XIX CONGRESSO NAZIONALE AIDAA
17-21 settembre 2007
FORLÌ (FC)

The INFN-LNF Space Climatic Facility

A. BONI[1], C. CANTONE[1], I. CIUFOLINI[2], S. DELL'AGNELLO[1], G. O. DELLE MONACHE[1],
M. A. FRANCESCHI[1], M. GARATTINI[1], N. INTAGLIETTA[1], A. LUCANTONI[1], M. MARTINI[1],
T. NAPOLITANO[1], A. PAOLOZZI[3], R. VITTORI[4]

[1]*Istituto Nazionale di Fisica Nucleare (INFN) – Laboratori Nazionali di Frascati (LNF)*
[2]*Università ed INFN di Lecce*
[3]*Scuola di Ingegneria Aerospaziale, Università "La Sapienza" di Roma*
[4]*Aeronautica Militare Italiana*

The Space Climatic Facility (SCF) is an experimental apparatus built in 2006 at the Frascati National Laboratories (LNF) of INFN. The initial purpose of the SCF was to study the thermal thrusts of the LAGEOS I and II satellites and to perform the full space-climatic and laser-optical characterization of the new LARES laser-ranged test mass. The results of this work will improve the accuracy of the measurement of "frame-dragging" in the field of the Earth (Lense-Thirring effect), predicted by General Relativity. The simulation and measurement activities at the SCF are interesting not only for Fundamental Physics, but also for Space Geodesy and Satellite Navigation. Later on, the modular and evolutionary design of the SCF proved to be well suited to characterize the thermal and laser performance of corner cube retro-reflector arrays deployed on Global Navigation Satellite System (GNSS) constellations. The SCF is a cylindrical cryostat (1 m diameter, 2 m length) where a realistic space environment is established in terms of pressure, temperature and electromagnetic radiation (solar constant and Earth infrared emission). Inside the vacuum shell there is a shield black painted with the high emissivity paint Aeroglaze® 306; when this shield is cooled down to 77 K the vacuum is typically 10-6÷10-5 mbar. The thermal input loads are provided by a solar simulator and an infrared earth simulator.

1. Probing Gravity in NEO with LAGEOS satellites and the new LARES experiment

The LAGEOS[1] I and II satellites have been launched, respectively, in 1976 (by NASA) and 1992 (NASA-ASI) into orbits with high inclinations (i = 109.9° and 52.65°), low eccentricities (e = 0.004 and 0.014) and large semi-major axes (a = 12,270 and 12,163 km). They are high-accuracy, completely passive, spherical test masses, whose orbit is tracked with <1 cm precision by the 40+ stations of ILRS (International Laser Ranging Service) scattered all over the Earth. Both satellites have a weight of about 400 Kg, a 60 cm diameter and 426 fused silica cube corner retro-reflectors (CCRs) for the satellite laser-ranging measurement (SLR). The primary purpose of LAGEOS I was Space Geodesy. Later it was shown that a pair of these satellites with supplementary inclinations was a good tool for experimental tests of General Relativity [1]. The LAGEOS data were used in 1998 for the first-ever measurement [2] of the phenomenon of dragging of inertial frames by a central rotating mass (the Earth in this case) acting on its orbiting satellite. This effect was predicted by Einstein (who named it "frame

---

[1] Laser GEOdymamics Satellite

dragging"), Lense and Thirring in 1916-1918. For its formal similarity with electromagnetism, it is also referred to as the Earth "gravitomagnetism". Recently, a larger set of LAGEOS data (about 11 years), in conjunction with a very improved determination of the Earth geopotential field (mainly due to the two GRACE satellites), were used to re-measure the frame dragging effect in NEO (Near Earth Orbit) with a 10% accuracy [3]. The measured value of the frame dragging precession of the two combined orbital nodes, $\dot{\Omega}_{FD} = 47.9\,\text{mas/yr}$ (milliarc-sec/yr), is in good agreement with the GR prediction, $\dot{\Omega}_{FD} = 48.2\,\text{mas/yr}$. For the LAGEOS altitude h ~ 6000 km, this amounts to a nodal precession of about 2 m/yr. Among non gravitational perturbations (NGPs), the main sources of error are non-conservative thermal thrusts (TTs) due to the varying and asymmetric space climatic conditions; the planned thermal characterization on these satellites has never been done before and it is necessary to take correctly account of TTs. Due to the relentless improvements of the SLR accuracy and of the Earth Gravitational Models (EGMs), soon NGP, SLR and EGM uncertainties will have a comparable effect on the overall error budget.

The effect of TTs is driven by the value of the thermal relaxation time of the CCRs, τ_{CCR}, which was never measured. For LAGEOS, the uncertainty on τ_{CCR} estimates from the literature vary from ~2,000 sec to ~7,000 sec (by ~250%) and are comparable with the maximum duration of the eclipse (~4,400 sec) and the orbit time (~13,300 sec). The SCF has been designed to measure τ_{CCR} at $\leq$10% accuracy. As shown in [4] this will make the error on the Lense-Thirring effect due to TTs negligible (permil level). Simulations studies indicate that measuring τ_{CCR} at 10% relative accuracy with the SCF, requires a temperature uncertainty of 0.5 to 1 K, which is a moderate experimental constraint.

