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PROBING GRAVITY IN NEO'S WITH HIGH-ACCURACY LASER-RANGED TEST MASSES

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Gravity can be studied in detail in near Earth orbits NEO's using laser-ranged test masses tracked with few-mm accuracy by ILRS. The two LAGEOS satellites have been used to measure frame dragging (a truly rotational effect predicted by GR) with a 10% error. A new mission and an optimized, second generation satellite, LARES (I. Ciufolini PI), is in preparation to reach an accuracy of 1% or less on frame dragging, to measure some PPN parameters, to test the $1/r^2$ law in a very weak field and, possibly, to test select models of unified theories (using the perigee). This requires a full thermal analysis of the test mass and an accurate knowledge of the asymmetric thermal thursts due to the radiation emitted by the Sun and Earth. A Space Climatic Facility (SCF) has been built at INFN-LNF (Frascati, Italy) to perform this experimental program on LAGEOS and LARES prototypes. It consists of a $2\,\mathrm{m} \times 1\,\mathrm{m}$ cryostat, simulators of the Sun and Earth radiations and a versatile thermometry system made of discrete probes and an infrared digital camera.

The SCF commissioning is well underway. A test of all its subsystems has been successfully completed on August 4, 2006, using a LAGEOS 3×3 retroreflector array built at LNF. This prototype has been thermally modeled in detail with a commercial simulation software. We expect to demonstrate the full functionality of the SCF with the thermal characterization of this LAGEOS array by the beginning of September 2006.

Keywords: Gravitomagnetism; climatic test; thermal analysis.

1. Probing Gravity in NEO's with LAGEOS

The LAGEOS[a] 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 semimajor axes ($a = 12{,}270$ and $12{,}163\,\mathrm{km}$). They are high-accuracy, passive, spherical test masses, whose orbit is tracked with $< 1\,\mathrm{cm}$ precision by the 40+ stations of ILRS (International Laser Ranging Service) scattered all over the Earth. They have a weight of about 400 kg, a 60 cm diameter and 426 fused silica cube corner retroreflectors (CCR's) 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

[a]LAser GEOdynamics Satellite.

in this case) acting on its orbiting satellite. This effect was predicted by Einstein (who named it "frame dragging"), Lense and Thirring in 1916–1918. For its formal similarity to electromagnetism, it is also referred to as the Earth "gravitomagnetism." Frame dragging can be observed also with pointlike spinning bodies (i.e. gyroscopes): this is the goal of the Gravity Probe B mission, launched in 2004, which ended its data-taking in 2006. GP-B is an active, high-technology satellite (probably one of the most sophisticated ever), aimed at a one-time-only measurement of frame dragging with an accuracy $\leq 1\%$.

Recently, a larger set of LAGEOS data (about 11 years), in conjunction with a much-improved determination of the Earth geopotential field (mainly due to the two GRACE satellites), was used to remeasure the frame dragging effect in NEO's with 10% accuracy.[3] The measured value of the frame dragging precession of the two combined orbital nodes, $\dot{\Omega}_{\mathrm{FD}} = 47.9\,\mathrm{mas/yr}$ (milliarc-sec/yr), is in good agreement with the GR prediction, $\dot{\Omega}_{\mathrm{FD}} = 48.2\,\mathrm{mas/yr}$. For the LAGEOS altitude $h \sim 6000\,\mathrm{km}$, this amounts to a nodal precession of about $2\,\mathrm{m/yr}$.

In the next few years, the knowledge of the geopotential is expected to improve thanks to the GRACE, CHAMP and GOCE missions. Since LAGEOS has a virtually limitless orbit lifetime (~ 1 million years), the nongravitational perturbations (NGP's) will become an important experimental error on $\dot{\Omega}_{\mathrm{FD}}$. Among NGP's, the main sources of error are nonconservative thermal forces due to the varying and asymmetric space climatic conditions. These contribute to $\sigma(\dot{\Omega}_{\mathrm{FD}})$ with a few %. A very detailed error analysis and error budget can be found in Ref. 4.

2. The New LARES Mission

This paper describes the focussed R&D effort which is being carried out by the LARES Collaboration, within the infrastructure of the Frascati National Laboratory of INFN (LNF) near Rome, Italy, to address the significant issue of the thermal NGP's. This work builds upon an extensive analysis on this subject performed by several authors in the past. At LNF, experimental measurements in a NEO space climatic facility will be done for the first time. This program has two main goals:

- Climatically characterize LAGEOS prototypes to reduce NGP's errors on $\dot{\Omega}_{\mathrm{FD}}$. A significant improvement can be reached on this, but we have to accept the unavoidable limitation that we are testing prototypes and validating models, not the original satellites (but we are trying to get hold of the original engineering models).
- 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 an accuracy $\sigma(\dot{\Omega}_{\mathrm{FD}}) \leq 1\%$. Such a follow-up mission, LARES,[b] has been considered since the late 1990's. Because SLR is a consolidated technique, the LAGEOS

[b] LAser RElativity Satellite.

data analysis is mature, and thanks to the SCF, the time is right to launch a modern, second generation test mass.

