and at STP (right).

- Repeat the above for different Sun illumination conditions:
    1. transition from SS turned off to on and vice versa (effect of Earth shadow)
    2. varying incidence angles of the Sun illumination
    3. different times along the thermal relaxation curve.
- Tune the TRS models to the *SCF data* for "static" climatic conditions, in which the Sun Simulator and Earth Simulator are turned on and off alternatively.
- Use validated TRS and CODEV simulations to model the LRA behavior for generic orbit and spin configurations (ie, *SPACE data*).

FFDP Test in Air/Isothermal Conditions of the GPS3 at 632 nm

We performed the FFDP test of each single CCR in air and isothermal conditions at 632 nm laser wavelength in the Optics Lab [2]. Figure 3 shows FFDPs of 4 CCRs mounted with different relative orientations. For 12 CCRs, like the bottom left of Fig. 3, the two peaks are almost blend into one. In the presence of thermal perturbations "blended" peaks will separate into two peaks; this has been demonstrated by the GLONASS SCF-Test reported in [1].

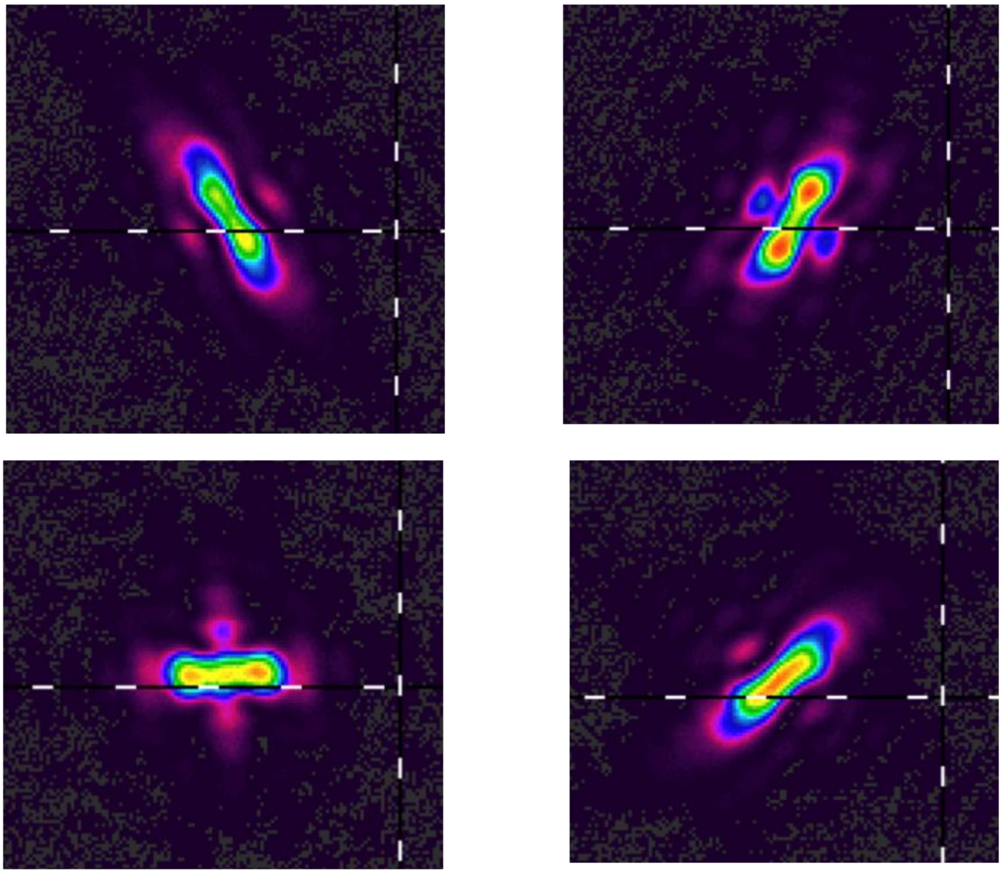

Figure 3. FFDPs of flight GPS3 retroreflectors in air, T = 22^{o}C and 632 nm.

Fig. 4 shows the distance between the two peaks of the 20 CCRs whose FFDP has two cleanly separated peaks. The CodeV prediction assumes the nominal 50 μrad central value of the GPS velocity aberration and a uncertainty of 5 μrad related to the inaccurate knowledge of the FFDP circuit.

