THERMAL INFLUENCE OF THE SCREW AXIAL LOAD ON A ONE-MILLIMETER ACCURACY LASER RANGED SATELLITE

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This study is an excerpt from my M.Sc. thesis 'Thermal analysis of the nextgeneration laser retroreflector payloads for advanced space application', developed at SCF_Lab of INFN. It explores the role of the screw axial load on the temperature experienced by the mounting set of a CCR in a spherical satellite, designed to achieve one-millimeter accuracy in SLR. Since thermal gradients inside CCRs induce refractive index gradients, changing the optical behaviour, thermal analysis and simulation are needed in order to ensure the best performances. The screw axial load influences the thermal interface resistances between the rings of the mounting set, changing their thermal behaviour. It is important to study the temperature not only for the thermal gradients inside a CCR, but also to check that the Kel-F mounting rings do not overcome their maximum operative temperature. Two models have been realized in the commercial software C&R Thermal Desktop: a model to simulate the entire satellite behaviour and a detailed model to represent the cavity within which CCR and mounting set are placed. Different on-orbit scenarios are analyzed, focusing on the influence of the screw axial load in each of them. The paper is organized as follows: first CCR and SLR are introduced, with particular emphasis on the satellite studied in the work; then the models and their building steps are highlighted; finally, the results are presented showing the screw axial load influence.

Nomenclature

Acronyms / Abbreviations

ASI	=	Agenzia Spaziale Italiana (Italian Space Agency)
CCR	=	Cube Corner Retroreflector
COTS	=	Commercial-Of-The-Shelf
DAO	=	Dihedral Angle Offset
INFN	=	Istituto Nazionale di Fisica Nucleare (National Institute for Nuclear Physics)
ITRF	=	International Terrestrial Reference Frame
FFDP	=	Far-Field Diffraction Pattern

$LAGEOS$	=	LAser GEOdynamics Satellites
$LARES$	=	LAser RElativity Satellites
LRA	=	Laser Retroreflector Array
$NASA$	=	National Aeronautics and Space Administration
SAL	=	Screw Axial Load
SCF_Lab	=	Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory
SLR	=	Satellite Laser Ranging
TD	=	Thermal Desktop

I. Introduction

SLR is an accurate positioning technique based on the ToF measurement of ultra-short laser pulses, transmitted from a ground station to a satellite equipped with CCR arrays. It provides range measurements with an accuracy of some millimeters, which are used to compute the geocentric position of Earth satellites: this technique provides the standard long wavelength gravity field reference model to support precision orbit determination. SLR is the most accurate technique that provides satellites positioning in space with the respect to the ITRF. [1]

CCRs are retroreflector prisms, obtained from a cube corner. Their main characteristic is to reflect an electromagnetic wave in the same incident direction, thanks to the total internal reflection of the incident ray (coming from the front face) on the back faces. To allow the retroreflection, it is not needed that the ray comes orthogonal to the face of the CCR, but there is a critical angle: if the incidence angle is lower, the ray is totally reflected by the CCR, whereas it is larger, the ray does not go out the prism. Spherical satellite for SLR are equipped solid uncoated CCRs: they are quartz prisms obtained from a fused silica cube corner.[2]

The first attempt to realize a satellite devoted to laser ranging goes back to the first LAGEOS NASA mission. The satellite, launched on 4 May 1976, is an aluminium-covered brass sphere, with radius of 30 cm and it is covered by 426 CCRs. An identical satellite, called LAGEOS-2, has been deployed on 23 October 1992. Both satellites are on a low eccentricity orbit with an altitude around 5900 km. LAGEOS-1 has an inclination of 109.83°, whereas LAGEOS-2 has an inclination around 52.65°; this has been done to obtain complementary measurements.[3] LARES is a new generation CCRs satellite, designed by NASA-ASI and launched on 13 February 2012. The principle of the satellite is the same with LAGEOS, but its design is slightly different from them. It is a tungsten alloy sphere (with radius 18.2 cm) covered by 92 CCRs. The orbit is characterized by very low eccentricity, an altitude of 1450 km and an inclination of 69.5°. [4]

