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THE DESIGN OF LARES: A SATELLITE FOR TESTING GENERAL RELATIVITY

Authors

Prof. Ignazio Ciufolini (P.I.), University and INFN, Lecce , ITALY
ignazio.ciufolini@unile.it
Prof. Antonio Paolozzi, Scuola di Ingegneria Aerospaziale and INFN, “Sapienza” University of Rome, ITALY
antonio.paolozzi@uniroma1.it
Dr. Simone Dell'Agnello, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
simone.dellagnello@lnf.infn.it
Prof. Isidoro Peroni, Scuola di Ingegneria Aerospaziale, “Sapienza” University of Rome, ITALY
isidoro.peroni@uniroma1.it

Coauthors:

Prof. Filippo Graziani, Scuola di Ingegneria Aerospaziale, “Sapienza” University of Rome, ITALY
filippo.graziani@uniroma1.it
Dr. Giampiero Sindoni, DIAA Dipartimento di Ingegneria Aerospaziale e Astronautica, “Sapienza” University of Rome, ITALY
giampiero.sindoni@uniroma1.it
Dr. Claudio Paris, DIAA Dipartimento di Ingegneria Aerospaziale e Astronautica, “Sapienza” University of Rome, ITALY
claudio.paris@yahoo.it
Mr. Cristian Vendittozzi, DIAA Dipartimento di Ingegneria Aerospaziale e Astronautica, “Sapienza” University of Rome, ITALY
c.vendittozzi@gmail.com
Dr. Paolo Ialongo, DIAA Dipartimento di Ingegneria Aerospaziale e Astronautica, “Sapienza” University of Rome, ITALY
memento80@hotmail.it
Ms. Chiara Cerruti, Scuola di Ingegneria Aerospaziale, “Sapienza” University of Rome, ITALY
acerruti1@tin.it
Dr. Alessandro Lucantoni, Scuola di Ingegneria Aerospaziale, “Sapienza” University of Rome, ITALY
lukkio79@yahoo.it

Dr. Alessandro Boni, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
alessandro.boni@lnf.infn.it
Dr. Claudio Cantone, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
claudio.cantone@lnf.infn.it
Dr. Giovanni Delle Monache, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
giovanni.dellemonache@lnf.infn.it

Dr. Alberto Franceschi, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
alberto.franceschi@lnf.infn.it
Dr. Tommaso Napolitano, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
tommaso.napolitano@lnf.infn.it
Mr. Nicola Intaglietta, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
nicola.intaglietta@lnf.infn.it
Mr. Manuele Martini, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
manuele.martini@lnf.infn.it
Dr. Marco Garattini, Istituto Nazionale di Fisica Nucleare (INFN), Frascati (Rome), ITALY
marco.garattini@lnf.infn.it
Prof. Giovanni Bellettini, Department of Mathematics, University “Tor Vergata”, Rome, ITALY
belletti@mat.uniroma2.it
Dr. Roberto Tauraso, Department of Mathematics, University “Tor Vergata”, Rome, ITALY
tauraso@axp.mat.uniroma2.it

Dr. Laura Caputo, OMPM srl, Angri (SA) ITALY
lcaputo@ompm.it
Dr. Francesco Passeggio, OMPM srl, Angri (SA) ITALY
fpasseggio@ompm.it
Dr. Francesco Longobardo, OMPM srl, Angri (SA) ITALY
flongobardo@ompm.it

Prof. Erricos Pavlis, University of Maryland, Baltimore & NASA Goddard, MD, USA
epavlis@umbc.edu
Prof. Richard Matzner, University of Texas at Austin, Austin, TX, USA
matzner2@physics.utexas.edu
Dr. David P. Rubincam, NASA Goddard Space Flight Center, Greenbelt, MD, USA
David.P.Rubincam@nasa.gov
Prof. Douglas Currie, University of Maryland, College Park, MD, USA
currie@umd.edu
Dr. Victor J. Slabinski, US Naval Observatory, Washington DC , USA
slabinski.victor@usno.navy.mil
Dr. David. A. Arnold, 94 Pierce Road, Watertown, MA, USA
david-arnold@earthlink.net

