# LARES: A NEW ASI MISSION TO IMPROVE THE MEASUREMENT OF LENSE-THIRRING EFFECT WITH SATELLITE LASER RANGING

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ABSTRACT. LARES, Laser Relativity Satellite, is a spherical laser-ranged satellite, passive and covered with retroreflectors. It will be launched with ESA's new launch vehicle VEGA (ESA-ELV-ASI-AVIO) in early 2012. Its orbital elements will be: inclination 70° ± 1°, semi-major axis 7830 km and near zero eccentricity. Its weight is about 387 kg and its radius 18.2 cm. It will be the single known most dense body orbiting Earth in the solar system, and the non-gravitational perturbations will be minimized by its very small 'cross-section-to-mass' ratio. The main objective of the LARES satellite is a test of the frame-dragging effect, a consequence of the gravitomagnetic field predicted by Einstein's theory of General Relativity. Together with the orbital data from LAGEOS and LAGEOS 2, it will allow a measurement of frame-dragging with an accuracy of a few percent.

## 1. INTRODUCTION

Einstein's theory of General Relativity (GR) states that the gravitational field is locally 'unobservable' in free-falling frames and in these local inertial frames the laws of physics are those of Special Relativity (Weinberg 1972, Misner, Thorne and Wheeler 1973, Ciufolini and Wheeler 1995). The axes of the non-rotating local inertial frames are determined by free-falling, torque-free gyroscopes. According to GR, gravitation is the curvature of spacetime. One of several tests of GR concerns dragging of inertial frames and gravitomagnetism. The free-falling gyroscopes are dragged by the flow and rotation of nearby matter, such as a spinning mass, i.e., their orientation changes with respect to the distant stars: this is the "dragging of inertial frames" or "frame-dragging", as Einstein called it in a letter to Ernst Mach (Einstein 1913). Mach thought that centrifugal and inertial forces are due to rotations and accelerations with respect to all the masses in the Universe (Mach's principle). In GR the inertial and centrifugal forces are due to our accelerations and rotations with respect to the local inertial frames. Frame-dragging phenomena, which are due to mass currents and mass rotation, can be described as gravitomagnetism (Thorne, Price and Macdonald 1986, Ciufolini and Wheeler 1995) because of a formal analogy of electrodynamics with the general theory of relativity, in the weak field and slow motion approximation (see Figure 1).

In General Relativity, a torque-free spinning gyroscope defines an non-rotating axis relative to the local inertial frames, however, the orbital plane of a test particle is also a kind of large gyroscope that is affected by GR effects. The LAGEOS (LAser GEOdynamics Satellite) experiment measured the frame-dragging effect on the orbital plane of the two LAGEOS satellites (Ciufolini and Pavlis, 2004), and LARES (LAser RElativity Satellite) will test this effect with improved accuracy by observing the orbital plane's precession for LARES and two LAGEOS satellites. The Gravity Probe B space experiment tested frame-dragging of small gyroscopes. The frame-dragging effect on an orbiting test-particle is represented by the rate of change of its angular momentum vector. This is also known as the Lense-Thirring effect, that is, the precession of the nodes of a planet, moon or satellite described by the rate of change of its nodal longitude: $\dot{\Omega}^{L-T} = \frac{2GJ}{c^2 a^3 (1-e^2)^{3/2}}$ , where $\Omega$ is the longitude of the nodal line of the satellite, $J$ is the angular momentum of the central body, $a$ the semi-major axis of the orbiting test-particle, $e$ its orbital eccentricity, $G$ the gravitational constant and $c$ the speed of light. The Lense-Thirring effect is ≅31 mas/yr on the node of LAGEOS (Ciufolini, 1986) and ≅31.5 mas/yr on the node of LAGEOS 2.