The LARES[2] collaboration, using the infrastructure of the Frascati National Lab of INFN (LNF), is addressing this significant issue of the thermal NGPs. The program has two main goals:

1. Climatically characterize LAGEOS prototypes to reduce NGP errors on the calculation of frame dragging.
2. Design a new mission and build a fully characterized satellite, which avoids as much as possible the weaknesses of LAGEOS and is capable of reaching 1% accuracy on frame dragging calculation.

Such a follow-up mission, LARES, is being considered since the late '90s. Because SLR is a consolidated technique, the LAGEOS data analysis is mature, and thanks to the SCF, the time is right to launch a modern, second generation test mass. In November 2006, in fact, the second national scientific committee of INFN approved the LARES experiment.

In 2006 an engineering prototype of LAGEOS I (the "sector", built in 1992) was sent to LNF by NASA-GSFC for an SCF test.

These measurements will make the LAGEOS nodes more robust observables under the effect of thermal NGPs, but LARES will be needed to get the ultimate accuracy, both for physics and for Space Geodesy[3]. Unlike LAGEOS, the LARES perigee will be usable in the analysis, in addition to the node (which is much less perturbed by NGPs). LARES can be the beginning of the implementation of a high-accuracy SLR constellation.

2. The ETRUSCO experiment

The SCF turned out to be well suited to characterize the thermal and laser-ranging performance of cube-corner retro-reflector (CCR) arrays deployed on GNSS constellations, like the existing US GPS-2, the imminent European GALILEO and the future GPS-3. The integration of SLR with the standard microwave ranging (MWR) to improve the satellite navigation capabilities has become another SCF goal. With minor upgrades, the SCF can also test the laser-ranging performance of spherical test masses in the outer Solar System for DSGP (Deep Space Gravity Probe), which is a satellite formation of an active spacecraft and a few masses (passive satellites CCRs equipped and similar in design to LAGEOS-LARES satellites) laser-tracked by the active spacecraft. The results of this tracking and the overall communication with Earth will be via MWR. DSGP is being conceived to accurately study the Pioneer effect (ie, deviations from the $1/r^2$ gravity force law) and to perform important (inter)planetary science investigations. For this purpose, the groups of INFN-LNF, Rome-Tor Vergata, plus R. Vittori[4] in 2006 proposed to INFN a new experiment, ETRUSCO (Extra Terrestrial Ranging to Unified Satellite COnstellations). ETRUSCO was approved by INFN in October 2006, with the recommendation to focus the activity on GNSS applications. The R&D for DSGP will be reconsidered at a later stage. We describe the first preliminary thermal measurements on a flight model of CCR array to be deployed soon on the GPS-2 constellation and the upgrade of the SCF to perform simultaneous thermal and laser-ranging tests A

---

[2] LAser Relativity ExperimentS

[3] At the 2005 ILRS conference in Eastbourne (UK), it was pointed out that the next frontier mm SLR accuracy.

[4] Italian Air Force and European Astronaut Corps.

space-climatic characterization of the detailed thermal properties and of the laser ranging response of the GALILEO CCR arrays will strongly enhance the integration ("unification") of SLR with MWR. For each CCR of the array, the characterization will include the measurement of the thermo-optical parameters (emissivity, ε, and reflectivity, ρ), the thermal relaxation time and the variation of the laser far field diffraction pattern in a realistic space environment. This will be done with the arrays inside the SCF, exposed to simulators of the Sun and Earth illuminations. Since SLR gives a fundamental contribution to the definition of the Earth center of mass and of the absolute scale of length, this test program will improve the accuracy and long-term stability of the determination of the GALIELO orbits. The ultimate satellite positioning accuracy that can be reached is less than 1 cm. This in turn will propagate to the final end used on the Earth and all civil and commercial services provided by GALILEO will benefit from it. Since the large-scale deployment of SLR on GALILEO will be a world-first in GNSS, it is of the utmost importance that a full-fledged space-climatic characterization is performed. The experience of SLR with GPS-2 (only two satellites on 24 of the overall constellation) and GLONASS was a test more than a mission critical deployment. The laser ranging to GNSS is more difficult because its altitude is larger (~20,000 Km) than the LAGEOS (~6,000 Km) and because operational experience has shown that it is affected by climatic changes. Over several years, these few satellites have indicated how crucial the proposed characterization is and how difficult it is to model climatic effects without experimental measurements. A third CCR array exists, which will be deployed soon on a satellite of current GPS-2 constellation. This array is property of the University of Maryland (UMD, College Park, MD, USA) and is now at INFN-LNF for space climatic tests, following a special agreement with NASA-GSFC, IRLS and UMD (C. O. Alley, D. G. Currie). Testing this third array is very important because the previous identical versions of the arrays when tracked with lasers show significant periods of low light returns. Climatic tests and simulations are important to assure that no failures occur in GALILEO, in the long term and with a large multiplicity of satellites. The Frascati SCF offers the unique possibility to understand in detail the effects of the severe space environment on the many years of expected lifetime of the CCR arrays of GALILEO. In addition, the proposed test program can help keep GALILEO competitive with the next generation of GPS-3 (about 2011-2012), which indeed might take advantage of proposed innovative retro-reflectors, like the hollow type, as opposed to the traditional solid, fused-silica reflectors used by GLONASS, GPS-2 and GALILEO.