II. Thermal effect on CCR and spherical satellite design for one-millimeter accuracy

Fused silica CCRs are characterized by very low thermal expansion, so this effect can be neglected. There are two temperature effects that have to be studied because they can change the CCR optical behaviour. The first one is related to the absolute mean temperature, but, over a large scale of temperatures, it is negligible and it does not affect the CCR optical performance. The second effect is related to the thermal gradient inside the CCR: they imply refractive index gradients proportional to $10^{-5}/K$ (at 300K for fused silica). This is dangerous because for small CCR, the FFDP is seriously altered, degrading the laser return at the ground. This is the reason why the mounting structure of the CCR has to be designed carefully: FFDP is extremely sensitive to the detailed mechanical and thermal properties of the structure in which CCRs are mounted to form the LRA. Thermal gradient effects can be minimize in two ways: using smaller CCRs to reduce the optical path length and reducing front face thermal radiation keeping the CCR as cold as possible. This second thermal behaviour effect and its coupling with the surrounding structure is one of the focus of this study. [5]

In the early 1970s, before the launch, studies done for LAGEOS showed that the use of smaller CCRs would increase the accuracy and decrease thermal gradients. The lower is the dimension of the CCRs, the higher is the number of them needed to obtain the necessary cross-section; this leads clearly to a significant cost impact. During those years, simulations showed that the accuracy goal could be meet by using less uncoated CCRs, but with larger diameter (38.1mm); so, for financial reason, the smaller CCRs have been shelved. During the last years, COTS CCR's development eliminated the cost obstacle for small CCR payload arrays. These commercial CCRs have no DAO, but to maximize the cross-section it is possible to choose their diameter properly. It has been shown that for LAGEOS altitude, 25.4mm diameter CCRs with no DAO maximize the cross-section. Due to manufacturing errors, COTS CCRs may always present some DAOs, so they have to be accurately analysed in size and thermo-optical behaviour. To further decrease the thermal gradient effects, it has been thought to decouple the CCRs from the core, by means of floating mounts (already used on LAGEOS and LARES) and a low emissivity of the mounting cavity, to reduce the radiation heating of the cube corner. The floating mount is characterized by a reduced contact between the CCR and its surrounding. Its thermal and mechanical behaviours have to be analyzed accurately in order to ensure its feasibility. So, to reach an accuracy of 1mm, despite the LAGEOS goals of 5mm, it has been thought a Nickel alloy spherical satellite (with radius around 202mm) made of 303 CCRs with diameter of 25.4mm and characterized by floating mounts.[6]

III. Satellite Model

Thermal modelling and simulations have been performed with the commercial software Thermal Desktop by Cullimore&Ring. To represent the real behaviour, two models have been realized: one to model the entire satellite, without modelling the real shape of the components, needed to obtain the satellite surface temperature and a second detailed model representing the real shape of a cavity with its components.

A. Sphere

The satellite is a Nickel alloy sphere with radius 202mm. It is covered by 303 CCRs (25.4mm diameter), needed to obtain the necessary cross-section. The CCRs have been placed on a fictitious sphere slightly larger (about 3mm) than the solid, so that modelling is easier and the average distance between core and CCR is represented properly for the thermal radiation exchanges. The CCRs configuration is inspired by LAGEOS satellites, where circular arrays of retroreflectors are placed on the sphere parallels (Fig. 1). The real architecture will depend on the required optical

