Overview of the LARES Mission: orbit, error analysis and technological aspects.

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Abstract. LARES (LAser RElativity Satellite), is an Italian Space Agency (ASI) mission to be launched beginning of 2012 with the new European launch vehicle, VEGA; the launch opportunity was provided by the European Space Agency (ESA). LARES is a laser ranged satellite; it will be launched into a nearly circular orbit, with an altitude of 1450 km and an inclination of 69.5 degrees. The goal of the mission is the measurement of the Lense-Thirring effect with an uncertainty of few percent; such a small uncertainty will be achieved using LARES data together with data from the LAGEOS I (NASA) and LAGEOS II (NASA and ASI) satellites, and because GRACE mission (NASA-CSR and DLR-GFZ) is improving Earth’s gravity field models. This paper describes LARES experiment along with the principal error sources affecting the measurement. Furthermore, some engineering aspects of the mission, in particular the structure and materials of the satellite (designed in order to minimize the non-gravitational perturbations), are described.

1. Introduction

1.1. Dragging of Inertial Frames and the Lense-Thirring Effect

In Einstein’s Theory of General Relativity, local inertial frames are influenced and dragged by the distribution and flow of mass energy in the Universe. In particular, they are dragged by the motion and rotation of nearby bodies; this phenomenon is known as Frame Dragging [1, 2]. Frame Dragging influences both the motion of bodies and the flow of time around spinning bodies. In any rigid frame non rotating relative to fixed stars, synchronization of two clocks orbiting around a spinning body is not possible if the clocks are moving in opposite directions on the same path; indeed the clock traveling on the orbit in the opposite direction of the rotation of the central spinning body will experience a time delay with respect to the clock traveling in the same direction of the rotation of the spinning body. Similarly, the orbital period of a particle co-rotating around a spinning body would be longer than the orbital period of a particle counter-rotating on the same orbit. [3, 4, 5, 6, 7].

In 1916 Willem de Sitter derived the Mercury perihelion precession due to the Sun angular momentum, on the basis of General Relativity. In 1918 Josef Lense and Hans Thirring gave a description of the frame dragging effect of a test particle orbiting around a spinning body; the so-called Lense-Thirring effect predicts the precession of the nodal line of the orbit, because the plane of the orbit is dragged by the rotation of the spinning body. The de Sitter effect is the precession of the pericenter (Geodetic Precession), but it is due simply to the presence of the central mass, that could be either spinning or not spinning, while the Lense-Thirring
effect requires the presence of a spinning mass. Frame-dragging can be usefully described by a formal analogy of General Relativity, in a weak gravitational field and for slow motion, with electrodynamics [1, 8].

1.2. Measurement of the Lense-Thirring Effect with Laser Ranged Satellites

The idea of measuring the Lense-Thirring effect using the node of two laser ranged satellites dates back to 1984 [9, 10]; the proposal was to use the LAGEOS satellite (launched in 1976) and a second satellite to be launched on an orbit with all the orbital parameters identical to the ones of LAGEOS, except for the inclination that should have been supplementary (i.e. 70 degrees). The supplementary inclination was needed in order to cancel out all the secular effects on the nodes of the two satellites due to the deviations of the Earth’s gravitational field from spherical symmetry and in particular due to the Earth’s even zonal harmonics. The LAGEOS II satellite (a replica of LAGEOS I) was launched in 1992, but it was not possible to launch it on an orbit with the needed 70 degrees inclination (LAGEOS II orbit inclination is 52.64 degrees). However, to cancel the uncertainties due to the first N-1 even zonal harmonics, it is possible to use the nodes of N laser-ranged satellites [11, 1, 12, 13], as a possible alternative to the concept of the supplementary inclination satellites. An alternative possibility is to use N observables instead of N satellites; so the nodes of LAGEOS I and LAGEOS II, and the perigee of LAGEOS II, provide 3 observables that can be used to cancel the effect of the uncertainty due to the J2 and J4 harmonics in order to measure the Lense-Thirring effect. The above mentioned method was proposed in 1989 [11], before the launch of LAGEOS II, and described in detail in 1996 [13]. With this technique it was possible a first observation of the Lense-Thirring effect, applying the gravity field model EGM96 [14, 15]; however improved models of the Earth’s gravitational field provided by GRACE mission [16, 17, 18, 19] lead to a measurement of the Lense-Thirring effect with an uncertainty of about 10% [12, 20, 21, 22]. To further improve the measurement, and to reach an uncertainty of the order of 1%, a new laser ranged satellite is needed.