This array is identical to the ones installed on the GPS-35 and GPS-36 satellites in orbit. The three arrays have been manufactured in Russia. Mechanical drawings for its correct modeling have been provided courtesy of V. P. Vasiliev of the Russian IPIE (Institute for Precision Instrument Engineering of the Federal Space Agency of Russia, Moscow). Since this is a *flight* model, in 2006 it was decided not to start with a full test in the SCF.

Figure 1 shows a photo of the GPS3 and the warm-up and cool-down curve of a central retro-reflector, measured with a digital infrared camera. This preliminary test was conducted with the Solar simulator as the main thermal load, at 75% of its nominal intensity. A space-climatic test in the SCF will follow in 2007, under the supervision of D. G. Currie of UMD.

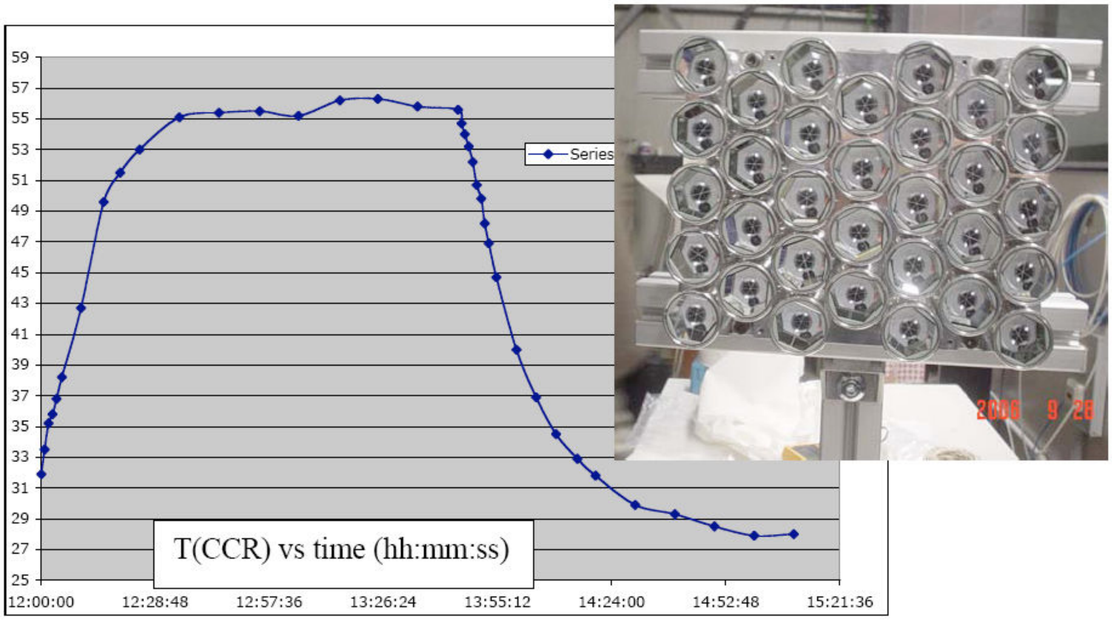

Figure 1: Warm-up and cool-down curves of the GPS3 array, in air at STP.

In order to perform integrated and concurrent space-climatic and laser-ranging tests in 2007 the SCF has been significantly upgraded with laser test equipment and with optical analysis software capabilities.

3. The SCF Apparatus

A schematic view of the SCF is shown in Figure 2. The size of the steel cryostat is approximately 2 m length by 0.9 m diameter. The inner copper shield is painted with the Aeroglaze Z306 black paint (0.95 emissivity and low out-gassing properties) and is kept at T = 77 K with liquid nitrogen. When the SCF is cold, the vacuum is typically in the $10^{-6} \div 10^{-5}$ mbar range. A support fixture on the ceiling holds the prototype spacecraft in front of the Earth infrared simulator (inside the SCF). The Solar Simulator (SS) is outside, behind a quartz window (36 cm diameter, 4 cm thickness), which is transparent to the solar radiation up to 3000 nm. A side flange with a Germanium window allows for taking thermograms of the prototypes with an infrared (IR) digital camera.

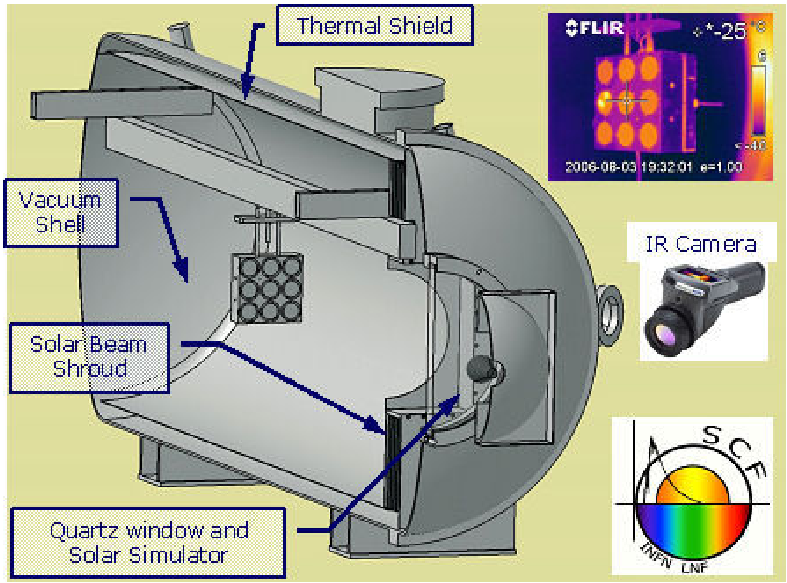

Figure 2: The SCF with a 3x3 LRR array of the LAGEOS satellite built at LNF. A temperature photo taken with the IR camera and the camera are shown at the right.