ABSTRACT

The measurement of distance has always been a fundamental issue in science, engineering and astronomy in general. So far, laser ranging has been the most accurate technique for measuring the distance to the Moon and to artificial satellites and can therefore give a significant contribution to measure the tiny effects on orbital parameters due to General Relativity. LARES satellite design and its orbit will be optimized to perform high precision tests of Einstein's theory of General Relativity, in particular the direct measurement of the "frame dragging" effect. The paper will mainly address LARES design issues.

Introduction

LARES mission was first presented in response to an Italian Space Agency (ASI) call for ideas issued in 1997 [1,2]. LARES mission is an improvement of the LAGEOS III project proposed in 1986 by I. Ciufolini [3]. Some further developments are described in [4-7]. In 2004 INFN started to fund R&D for LARES in view of a future construction and launch of the satellite, in Ref [8] are reported preliminary thermal tests and simulation performed within this context.

"Frame dragging" effect

In 1918 Austrian physicists J. Lense and H. Thirring derived from Einstein's equations of General Relativity the twisting of the fabric of space-time around a spinning object, in other words, rotating masses drag space-time around themselves as they rotate. Similarly, as the Earth rotates, it pulls space-time in its vicinity and therefore will shift the orbits of satellites near the Earth.

This effect is called Frame dragging, or Lense Thirring (LT) effect (Fig. 1), it is so small that it has been hard to measure. The LAGEOS series (Tab. 1) was designed to be a passive long-lived satellite with a stable, well-defined orbit. As such, it functions as a reference point in inertial space.

An international ground-based network of laser ranging station is using the LAGEOS as passive reflectors to obtain ranges to the satellite by precision laser echo-bounce techniques. When a laser pulse is transmitted towards a Cube Corner Reflector (CCR) from a distance *R*, it is reflected back towards the source by the cube corner and arrives back at the sources at time $t=2R/c$.

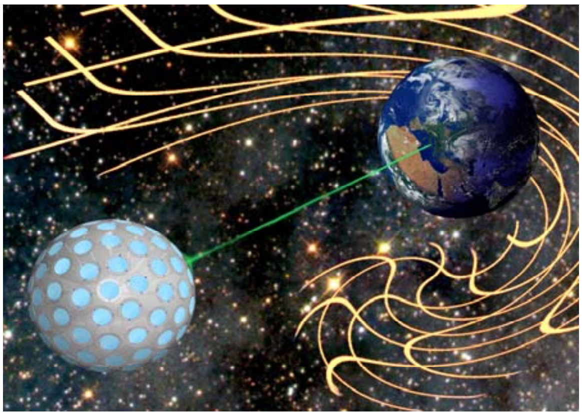

Fig. 1– Artistic view of the "Frame dragging" effect.

LAGEOS	DATE	VEHICLE	ORBIT (km)	MASS (kg)
I	05/04/76	DELTA 2913	5858 x 5958 incl. = 109.8 °	406.965
II	10/22/92	STS 52	5616 x 5950 incl. = 52.6 °	405.38

Tab.1 Main information on LAGEOS I and II.

Since *c* is known (actually one source of error is due to small uncertainties in the atmospheric portion of light propagation), then if time *t* can be measured accurately, the *R*-distance of the cube corner can be derived. This is the classic echo bounce experiment used in sonar and radar for many decades and the time-of-flight techniques used in particle physics. Since the position of the satellites is determined by some laser ranging stations with uncertainties of less than one centimeter, there was a potential for measuring the two meters per year drift of the nodes of LAGEOS due to the LT effect (Fig. 2). However, uncertainties in gravitational and non gravitational perturbations, on one single satellite, are bigger than the LT effect. Using a combination of satellites it is possible to reduce those uncertainties at about 10% of the LT effect [9]. The launch of LARES satellite can significantly reduce those uncertainties.

