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First results from LARES: An analysis

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HIGHLIGHTS

- The estimated residual along-track LARES acceleration is 4×10^{-13} ms^{-2}.
- The predicted frame-dragging along-track LARES acceleration is 3×10^{-14} ms^{-2}.
- The 1PN Schwarzschild along-track LARES effect is indirectly confirmed at 5%.
- The along-track LARES effects of modified gravities are orders of magnitude smaller than 4×10^{-13} ms^{-2}.
- The estimated geopotential coefficients are less accurate than those by GRACE/GOCE by orders of magnitude.

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ABSTRACT

In this paper, I critically examine the first published results of the LARES mission targeted to measure the relativistic Lense-Thirring drag of the orbit of a satellite around a rotating mass.

1. Introduction

LARES (LAser RElativity Satellite) (Paolozzi et al., 2011), the heir of the LAGEOS X/LAGEOS 3 concept (Ciufolini, 1986), was launched on February 13th 2012 into an orbit characterized by[1] semimajor axis $a = 7,820$ km, eccentricity $e = 7 \times 10^{-4}$, orbit inclination to the Earth's equator $I = 69.5^\circ$, orbital frequency $n = 9.1 \times 10^{-4}$ s^{-1}.

Its main goal (Ciufolini et al., 2012) is a 1% measurement of the general relativistic frame-dragging, known also as Lense–Thirring effect (Lense and Thirring, 1918; Ashby and Allison, 1993; Iorio, 2001; Pfister, 2007) and consisting of small cumulative shifts of the orbit of a test particle geodesically moving in the field of a massive rotating object such as the spinning Earth. For another recent scenario based on the use of a different proposed relativity-dedicated satellite, see, e.g., Iorio et al. (2004); the idea of using the orbits of Earth's artificial satellites to measure the Lense-Thirring effect dates back to the Ginzburg's pioneeristic works (Ginzburg, 1956a,b, 1957, 1958, 1959). First traces for its existence has previously been obtained with the LAGEOS and LAGEOS 2 satellites (Ciufolini and Pavlis, 2004; Ciufolini et al., 2010), although some aspects of these tests are still controversial (Ciufolini et al., 2009, 2010; Iorio, 2006, 2009, 2010, 2011; Iorio et al., 2011). Other (somewhat controversial as well) measurements of the Lense-Thirring drag were made with the Mars Global Surveyor (MGS) spacecraft and Mars (Iorio, 2006; Krogh, 2007; Iorio, 2010), and proposed with the Sun and some of its planets (Iorio, 2005, 2007). Another general relativistic orbital effect caused by the rotation of a central mass is the gravitomagnetic clock effect (Vladimirov et al., 1987; Cohen and Mashhoon, 1993; You, 1998; Mashhoon et al., 2001; Iorio et al., 2002; Tartaglia, 2000). It affects the orbital periods of two counter-rotating test particles along otherwise identical trajectories in such a way that if one of them revolves in the same direction as the primary spins, it takes longer time to describe a full orbital revolution, whereas the orbital period of the other one gets shorter if it moves oppositely with respect to the mass rotation. The possibility of measuring the gravitomagnetic clock effect in space experiments was the subject of several works (Mashhoon et al., 1999; Iorio, 2001; Iorio and Lichtenegger, 2005). A further form of general relativistic frame-dragging caused by the spin of a massive object is the precession of a gyroscope (Pugh, 1959; Schiff, 1960a,b); a successful measurement of it in a dedicated space-based experiment was recently reported by Everitt et al. (2011). For a recent review on the phenomenology of the Lense–Thirring effect in the Solar System, see Iorio et al. (2011).

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[1] See on also http://www.calsky.com/observer//tle.cgi?satid=12006A&tdt=2456146.41756944 on the WEB.

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The actual attainability of the expected 1% accuracy in the LARES mission raised a debate (; Iorio, 2009a,b; Iorio, 2010; Ciufolini et al., 2010; Renzetti, 2012).

Ciufolini et al. (2012) recently analyzed the first 105 days of LARES; in this communication, I critically discuss some aspects of the results released in Ciufolini et al., 2012 and the interpretation offered by their authors.

2. My analysis

- The along-track frame-dragging acceleration is (Soffel, 1989; Linsen, 1991; Joos et al., 1991)

$$A_t^{\rm fd} = -\frac{2GJne\cos I\sin f(1+e\cos f)^3}{c^2a^2(1-e^2)^{7/2}}, \tag{1}$$

where G is the gravitational constant, c is the speed of light, J is the spin of the Earth, and f is the satellite's true anomaly. Since $J_\oplus = 5.86\times10^{33}$ kg m^2 s^{-1}, the maximum along-track frame-dragging acceleration for LARES is

$$A_t^{\rm fd}\Big|_{\rm max} = 3.2\times10^{-14}\ {\rm ms}^{-2}. \tag{2}$$

The estimated residual along-track empirical acceleration is Ciufolini et al., 2012

$$A_t^{\rm emp} = 4\times10^{-13}\ {\rm ms}^{-2} = 12.6\,A_t^{\rm fd}\Big|_{\rm max}. \tag{3}$$

It implies that frame-dragging cannot be extracted from the residuals of the LARES along-track acceleration.