2. LARES, a new laser-ranged satellite on a lower orbit than LAGEOS I and II

The proposal of a third laser ranged satellite, to be called LAGEOS III, dates back to 1989 [23, 24]. The possibility of launching such a third LAGEOS replica was discussed in a number of papers and PhD dissertations [23, 24, 25, 26]; however the mass (about 400 kg) and the high altitude of the orbit (about 6,000 km) required an expensive launch vehicle. For this reason a lighter satellite (about 100 kg), called LARES, was later designed [27], nevertheless the high altitude of LARES was still somehow expensive to achieve. In 2007 the possibility to use the qualification flight of the new European launcher VEGA to orbit LARES was proposed [28]. However, this launch will put LARES on a lower orbit (1450 km) than the originally planned one. The possibility of using a lower orbit was supported by further studies and works the next year [29]. Even if VEGA could achieve a 6000 km orbit, the objective of the qualification flight did not allow to exceed an altitude of 1500 km. For this reason LARES was redesigned to have a more favourable mass-to-surface ratio ($M/S$) than LAGEOS; indeed LARES $M/S$ ratio will be about 2.6 times the LAGEOS $M/S$ ratio. The greater $M/S$ ratio would help reducing the errors due to surface perturbations such as the thermal thrust and the atmospheric drag.

3. LARES Orbit

A suitable orbit for LARES would:
- minimize the effect of even zonal harmonics on the motion of the node;
- have small uncertainties due to the effects of other harmonics on the precession of the node;
- be perturbed by Earth’s gravitomagnetic field, in order to measure the Lense-Thirring effect;

A polar orbit was also studied for LARES [30]: for such an orbit the effects of all even zonal...
harmonics on the node will be theoretically absent. But at the same time it was demonstrated [26] that the uncertainty in the $K_1$ tide (tesseral, $m = 1$, tide) would make a polar orbit unsuitable for the Lense-Thirring measurement, since the corresponding uncertainty on the secular precession of the node would be too large. A better choice is a quasi polar orbit, with an inclination less than or equal to 86 degrees, or larger than or equal to 94 degrees (for an altitude of about 1500 km); this kind of orbit would have a periodical nodal precession, due to its departure from 90 degrees of inclination, and is also less demanding in terms of orbital injection deviation compared to a polar one. The analysis of LAGEOS I and LAGEOS II showed that the effect of $K_1$ tide can be fitted using a periodical signal exactly at the nodal frequency [14, 12]. By using the nodal rates of LARES, LAGEOS I and LAGEOS II as three observables, it is possible to eliminate the uncertainty in the first two even zonal harmonics, and the Lense-Thirring effect; the remaining uncertainties are due to the even zonal harmonics with degree strictly higher than 4. It turns out that some values of the inclination of LARES would minimize the error in the measurement of the Lense-Thirring effect since they would minimize the error due to the uncertainty in the largest (not cancelled using the combination of the three observables) even zonal harmonic $C_{60}$. The error as a function of the inclination of LARES orbit is shown in Figure 1, for an altitude of 1500 km (that is the altitude that can be reached with VEGA launch): the error would be minimized by an inclination of 70 degree or 110 degrees, but any inclination between 60 and 86 degrees and between 94 and 120 degrees could be used. The above results have been calculated assuming a circular orbit ($e=0$) and considering only the effects of the first 5 even zonal harmonics, $C_{20}$, $C_{40}$, $C_{60}$, $C_{80}$ and $C_{100}$ (by including higher degree even zonal harmonics, the results of Figure 1 would only change slightly). The uncertainties in the spherical harmonics are considered equal to those of the EIGEN-GRACE02S Earth’s gravity model [16]; EIGEN-GRACE02S was a preliminary 2004 model and by the time of the launch of LARES and of its data analysis, much improved Earth’s gravity field models based on much longer data set of GRACE observations would be available.

![Figure 1](image-url)  
**Figure 1.** Relative error due to the largest even zonal harmonics, as function of the inclination of LARES orbit (for an altitude of 1500 km and zero eccentricity).
Other relevant orbital perturbations that affect the measurement are: tidal effect, particle drag and thermal drag.