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

The construction and testing of LARES was formally proposed to INFN in mid-2004. In 2005, the mission was approved by INFN for R&D work in 2006 and 2007. The SCF was then built and completed by July 2006. In 2006 the Collaboration proposed the launch to space agencies. A proposal was submitted to the joint ASI-INFN committee for the qualification flights of the new ESA launcher, VEGA.

3. Thermal NGP's on LAGEOS

Laboratory measurements of the thermo-optical properties of the LAGEOS retroreflectors have been advocated for many years by the leading experts in this field (Rubincan, Farinella, Slabinski, etc.). Tests like these in a NEO SCF were not conducted on either LAGEOS I or LAGEOS II. Due to their larger temperature asymmetry and emissivity, the CCR's give rise to a thermal drag perturbation far much larger than that of the aluminum structure of the satellite. The orbital perturbations depend significantly on the Yarkovsky effects — specifically the diurnal Yarkovsky effect, the seasonal Yarkovsky effect (also known as *thermal drag* and first understood, in the case of LAGEOS, by Rubincam) and the Yarkovsky–Schach effect. The seasonal Yarkovsky effect is due to the Earth infrared radiation, while the Yarkovsky–Schach effect is due to the modulation of the solar radiation by the Earth shadow. The magnitude of these effects depends upon the spin axis orientation, the spin rate and the thermal properties of the satellites. Among the thermal properties, of particular importance and concern for the orbital dynamics of LAGEOS and LARES, is the *thermal relaxation time* of the CCR's (τ_{CCR}). There are semianalytical approaches to the calculation of τ_{CCR} and empirical ones based on the analysis of the orbit residuals. Both have limitations. In the literature, estimates vary by over 300% from 1625 s to about 7070 s.

The frame dragging effect on the node of each LAGEOS satellite (the *single* node, not the special linear combination of the two nodes used in the most recent analysis[3]) is about 31 mas/yr.[1] Taking the central value of the above wide range of τ_{CCR}, the thermal drag effects on the nodes turn out to have a very-long-period, secular-like amplitude $\dot{\Omega}_{\mathrm{TD}} = 1$–$2\,\mathrm{mas/yr}$ (the subscript TD indicates the *thermal drag* contribution to $\dot{\Omega}_{\mathrm{FD}}$). The size of this effect is, on the node, mainly due to the

[c] At the 2005 ILRS conference in Eastbourne, UK, it was pointed out that one of the next frontiers is to aim for mm-level SLR accuracy.

thermal drag during the satellite eclipses by the Earth. Indeed, when the satellite orbits are not entering the Earth shadow there is a reduction of the *nodal* thermal drag by a factor of the order e.

Let us now consider the uncertainty on the prediction for τ_{CCR} and let us take, for example, $\sigma(\tau_{\mathrm{CCR}})/\tau_{\mathrm{CCR}} \sim 250\%$. First of all, the orbital effects of the thermal drag are periodical and are, thus, averaged out or fitted for[2] over very long periods at the level of 90% and only a residual factor, $R_{\mathrm{TD}} = 10\%$, remains. Second, the long period nodal perturbations of the thermal drag during the eclipse season are linearly proportional to τ_{CCR}. Therefore

$$\frac{\sigma(\dot{\Omega}_{\mathrm{TD}})}{\dot{\Omega}_{\mathrm{TD}}} = \frac{\sigma(\tau_{\mathrm{CCR}})}{\tau_{\mathrm{CCR}}} \times R_{\mathrm{TD}} = 250\% \times 10\% = 25\%. \tag{1}$$

For $\dot{\Omega}_{\mathrm{TD}} = 1\text{–}2\,\mathrm{mas/yr}$ (see above), one then gets

$$\sigma(\dot{\Omega}_{\mathrm{TD}}) = 1\text{–}2\,\mathrm{mas/yr} \times 25\% = 0.25\text{–}0.5\,\mathrm{mas/yr}. \tag{2}$$