The SS (from www.ts-space.co.uk) provides a 40 cm diameter beam with close spectral match to the AM0 (Air Mass zero) standard of 1 Sun in space (1366.1 W/m ^{2}) in the range 400 ÷1800 nm (see Figure 3), with a uniformity better than ±5% over an area of 35 cm diameter. The spectrum is formed from a metal halide (HMI) arc lamp (UV-V; 6 KW), together with a quartz halogen, tungsten filament lamp (Red-IR; 12 KW). The resulting spectrum is also in reasonable agreement with the AM0 over λ = 1500 nm up to 3000 nm.

The absolute scale of the SS intensity is established with a reference device, the solarimeter, which is a standard (www.epply.com) thermopile (calibrated blackbody), accurate and stable over 5+ years to ± 2%.

The Earth simulator is a 30 cm diameter disk painted with Aeroglaze Z306, kept at the appropriate temperature (~260 K) and distance from the satellite prototype in order to provide the CCRs with the same viewing angle in orbit (~60° for LAGEOS).

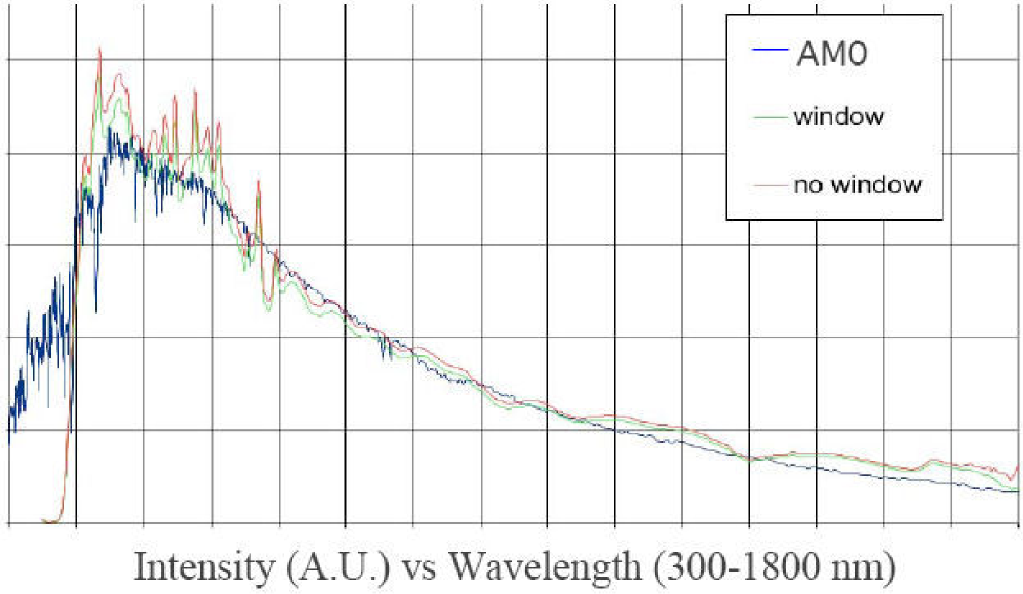

Figure 3: SCF SS spectrum (www.ts-space.co.uk) compared to the AM0 standard.

The temperature DAQ consists of an IR camera for non-invasive, high spatial granularity measurements (FLIR ThermaCAM® EX320, 320 x 240 pixels) and class-A PT100 probes with 4-wire readout. The PT100s are used to calibrate the IR camera. They are also used below 250K, outside the IR camera working range.

The upgraded SCF is shown in Figure 4: the existing left IR camera window, the new central window for far field diffraction pattern (FFDP) measurements and the new right spare window. The Sun AM0 beam enters from the left through the AM0 window. The specs of the LASER window are: fused silica material; 150 mm diameter, 36 mm thickness; deformations of transmitted wavefront < $\lambda/20$, surface quality 10-5 scratch/dig, anti-reflective coating on both sides, reflectivity = 0.2%, both for λ = 532 nm and 628 nm.

Each CCR will be first exposed to the Sun and the Earth simulators and its thermogram taken. Then, the CCR will be moved in front of the LASER window to take its FFDP. Figure 4 shows the LNF "matrix" prototype of LAGEOS viewed from the front AM0 window and from the side laser window. This prototype is an aluminum array with 9 CCRs that reproduces, in terms of materials and mounting solution, a spherical segment of LAGEOS, using a much more easy to manufacture block structure.

4. Far Field Diffraction Pattern Tests

The most basic test of laser ranging performance is the measurement of the absolute angular size and absolute intensity of single-CCR Far Field Diffraction Patterns (FFDPs) with linear polarized continuous wave lasers. The optical circuit for FFDP measurements is shown in Figure 5. The laser beam profiler (by Spiricon) uses a PtGrey CCD 2 MPix camera, readout via Firewire by a PC. These tests are currently done at STP, but final tests will be with the CCR in the SCF.