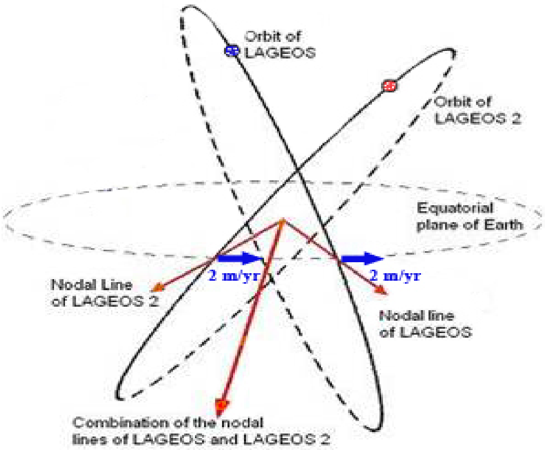

Fig.2 Frame dragging on LAGEOS I and II.

Main scientific objectives

- a series of high precision tests of Einstein's theory of General Relativity, in particular a measurement (about 1% accuracy) of the Lense-Thirring (frame dragging) effect due to the Earth's angular momentum and a high precision test of the Earth gravitomagnetic field;
- measurement of some Parametrized Post Newtonian (PPN) parameters;
- tests on the $1/r^2$ law in very weak field;

Requirements for the structure

Since the orbit of the LARES satellite will probably be lower than those of the two LAGEOS, the satellite should be designed in such a way to minimize all the non gravitational perturbations such as particle drag and thermal thrust, the latter induced by anisotropic blackbody radiation caused by the temperature difference over the satellite surface. Furthermore for a given satellite altitude, the gravitational perturbations can be reduced by choosing an optimal inclination of the orbit and by using a combination of data from LARES and the two LAGEOS as well as the new models of the gravitational field and the data from GRACE.

The non gravitational perturbations are of particular interest since, as mentioned, the orbit will probably be lower than those of the two LAGEOS. Therefore satellite design must be different with respect to that of LAGEOS. Fig. 3 shows a photograph of LAGEOS 2. The following will discuss the relevant aspects.

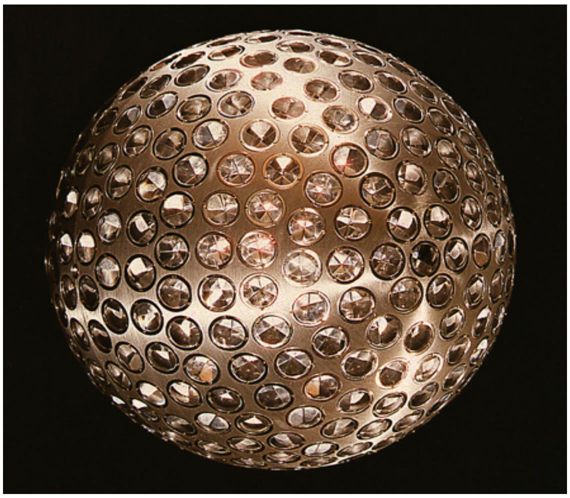

Fig.3 Photograph of LAGEOS II satellite.

Surface-to-mass ratio for the satellite

It is well known that the minimization of the cross-sectional area-to-mass ratio

$$\frac{S}{M}=\frac{3}{4\rho r}$$

where ρ is the mean satellite density and r its radius, is a critical parameter for a satellite to be used as proof-particle in the gravitational field of Earth. From this simple relation one deduces that the satellite should be very large. However due to obvious limitations on size and weight of space structures we cannot optimize looking only at parameter r. The main constraint in our case is the mass which at the moment has been established to be about 400 kg, i.e.

