Quality assessment of LARES satellite ranging data

LARES contribution for improving the terrestrial reference frame

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***Abstract*—LARES is an Italian Space Agency mission designed to test General Relativity in the weak field of Earth. In particular, the satellite will be able to measure frame-dragging with an accuracy of about 1%. The difficulty of the measurement is mainly due to the perturbations acting on the satellite and the relatively tiny size of the effect, amounting to about 118 milliarcseconds/year. LARES will also provide data to geodesists and it will contribute to GNSS by improving the origin definition of the International Terrestrial Reference Frame. The mission was designed and the satellite subsystems built and tested in less than four years. The short time to launch and the very limited budget of the LARES mission, raised doubts whether LARES could be, as expected by design, one of the best satellite laser ranging targets. The best way to confirm the success of the mission is to look at the range residuals from the primary stations of the International Laser Ranging Service (ILRS). In the paper it will be shown that from the majority of these stations LARES behaves as the best target.**

Keywords—LARES; laser ranging; general relativity; frame-dragging; CCR

I. Introduction

LARES is an acronym that stands for LAser RElativity Satellite. Although designed for testing frame-dragging predicted by general relativity [1], it will make important contributions in many areas of Earth science and in particular to the improvement of the International Terrestrial Reference Frame (ITRF) which in turn is important for precise orbit determination and for Global Navigation Satellite Systems (GNSS). LARES is a cost effective approach with respect to the previous proposal of a LAGEOS 3 mission, since the altitude of LARES is much lower (1450 km) than that proposed for LAGEOS 3 (6000 km). In other words, the launch cost for LAGEOS 3 would have been much higher. On the other hand, due to practically the absence of atmosphere, a small eccentricity for LAGEOS 3 would have allowed to perform other tests of fundamental physics other than frame-dragging. For LARES we chose a zero eccentricity since the perigee in a 1450 km altitude orbit is affected by high uncertainty due to the presence of the atmosphere, that although rarefied, it still has a significant influence on some orbital parameters. This consideration was indeed a driving factor in the engineering design of LARES that was built with a very low surface-to-mass ratio (see details later) [2]. The altitude of 6000 km is indeed the altitude of the two LAGEOS satellites launched in 1976 by NASA (LAGEOS 1) and in 1992 (LAGEOS 2) by NASA and the Italian Space Agency (ASI). The choice of this altitude for LAGEOS 3 satellite was due to the possibility of eliminating the effects of all the even zonal harmonics on the satellite node (intersection of equatorial plane with the orbital plane). The first even zonal harmonic, J_2, accounts for the dynamical Earth oblateness. In the LAGEOS 3 experiment as well as in a later version called LARES/Webersat, it was intended to use an orbital plane with supplementary inclination to the LAGEOS 1 satellite. In this configuration i.e., 6000 km altitude and 70° inclination for LAGEOS 3, the effects on the satellite nodes of all the J_{2n} harmonics of Earth's gravitational field are eliminated. In 2008 when the opportunity for a free launch on ESA's VEGA maiden flight was disclosed, ASI decided to sign a contract for the establishment of a dedicated mission to test the Lense-Thirring effect, a manifestation of frame-dragging on a test particle orbiting Earth. As it will be shown later, LARES is the best realization of a test particle [3]. The main contractor was CGS with a strong participation of the Universities of Salento and Rome (Sapienza). Although the VEGA launcher could reach the altitude of 6000 km, albeit with a lower payload mass, it was not allowed, during the qualification flight, to exceed 1500 km. LARES was successfully placed in orbit on February 13, 2012 [4]. In spite of the fact that it was a qualification flight the orbital parameters were extremely close to the nominal ones.