The combination of three nodes makes possible to cancel the effect of medium and long period zonal tides \((l = 2 \text{ and } m = 0)\) together with the static \(C_{20}\) uncertainty and the uncertainty in the time-dependent secular variations \(\dot{C}_{20}, \dot{C}_{40}\). As explained above, the effect of \(K_1\) tide will be fitted for over a period equal to the LARES nodal period, and the introduced uncertainty will be small [23, 24, 26].

In regard to the thermal drag, the effect of the unmodeled perturbation would be reduced with respect to the LAGEOS satellite by the greater \(M/S\) ratio (as stated above, it would be about 2.6 times than LAGEOS \(M/S\)); furthermore, measurements of the thermal properties of the LARES materials are planned, to help modeling the thermal drag effect.

The higher \(M/S\) ratio would also help reducing the effect of particle drag; nevertheless, the effect of drag on the node of an orbit with nearly zero eccentricity and an altitude of 1450 km would be negligible (indeed, the effect is proportional to eccentricity, and will be zero for \(e=0\))[11].

4. Analysis of Errors due to Gravitational Uncertainties

The largest gravitational perturbations on the orbit of the LAGEOS satellites and LARES are due to the non-sphericity of the Earth gravity field, described by the expansion of the potential in spherical harmonics [31, 11]. The spherical harmonics of even degree and zero order, e.g., the \(C_{20}\) harmonic describing the well known quadrupole moment of Earth, are the source of the only secular effects on the orbit.

As stated above, the error due to the uncertainties of the first two even zonal harmonics will be canceled using the nodes of three satellites; the error due to each even zonal harmonic of degree higher than 4 is considerably less than 1% and in particular that the error is substantially negligible for the even zonal harmonics of degree higher than 26. The total error in the measurement of the Lense-Thirring with LARES due to the even zonal harmonics has been calculated for the gravity field models EIGEN-GRACE02S (GFZ Potsdam, 2004) [16] and GGM02S (CSR 2004) [17], obtaining a value respectively of 1.4% and 2.1% [32]. The above mentioned models have been obtained in 2004 with data over less than 365 days of GRACE mission, therefore improved models would be available at the time of the LARES data analysis, based on longer GRACE observational periods. Moreover GOCE mission [33] is going to further improve the gravity field models, even if mainly the higher degree harmonics, whose contribution to the total error is only marginal. Indeed the contribution of high degree spherical harmonics of the gravity field to the satellite nodal precession decrease as the inverse power of the semimajor axis to the degree of the even zonal harmonic, thus quickly decreasing with the degree [31, 22].

5. Technological Aspects of LARES Satellite

LARES will be launched with the VEGA maiden flight; the satellite will be put on a nearly circular orbit, with a semimajor axis of 7830 km and an inclination of 69.5 degrees. Being on a much lower orbit than LAGEOS I and II, it is important that the design will minimize all the non gravitational perturbations, especially particle drag and thermal thrust (induced by the anisotropic thermal radiations from the satellite due to the anisotropic temperature distribution over the satellite surface). In Figure 2 is reported a photograph of the qualification model of LARES satellite. In the following subsection the principal design aspects are discussed.

5.1. Mass-to-Surface Ratio, thermal thrust and materials

The mass-to-surface (actually mass-to-cross-sectional-area) ratio, \(M/S\), should be maximized in order to minimize the non gravitational perturbations. For a spherical satellite, such as LARES,
a simple formula shows that $M/S$ depends only on satellite radius, $r$, and satellite mean density, $\rho$:

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

(1)

However, the launch vehicle imposes some limits on the maximum mass of the satellite. For LARES, the mass limit was 400 kg, so the most obvious decision was to maximize the density of the satellite. The satellite body will be machined from one single sphere of Tungsten alloy THA-18N, composition 95% W, 5% Cu and Ni, nominal density $\rho = 18000$ kg/m$^3$ [34, 35]. Higher density Tungsten alloys are available, that are magnetic alloys containing Fe; a non magnetic alloy (even if with a lower density) has been chosen to avoid interaction with the Earth magnetic field. Tungsten alloys have been preferred over other materials with even higher density, such as platinum, osmium and iridium, for both economical reasons (platinum price is about the same as gold, iridium is priced 0.75 times than gold), and technological reasons (availability, workability and procurement time).