Finally, the relative uncertainty in the measurement of the frame dragging effect from the thermal relaxation time *only* is

$$\frac{\sigma(\dot{\Omega}_{\mathrm{TD}})}{\dot{\Omega}_{\mathrm{FD}}} = \frac{0.25\text{–}0.5\,\mathrm{mas/yr}}{31\,\mathrm{mas/yr}} = 0.8\text{–}1.6\%. \tag{3}$$

Clearly, for LARES, it will be critical to have an accurate measurement of τ_{CCR} to use in the NASA GEODYNE orbit determination program used for data analysis. The SCF has been designed to achieve $\sigma(\tau_{\mathrm{CCR}})/\tau_{\mathrm{CCR}} \leq 10\%$ for the LARES retroreflectors, which, in the baseline design, are the same as the LAGEOS ones. Since τ_{CCR} is the basic observable which governs all thermal forces, this will put the climatic NGP's well under control for the LARES goals.

4. The LNF Space Climatic Facility

A schematic view of the SCF is shown in Fig. 1. The size of the steel cryostat is approximately 2 m length by 1 m diameter. The inner copper shield is painted with Aeroglaze Z306 black paint (0.95 emissivity and low outgassing properties) and is kept at $T = 77\,\mathrm{K}$ with liquid nitrogen. When the SCF is cold, the vacuum is typically in the 10^{-6} 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 is outside, behind a quartz window (40 cm diameter, 4 cm thickness), which is transparent to the solar radiation up to 3000 nm. A side flange with a germanium window allows one to take thermograms of the prototypes with a FLIR infrared digital camera.

The Earth simulator is a 30-cm-diameter disk painted with Aeroglaze Z306, kept at the appropriate temperature (250 K) and distance from the satellite prototype in order to provide the CCRs with the same viewing angle in orbit ($\sim 60°$ for LAGEOS). The sun simulator (from www.ts-space.co.uk) provides a 40-cm-diameter beam with a close spectral match to the AM0 standard of 1 Sun in space

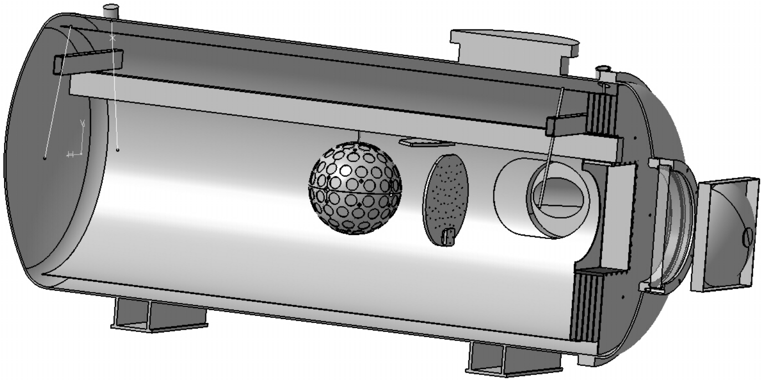

Fig. 1. Sketch of the LNF Space Climatic Facility.

(1366.1 W/m^2), with a uniformity of ±5% over an area of 35 cm diameter. The spectrum is formed from the output of two sources, namely an HMI arc lamp (UV-V), together with a tungsten filament lamp (Red-IR). The quartz halogen lamp (with the tungsten filament) has a power of 12 KW, while the metal halide lamp has 6 KW power. These two sources are filtered such that when the two beams are combined with a beam splitter/filter mirror, the resulting spectrum is a good match to AM0 in the range of 400–1800 nm (see Fig. 2). The spectrum has also been measured up to $\lambda = 3000$ nm (important for $\dot{\Omega}_{\rm TD}$) and found to be in reasonable agreement with AM0 (see Fig. 3).

The absolute scale of the solar simulator intensity is established by exposing the beam to a reference device, the *solarimeter*, which is a standard www.epply.com