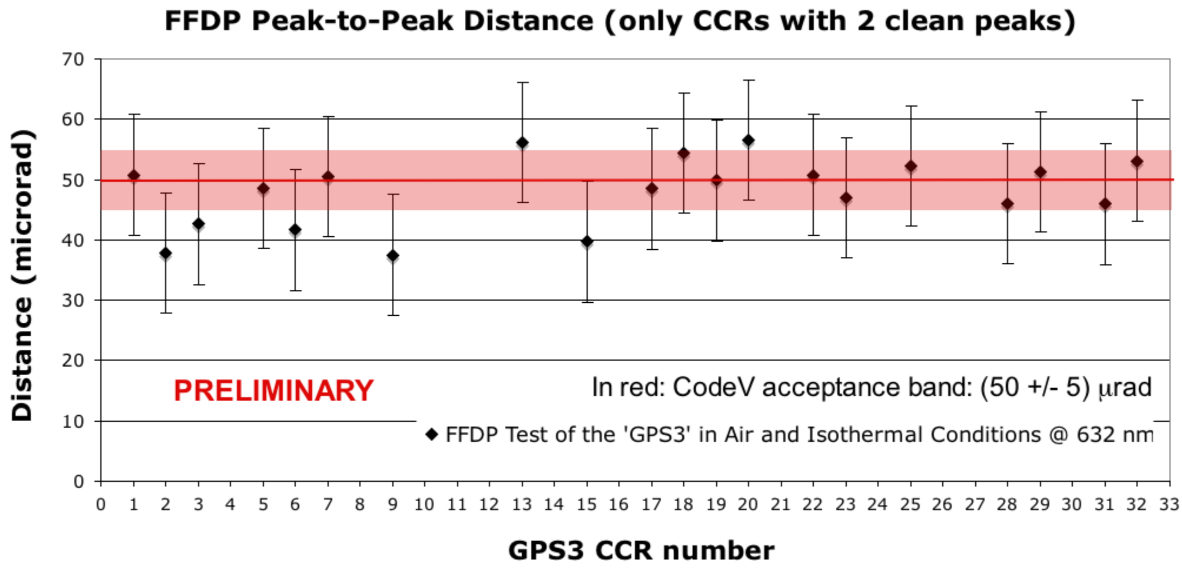

Figure 4. FFDP of the GPS3 retroreflectors with two separate peaks.

SCF-Test of the GPS3 at 532 nm

We performed the SCF-Test of four CCRs at 532 nm laser wavelength. The measurement and analysis is described in detail in [1]. The GPS3 temperature was controlled with a custom copper plate (Fig. 5, left) in thermal contact with the array Al base plate (Fig. 5, center) via indium washers. The copper plate is in turn thermally controlled with a fluid driven by an external chiller. The temperature of the array Al back plate is measured via a PT100 probe (Fig. 5, center) and during the test it was set to (19±1)^{o}C. The solar constant had a slightly reduced value of (0.92±0.02)×AM0 due to technical reasons.

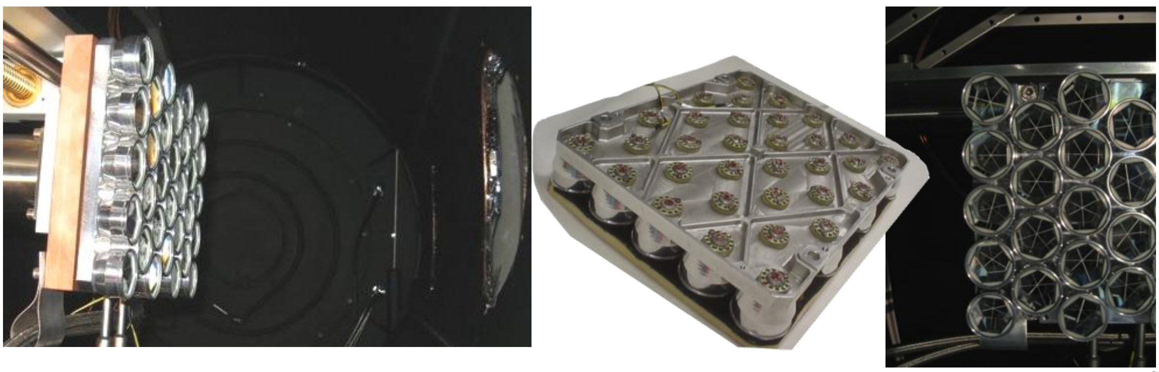

Figure 5. GPS3 in the SCF on the Cu thermal control plate and roto-translation system (left); GPS3 Al back with PT100s; (center); CCRs with staggered orientations (right).