A more accurate analysis confirms this conclusion. Indeed, by using the standard Gauss equations for the variations of the elements, it can be shown that an empirical 1CPR along-track acceleration

$$A_t^{\rm 1CPR} = A_t^{\rm c}\cos f + A_t^{\rm s}\sin f \tag{4}$$

causes a net secular precession of the perigee over an orbital period T

$$\langle\dot\omega_{\rm 1CPR}\rangle_T = -\frac{A_t^{\rm s}\left[2+2e^4-2\sqrt{1-e^2}+e^2\left(-4+\sqrt{1-e^2}\right)\right]}{2ae^3n} \approx \frac{A_t^{\rm s}}{aen}+\mathcal{O}(e). \tag{5}$$

For LARES, Eqs. (3) and (5) give a secular perigee precession as large as[2]

$$\langle\dot\omega_{\rm 1CPR}\rangle_T = 522\ {\rm mas\ yr}^{-1}; \tag{6}$$

the frame-dragging perigee precession of LARES is

$$\langle\dot\omega_{\rm fd}\rangle_T = -\frac{6GJ\cos I}{c^2a^3(1-e^2)^{3/2}} = -124\ {\rm mas\ yr}^{-1}, \tag{7}$$

while the Schwarzschild perigee precession of LARES is as large as

$$\langle\dot\omega_{\rm Schw}\rangle_T = \frac{3n\mu}{c^2a(1-e^2)} = 10{,}064\ {\rm mas\ yr}^{-1}, \tag{8}$$

where μ is the product of the gravitational constant G times the mass M of the Earth. The result of Eq. (6) will turn out to be useful later, when I will discuss the possibility of using LARES for other tests of fundamental physics. Ciufolini et al. (2012) write that, since all the general relativistic post-Newtonian corrections were included in their orbital analyses, Eq. (3) shows the level of agreement of the LARES orbits with the geodesic motion predicted by general relativity. Actually, such a statement could hold, at most, only for the Schwarzschild component of the LARES geodesic motion (to a relatively modest 5% level), not for its frame-dragging component which is too small to be sensed in the orbit analysis described by Ciufolini et al. (2012); modeling frame-dragging or not would have not had effect.

Thus, the main part of Ciufolini et al. (2012) dedicated to the residual along-track acceleration of LARES tells nothing about the actual measurability of frame-dragging from LARES observations.

- Ciufolini et al. (2012) did not estimate an empirical out-of-plane acceleration; thus, it is not possible to argue that it would have the same magnitude of Eq. (3), as done by Ciufolini et al. (2012). Actually, a 1 CPR empirical out-of-plane acceleration impacts the node with a long-period, harmonic precession without a secular component, contrary to what written by Ciufolini et al. (2012). The Gauss equation for the variation of the node, applied to[3]

$$A_o^{\rm 1CPR} = A_o^{\rm c}\cos f + A_o^{\rm s}\sin f \tag{9}$$

yields

$$\left\langle\dot\Omega_{\rm 1CPR}\right\rangle_T = \frac{A_o^{\rm c}(1+2e^2)\sin\omega + A_o^{\rm s}(1-e^2)\cos\omega}{2an\sin I\sqrt{1-e^2}}. \tag{10}$$

In fact, this is fine from the point of view of frame-dragging measurement since the perigee of LARES circulates with a period $T_\omega = 382$ d mainly due to the geopotential coefficient of degree 2 and order 0.

Nonetheless, the atmospheric drag and other nonconservative thermal forces may steadily impact the node of LARES through its secular effect on the inclination which, in turn, affects the disturbing node precession due to the geopotential coefficient of degree 2 and order 0, as pointed out by Iorio (2010).

- No dedicated general relativity parameters have been estimated by Ciufolini et al. (2012); this would have been crucial in effectively assessing the actual potential of LARES to directly test it. Generally speaking, the standard approach followed in usual orbit determination consisting of using the best available dynamical models and estimating certain parameters just to minimize the post-fit residuals of the observables may not necessarily be valid when testing general relativity is the main goal. Indeed, models potentially including a-priori bias of general relativity itself should be avoided even if they behave well in terms of the smallness of the residuals; moreover, if not explicitly solved-for, general relativity might partly or totally be removed from the signal in the estimation procedure of the other parameters.
- Ciufolini et al. (2012) write that LARES will be able to improve the existing bounds on some other theories of fundamental physics such as Brane-World models (Dvali et al., 2000), Yukawa-type deviations from the standard inverse-square law of gravity, certain possible low-energy consequences of string theory (Smith et al., 2008), etc.

In this respect, the orbit analysis of the along-track residual acceleration made by Ciufolini et al. (2012) yielding Eq. (3) is quite useful because all these alternative theories do have an impact just on the along-track part of the orbit, in particular on the perigee. Unfortunately, it does not support the expectations expressed by Ciufolini et al. (2012) themselves, at least as far as some theories are concerned.

[2] Here and in the following equations, mas yr^{-1} stands for milliarcseconds per year.

[3] It can be shown that a further constant term A_o^0 in Eq. (9) produces an additional periodic node rate proportional to $e\sin\omega$.