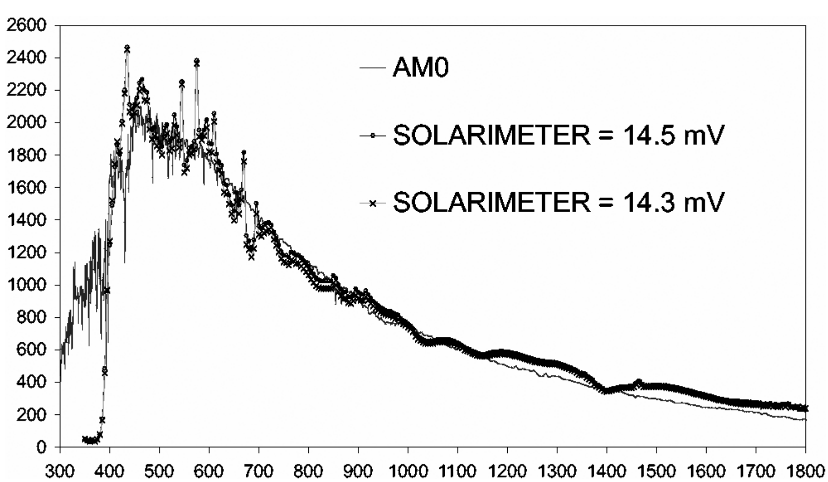

Fig. 2. AM0 spectrum (W/m^2/nm × 10^3) as a function of wavelength (nm) and two (almost undistinguishable) spectra measured with the SCF simulator, for two different values of the lamp currents and solarimeter readings. Typical currents are around 36 A (tungsten) and 29 A (HMI).

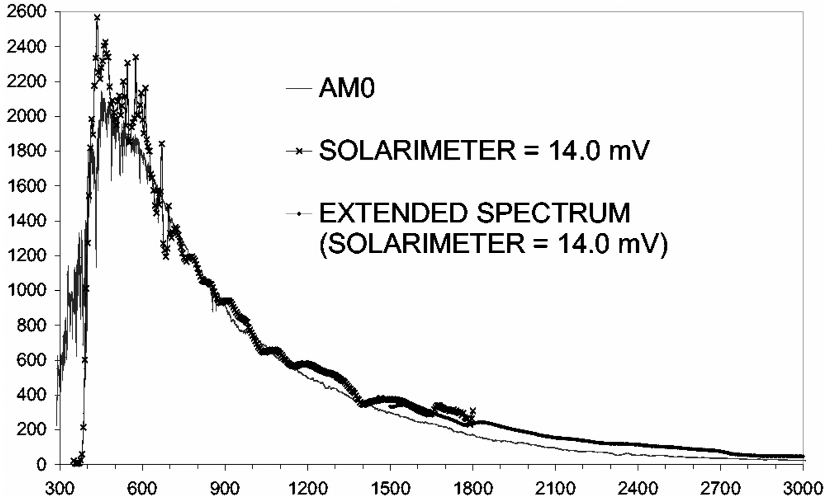

Fig. 3. Measured extended solar simulator spectrum ($W/m^2/nm \times 10^3$) for $\lambda > 1500$ nm.

thermopile. The solarimeter is basically a calibrated blackbody, accurate and stable over 5+ years to $\pm 2\%$. It is used over long times to adjust the power of the lamps and compensate for their ageing. During continuous operation, the beam intensity is monitored and controlled by means of a feedback PID photodiode which reads a portion of the beam with a small optical prism.

4.1. *The LAGEOS "matrix" prototype*

An array of 3×3 CCR's has been built at LNF, following the traditional LAGEOS CCR mounting configuration (see Fig. 4). This matrix contains nine LAGEOS-type CCRs, KEL-F plastic mounting rings, Al retainer rings and screws (three per CCR).

5. Thermal Simulations and Experimental Measurements

The simulations have been performed with a commercial specialized satellite software by C&R–Tech (www.crtech.com), Thermal Desktop (geometric thermal modeler) + RadCad (radiation analysis module) + Sinda-Fluint (solver) + orbital simulator, indicated with TRS in the rest of the paper. We expect to iterate several times between SCF measurements and TRS simulations.

The overall strategy of the program is described in the following:

(i) Hold the average temperature of the Al body of the prototype, $T(\mathrm{AL})$, to the expected value of $300\,\mathrm{K}^5$ and measure in the SCF:

   (a) emissivity (ϵ) and reflectivity (ρ) of CCR's and Al retainer rings;
   (b) τ_{CCR} and, similarly, for the Al retainers, τ_{AL};
   (c) surface temperature distribution (i.e. thermal forces).

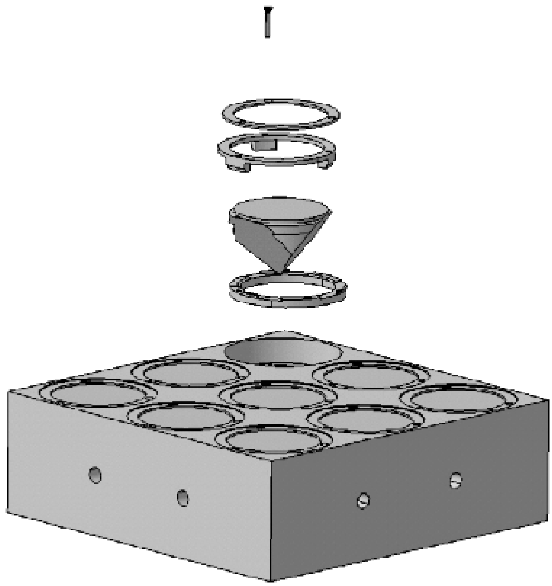

Fig. 4. LAGEOS CCR assembly. The assembly elements facing outside (and, therefore, causing thermal thrusts) are the CCR's and the Al retainer rings (screws can be neglected).