$$\frac{4}{3}\pi r^{3}\rho = 400kg$$

Consequently our optimization problem simplifies because the optimal condition will be obtained by taking the highest value for ρ. Fig. 4 shows all the elements with the highest densities in the periodic table: the bar length is proportional to the element density. The highest value is provided by osmium which reaches 22600 kg/m3. Second in the list is iridium. Osmium and iridium are valued, 12000 $/kg and 14000 $/kg, respectively, which is a bit over half the price of gold, at 22000 $/kg. Platinum's density is very high but price of 43000 $/kg is around twice that of gold. The price of rhenium put it out of the question since at the moment it is selling at 190000 $/kg. So in the hypothesis to be able to collect as much osmium as 400 kg, the cost of the row material would be about 4 million euros, iridium is a bit more expensive, but with a melting temperature much lower, 2410 °C instead of that of osmium of 3045 °C, which makes casting process much easier. The cost is certainly compatible with typical satellite cost budgets. However workability and procurement time for osmium or iridium would need to be checked. Consequently it seems at the moment that the best compromise is to use tungsten with a density of 19350 kg/m^3. However, pure tungsten is not workable and therefore a tungsten alloy should be considered for LARES. There are a variety of tungsten alloys some of which can reach a density as high as 18500 kg/m^3.

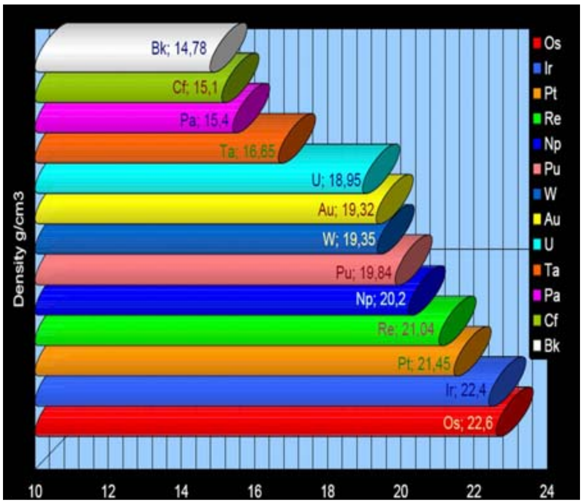

Fig. 4 - Element density.

Another parameter that affects the *S/M* ratio is the geometry of the cavity containing the CCRs. In order to minimize *S/M*, this cavity should be as small as possible. Fig. 5 and 6 show two possible solutions: i) cylindrical cavities (design directly derived from LAGEOS cavities) (Fig. 5) and ii) conical cavities that minimize *S/M* (Fig. 6).

Fig. 5 - LARES satellite with cylindrical cavities.

Fig. 6 - LARES satellite with conical cavities.

Fig. 7 shows the normalized *M/S* ratio as a function of satellite radius (lower curve). By normalized *M/S* ratio we mean:

$$\frac{M/S_{LARES}}{(M/S)_{LAGEOS}}$$

This quantity is very useful because it provides approximately the improvement factor for the error due to non gravitational perturbations. The red curve with triangular points provides the mass of the satellite as a function of satellite radius. The two curves are relevant to conical cavities and refers to the satellite completely assembled, i.e. containing all the CCRs and mounting systems. The tungsten alloy considered had a density of 18000 kg/m^3. If the cavities were cylindrical the values of *M/S* would be slightly worse. By considering an alloy at 18500 kg/m^3 the *M/S* ratio will be more favourable. The availability, workability and compatibility with respect to CCR and space environment need to be checked for such an alloy. From Fig. 7 it can be seen that with a radius of 180 mm the mass is about 390 kg with a *M/S* ratio 2.65 times higher than LAGEOS satellites. If extra payload mass is available on the launch vehicle one could gain more on the *M/S* ratio. For instance, for payload mass of 700 kg the normalized *M/S* ratio would reach about 3.4.

