LARES Laser Relativity Satellite

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ABSTRACT

After almost three decades since the first idea of launching a passive satellite to measure gravitomagnetism, launch of LARES satellite is approaching. The new developed VEGA launcher will carry LARES in a nominally circular orbit at 1450 km altitude. This satellite, along with the two LAGEOS satellites, will allow to improve a previous measurement of the Lense-Thirring effect by a factor of 10. This important achievement will be a result of the idea of combining orbital parameters of a constellation of laser ranging satellites along with a specific design of LARES satellite. Other key points of the experiment are: the ever improving knowledge of the gravitational field of Earth, in particular the lower degree even zonal harmonics with GRACE satellites, and an accurate estimate of all the classical perturbations such as atmospheric drag and solar radiation pressure. In the paper both the scientific aspects as well as the design consideration will be described.

1 Introduction

The Italian Space Agency supported the LARES space experiment, in occasion of the foreseen qualification launch of the new launch vehicle VEGA. LARES (LAser RElativity Satellite),is a new laser ranged satellite, it will have an altitude of about 1450 km, and orbital inclination of about 70° and nearly zero eccentricity. The achievement of reaching a few percent uncertainty of Lense-Thirring effect will be the combination of several aspects. The first one is the combined use of three satellites LAGEOS (NASA) LAGEOS 2 (NASA and ASI) and LARES; the second one is the use of the new and ever improving gravitational field of Earth provided by the team of the GRACE (NASA-CSR and DLR-GFZ) satellites. The third one is an optimized design of LARES satellite and relevant orbit.

The original idea of measuring the Lense-Thirring effect dates back to 1984 and required the use of the nodes of two laser ranged satellites in supplementary orbit, one of which (LAGEOS) was already orbiting.

An excellent occasion to materialize that idea was offered by the LAGEOS II satellite in 1992. However it was not possible at that time to launch it in the optimal orbit that should have been supplementary to the one of LAGEOS. Neverthelss Ciufolini and Pavlis were able to obtain an accurate measurement of the Lense-thirring effect at the level of about 10%. The optimal orbit would have allowed a complete cancellation of the static Earth's spherical harmonics secular effects on the satellite nodes in order to measure the much smaller Lense-Thirring effect. Later, Ciufolini proposed a third satellite called LAGEOS III but the weight of about 400 kg (same mass as the LAGEOS satellites) and especially the high altitude of its orbit (about 6000 km) would have required an expensive launch vehicle. In response to a call for proposal of ASI, in year 1998 it was proposed for the first time LARES satellite that was an economic evolution of the predecessor LAGEOS satellites. The satellite orbit should have been supplementary to the one of LAGEOS I and the weight much lower (about 100 kg). But later, aside the difficulty of finding a launch for that altitude, new factors have changed the need of such a high altitude orbit for LARES: in 2002 GRACE spacecraft was launched, making possible the publication of a new generation of very accurate Earth's gravity field models; the idea to use the nodes of N laser-ranged satellites was proposed, to cancel the uncertainty due to the first N-1 even zonal harmonics responsible of the error higher than 1% on the measure of Lense-Thirring effect.

2 LARES orbit.

The node motion of a satellite in polar orbit will not be affected by the even zonal harmonics, making in principle possible to measure the Earth's gravitomagnetic field and the Lense-Thirring effect, since those are not canceled at that particular inclination i.e., the Earth will drag its orbit anyway. However, it was pointed out in the 1989 LAGEOS III NASA/ASI study that the uncertainty in the K_1 tide (tesseral, m=1, tide) is too high to make such an orbit useful for the measurement of the Lense-Thirring effect. Furthermore this consideration is confirmed by Peterson calculation (1997). Finally, to impose a small orbital injection error, as far as inclination goes for the polar orbit, would be too demanding for the launch vehicle. In fact it can be shown that, a quasi-polar orbit would have a nodal precession, due to its departure from 90 degrees of inclination, that would make the measurement of Lense-Thirring effect almost unrecoverable unless a combination with a second satellite is considered. The analysis of the effects of the tides has actually been done with the LAGEOS I and LAGEOS II and it is shown that it is the largest periodical amplitude observed in the combined residuals. If one considers also LARES satellite, the combinations of the three satellites provides as an error in the measurement of the Lense-Thirring effect due to the inclination, the results reported in Fig. 1 for an altitude of 1500 km, i.e., a LARES semimajor axis of about 7880 km (under reasonable assumptions such as zero eccentricity for the LARES orbit).