II. LENSE-THIRRING EFFECT AND THE LARES MISSION

The Lense-Thirring effect (LT) was shown to be a consequence of general relativity by the two Austrian physicists Lense and Thirring [5]. A rotating body, in addition to the space-time deformation it will produce a further small warping around Earth, measurable with the laser ranging technique. This effect vanishes with the cubic of the distance from the centre of the body, as in equation (1), where vector Ω is the precession of the node, G is the gravitational constant, vector J is Earth's angular momentum, c is the speed of light, e and a are the eccentricity and the semi-major axis of the satellite orbit.

$$\vec{\Omega} = \frac{2G\vec{J}}{c^2 a^3 (1 - e^2)^{3/2}} \quad (1)$$

It is therefore more pronounced for LARES (118 milliarcseconds/year) than for LAGEOS (31.5 milliarcseconds/year). To have a better quantification of the effect one can easily calculate that the node of LARES will move, in an inertial reference frame, by 4.5 m/year while for LAGEOS by only ~2 m/year. Considering that the objective of the mission is to improve the measurement of LT, already obtained with an accuracy of 10% in [6,7] and of 19% in [8], by a factor of ten, that means the expected outcome of the mission is to measure the node shift with an accuracy of a few centimetres. The laser ranging technique is well suited for this task being able to position the satellites with centimetre level accuracy and from some of the better stations even at a few millimetres. An obstacle to this approach is the classical perturbations acting on the satellite and having several orders of magnitude larger influence on the motion of the node. Furthermore, the knowledge of the effects of non-gravitational perturbations is not perfect and reaches accuracies of several centimetres. It therefore has also an influence on the final accuracy expected from the LARES experiment and for this reason LARES was manufactured with the lowest surface-to-mass ratio ever used for any orbiting object. That was made possible by using a single piece of tungsten alloy for the satellite body. As a consequence, LARES is now the densest and the best test particle orbiting in the solar system. Due to the smallness of that ratio (a factor about 2.6 times better than that for LAGEOS) it is possible to reduce the uncertainty of the effects of those non-gravitational perturbations by a factor of 2.6 [9]. Concerning the gravitational perturbations, there is no engineering design that will be able to minimize them, so a different approach is required. The first aspect is to have the best knowledge of the Earth gravitational field, i.e., the most accurate values of its representation in spherical harmonics. That has been obtained with the GRACE and GOCE missions that provided uncertainties for the J_{2n} with $n > 2$ which are below the centimetre level. The effect due to the uncertainties of J_2 and J_4 are instead eliminated by use of a combination of the nodes' motion for the two LAGEOS satellites and LARES.

The design of LARES was conceived specifically for testing frame-dragging of general relativity [10-13]. The body of the satellite is a single spherical piece of tungsten alloy weighing 386.8 kg. The radius is 0.182 m. The surface is covered with 92 cube-corner retroreflectors (CCRs) evenly distributed and arranged with regular spacing in 8 parallels plus two CCRs in polar positions. This arrangement is optimized to allow attitude detection from ground-based measurements. Fig. 1 is a photograph of the LARES satellite. The CCRs are clearly visible on the surface of the satellite. Two of the four retaining brackets engaging on proper cavities on the satellite are shown at left and right on the picture, They are part of the separation system of the satellite [14]. In the foreground two cables are visible that are connected to strain gauges to monitor the pre-load exerted by the brackets on the satellite [15].

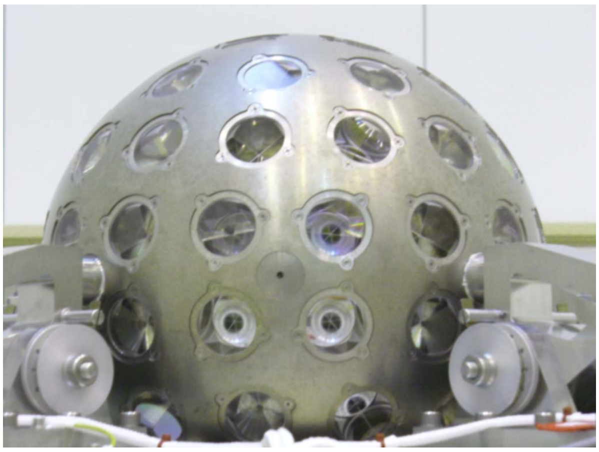

Fig. 1. The satellite LARES.