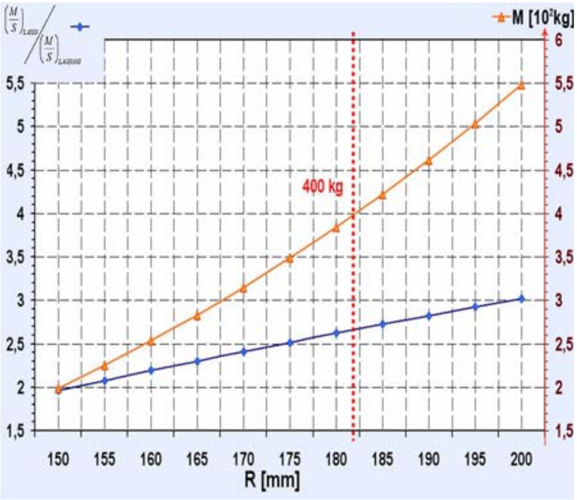

Fig. 7 - Normalized M/S ratio and mass as a function of LARES radius

It may be asked whether it could be more advantageous to have a higher density alloy, even if much more expensive (see above), or to have a heavier and bigger satellite made of tungsten alloy and pay more for the launch. To answer this question a relatively quick study can be performed but it is worth while only if a more expensive mission can be funded.

Number and position of CCRs on satellite surface

Another important issue to be addressed is the number of CCRs to mount on the satellite surface. Fig. 8 shows a sketch of the 15 cm radius LARES satellite with 102 CCRs.

The optimal number and position of CCRs depends on the following considerations:

1. A higher number of CCRs reduces the *M/S* ratio. The reduction is not drastic but needs to be considered.
2. A higher number of CCRs increases the reflective area of the satellite. For instance for a LARES satellite with 102 CCR arranged on a 15 cm diameter sphere the number of CCRs capable of reflecting light varies from 1.3 to 2.0 CCR equivalent, depending on the attitude of the satellite. So, for instance, a value of 1.5 could mean that

say three CCRs are reflecting half the maximum energy because of the non optimal orientation. In fact the energy reflected by a CCR is a function of: (i) the angle the incident light rays make with the normal to the front surface and (ii) the angle between the light polarization vector and the mounting azimuth that in Fig. 8 is represented by the three screws. In Fig. 8 for simplicity this last angle has been assumed equal for all the CCRs, but, as for LAGEOS, all adjacent CCRs will be rotated by a relative angle which must be calculated to optimize the average laser return for all attitudes.

3. A higher number of CCRs theoretically increases slightly the ranging accuracy, but on the other hand the laser return could become a composition of laser returns from different CCRs. That results in a wider (time wise) laser return pulse and in a more difficult accurate ranging determination. In order to have single CCR laser return, a large recess (the distance between CCR top surface and the circular upper edge of the cavity) would need to be considered. Single CCR return reduces reliability on laser return because there is no redundancy if one CCR should not work properly. However it should be noted that existing satellites intentionally built with a significant recess performed worse than expected. In addition, a recess on the CCRs will introduce an unknown effect induced by particle drag. It is therefore very likely that we are not going to apply any significant recess on the CCR.

4. One of the perturbations more difficult to estimate is the thermal thrust that is due to uneven temperature distribution over the satellite surface. The LARES team is working on dedicated measurements and software simulations to fully address this issue (Ref. [6]). Such an estimate will be improved by determining the satellite attitude from ground based photometric measurements of sun glints from the satellite or from spin signature contained on the returned laser pulses. Both techniques require a particular choice of CCR arrangement on the surface.

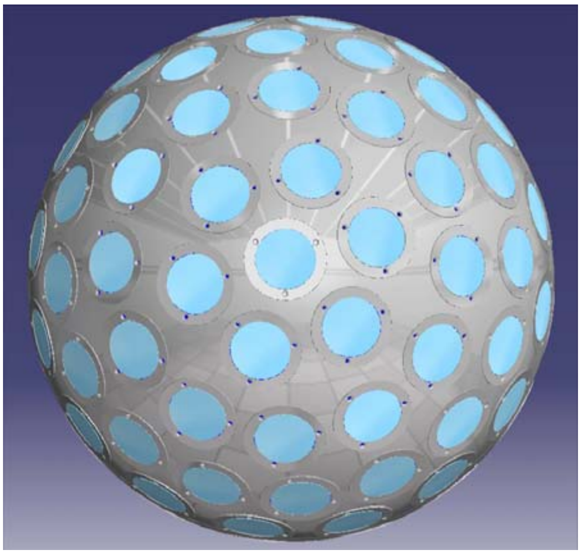

Fig. 8 - Drawing of one version of LARES satellite.