(ii) Repeat all of the above for $T(\mathrm{AL})$ different from 300 K; we are also considering changing ϵ and ρ of the Al body by modifying the surface finish, in both a uniform and a nonuniform way.

(iii) 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.

(iv) Use the validated TRS models to predict the LAGEOS and LARES behavior along their full orbits using the TRS orbital simulator.

(v) The sequence of the prototype simulations and measurements will be:

   (a) Test the LNF LAGEOS matrix in detail; a LAGEOS I sector from NASA-GSFC may become available for testing at the SCF in September 2006.
   (b) Use the matrix results to simulate and optimize the design of LARES in order to reduce the thermal forces wrt LAGEOS.
   (c) Build a LARES prototype and test it in the SCF.

(vi) Test the effect of satellite spin, first in the simulation and then in the SCF.

5.1. *Simulation results for the matrix*

τ_{CCR} has been estimated from TRS for various climatic conditions and values of $T(\mathrm{AL})$. For example, Fig. 5 shows the temperature variation of the front face of the CCR, $T(\mathrm{CCR})$, in the case of illumination by the Sun for $T(\mathrm{AL}) = 300\,\mathrm{K}$. Figure 6 shows τ_{CCR} vs $T_{\mathrm{avg}} = \frac{1}{2}(T_{t=\infty} + T_{t=0})$. $T(\mathrm{CCR})$ is a strong function of the CCR

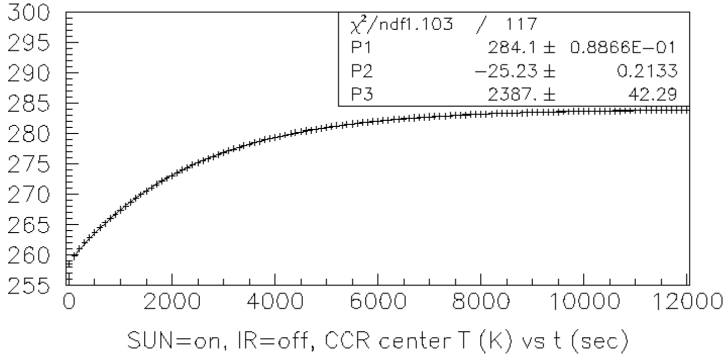

Fig. 5. LAGEOS matrix. Exponential fit to T(CCR) vs time in the simulation when the Sun is turned on at t > 0, $\alpha_{\mathrm{Sun}} = 15\%$ and $T(\mathrm{AL}) = 300\,\mathrm{K}$. P3 = τ_{CCR} in seconds. This data assume a temperature accuracy of 0.5 K.

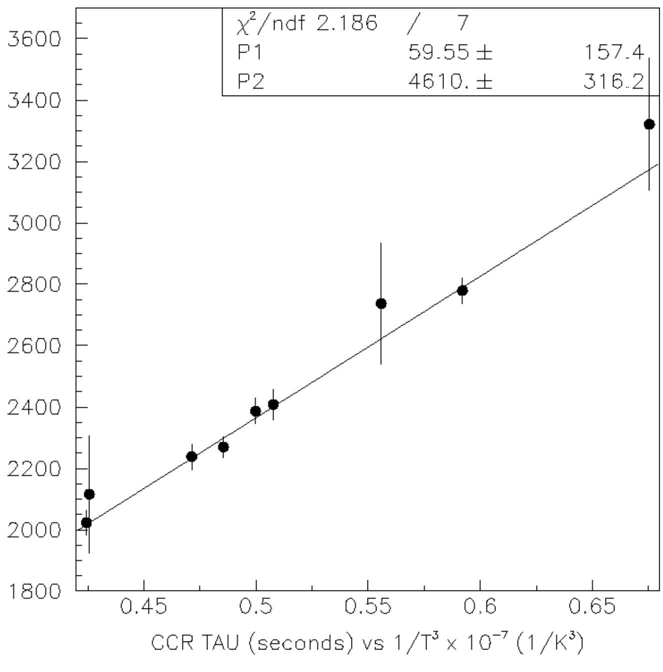

Fig. 6. LAGEOS matrix. τ_{CCR} vs $1/T^3_{\mathrm{avg}} \times 10^{-7}$ in the simulation for $\alpha_{\mathrm{Sun}} = 15\%$. Each point is a different set of conditions in terms of the Sun and Earth radiations, angle of exposure and value of T(AL). For example, the first point is for $T(\mathrm{AL}) = 320\,\mathrm{K}$, Sun = on, IR = off; the last point is for $T(\mathrm{AL}) = 280\,\mathrm{K}$, Sun = on, IR = on. All other points are for $T(\mathrm{AL}) = 300\,\mathrm{K}$.