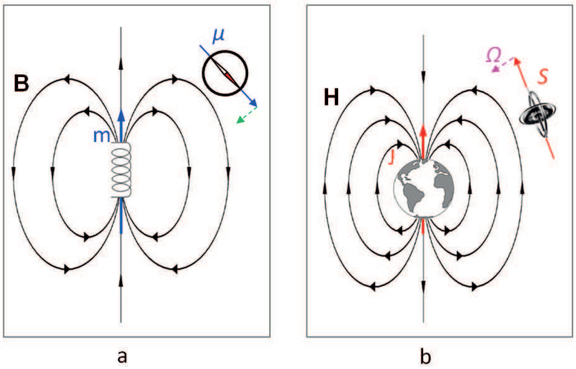

Figure 1: Frame-dragging and the gravitomagnetic analogy in GR with electrodynamics. In (a) the magnetic field B generated by a magnetic dipole m and a test magnetic dipole $\mu$, that is, a magnetic needle, which tends to be aligned along B. In (b) the gravitomagnetic field H generated by the spin J of a central body and frame dragging $\dot{\Omega}$ of a test gyroscope S

## 2. SATELLITE LASER RANGING, THE GRACE GRAVITY MODELS AND LARES

Satellite Laser Ranging (SLR), a geodetic technique with a precision of a few millimeters, has already proven to be a powerful technique for fundamental physics experiments. With the recent development of the high resolution and high accuracy gravity models from the GRACE mission (Pavlis, 2002), the limitations due to the Newtonian effects' errors were overcome. Frame-dragging was initially measured in 2004–2010, using the two LAGEOS satellites, with an accuracy of about 10% (Ciufolini and Pavlis, 2004; Ciufolini et al. 2010b) and, in 2011, the Gravity Probe B team reported a measurement of frame-dragging with accuracy of about 20% (Everitt et al. 2011). The measurement of frame-dragging was possible despite the much larger error in the dominant first even zonal harmonic $J_2$ thanks to the approach described in (Ciufolini, 1989), that eliminates the influence of that error. This approach can be extended to eliminate the influence of additional even zonal harmonics as additional orbits become available and provide additional independent data. This is exactly where LARES is entering the picture. The addition of LARES data will allow us to eliminate the error due to the uncertainty in the next even zonal harmonic, $J_4$.

Studies at the University of Salento, Sapienza University of Rome, University of Maryland, BC, GFZ Potsdam/Munich, and at the Center for Space Research of the University of Texas at Austin have confirmed the accuracy of the measurement of the Lense-Thirring effect using the LAGEOS and LAGEOS 2 orbital data. However, for a measurement of the Lense-Thirring effect accurate to 1%, it will be necessary to use the LARES satellite together with the LAGEOS satellites, in order to eliminate the error from the present day uncertainty in $J_4$.

## 3. THE LARES EXPERIMENT

ASI's LARES space experiment is based on the launch of the laser-ranged satellite LARES (LAser RElativity Satellite), using ESA's new launch vehicle VEGA. LARES will have an altitude of about 1450 km, orbital inclination of about 70° ± 1° and near zero eccentricity. The LARES satellite together with the LAGEOS (NASA) and LAGEOS 2 (NASA and ASI) satellites and using the GRACE-derived Earth's gravity field models will allow a measurement of Earth's gravitomagnetic field and of the Lense-Thirring effect with an uncertainty of a few percent (Ciufolini et al., 2010a; 2011). The design of LARES was dictated by the need of reducing the surface perturbations such as thermal and atmospheric drag at an altitude of 1450 km. The body of LARES was thus designed as a solid piece in contrast to the LAGEOS satellites (Paolozzi, Ciufolini and Vendittozzi, 2011). Reduction of sub-components reduces contact conductance that in turn cause temperature gradients on the surface of the satellite. To reduce the effect of surface perturbations further, a non-typical material for aerospace constructions has been chosen: a tungsten alloy (Paolozzi et al. 2009a). The density of the chosen non-magnetic alloy was 18000