Figure 5 shows the measured FFDP of a flat mirror (top right), in place of the CCR. Optical flats with known reflectivity are used as a normalization to determine the absolute intensity of the SLR return to Earth. Figure 5 (bottom right) also shows the FFDP measured for a LAGEOS CCR with 3 non-zero dihedral angle offsets.

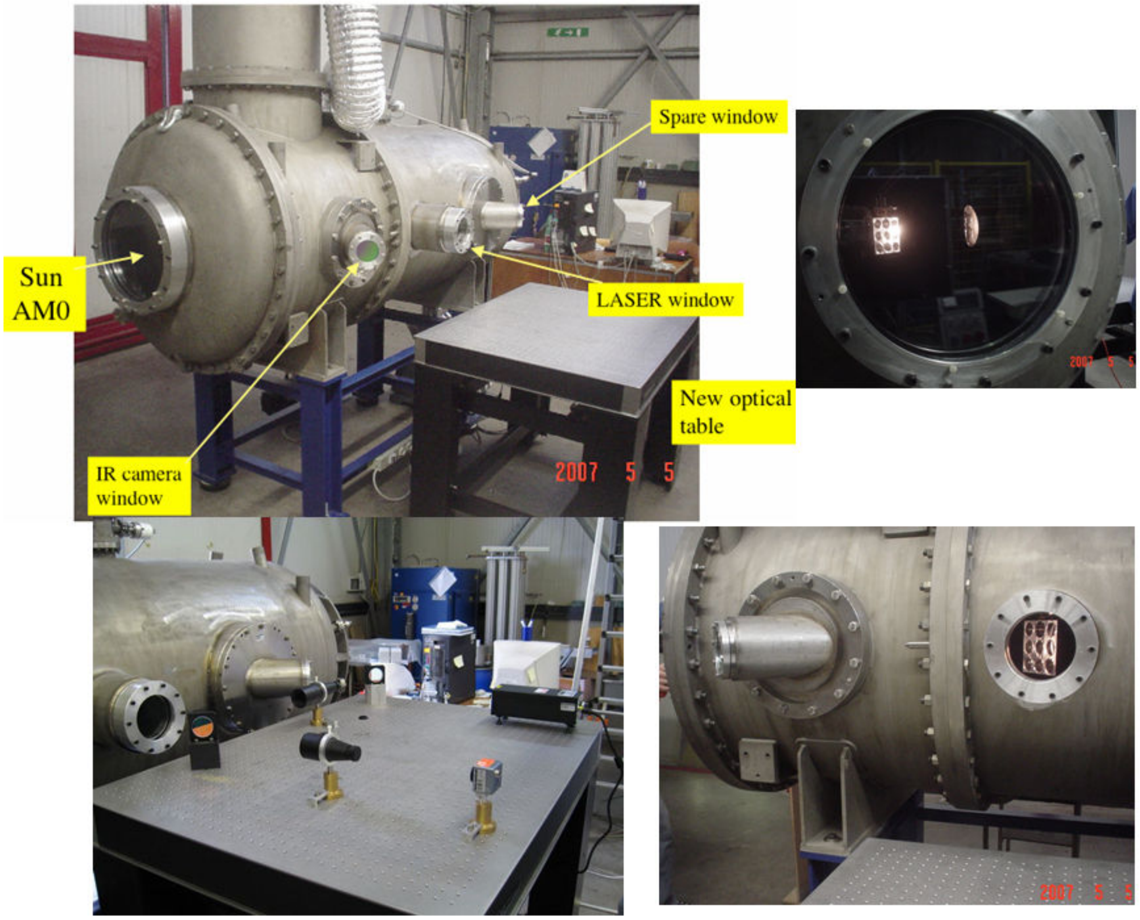

Figure 4: The SCF upgraded for optical test (May 5, 2007).

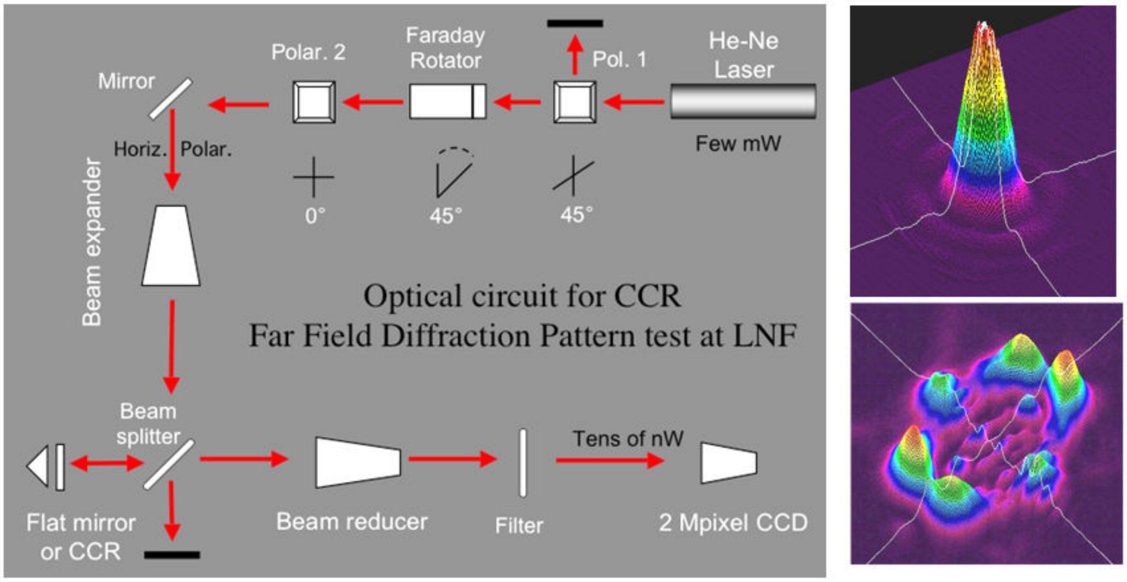

Figure 5: Scheme of the FFDP optical circuit (left) and measured FFPDs.