solar absorptivity, α_{Sun}. Figure 7 shows the effect of a change of α_{Sun} from 15% (adopted in Ref. 5) to 1.5%.

We also studied the effect of ageing of the satellite aluminum surface, by varying its emissivity from $\epsilon(\mathrm{AL}) = 0.05$ (the value for LAGEOS II before launch[5]), 0.2

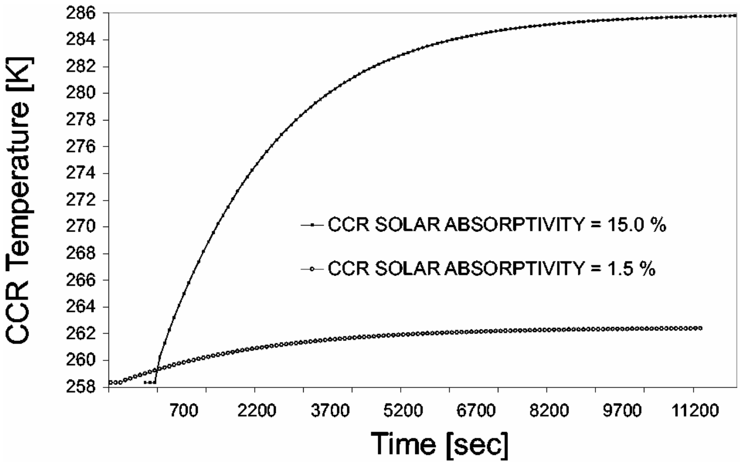

Fig. 7. LAGEOS matrix. Warm-up time of the CCR for $\alpha_{\mathrm{Sun}} = 15\%$ (top) and 1.5% (bottom).

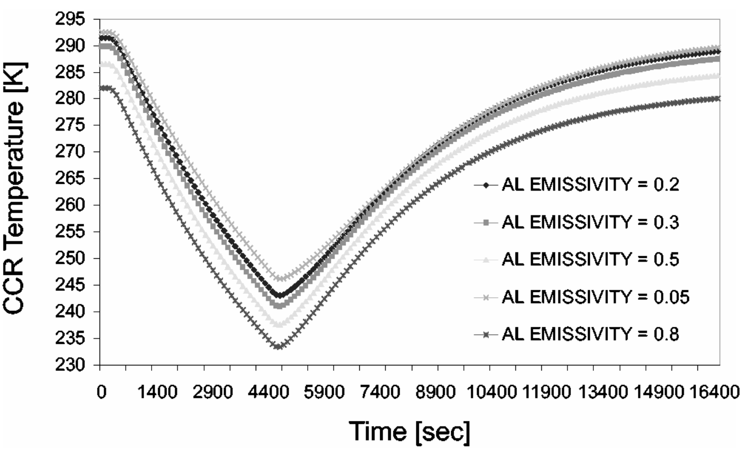

Fig. 8. LAGEOS matrix. Effect of Al ageing on $T(\mathrm{CCR})$ for $\alpha_{\mathrm{Sun}} = 15\%$. Sun off between 200 s and 4700 s (Earth shadow). The higher the value of $\epsilon(\mathrm{AL})$, the lower the $T(\mathrm{CCR})$ curve.

(the value for LAGEOS I before launch[5]) to 0.3, 0.5 and 0.8. This causes $T(\mathrm{AL})$ to change wrt 300 K (the value for no ageing). $T(\mathrm{CCR})$ is also changed by the ageing of the aluminum (see Fig. 8), but the variation of τ_{CCR} (i.e. the shape of $T(\mathrm{CCR})$ vs time) is not significant within our target accuracy, $\sigma(\tau_{\mathrm{CCR}})/\tau_{\mathrm{CCR}} \leq 10\%$.

5.2. *Parametric model of the LAGEOS thermal forces*

A full thermal analysis of LAGEOS is in progress, but it will be completed after the detailed analysis of the matrix. However, in the meantime, a simplified and parametric model of the thermal forces experienced by LAGEOS has been done, which shows the capability of the TRS software and some of the basic features of the thermal NGP's.