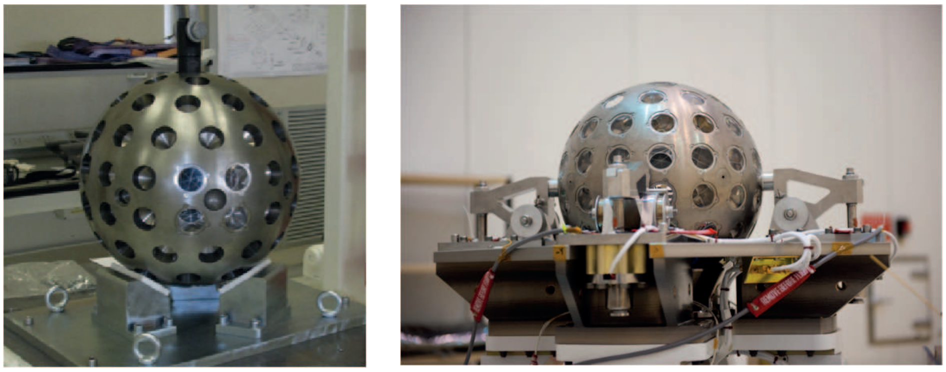

Figure 2: Left: The LARES satellite on the assembly line, with the retroreflectors being installed. Right: LARES mounted on the interface with the payloads pallet, prior to its mounting on the rocket

kg/m$^3$ that brought the overall density of the satellite (including the cavities for the retro-reflectors) just over 15000 kg/m$^3$. This resulted in a cross-section-to-mass ratio that is about 2.7 times better than the LAGEOS design. Roughly speaking, this number is a reduction factor to be applied to the uncertainties of the non-gravitational perturbations. The high density will make LARES the object with the highest mean density in the solar system.

In spite of its small dimensions (radius of 182 mm) the total mass is still 387 kg. Being in principle a test particle, like the LAGEOS satellites, LARES is spherical and completely passive, carrying 92 evenly distributed Cube Corner Reflectors (CCRs). The optical quality of the CCR material is extremely uniform and isotropic (Suprasil 311). The surface quality of the three back faces is 1/10th of the light wavelength while for the front face 1/8th, resulting in a quality of the reflected waveform of 1/4th of the wavelength. To compensate for the satellite motion the CCR dihedral angles of all the three back faces have been offset by an amount that is between 1 and 2 arcseconds. This procedure is well known for space CCRs and it is required to modify the Far Field Diffraction Pattern (i.e. the power distribution expected on the ground) so that the maximum power will be shifted from the center of the pattern by the amount the satellite travelled during the laser pulse flight. The distribution of the CCRs was organized on parallels, symmetrically disposed with respect to the equatorial circle. This distribution will allow an easier satellite spin axis determination from ground station telescopes using sun glints: when the direction Sun-CCR front face and the direction ground observer-CCR front face will agree with the laws of reflection a sun glint will be recorded. Estimation of the spin axis of the satellite will help estimating the thermal thrust vector perturbation. In the equatorial region of LARES there are no CCRs but eight cavities used for handling and for interfacing with the separation system. Four of the handling holes will be covered with tungsten alloy caps before launch, to slightly improve the surface-to-mass ratio. The other four cavities required for the separation system of the satellite will remain as such after the separation (right part of Figure 2). However the size (volume and depth) of those cavities have been minimized so that the estimated effect on the orbit is negligible. The minimization of the cavity size was possible by tightening the manufacturing tolerances at the technological limit possible today (Paolozzi et al. 2009b). Design and main tests of the LARES satellite and its separation system (Paolozzi et al. 2009c, Paolozzi et al. 2011) have been performed at Sapienza University. The construction of the Mechanical Ground Support Equipment and some prototypes were the responsibility of the universities. Launch is foreseen at the beginning of 2012[1].

## 4. CONCLUSIONS

ASI's mission LARES, a new design of laser-ranged-satellite, is ready and awaiting launch from Kouru, in early 2012, on ESA's new launch vehicle VEGA. LARES, together with the two LAGEOS satellites and the Earth gravity field models from the GRACE mission, will test Einstein's theory of General Relativity by measuring the frame-dragging effect with an accuracy of a few percent. Furthermore, simulations indicate that the addition of LARES to the current geodetic targets used for the development of the

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[1] LARES was successfully launched on 10:00 UTC Feb. 13, 2012.

ITRF will make a significant contribution towards the future accuracy goals for the ITRF as set by GGOS (Pavlis et al., 2009).

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