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Orbital predictions for the LARES satellite mission

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Abstract—LARES is an Italian Space Agency satellite specifically designed, built and launched to test general relativity. It is a passive satellite covered with Cube Corner Reflectors that reflect laser pulses from tracking stations, thus allowing accurate measurement of the distance. That in turn enables accurate orbit reconstruction that is a key ingredient to allow the measurement of the tiny Lense-Thirring effect predicted by general relativity. The International Space Time Analysis Research Center provides the International Laser Ranging Service-ILRS, the orbital predictions for LARES for pointing of the tracking telescopes toward the target. The paper describes the technical aspects of generating the orbital predictions.

Keywords—LARES, General Relativity, Frame-Dragging, Lense-Thirring effect, SLR, Orbital Determination, ILRS

I. INTRODUCTION

Various predictions of the theory of general relativity have been confirmed starting from the Mercury perihelion shift [1] to the deflection of light rays [2]. The accuracy of the equivalence principle measurement has also steadily increased [3] and more experiments are proposed for even further improvements. There are basic predictions however, such as "gravitational waves", that although they have been indirectly observed from the energy loss of binary pulsars [4-6], they still need to be detected directly. "Frame-dragging" has already been measured with reasonable accuracy with the LAGEOS satellites (10% accuracy) [7,8] and Gravity Probe B (19% accuracy) [9]. To improve the measurement accuracy at the level of 1% it was necessary to launch a third satellite [10,11], to be used in combination with LAGEOS (launched by NASA in 1976) and LAGEOS 2 (launched by NASA and ASI in 1992).

II. LARES MISSION

A. Objectives

The original LARES mission was conceived with the satellite in an orbit supplementary to that of LAGEOS satellite

[12], similarly to what was proposed through a LAGEOS 3 study (ca 1991). Fig. 1 illustrates the original concept of the mission. We specifically desired a small eccentricity for the orbit to allow the observation of the perigee position and variation, thus giving the opportunity to verify other aspects of general relativity. With this configuration by combining the data from the two satellites it would have been possible to eliminate the uncertainty in the effects due to Earth's oblateness and of other, higher order non-sphericity effect of Earth (more rigorously of all the even zonal harmonics) on the satellite node line (intersection of the equatorial and the orbital planes). For LAGEOS that nodal shift is of 231.09 degrees/year while the relativistic effect ("Frame-Dragging"), called the Lense-Thirring Effect (LTE), only 31.5 milliarcsec/year. The combination of data from the two satellites is crucial to the proposed experiment since the uncertainty on the knowledge of the gravitational field of Earth produces an effect that is much bigger than LTE. Reaching 6000 km altitude however was not possible with the qualification flight of ESA's VEGA rocket that succeeded in placing LARES in orbit on February 13th, 2012, albeit on a 1450 km orbit. Therefore, in 2008 when the Italian Space Agency (ASI) signed the contract for LARES, the approach proposed in [13] was chosen for the LARES mission (Fig. 2). In fact the combination of three satellites in three non-equatorial orbits with different inclinations would allow to eliminate the effects on the node of the first two even zonal harmonics (denoted by J_2 and J_4) and relevant uncertainties, leaving as a perturbing effect only the uncertainties of the higher even zonal harmonics which are well below 1% of the LTE [14] in total.

B. Satellite and Separation System

Figure 3 shows the LARES flight unit mounted on the separation system. Some of the 92 Cube Corner Reflectors

(CCRs) are visible on the surface of the satellite that is manufactured out of one single piece of tungsten alloy.



Fig. 1. Original concept of LARES mission



Fig. 2. In-orbit version of LARES mission.

This material was never before used so massively for a satellite and it was not easy to manufacture and in particular it was not easy to fulfill the tolerance requirements [15]. The

overall density of the satellite is about 15000 kg/m^3 and so its surface-to-mass ratio is the smallest of any artificial orbiting object. This was the result of different designs developed over several years [16-19]. The surface-to-mass ratio is proportional to the acceleration produced by the non-gravitational perturbations acting on the surface of the satellite. In particular this results in the minimization of the thermal thrust [20]. In brief LARES is the best artificial test particle available in the solar system and is therefore an ideal instrument not only for fundamental physics but also for geodesy and geodynamics [21]. The separation system comprises a main spring, located below the satellite, and four brackets [22] that engage on four equatorial hemispherical cavities machined on the tungsten alloy with the smallest tolerances possible with today's technology. In the event the main spring and/or one bracket failed, separation was still guaranteed with minimal loss of the scientific objectives.