Here we present the FFDP variations vs. time for one CCR of the GPS3. The temperature variation of the front face of this CCR, its “hot” and “cold” FFDPs are shown in Fig. 6. The FFDP behavior vs. time is shown in Fig. 7. The oscillation of the FFDP peak heights shown in Fig. 7 (top) for times above 2000 sec is due to a few degree instability of the thermal control system. This technical issue has now been solved, but it shows that small LRA bulk temperature changes directly influence the LRA optical performance. This is a 20% effect due to a few-degree change.

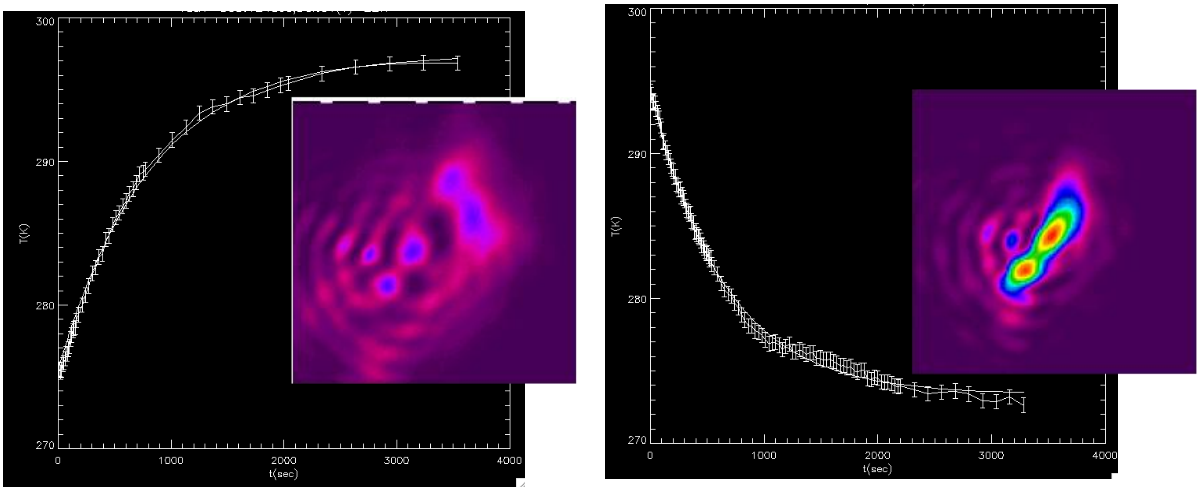

Figure 6. Front face CCR temperature and CCR FFDP at the end heating (left). Front face CCR cool-down curve and its FFDP 3000 sec after the SS has been turned off.