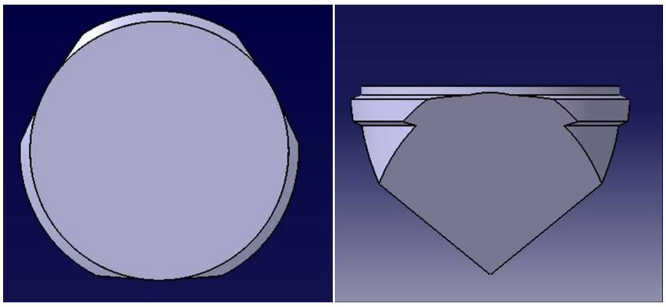

Fig. 2. Cube Corner Reflector. Front face (on the left) and side view (on the right) of a CCR.

III. QUALITY ASSESSMENT AND LARES CONTRIBUTION TO ITRF

The most accurate technique to measure distances is laser ranging [16]. It is a kind of optical radar for which the target has to carry an optical retroreflector for the highest possible accuracy. When distances are thousands of kilometres or even hundreds of thousands of kilometres as in the case of the Moon (in this case the technique is called Lunar Laser Ranging or LLR), the retroreflectors have to be manufactured with extremely high accuracy. In the case of LARES for instance the retroreflectors are uncoated CCRs; Fig. 2 shows the shape of such a CCR. All surfaces are manufactured with accuracies up to $\lambda/10$ (where λ is the laser wavelength) and the dihedral angles between the back faces need to be manufactured with a maximum error angle of 0.5 arcsec. The presence of retroreflectors on the target is not strictly necessary if high accuracy is not required. Recently in fact, laser ranging has been used to improve the orbital accuracy of space debris with respect to radar or telescope detection. That could be achieved using high-energy laser pulses of 2 J at 20 Hz repetition rate [17] or high repetition rate lasers working at 2 kHz and 25 mJ/pulse coupled with a single photon detector [18]. With this last approach it was possible to improve the position accuracy of debris down to 0.7 m. Since few days after the launch, the International Laser Ranging Service (ILRS) started tracking LARES. Nearly three years of data are already acquired and available to researchers for their studies.