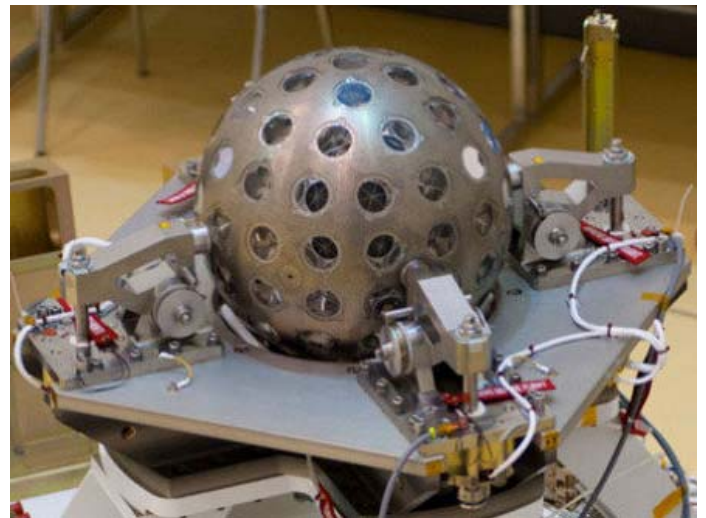


Fig. 3. LARES satellite resting on the separation system.

C. Ground Segment

The ground segment comprises of a global network of laser ranging systems and it is coordinated by the International Laser Ranging Service (ILRS) [23]. The network uses the orbital predictions, provided by a limited number of accredited centers (22), to point accurately the instruments towards anyone of the over than seventy targets in orbit today. By measuring accurately the amount of time a laser pulse takes for the round-trip from the station to the target and back to the station it is possible to estimate distances of thousands of kilometers with the precision of a millimeter.

Concerning LARES, about forty stations provide Normal Point (NP) data in ILRS' CRD format: [http://ilrs.gsfc.nasa.gov/data_and_products/formats/crd.html], nineteen of which provide also full rata data in CRD format. Thirty-four stations provided normal points in CSTG format until May 2012.

A few days after the launch, the first laser return was received at Yarragadee, Australia, on the February 17, 2012.

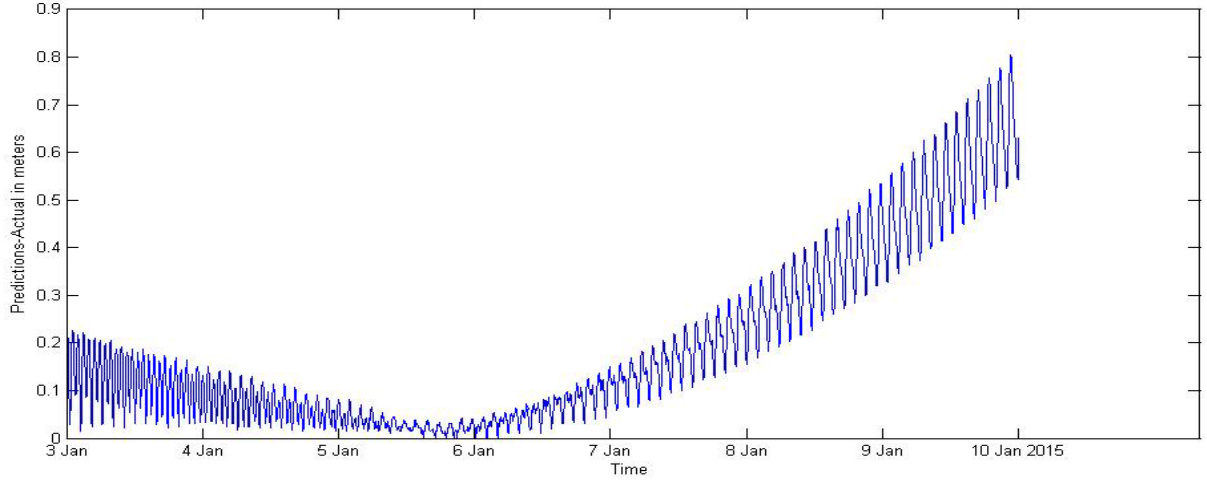


Fig. 4. LARES orbital predictions accuracy.

TABLE I. STATIONS WITH LASER RETURNS IN THE FIRST WEEK

Stations		Normal Point Tracking Stat. (CDR) from 2012-02-17 to 2015-01-10	
City	Country	Date of first laser return	No. of observ.
Yarragadee	Australia	2012-02-17 10:34:54	43723
Graz	Austria	2012-02-17 13:53:12	21674
Greenbelt, MD	USA	2012-02-17 21:41:37	16644
Monument Peak, CA	USA	2012-02-18 01:36:49	11953
Matera	Italy	2012-02-18 04:49:34	13040
Katzively	Ukraine	2012-02-19 03:55:07	3406

Tab. 1 lists the stations that obtained the first laser returns from LARES in the first week after the launch. The number of observations shown in the table is the cumulative number of NP until the January 10, 2015. NPs are obtained through a standard procedure at each station that involving averaging many single-shot range data and an orbital propagation fit through them. It reduces the noise in the data and significantly reduces the volume of the laser ranging data without loss of accuracy. The NP data are in fact the data used by scientists in their research studies. The orbital predictions are produced starting from the past satellite orbits based on the NP rather than the full-rate data. An example of the quality of the predictions is demonstrated in Fig. 4 where it is shown the maximum error seen after seven days is less than a meter.