Mounting system for CCRs and thermal thrust

The CCR and retainer aluminium rings were the major cause of thermal thrust on the LAGEOS satellites. The thermal thrust induced by the metallic structure of the satellite body was negligible. An increase of the *M/S* ratio as described earlier will anyway reduce the importance of thermal thrust. In order to further reduce such an effect, retainer rings should be modified or eliminated.

The LAGEOS mounting system is shown in Fig. 9 where one can see the two plastic mounting rings in contact with the CCR and the aluminum retainer ring (in grey) that is exposed to space. The advantage of this solution is that it is a proven design, however thermal thrust for the aluminum ring (that in LARES case should be tungsten) has to be evaluated.

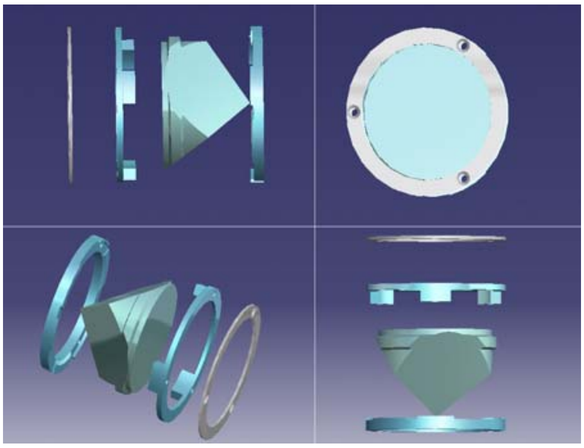

Fig. 9 - LAGEOS CCR mounting system.

One solution is shown in Fig. 10 where the retainer ring has been completely eliminated and so its thermal thrust. The CCR will be mounted in two steps: first it will be translated inside the cavity until it stops on the proper cavity-shoulder, then it will be rotated around the axis normal to the CCR front surface, until the screw holes on the satellite surface and on the caps are aligned. Note that in this solution the upper plastic mounting ring have been substituted with three tab-caps.

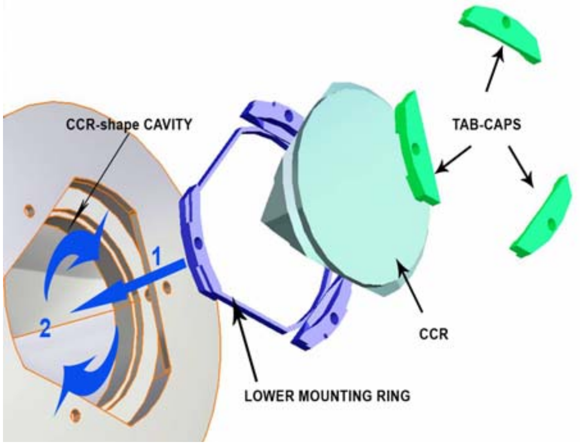

Fig. 10 - CCR cavity for mounting system without retainer ring .

The disadvantage of this solution is shown in Fig.11; in fact, once the last rotation is performed, three small cavities at 120 degrees one from the other remain on the satellite body surface and may introduce an unknown small additional atmospheric drag which could be of the same order of magnitude of the eliminated retainer ring thermal thrust.