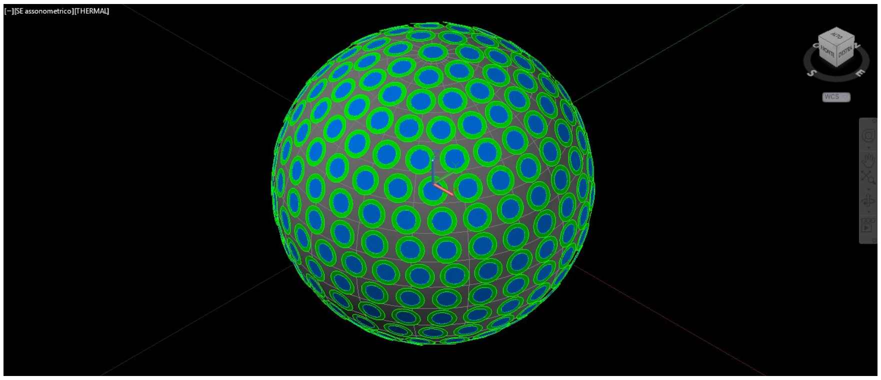

Fig. 1 3D sphere model in TD.

behaviour of the satellite and it is outside the scope of this study. For this study, the configuration represented in Table 1 has been chosen: there is one CCR per pole, while the others are distributed over 15 parallels arrays.

Table 1 CCR arrays configuration

Parallel Latitude	Number of CCRs
0°	29
10.5°	27
21°	26
31.5°	24
42°	21
52.5°	18
63°	13
73.5°	7

It is important to note that a different configuration would affect the optical performance, but not significantly the thermal behaviour of the satellite, so the results came out from this simulation can be used also for another CCRs configuration. This happens because the total area of the core sphere exposed to the thermal radiation (from the Sun and the Earth) is the same, no matter on the CCRs configuration; so, the number of CCRs is the important parameter, because it defines the exposed surface, but once it has been fixed, the configuration does not change the average sphere thermal behaviour. This is valid if the configuration is isotropic or at least not strongly anisotropic.

B. Cavity

The cavity is composed by the hole in the core, the mounting set and the CCR. Also the mounting rings set is inspired by LAGEOS one, but it has to be modified in order to sustain a CCR without tabs. The mounting set for the new satellite presents: Nickel alloy retainer ring, two Kel-F mounting rings, ring spacer between Kel-F rings and three Nickel alloy screws. It has been designed in this way to simplify the geometry of the rings and to support a CCR without tabs. The cavity has the same LAGEOS one's shape. Each component has been represented in the detailed TD model (Fig. 2, Fig. 3 & Fig. 4).

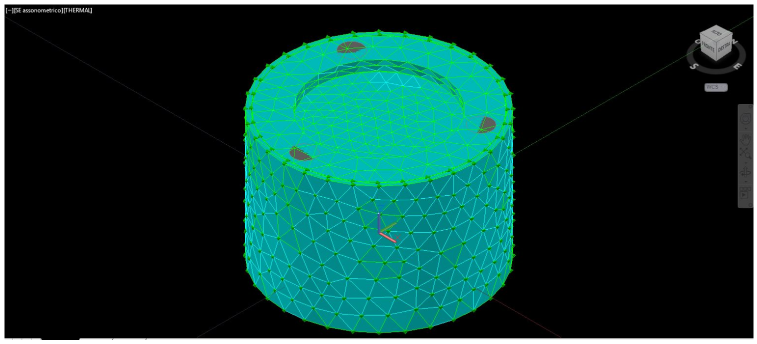

Fig. 2 3D full cavity model in TD.

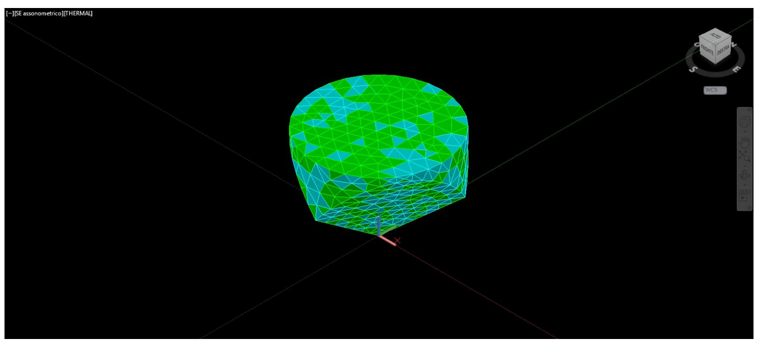

Fig. 3 3D CCR model in TD.