5. Simulation Software Suite

SCF measurements are also modeled with thermal and optical simulations done with:

1. For finite elements modeling, ANSYS, by ANSYS Inc. (www.ansys.com).
2. For satellite thermal simulation the LNF group adopted since 2005 a specialized suite by C&Rtech (www.crtech.com), used by several space agencies and industries: (i) Thermal Desktop, the CAD-based geometric thermal modeler, (ii) RadCad, the radiation analysis module, (iii) Sinda-Fluint, the solver and orbital simulator (TRS). TRS can handle up to 20000 FEM nodes, satellite spin and the orbital motion of the Moon and of Earth artificial satellites.
3. Optical design and analysis software: CODEV, by Optical Research Associates because TRS has built-in provisions for integration with CODEV.

6. The "SCF Test" of LARES

The "SCF test" consists of:

- Hold the average temperature of the CCR support (now a tungsten cavity, T(W), instead of aluminum cavity like for LAGEOS), to the expected value (if known), T_{AVG}. Then measure in the SCF:
    1. emissivity/absorptivity (ε/α) and reflectivity (ρ) of CCRs and of their retainer W rings:
        - ε_{IR} and ρ_{IR} will be measured separately using the IR Earth simulator.
        - α_{SUN} and ρ_{SUN} will be measured separately using the Sun simulator.
    2. τ_{CCR} and τ_{WRING}.
    3. surface temperature distribution (from which thermal thrusts are computed).
- Repeat the above for T(W) different from T_{AVG}.
- Measurement of the far field diffraction pattern (FFDP) with the external laser beam.
- Repeat the above for different Sun illumination conditions:
    1. transition from SS turned off to on and vice versa (Earth shadow).
    2. varying incidence angles of the Sun illumination
    3. different times along the thermal relaxation curve (driven by τ_{CCR})
- Tune the TRS models to the SCF data for "static" climatic conditions, in which the Sun and Earth radiations are turned on and off alternatively.
- Use the validated TRS models to predict the LRR behavior along full orbits.
- Test the effect of satellite spin, first in the simulation and, if possible, in the SCF.
- Measure the RC of the Sun-lit, dark side and half-lit/half-dark hemisphere.

The integrated measurement of τ_{CCR}, FFDP and RC are the core of the "SCF-test".
TTs (thermal forces) are computed by vector sum of the energy radiated per second by all surface FEM elements (divided by the speed of light, c) with a validated TRS model.

7. True Laser Ranging Timing Tests (the "Range Correction")

For LAGEOS and LARES a correction to the measured laser ranging distance is needed in order to get the position of satellite centre of mass. This calibration (the so-called "range correction", RC) is a true timing measurement, to be done with short pulse lasers. For LAGEOS I and II this was performed by a skilled team of NASA-GSFC in air at STP.

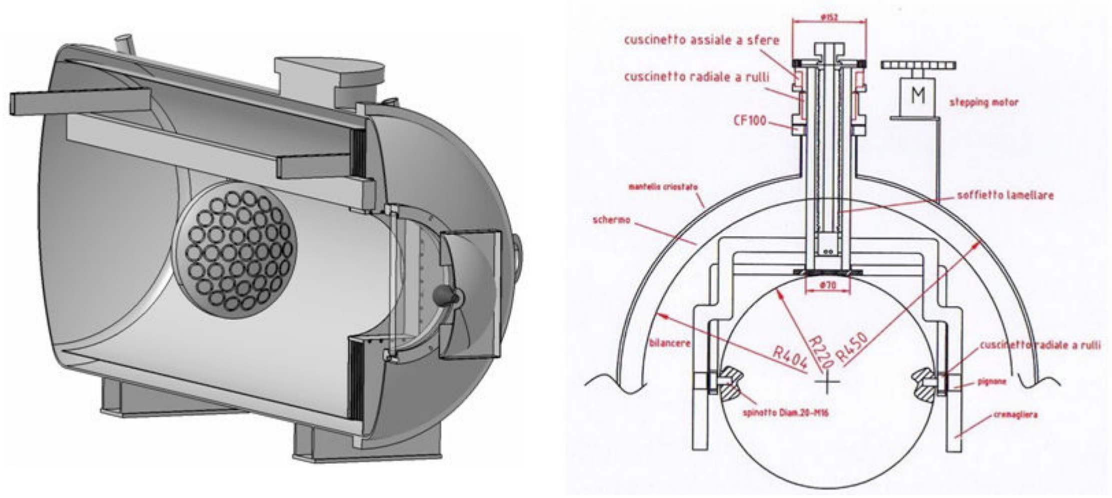

Figure 6: GSFC LAGEOS sector at LNF and the system for rotation-tilt in the SCF.