The simulated SCF 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 s, (4) zero thermal conductance between the Al retainer screws and the Al satellite body. This configuration can be easiily implemented in the SCF and it mimics, approximately, the satellite passage through the Earth shadow and a satellite spin directed along the ecliptic plane. The thermal thrusts are estimated in a parametrized way, using a single CCR in a cavity of an aluminum block held fixed at 300 K. For each 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 CCR's in a row, of all rows and of the two hemispheres, is then summed. The results are shown in Fig. 9 (same climatic conditions as in Fig. 8).

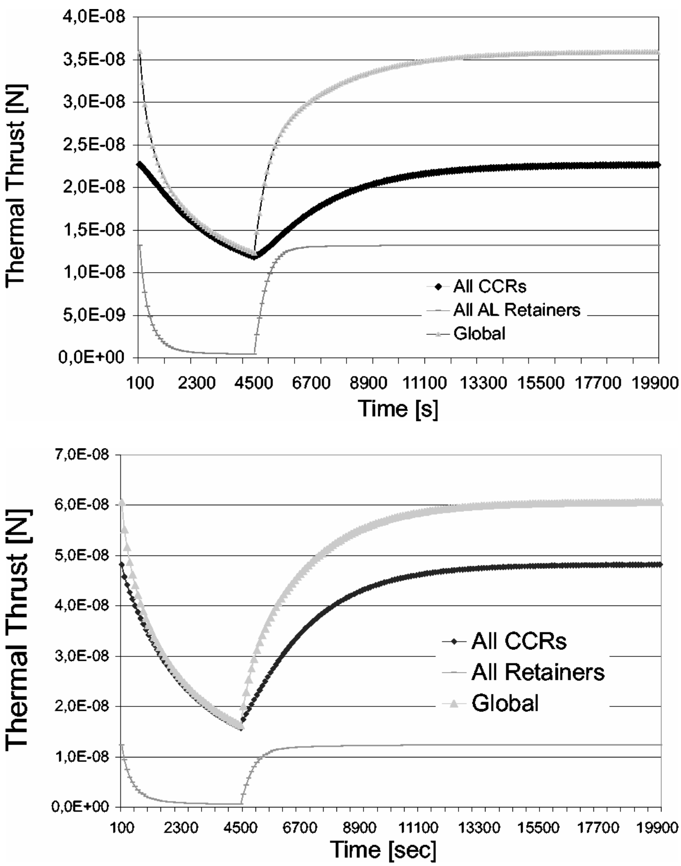

Fig. 9. LAGEOS parametric model. Estimate of the thermal thrusts on the satellite due to the SCF Sun and Earth simulators for $\alpha_{\mathrm{Sun}} = 1.5\%$ (top plot) and $\alpha_{\mathrm{Sun}} = 15\%$ (bottom plot).

6. Proposal of a New LARES Design

An original design has been developed at LNF[6] to strongly suppress thermal forces. This "shell-over-the-core" design consists of two outer aluminum half-shells, which host the CCR's, and an inner massive spheroidal core, which provides an area–mass ratio less than or equal to the LAGEOS value. The basic idea is to mount CCR's from the inside on the shells, which in turn are screwed over the core, leaving a vacuum gap in between. Since the Al retainer rings will be replaced by retainer seats machined directly from the Al shells, this CCR "back-mounting" option will entirely remove the significant thermal forces due to the Al rings. In addition, some significant thermal radiation released in the gap by warm, illuminated CCR's can thus propagate to colder CCR's in a dark region. This must be aided by a proper choice of the thermo-optical parameters of the inner core, which has yet to be optimized. The goal is to make $T(\mathrm{CCR})$ more uniform than for LAGEOS. A full thermal simulation is in an advanced stage and a 1:2 scale prototype has been built at LNF to test the effectiveness of this new design at the SCF (see. Fig. 10).

7. Completion of the SCF "System Test"

The last major component of the SCF, the solar simulator, has been delivered to LNF at the beginning of July 2006. The following month has been devoted to a system test of the whole apparatus and of the main procedures using the LAGEOS matrix. The test included the combined operation of: cryostat (cooled down to 85 K in a few hours), vacuum vessel (down to 3×10^{-6} mbar), temperature measurement with PT100 probes, temperature control of the Al matrix block with thermocoolers, use of vacuum feedthroughs and irradiation with the AM0 beam (with reduction of the beam to the matrix size with a shroud). The test has been successful and

Fig. 10. 1:2 scale prototype of the new shell-over-the-core LARES design built at LNF.