Another solution to increase the $M/S$ ratio is the adoption of conical cavities to house the CCRs; indeed, while the CCR design is inspired to the LAGEOS satellites, the cylindrical cavities used on LAGEOS satellite would decrease the $M/S$ ratio of LARES.

To minimize perturbations due to the thermal thrust, the satellite is made of a single piece of metal. This way thermal contact conductances are eliminated on the satellite body thus reducing drastically temperature differences. To reduce risk of differential charging all the metal components, i.e. screws and CCR retaining rings, are made of the same alloy [35, 36, 37].

Given the aforementioned decision about the materials and the design, LARES satellite will have a radius of about 18 cm and a mass of about 390 kg; indeed it will become the densest known single object orbiting in the Solar System.

5.2. Cube Corner Reflectors

The most critical components of the LARES satellite are the Cube Corner Reflectors (CCRs). The CCRs are designed to redirect the laser pulses back to the ground station, to allow Laser Ranging. The dihedral angles between back faces of a CCR is exactly 90 only if the target motion is zero or negligible (this is the case of the CCR used for Lunar Laser Ranging); in the case of a satellite in Earth orbit, the dihedral angle should have a small offset (Dihedral Angle Offset, DAO) to spread the reflected signal over a wider area to compensate for the satellite motion. LARES CCRs have a DAO of 1.5 arcsec, with a tolerance of +/- 0.5 arcsec.

LARES carries 92 CCRs. A higher number of CCRs would have reduced slightly the $M/S$ ratio, and increased the thermal thrust perturbation; moreover, even if a higher number of CCRs would have increased the reflective area, a higher number of CCRs reflecting at the same time the laser pulse would have decreased the laser ranging accuracy. A spare unit of a CCR made for LARES mission is shown in Figure 3.

5.3. CCRs Mounting system

On the LAGEOS satellites, the CCRs and their retainer rings (made of aluminium) were found to be the major cause of unmodeled thermal thrust. LARES will employ a CCR mounting system inspired to the LAGEOS system (that has been proven to be reliable), with the main difference that the metal mounting rings and the screws are made of the same tungsten alloy as the satellite body. Methods to improve thermal conductivities between the CCRs and the satellite body are possible but were not recommended. For instance the application of a coating with a high infrared emissivity on the CCR cavity would have increased the thermal flux towards the CCR back faces reducing the temperature difference between CCR and satellite body. On the other hand this flux would have possibly increased the axial thermal gradients on the CCR
Figure 2. Qualification Model (QM) of LARES, with four CCRs installed. LARES QM is made of the same material and has the same dimensions of LARES Flight Unit. Between the four CCRs there is clearly visible one of the four hemispherical cavities that interface the Separation System.

Figure 3. Front view (left) and side view (right) of a LARES CCR (spare unit).
causing a dangerous CCR deformation that would have changed its Far Field Diffraction Pattern ultimately reducing the energy at the ground station of the returning laser pulse.

5.4. Separation System
To avoid unmodeled effects due to particle drag, LARES satellite has been designed avoiding any component protruding from the spherical surface. This requirement called for a dedicated separation system. The system holds the satellite by 4 brackets with spherical heads interfacing 4 corresponding spherical slots spaced 90 degrees along the equatorial plane of the satellite. Each bracket is operated by a non-pyrotechnical actuator; the four mechanisms will be operated simultaneously to release the satellite once in orbit. A spring will then push LARES away from the VEGA upper stage, with a nominal separation speed of 0.75 m/s. The system has been designed to be robust against failures: in case of failure of one mechanism, the remaining three will allow to release the satellite, even if in this case the polar spin axis will be lost.

Figure 4. A 3D model of LARES Separation System, showing the four brackets holding the satellite.

6. Conclusions
The particular design of LARES satellite, together with the improved gravity field models from GRACE mission, will improve the accuracy in the measurement of Earth gravitomagnetic field. The VEGA launch vehicle imposes some constraints on LARES mass and orbit; however the orbital parameters, in particular eccentricity and inclination, are chosen to reduce the errors due to the effect of even zonal harmonics and Earth tides. The robust mission design allow big orbital injection errors if the final orbit has an altitude higher than 1200 km. The semimajor axis has been decided after a trade off with the launch vehicle responsible.
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