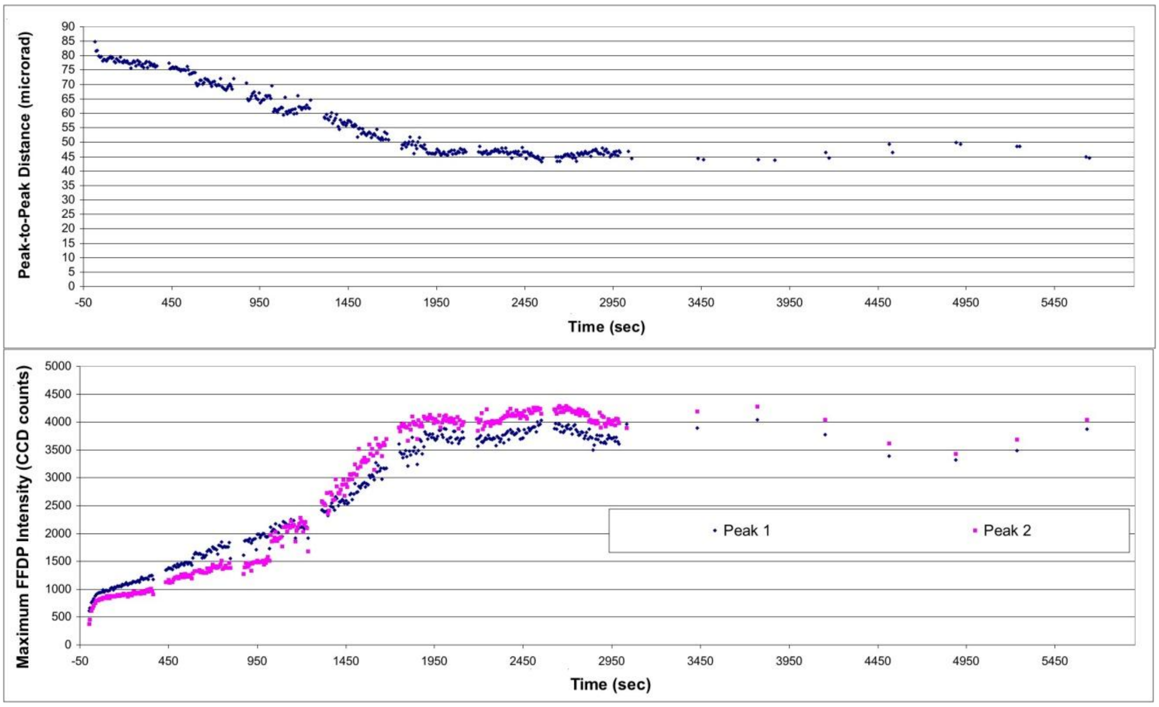

Figure 7. CCR cool-down: FFDP peak distance vs. time (top); maximum FFDP intensities at the average velocity aberration of ILRS stations vs. time (bottom).

These data show that the optical performance is significantly degraded for this geometric and thermal configuration. The FFDP peaks are disrupted and the FFDP intensity is scattered all over the place. For the first 10-20 seconds it is hard to define peaks. The fast decrease/increase of the peak distance/height that is clearly visible for the SCF-Test of the GLONASS 2007 CCRs [1] is less clearly visible for these late ‘80s GPS-2 CCR. The degradation of the initial “hot” FFDP is worse than for the GLONASS prototype, probably because the GPS3 is an older and less optimized payload. However, the reduction in intensity between the hot and cold conditions is a factor about 7, exactly like for the SCF-Test of the more recent GLONASS CCR.

Based on their nominal specifications (number of cubes, their size, Al-coating, etc) and assuming isothermal conditions, the GPS LRAs are known to provide a LIDAR optical cross section about a factor 5 lower than the 100 million m^2 required by ILRS for GPS altitudes [3][4]. Thermal perturbations like those measured with our SCF-Test represent a dramatic degradation of this cross section, by a factor of about 7.
SCF-Tests help predict the SLR signal strength of the GPS3 in orbit. This requires correcting the data for the residual instrumental effects, differences between the SCF and orbital configurations, computing the optical cross section and correcting that for the $(\text{distance})^{-4}$ reduction. Since GALILEO is higher than GPS/GLONASS/Compass, greater care must be taken to make the return pattern uniform when the satellite moves across the sky and to avoid degradations due to on-board thermal effects. Our ultimate goals is provide data useful to optimize the LRA design and boost the signal strength to allow for daylight ranging by the majority of ILRS stations (unlike now). This in turn will allow SRL-only orbits to be computed more frequently than weekly. Week-average SLR-only orbits were computed during the important SLR tracking campaign of GIOVE-A in 2006 [5].

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[2] *Optical Far Field Diffraction Pattern Test of Laser Retroreflectors for Space Applications in Air and Isothermal Conditions at INFN-LNF*, A. Boni, C. Cantone, S. Dell’Agnello, G. O. Delle Monache, M. Garattini, N. Intaglietta, C. Lops, M. Martini, L. Porcelli, INFN-LNF Report LNF-08/26(IR), 2008.
[3] The following document describes the rationale for LRAs on GNSS: http://ilrs.gsfc.nasa.gov/docs/retroreflector_specification_070416.pdf.

[4] This document reports the up-to-date *ILRS Standard for Retroreflector Arrays at GNSS Altitudes*: http://ilrs.gsfc.nasa.gov/docs/ILRSRetroreflectorStandards_200812.pdf. The ILRS has established a standard for the "effective cross section" (or active area times gain) to provide sufficient return signal strength.
[5] *GIOVE's Track*, M. Falcone, D. Navarro-Reyes, J. Hahn, M. Otten, R. Piriz, M. Pearlman, GPS World, page 34, November 2006; www.gpsworld.com.