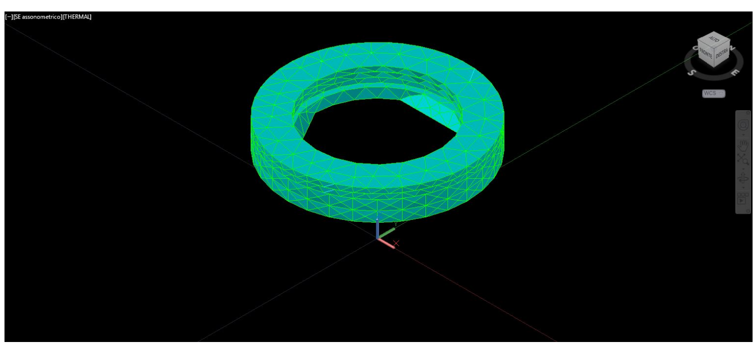

Fig. 4 3D rings model in TD.

C. Thermal Model and Screw Axial Load

In TD it is possible to assign a material to each surface or solid element. Each material is characterized by its thermal and optical properties, which are needed from the software to compute the radiation on-orbit exchanges. Conductive exchanges are simulated by means of contactors, which are TD's elements that allow to link thermally two surfaces defining the conductance between them. To obtain the interface conductance between the components, the Mikic model has been used [7]. The theory is based on materials properties and on some basic relations. The following formula describes the interface conductance:

$$h_c = 1.55\frac{Km}{\sigma}\left(\frac{\sqrt{2}P}{Em}\right)^{0.94} \left[\frac{W}{m^2K}\right] \tag{1}$$

where K is the effective interface conductivity, dependent on the materials conductivity, σ and m are respectively the Root Mean Square values for surface roughness and asperity slopes, E is the effective elastic module, dependent on materials Young's module and Poisson coefficient and P is the apparent contact pressure. It is not common to know the real value of the asperity slope, so it is possible to use the approximated value obtained from the correlation equation proposed by Antonetti et al. [8]:

$$m = 0.125(\sigma 10^6)^{0.402} \tag{2}$$

which is valid in a surface roughness range:

$$0.216\mu m < \sigma < 9.6\mu m \tag{3}$$

In the first model it is necessary to calculate the total conductance between the 303 retainer rings and the sphere, which depends on interface conductances and thermal resistances of each component. In the second model it is necessary to specify each interface conductance, but not the resistance along the component.

The mounting set is characterized by three screws providing an axial load to the rings. The value has to be as low as possible to reduce the conduction, but it has to be enough to allow the floating mount and to respects the structural requirements. Another important parameter for the computation is the surface roughness, but it is not easy to evaluate: experimental tests are needed to obtain the real value. Kel-F and INCONEL-718 (Nickel alloy chosen for these simulations) rings are manufactured by milling and the mean value of surface roughness obtained with this manufacturing process is around $3.2\mu m$. Two kinds of contact have to be analyzed:

- INCONEL-718-INCONEL-718, for the contacts screws-retainer ring and screws-sphere;
- Kel-F-INCONEL-718, for the contacts between rings.

So it is possible to compute the parameter needed for the equivalent conductance calculation. The ratainer ring is connected to the sphere by the mounting system, composed by seven resistances in series: three rings resistances and four interface resistances. The retainer ring is also connected to the sphere by means of the three screws, which are other three series of resistances, that have to be considered in parallel with the mounting set. Each equivalent screw resistance is composed by the interface resistance between ring and screw head, the interface resistance between the sphere and the helical part of the screw (assumed equal to the first one) and the resistance along the screw length. In this study, radiation exchange resistances are negligible because the expected temperatures are well below 300°C.