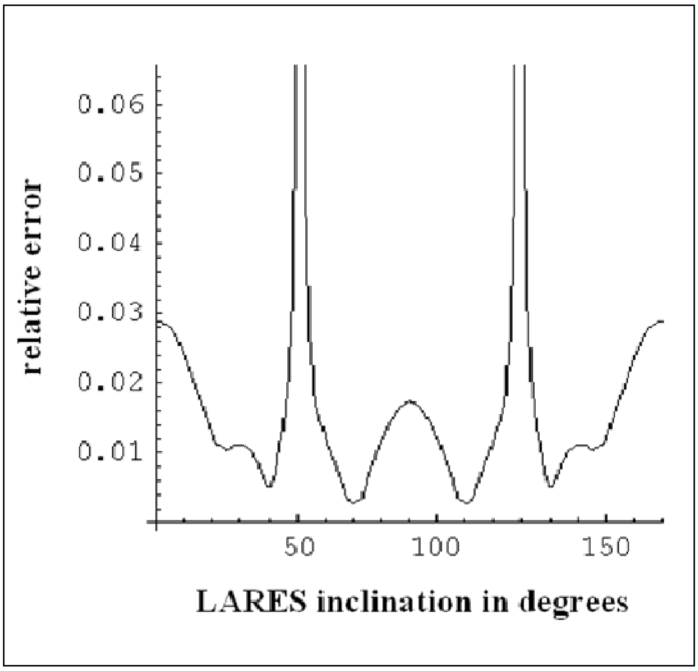

Figure 1

Uncertainty in the measurement of the Lense-Thirring effect, due to the even zonal harmonics uncertainties, as a function of the inclination of LARES, using LARES, LAGEOS and LAGEOS II. The altitude of LARES is here 1500 km.

The error sources of gravitational origin, i.e., those due to the uncertainties in the Newtonian gravitational field, are by far larger than the uncertainties of non-gravitational origin, i.e. radiation pressure, both from Sun and Earth, thermal thrust and particle drag; indeed the LAGEOS satellites and especially the LARES satellite are extremely dense spherical satellites with very small cross-sectional-to-mass ratio.

In consideration of the results shown in Fig.1 it was proposed for LARES an inclination at nearly 70 degrees. That would allow a total error in the measurement of the Lense-Thirring of just a few percent.

3 The LARES satellite.

As mentioned earlier, the go to the LARES mission has been given by the availability of a qualification flight of the VEGA launcher, developed by an ASI-AVIO joint venture (ELV S.p.A.) under the European Space Agency (ESA). Since the altitude foreseen for the qualification flight could not exceed 1500 km the design of LARES was quite demanding because it should have been optimized for reducing the surface perturbations such as atmospheric drag. Salento and Sapienza University had a major role in the development of LARES mission and satellite since those were in charge of the design and main tests of both LARES satellite and separation systems. Also the construction of the Mechanical Ground Support Equipments and of some prototypes have been under the responsibility of the universities. The prime contractor for LARES system is CGS. In Fig. 2 is reported a drawing of the LARES system, whose main parts are indicated.

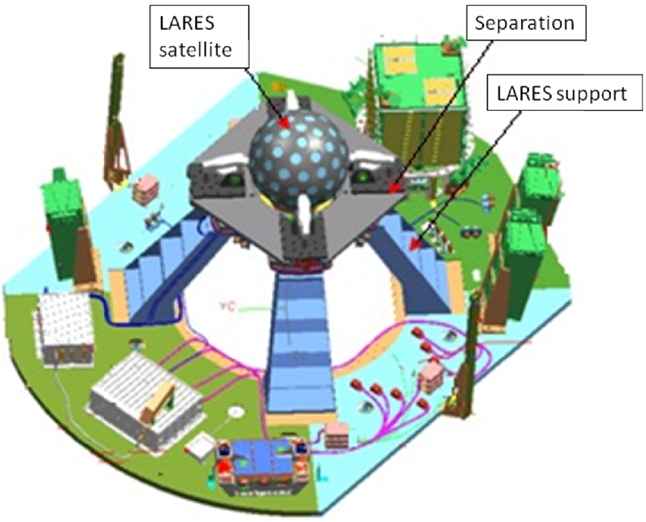

Figure 2 LARES System. Image taken from reference "Objectives of LARES Satellite".