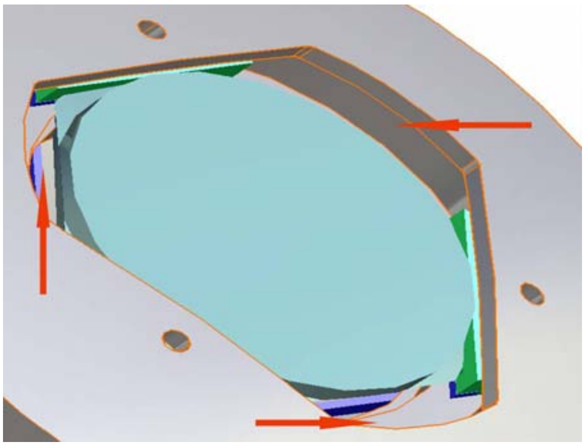

Fig. 11 - The red arrows point to the small cavities left between the CCR and CCR cavity.

Another possible improvement in this respect could be to increase the ring mass, as shown in Fig.12, and thereby increase the thermal inertia. The result is a decrease in temperature variation in going in and out of Earth eclipse. Concerning the thermal thrust induced by the CCRs, all that can be done is to increase thermal exchange between the glass and the metal of the cavity using proper coatings both for the back faces of the CCRs and the cavities. These coatings, chosen with the proper emissivity and absorptivity could improve the radiation exchange between the satellite and the CCR. The disadvantage of this solution is that thermal gradients will increase on the CCR volume causing undesirable distortions.

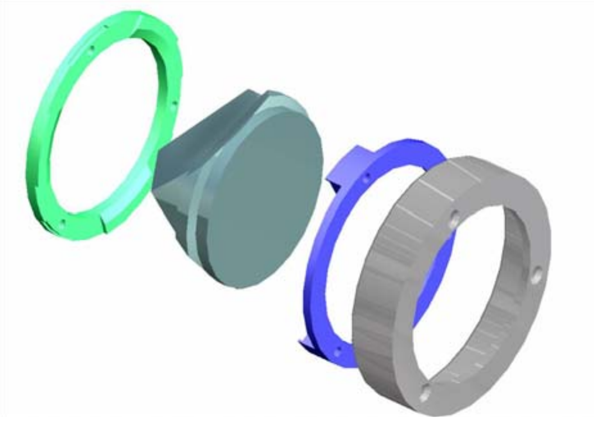

Fig.12 A possible retainer ring modified design.

CCR specifications

The most important parts of LARES satellite are the CCRs (Fig. 13). The Far Field Diffraction Pattern (FFDP) of each CCR has to be accurately checked and certified by the manufacturer. However the design team of LARES needs to give the proper specifications. In particular, the so called dihedral angle offset between the CCR back faces must be calculated very reliably before the construction of CCRs starts. This angle is a deviation form the 90° dihedral angle: it is necessary to compensate for the velocity aberration induced by the satellite motion and it is required to be able to receive the laser pulses back to the ground station.

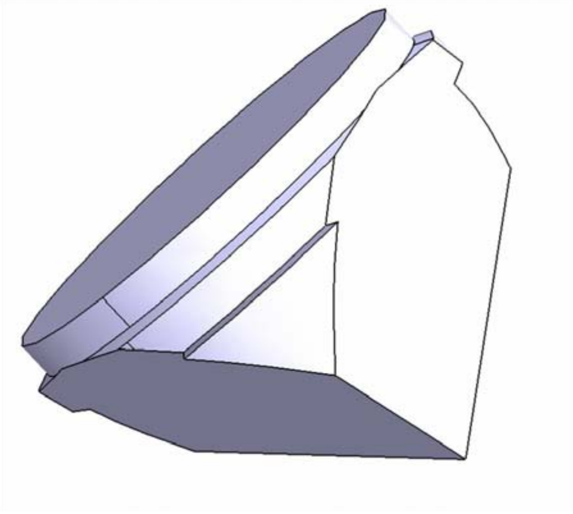

Fig. 13 View of the cube corner reflector.