For LARES we are developing in Italy the capability to perform this test; possibly with the LRR target inside the SCF, thus adding also an original contribution to this field. We are preparing for LARES using the NASA-GSFC LAGEOS sector prototype.

Figure 6 shows on the left the sketch of the mechanical system purchased by LNF to move (rotate and tilt) LARES inside the SCF to alternate between Sun illumination, thermography and laser ranging measurements (either FFDPs or RC or both). As shown on the right of Figure 6, the payload could also be the NASA-GSFC LAGEOS sector, which has a radius of 200 mm and a weight ~20 Kg. The maximal accepted radius (shown on the right in Figure 6) for LARES is 220 mm. For the full-tungsten design of LARES, this radius corresponds to a weight of ~750 Kg. Both the rotation-tilt system and the SCF itself can stand the 220 mm maximal radius and the 750 Kg maximal weight of LARES.

8. Thermal Measurements on the LAGEOS Matrix

The first preliminary SCF measurement on the matrix was performed with the ES as the only thermal input and T(Al) held at 300 K. The measured steady-state temperature of the CCR shows a fair match with the simulated thermal model of the matrix (see Figure 7).

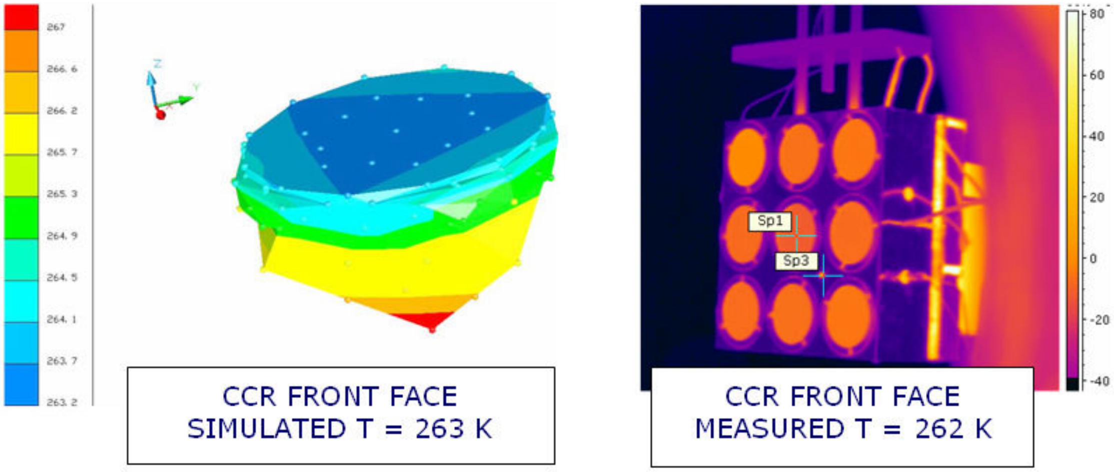

Figure 7: Earth simulator only: comparison of measured simulated CCR temperature.

The second preliminary SCF test was performed with the Solar Simulator as the only input load (Figure 8). The value of T(Al) controlled w/TECs and is varied in 5 steps.

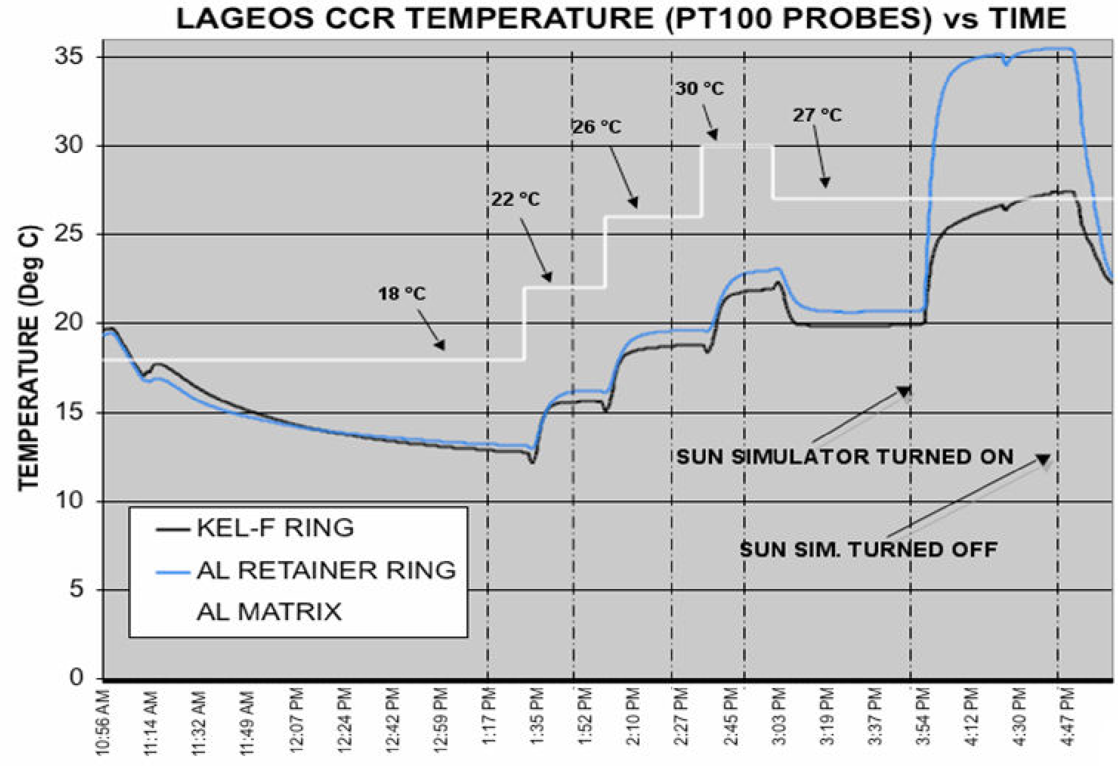

Figure 8: Solar simulator only: measurement of the T variation of CCR assembly rings.