The key decision to achieve a surface-to-mass ratio 2.7 times smaller than the one of LAGEOS was that one of using a high density material: a tungsten alloy with 18000 kg/m^3 making it the densest known single object in the solar system.. The alloy chosen was not-magnetic to avoid unknown effects on LARES orbit due to the interaction with the magnetic field of Earth that even if small could affect the accuracy expected for the experiment. LARES has a radius of only 182 mm with a mass of about 400 kg. Also thermal thrust perturbation needed to be reduced as much as possible. For this reason the main body of LARES was therefore conceived as a single piece (differently from the LAGEOS satellites). The reduction of components will reduce the number of contact conductances that in turn are the main cause of temperature gradients on the surface of a satellite.

One of the most important components of LARES satellite are the Cube Corner Reflectors (CCRs) that provide the return signal of the laser pulses sent by the laser ranging ground stations. The 102 CCRs were positioned on the surface of the satellite in such a way to allow an easier attitude determination that is useful to a better estimate of thermal thrust. Spin axis determination can be performed using for instance the Sun glints, that is sun flashes at the observer location obtained when Sun, CCR front face and observer have a geometrical position which fulfill the law of reflection.The material used for the CCRs is Suprasil 311 with excellent property of homogeneity and isotropy. Surface finish of CCRs were the same as the ones used for LAGEOS satellites: the three back faces are 1/10th of the light wavelength while for the front face is 1/8th, resulting in a reflected wavefront 1/4th of wavelength (Peak-to-valley, not RMS). As well known a dihedral angle offset is required to compensate for the satellite motion. Being LARES at lower altitude than LAGEOS this value has been set for all the three back faces to: 1.5 arcsec +/- 0.5 arcsec, while for the two LAGEOS it was 1.25 arcsec.

The effect of thermal condition in orbit on the CCRs was tested in a thermal vacuum facility of Sapienza University. A breadboard simulating the satellite material, carrying a CCR, was positioned inside a thermal vacuum chamber. Temperature of the breadboard was controlled using resistive heaters. The wall of the chamber were cooled by a liquid nitrogen shroud to simulate irradiation toward deep space; a window allowed to illuminate the CCR with a Sun simulator (AM0 spectrum), while a black disk maintained at 250 K simulated the infrared irradiation from Earth. An optical circuit outside the chamber collects the Far Field Diffraction Pattern (FFDP) of the CCR; the laser beam from the optical bench passes through a high quality optical window (λ/20 surface flatness) to reach the CCR inside the chamber. The FFDP acquired in simulated space environment is then compared to the FFDP collected at room temperature (T=20° +/- 5℃) to verify that the pattern shape and the intensity will not significantly change. In Fig. 3 are reported, as an example the results of the CCR exposed to the simulated deep space. In the horizontal axis are reported the velocity aberrations expressed in microradians. The two vertical lines in the bottom figure delimitate the range of interest (30-50 microrad). The figure shows that in the range of interest, the minimum value of energy is about 60% of the one that the CCR would return if it would be in steady state condition at room temperature. Considering that LARES is much lower altitude than LAGEOS this value is completely acceptable. Similar results were obtained with the CCR pointing towards the sun simulator or towards the Earth. The tests have therefore proven that LARES CCR can work even in the worst cases of thermal conditions.

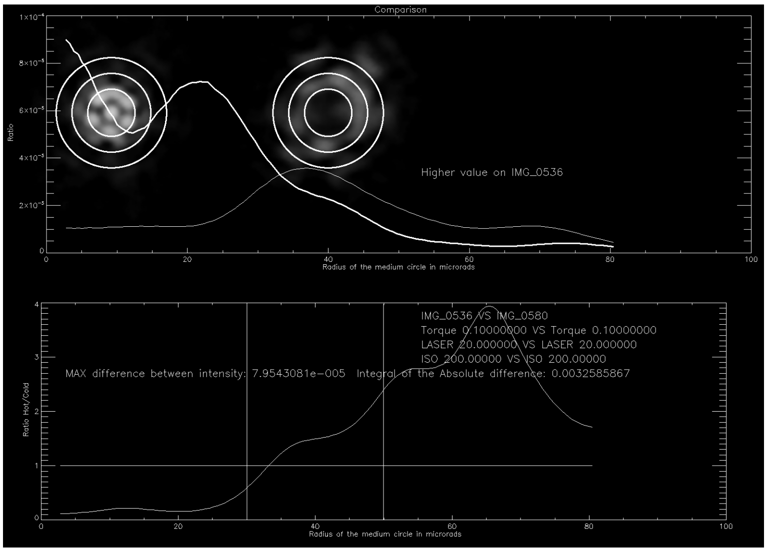

Figure 3 FFDP comparison during one test in Thermal Vacuum Chamber.