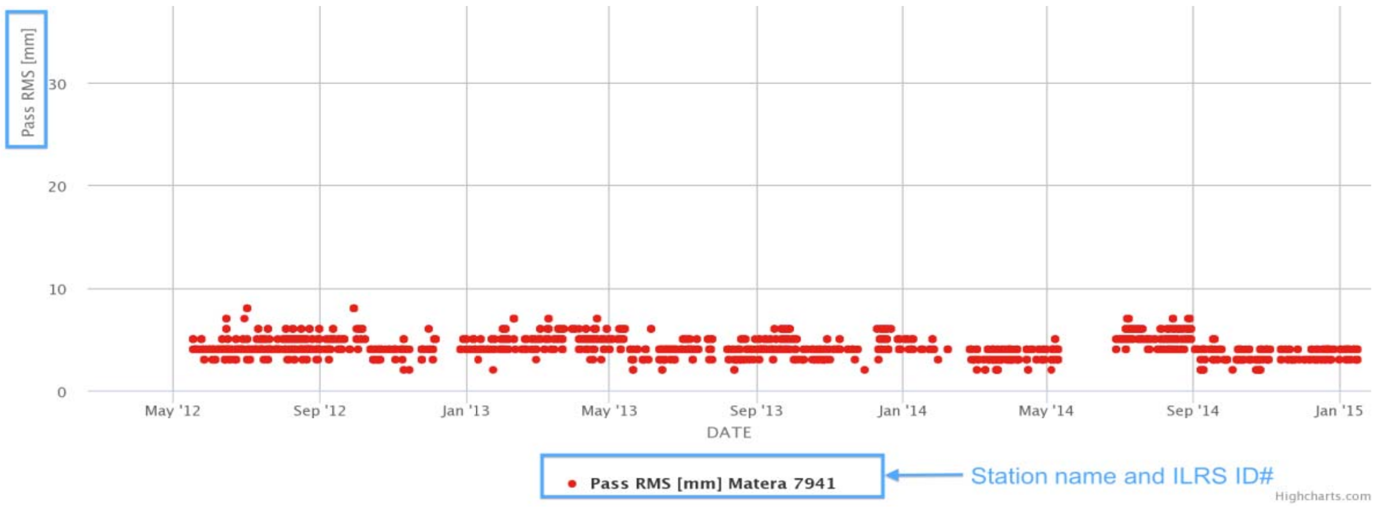

Fig. 3. RMS of range residuals of LARES. Mean 4.34 mm, standard deviation 0.90 mm.

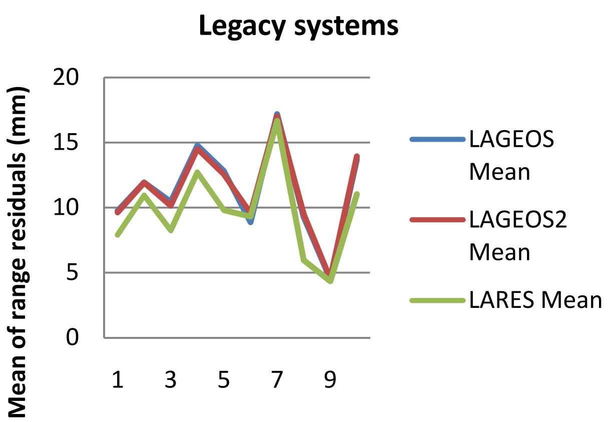

Fig. 4. Mean of range residual of legacy laser ranging stations. Horizontal axis reports the station as in table 1

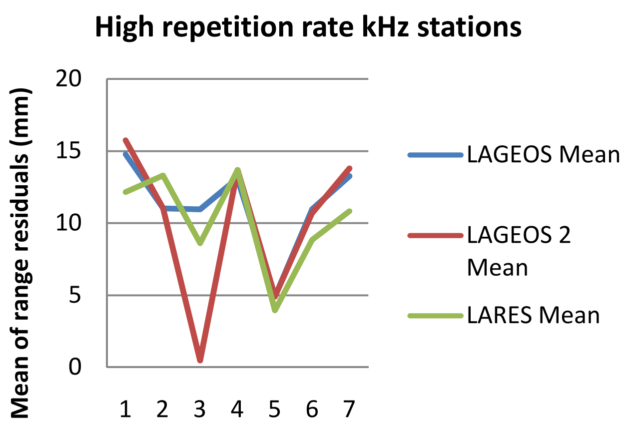

Fig. 5. Mean of range residual of high frequency stations. Horizontal axis reports the station as in table 1.

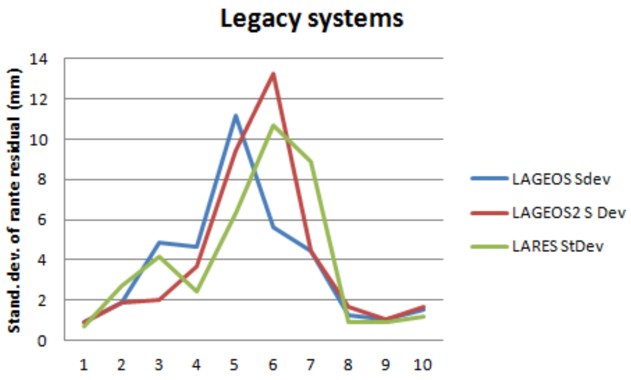

Fig. 6. Standard deviation of range residual of legacy laser ranging stations. Horizontal axis reports the station No. from Table 1.