III. ORBITAL PREDICTIONS

ILRS makes the ranging data available to researchers via its official Data Center archives at NASA Goddard (CDDIS) and the European Data Center (EDC) in Munich, Germany. In order to successfully range to the targets, LARES in particular, ILRS stations require orbital predictions. In fact the stations need to know at each instant the exact location of the target to

be able to correctly point their instruments to the target. The accuracy required depends on the orbital altitude of the target; in general it is few tens of meters since laser beams expand considerably at the distance of several hundreds of kilometers.

In Fig. 5 the orbital predictions, provided by ISTARC located in Rome, are plotted from a view-point located over the North Pole axis. Those predictions are practically coincident with the actual orbit of the satellite, as demonstrated in Fig. 4, and cannot be resolved one from each other in figure 5. The inner “circle” describes the envelope of the maximum and minimum latitude reached by the satellite (equal to the satellite’s inclination). The axes show the x and y coordinates in meters. Fig. 6 illustrates Earth in true scale. ISTARC prediction files contain the Cartesian coordinates of the satellite every 240 seconds, i.e. the amount of time Earth takes to rotate by 1 degree.

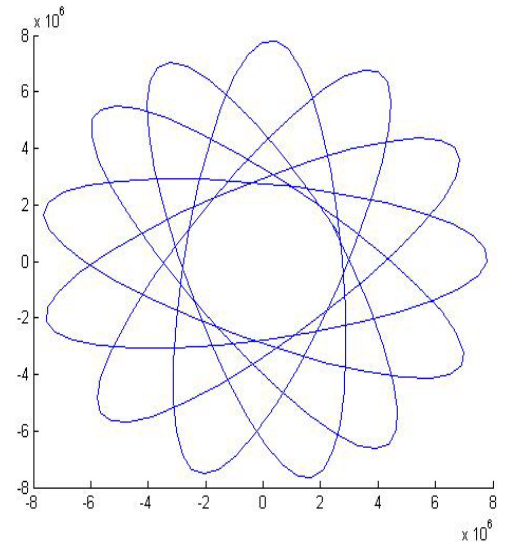


Fig. 5. Projection in the equatorial plane of the orbit of LARES. The reference frame is geocentric Earth-fixed.

The geocentric Earth-fixed trajectory shown in Fig. 5 and 6 corresponds to 188 prediction points. The orbit of LARES in an inertial reference frame would rotate only because of Earth oblateness (even zonal harmonics) with a period of about 211 days, i.e. about 1.7 degrees per day. Therefore in a half day, the orbit evolution would not be visible in a plot referred to that frame. Additionally, there is also the tiny contribution of the Lense-Thirring effect that cannot be observed directly, but only after a proper combination of data from three satellites taking into account the actual gravitational field of Earth. In Figs 5 and 6 one can count about 6 pseudo-ellipses each one travelled in an orbital period of about 115 minutes for a total of about 12 hours.

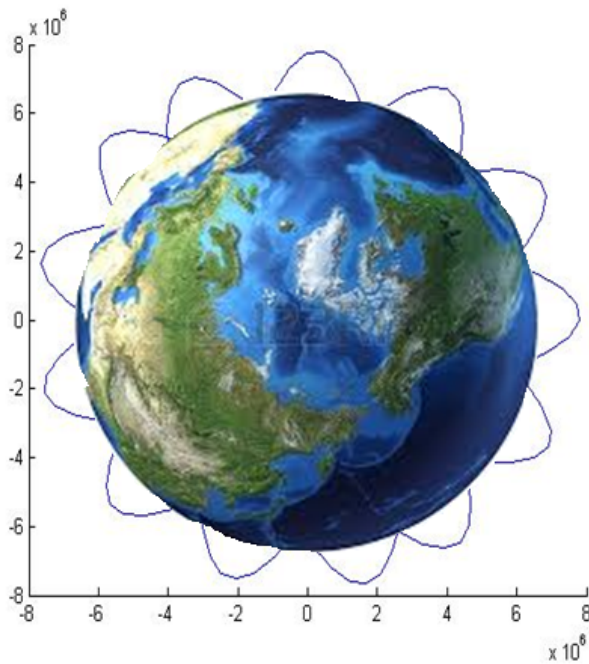


Fig. 6. LARES orbit viewed from the north pole superimposed to the Earth.. The reference frame is geocentric fixed and rotating with the Earth

IV. CONCLUSIONS

Orbital predictions are essential to allow accurate pointing of laser telescopes at the ILRS tracking stations. ISTARC is producing routinely very accurate predictions to support the ILRS network since the launch of LARES.

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