FFDP at Room Temperature (RT) (top left). FFDP in simulated space environment (SPE) (top center). Thick curve is relevant to FFDP at RT. The lower curve is the ratio between the intensity of the two FFDPs.

References

Ciufolini, I., 1984: Theory and Experiments in General Relativity and other Metric Theories, Ph.D. Dissertation, Univ. of Texas, Austin (Ann Arbor, Michigan).

Ciufolini, I., Pavlis, E. C., 2004: A confirmation of the general relativistic prediction of the Lense-Thirring effect. Nature, 958-960 (2004).

Ciufolini, I., 1986: Measurement of the Lense-Thirring drag on high-altitude laser-ranged artificial satellites. Phys. Rev. Lett., 278-281 (1986).

Ciufolini, I., 1986: On A New Method to Measure the Gravitomagnetic Field Using Two Orbiting Satellites. Nuovo Cimento, 1709-1720 (1996).

Ciufolini, I., Paolozzi, A., Pavlis, E. C., Ries, J. C., Koenig, R., Matzner, R. A., Sindoni G. and Neumayer, H., 2009: Towards a One Percent Measurement of Frame-Dragging by Spin with Satellite Laser Ranging to LAGEOS, LAGEOS 2 and LARES and GRACE Gravity Models. Space Science Reviews, 71-104 (2009).

Tapley, B., Ries, J.C., Eanes, R.J., and Watkins, M.M., 1989: NASA-ASI Study on LAGEOS III, CSR-UT publication n. CSR-89-3, Austin, Texas.

Ciufolini, I., et al., 1989: ASI-NASA Study on LAGEOS III, CNR, Rome, Italy.

Ciufolini, I., Paolozzi, A. et al., 1998: LARES, Laser Relativity Satellite, for the study of the Earth gravitational field and general relativity measurement, Phase A Report for ASI.

Peterson, G. E., 1997: Estimation of the Lense-Thirring Precession Using Laser-Ranged Satellites, Ph. Dissertation, Univ. of Texas, Austin.

Iorio, L., 2005: The impact of the new Earth gravity models on the measurement of the Lense-Thirring effect with a new satellite, New Astronomy, 616-635.

Ciufolini, I., 2006: On the Orbit of the LARES Satellite. arXiv:gr-qc/0609081.

Ciufolini I., Paolozzi A., Pavlis E. C., Ries J. C., Koenig R. and Matzner R., 2010: The LARES Relativity Experiment, in: General Relativity and John Archibald Wheeler, I. Ciufolini and R. Matzner eds. (Springer) 467-492.

Paolozzi A., Ciufolini I., Vendittozzi C., 2011: Engineering and scientific aspects of LARES satellite. Acta Astronautica, 127-134, 2011.

Paolozzi A., I. Ciufolini, C. Vendittozzi, F. Passeggio, L. Caputo, G. Caputo, 2009: Technological challenges for manufacturing LARES Satellite. In: IAC Proceedings. Daejeon, Republic of Korea, 12-16 October 2009, p. 1-6.

Paolozzi A., I. Ciufolini, I. Peroni, C. Paris, M. Ramiconi, F. M. Onorati, L. Acquaroli, 2009: Testing the LARES separation system breadboards. In: IAC Proceedings. Daejeon, Republic of Korea, 12-16 October 2009, p. 1-6.

I. Ciufolini, A. Paolozzi, G. Sindoni, E. Pavlis, A. Gabrielli, S. Pirrotta, D. Barbagallo, E. Mangraviti, 2009: Objectives of LARES Satellite. Proceeedings of XX AIDAA Congress, Milano, Italy, June 29–July 3, 2009.

Paolozzi A., I. Ciufolini, C. Paris, 2011: Contribution of strain measurements to the LARES satellite mission. International Conference on Structural Engineering Dynamics (ICEDyn), Tavira, Portugal, 20-22 June 2011, pp. 1-7.

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