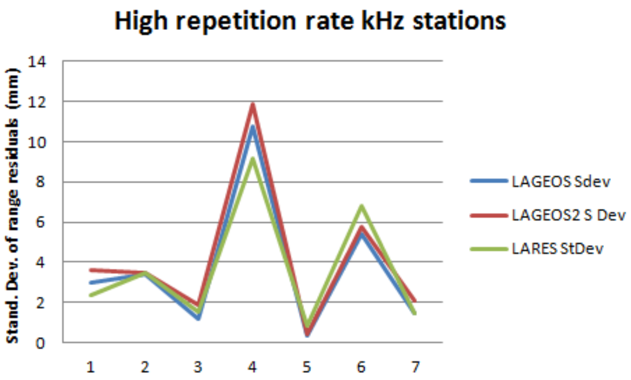

Fig. 7. Standard deviation of range residual of high repetition stations. Horizontal axis reports the station No. from Table 1.

TABLE I. LIST OF STATIONS USED IN THE ANALYSIS OF RANGE RESIDUALS.

	Legacy Station		**High rep. stations**
1	Yarragadee	1	Changchun
2	McDonald, TX	2	San Juan
3	Greenbelt, MD	3	Zimmerwald
4	Monum. Peak, CA	4	Shanghai
5	Haleakala, HI	5	Graz
6	Arequipa	6	Herstmonceux
7	Concepcion	7	Potsdam
8	Mt. Stromlo		
9	Matera		
10	Wettzell		

However, for the accurate and reliable measurement of frame-dragging, about seven years of data are required to allow averaging out the effects of luni-solar tide errors on the orbital parameters of the satellite. LARES is also very useful to the space geodesy community and already LARES data have been used by several groups in combination with LAGEOS and other Satellite Laser Ranged (SLR) satellites to generate station positions, Earth Orientation Parameters (EOP) and low degree gravitational harmonics estimates. There is a clear improvement in geodetic results that include LARES data: in the station positions well over 20% and in terms of their stability, well over 30%, with similar improvements in EOP and low-degree gravitational harmonics [19].

The range residuals are an elaboration of the prediction residuals. These last ones are the difference between the observations and the orbital predictions. The elaboration includes an orbit determination through the data in an iterative procedure until convergence is reached. In brief, the range residuals provide quantitative information on the quality of the target from an optical point of view. In Fig. 3 are reported the LARES range residuals of the laser ranging station located in Matera (Italy) since the date of launch. A small value of the mean of the range residuals is an indication of good quality of the target and the ranging system. In Fig. 4 are reported the mean values of the range residuals of LARES in comparison to those of the two LAGEOS satellites from the legacy laser ranging systems. It can be seen that the values corresponding to LARES are the smallest with the exclusion of the station of Arequipa where LAGEOS 1 has a better behaviour with respect to LARES. In Fig 5 are reported the analogous values for the high repetition rate kHz stations. Here also the corresponding values for LARES are the smallest with the exception of San Juan station (which is due to the local system, not to LARES). A small standard deviation is also a guarantee of reliability and stability of the ranging quality. In Figs 6 and 7 are reported the standard deviations of the range residuals from LARES, compared to those of the two LAGEOS satellites.

We can summarize that the standard deviations of the range residuals are the smallest for LARES in about 50% of the stations analyzed. The comparison of the data has been performed only with the LAGEOS satellites because they have been up to now widely accepted as being the best targets for laser ranging.

IV. CONCLUSIONS

As shown in several papers, LARES can be considered the best test particle orbiting Earth. In this paper it has been shown that LARES is also one of the best targets for laser ranging as demonstrated by the smallest mean values of the range residuals from the best ILRS stations. The standard deviation in about 50% of cases is also better than that of the two LAGEOS satellites. The addition of LARES data to those of LAGEOS has produced an improvement in the geodetic results, useful also for GNSS applications.

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