Optical and thermal tests

- As mentioned, FFDP tests of the CCRs or direct measurements of the dihedral angles are mandatory by the manufacturer. In addition direct measurement of the FFDP of each CCR will be performed in house by the LARES team.
- A range correction test has been performed on the LAGEOS satellites and it is required to be performed also on LARES satellite. This test requires the flight unit of the satellite or an identical copy of it (at the level of about 0.1 mm accuracy) or at least a sector of the satellite covered with CCRs. Aim of the test is to detect from CCR reflections the geometrical center of the satellite at sub-millimeter level.
- Besides all the design tricks used to reduce thermal thrust it is important to perform a series of thermal test in vacuum with Sun and Earth simulators to better estimate the perturbation itself. This will be done in the LNF Space Climatic Facily (SCF). During the test, temperatures over the CCR and retainer rings (if any) will be measured under different orientation and illumination conditions. An accurate numerical thermal model made by up to about 20,000 FEM nodes will be built, tuned to the experimental data and used once the satellite is in orbit. One of the most important parameters to measure is the CCR thermal relaxation time.
- To improve the range accuracy, FFDPs will be measured while the CCR is mounted in its cavity and exposed to the simulated space environment in the LNF SCF. These tests have never been done for the LAGEOS satellites.

Conclusion

The objectives of the LARES mission is to perform an accurate measurement of the Lense-Thirring effect, predicted by Einstein’s General Relativity, in the Earth gravity field. Preliminary designs of LARES satellite have been shown along with different CCR mounting systems. It has been described how proper design and specific tests can minimize non gravitational perturbations. In fact, differently from other satellites, where thermo-vacuum tests are required to verify survival to space environment, specific thermal tests are planned only for the purpose of better modelling the thermal thrust perturbation.

References

[1] I. Ciufolini, A. Paolozzi, I. Peroni, A Preliminary Study for a Satellite Minimizing Solar Radiation Perturbations, Atti del XIV AIDAA Congress, (Oct. 1997 Naples, Italy) Vol. II, pp. 521-530

[2] I. Ciufolini, A. Paolozzi, I. Peroni, et al. (1998). LARES, Laser Relativity Satellite, for the study of the Earth gravitational field and general relativity measurement. Phase A report, studio piccole missioni ASI.

[3] I. Ciufolini, Measurement of the Lense-Thirring drag on high-altitude laser-ranged artificial satellites, Phys. Rev. Lett., 56, 278–281, 1986.

[4] I. Ciufolini, A. Paolozzi, I. Peroni, A. Gabrielli, A study for a laser-ranged relativity satellite, Applied Mechanics in the Americas, Proc. of the PACAM VI. (vol. 6, pp. 467-470).

[5] A. Paolozzi. (2002). A New Laser Ranged Satellite for Testing General Relativity. Ninth Marcel Grossmann Meeting on General Relativity. (pp. 1766-1770). Edited by V.G. Gurzadyan, R.T. Jantzen and R. Ruffini, published by World Scientific.

[6] I. Ciufolini, D.G. Currie, A. Paolozzi (2003). The LARES Mission for Testing the Dynamics of General Relativity. IEEE Aerospace Conference. March. Montana, USA.

[7] I. Ciufolini, A. Paolozzi. (1999). LARES: A New Laser-ranged Satellite for Fundamental Physics and General Relativity. Actual problems of aviation and aerospace systems. vol. 1, pp. 61-73 ISSN: 1727-6853.

[8] A. Bosco, C. Cantone, S. Dell'Agnello, G.O. Delle Monache, M. A. Franceschi, M. Garattini, T. Napolitano, I. Ciufolini, A. Agneni, F. Graziani, P. Ialongo, A. Lucantoni, Paolozzi A., I. Peroni, G. Sindoni G. Bellettini, R. Tauraso, E. C. Pavlis, D.G. Currie, D.P. Rubincam, D. A. Arnold, R. Matzner, V. J. Slabinski. (2006). Probing gravity in neo with high-accuracy laser-ranged test masses. International journal of modern physics D. ISSN: 0218-2718.

[9] I. Ciufolini, E. Pavlis, Nature 431, 958 (2004).