To compute the equivalent resistance it is not possible to use thermal specific resistances, since along the series the apparent contact area changes depending on the interface considered:

$$R = \frac{l}{\lambda A} \tag{4}$$

where l is the characteristic length, A the area trough which the heat flows and λ is the thermal conductivity. So the equivalent conductance between a retainer ring and the sphere can be computed as follows:

$$R_{tot} = \frac{R_{ms}R_{scr}}{3R_{ms} + R_{scr}} \tag{5}$$

where R_{ms} and R_{scr} are respectively the equivalent resistances of the mounting set and the screw, considered in parallel. So the conductance is:

$$C_{eq} = R_{tot}^{-1} \tag{6}$$

Since this value corresponds to one mounting set, it has to be multiplied by 303 to obtain the total equivalent conductance between retainer rings and sphere (value required by TD):

$$C_{tot} = 303C_{eq} \tag{7}$$

The screw axial load does not influence the along-thickness resistances of the components, but as it has been remarked several times, it influences the interface resistances, because the pressure P in the Mikic formula is defined as:

$$P = \frac{F}{A_{contact}} \tag{8}$$

where $A_{contact}$ is the interface apparent contact area. The plot (Fig. 5) represents the total equivalent conductance between retainer rings and sphere with different axial loads. As long as the load increases, the contact pressure rises and so on also the contact area is higher. More contact means more heat conduction, so, as the plot shows, an increase of the axial load will produce an increase of the heat conduction and subsequently the temperatures of the components under examination (Kel-F Rings and CCR) can rise. So the nominal axial load has to be chosen carefully to allow an acceptable thermal behaviour of the components but also a mechanical stability: a compromise is needed. Slabinski in its work reported, for LAGEOS, an axial load of 7N for each screw, so, for this study, two cases have been selected for the simulations: 10N and 30N. Thanks to these two cases, it is possible to check different behaviours depending on the screws axial load.

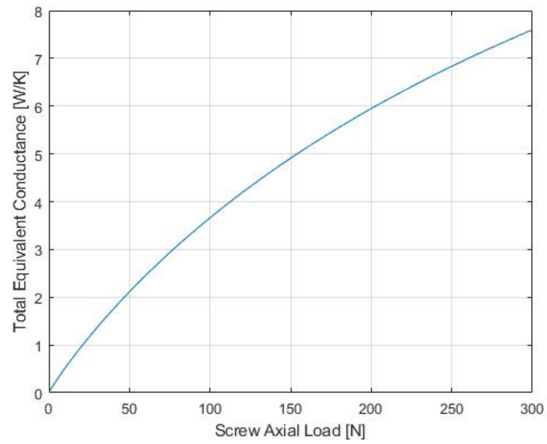

Fig. 5 Total Equivalent Conductance vs Axial Load.

IV. Simulations and results

Orbit parameters can be specified (the same with LAGEOS, but with LARES inclination), as well as the angle between the orbital plane and the Sun direction, called Beta Angle. It quantifies the on-orbit satellite thermal budget, since it defines the solar incidence and the time spent by the satellite in the Earth's shadow cone. The BA varies through time due to the solar motion across the ecliptic and to Earth's oblateness perturbation [9]. Studies showed that in around two years, no matter on the initial condition of the orbit, the satellite would encounter all the BAs between -90° and 90°, so, since the satellite's operative life is well larger than two years, four BAs have been considered for the simulation: 0°, 20°, 45° and 80°, to cover all the possible on-orbit scenarios.

Simulations showed that the sphere's maximum temperature increases with the increase of the BA, as it was easy to expect, since as long as the angle increases, the satellite spends less time in the Earth's shadow cone where its temperature decreases.

Moreover, to cover more on-orbit situations, three cavities (with CCR and rings) have been considered:

- N=cavity in the direction normal to the orbit;
- T=cavity in the Earth direction;
- V=cavity aligned with the orbital velocity of the satellite.

A. Thermal gradient

Simulation showed a temperature differences between the top and the bottom of the CCR within 3K (Table 2).