9. Thermal Simulation Results: τ_{CCR} and Thermal Thrusts

τ_{CCR} has been estimated from TRS for various climatic conditions and values of T(AL). For example, Figure 9 shows the temperature variation of the front face of the CCR, T(CCR), in the case of illumination by the sun for T(AL) = 300 K. The temperature accuracy is of 0.5 K

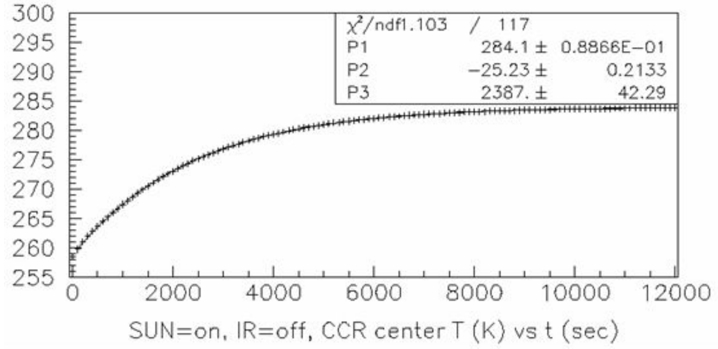

Figure 9: Exponential fit to T(CCR) vs time in the simulation when the Sun is turned on at t > 0, CCR solar absorptivity α_{SUN} = 15% and T(AL) = 300 K. P3 = τ_{CCR} in seconds.

The results from a parametric model of the thermal forces experienced by LAGEOS is show in Figure 10. It shows the capability of the TRS software and some of the basic features of the thermal NGPs.

The simulated configuration is: (1) satellite pole facing the Sun and Earth simulators, (2) steady state with both simulators turned on at t=0, (3) Sun turned off between t = 0 and 4500 sec, (4) zero thermal conductance between the Al retainer screws and the Al satellite body. This configuration can be easily implemented in the SCF and it mimics the satellite passage through the Earth shadow and a satellite spin directed along the ecliptic plane. The thermal thrusts are estimated in a parameterized way, using a single CCR in a cavity of an aluminum block held fixed at 300 K. For each LAGEOS row, the single CCR is illuminated by the solar lamp at the appropriate angle and the thermal thrust is computed from the software. The contribution of all CCRs in a row, of all rows and of the two hemispheres is then summed.

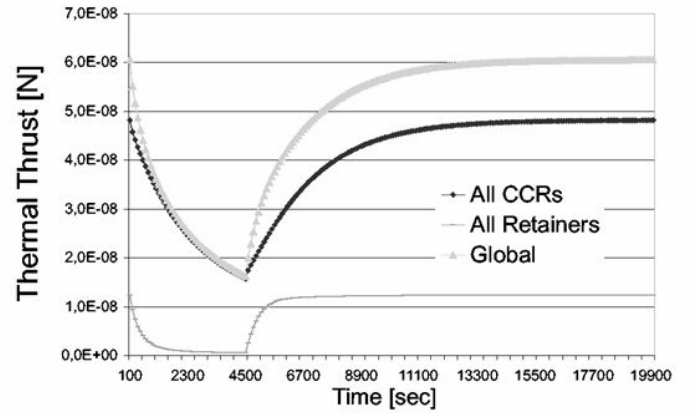

Figure 10: Estimate of the thermal thrusts on the whole satellite due to the Sun and Earth simulators in the SCF for CCR α_{SUN} = 15%.

10 Conclusions

In September 2006 the SCF has become a permanent, small-size, experimental apparatus of INFN-LNF. During the last two years the collaboration of LNF with ILRS has been very fruitful. The current upgrade of the SCF, consisting of the integration of the thermal and the laser-ranging tests has been funded by INFN, and by LNF, explicitly for GNSS studies. An additional, dedicated optical table can thus be operated next to the SCF, when alternating among exposure to the heat simulators, IR thermography and laser ranging. At the end of 2006, LNF has become member of the "Signal Processing" Working Group of the IRLS.

References

[1] I. Ciufolini, Physical Review Letters 56, 278-281 (1986).
[2] I. Ciufolini. E.C. Pavlis, F. Chieppa, E. Fernandes-Vieira, J. Perez-Mercader, Science 279, 27 March 1998.
[3] I. Ciufolini, E. C. Pavlis, Nature 431, 21 October 2004.
[4] Probing Gravity in NEO with High-Accuracy Laser-Ranged Test Masses, A. Bosco et al, Report INFN-LNF-06-24(P): http://www.lnf.infn.it/sis/preprint/pdf/LNF-06-24(P).pdf. Presented by S. Dell'Agnello at the "Quantum to Cosmos" NASA Int. Workshop, Warrenton (VA), USA, May 2006; to be published in a special issue of Int. Jour. Mod. Phys. D.