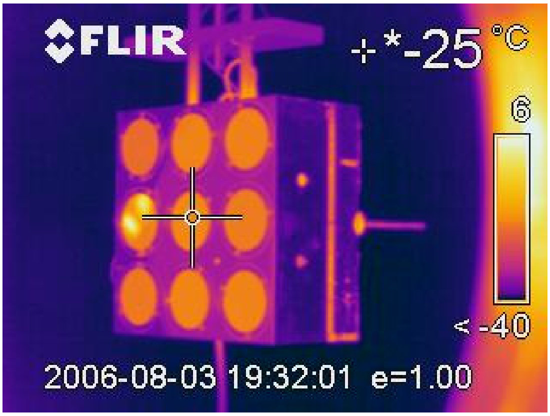

Fig. 11. Thermogram of the LAGEOS matrix taken with the IR camera through the Ge window.

has shown two problems (already solved): one of the feedthroughs did not keep the vacuum and prevented temperature control; the tungsten lamp could barely be operated at maximum power (this was because the voltage in Italy is typically 220 V instead of the 240 V in the UK, where the simulator has been built). Two brand-new feedthroughs have been purchased and delivered; the spare 10 KW tungsten lamp has been swapped with a 12 KW lamp at no exta cost. Figure 11 shows a thermogram of the matrix taken during the cooldown of the SCF with the IR camera.

The digital IR camera has been extensively tested separately and its performance found to be within specs. In an inside test, in air and at room temperature, it was used to estimate the infrared emissivity and reflectivity of the CCR's and the aluminum of the LAGEOS matrix [ϵ(CCR) ~ 0.82, ϵ(AL) ~ 0.15] with a-few-% accuracy.

8. Other Applications of the SCF

An optical test is being set up at LNF for the measurement of far field diffraction patterns of retroreflector arrays in absolute units. Ultimately, this test will be done with the prototypes inside the SCF, thus merging, to a large extent, the thermal and the optical facilities.

Preliminary optical calculations of the expected laser performance of LARES have been carried out. These are based on the baseline assumption that the outer surface of the new satellite will look like LAGEOS, with the diameter scaled from 60 to 30 cm. LARES will have 102 CCR's, versus the 426 of LAGEOS. The calculations indicate that the laser return will be 1–1.5 CCR's and that the expected ranging fluctuations of LAGEOS and LARES will be similar (the smaller radius compensates for the larger number of CCR's).

The LNF group proposes to use these two facilities for the thermal and laser characterization of CCR arrays foreseen on future GNSS[d] constellations (GPS-3 and GALILEO), in close collaboration with ILRS, NASA-GSFC and UMCP.

Answering a call for proposals for the 2006–2008 study by ASI, LNF has also proposed to participate in the design and test of the laser-ranged test masses for the Deep Space Gravity Probe (DSGP) mission, which is being conceived to accurately study the Pioneer effect, as well as to perform important (inter)planetary science investigations. With minor upgrades, the SCF is capable of performing test measurements for SLR in the outer solar system for DSGP, which is a formation of an active spacecraft and a few SLR masses. These upgrades consist in the attenuation of the AM0 solar beam with a set of appropriate wire meshes (which do not distort the spectrum) and in the adoption of cryocoolers, in order to cool down prototypes to temperatures below that of liquid nitrogen. The first of these upgrades has been suggested by the vendor of the solar simulator, which comes with built-in provisions for installing the wire meshes. The IR radiation of planets of the outer solar system can be simulated with black disks of varying size and distance from the prototypes. Note that the observed and unexplained Pioneer 10 and 11 decelerations are about a-factor-of-10 *larger* than typical LAGEOS thermal accelerations. Finally, the typical distances which are foreseen between the active DSGP spacecraft (equipped with the laser) and the SLR test masses are in the kilometer range: therefore, the expensive complication of CCR dihedral angle offsets can be avoided.

9. Conclusions

This paper describes an 18-month preparation of a Space Climatic Facility at INFN-LNF dedicated to the complete thermal and (though less advanced) optical characterization of high-accuracy laser-ranged test masses to probe gravity in NEO's. The main goal is to improve the 10% measurement of the frame-dragging effect currently achieved with LAGEOS down to an accuracy $\leq 1\%$ with the new LARES mission. This second generation satellite, in addition to LAGEOS I and II, would be very valuable also in space geodesy, to strengthen and improve the definition of the International Terrestrial Reference Frame (ITRF). This latter application of the SCF will be further expanded in the near future with the proposed test of retro-reflector arrays for GPS-3 and GALILEO in collaboration with ILRS, NASA-GSFC and UMCP.

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