The time behaviour of the gradients is not completely constant, but it does not present huge oscillations. The worst case is for the BA=45° (Fig. 6). The results show that the screw axial load does not play a significant role in the CCR thermal gradient, as it was expected since the thermal contact between rings and CCR is not simulated, imaging a perfectly floating mount configuration.

Table 2 CCR thermal mean thermal gradients

BA-SAL	N	T	V
0°-10N	2.53	2.27	2.34
0°-30N	2.49	2.26	2.53
20°-10N	2.62	2.37	2.43
20°-30N	2.61	2.36	2.63
45°-10N	3.00	2.54	2.98
45°-30N	3.01	2.75	2.98
80°-10N	2.93	2.71	2.94
80°-30N	2.96	2.70	2.94

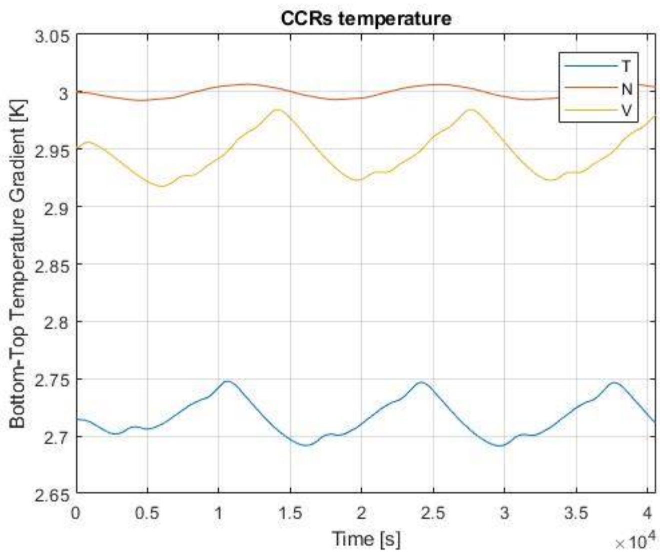

Fig. 6 Thermal gradients (BA=45° & SAL=30N).

B. Rings temperature

Rings temperatures vary across a wide range of values, depending on the cavity considered, the Beta Angle and the screw axial load. For the retainer ring, the lowest temperature, achieved by the N cavity for BA=0° and SAL=10N, is around 297K, while the worst condition is for BA=80° and SAL=10N, for the N cavity, when the ring reaches around 397K (Fig. 7). This is also the worst condition for the Kel-F rings, since the upper mounting ring reaches around 358K. Usually, an increase of the SAL produces a reduction of the retainer ring temperature and an increase of the Kel-F rings temperature; the differences (due to the SAL) depend on the scenario, but for the retainer rings they are between 5K and 25K, while for the Kel-F rings they are few degrees (until 7K). The highest difference in temperature of the retainer ring, due to an higher SAL, corresponds to the worst case already reported: in this scenario, an increase of the SAL to 30N would produce a decrease of the temperature from 397K to 372K. These effects are justified by the fact that usually the retainer ring is hotter than the sphere and mounting rings, so an increase of the load would produce an increase of the conduction coefficient with a consequent increase of the mounting rings temperature (and of course a decrease of the

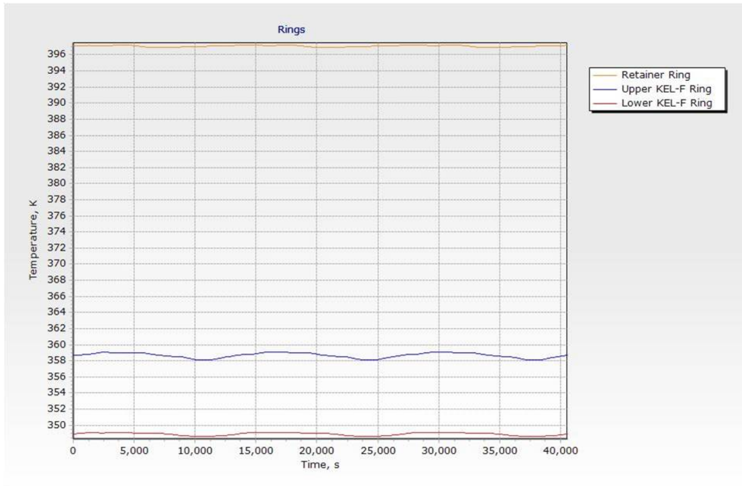

Fig. 7 N Rings temperature (BA=80° & SAL=10N).

retainer ring's temperature). This happens until the retainer ring temperature is high, but there are two exceptions:

- when the BA is 0°, the N cavity is not directly lighted by the Sun and the major thermal input to the mounting set rings is given by the conduction from the sphere: an increase of the SAL in this scenario would produce an increase of all the rings temperature;
- similarly, when the BA is 80°, V and T cavities are not lighted significantly by the Sun, so also in this scenario, the rings temperature increases with the increase of the SAL.

V. Conclusions and future developments

The simulations have been successful: an advanced and complete modelling of the components, that rule the satellite thermal behaviour, has been realized. They showed the feasibility of this satellite equipped with laser retrorelfectors. Results reported in the previous sections and paragraphs are just a small part of all the on-orbit situations: besides, just three out of 303 CCRs are considered for the analysis report, but they represent the limit conditions for the Earth laser ranging, since they are placed in the part of the satellite which looks towards the planet. Nevertheless, the results show an expected behaviour of the components:

- the CCRs present a mean thermal gradients along the length of around 2.5K, which is in line with the previous studies on LAGEOS and with the expectations;
- the Kel-F rings do not overcome the limit temperature, but since the real contact resistances have to be computed experimentally, it is fair to consider the Upper Kel-F rings temperature equal to the one of their Retainer rings, so a more critical study can be performed;
- CCRs do not overcome the temperature beyond which the absolute mean temperature becomes a problem for the optical behaviour.

This work can be considered the starting point for the development of a new satellite, but the required tests are needed in order to validate the thermo-optical model in TD: the interface conductance has been computed analytically, but it has to be computed experimentally directly or indirectly, by measuring the surface roughness. Once the model has been validated, the simulations have to be correlated with experimental test on the specimens in the thermo-vacuum climatic chamber of the SCF_Lab, to find the correspondence between the simulated and the tested behaviours.

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References

[1] `http://www.lnf.infn.it/esperimenti/etrusco/`.

[2] Degnan, J. J., "Millimeter accuracy satellite laser ranging: a review," *Contribution of Space Geodesy to Geodynamics*, Vol. 25, 1993.

[3] Slabinski, V. J., "A Numerical Solution for LAGEOS Thermal Thrust: the Rapid-Spin Case," *Celestial Mechanics and Dynamical Astronomy*, Vol. 66, 1996, pp. 131–179.

[4] `https://earth.esa.int/web/eoportal/satellite-missions/l/lares`.

[5] Dell'Agnello, S., and all, "Creation of the new industry-standard space test of laser retroreflectors for the GNS and LAGEOS," *Advances in Space Research*, Vol. 47, 2011, pp. 822–842.

[6] Arnold, D., "Thermal-Optical Design of a Geodetic Satellite for One Millimeter Accuracy," *https://cddis.nasa.gov/lw21/docs/2018/papers/Session3_Arnold_Paper.pdf*, 2018.

[7] Savija, I., Culham, J. R., and Yovanovich, M. M., "Effective thermophysical properties of thermal interface materials: part I definition and models," *Proceedings of IPACK03*, 2003.

[8] Yovanovich, M. M., Culham, J. R., and Teerstra, P., "Calculating interface resistance," *Electronics Cooling and Thermal Control*, Vol. 3, 1997.

[9] `https://mediaex-server.larc.nasa.gov/Academy/Play/ec22d75a55464d3798fb25cb1d4eab3a1d?catalog=8e500782c73d4bc2ad69cf59aec8420c21`.