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# Contribution of LARES and Geodetic Satellites on Environmental Monitoring

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**Abstract**—LARES is the latest laser ranged geodetic satellite launched in orbit. It is an Italian Space Agency mission devoted mainly to test fundamental physics. However, it will be shown in the present paper that it will also contribute significantly to Earth science. The use of LARES together with the constellation of the other geodetic satellites will provide improvements in the measurement of the gravity field of Earth including its temporal variation measurements. In particular the latter carries signatures of mass redistribution due to several phenomena including global atmospheric and oceanic circulation, useful not only for monitoring global climate change but also to provide a means for climate model validation.

## I. INTRODUCTION

The LARES mission [1] was derived from the LAGEOS 3 proposal that was prepared based on the studies performed in [2]. The first approval for a phase A study of LARES mission was given by the Italian Space Agency (ASI) back in 1998, but the approval of the executive program (phases B to D) came 10 years later, when the VEGA launcher development was in its final stage. The main objective of the mission is to measure frame-dragging [3]–[5], one of the many predictions of general relativity: currents of mass and energy will distort space-time similarly to what happens, but generally to a bigger extent, with mass and energy itself. The first measurements of this effect have been performed in [6] and improved a few years later [7]. That result was achieved by using data from the two LAGEOS satellites launched by NASA in 1976 and NASA and ASI in 1992 respectively, reaching an accuracy of about 10%, confirmed also in [8]. Later on, also an independent experiment, determined frame dragging with an accuracy of about 19% by measuring the drift of four gyroscopes inside the Gravity Probe B spacecraft [9]. With the third satellite LARES, placed in orbit on 13th February 2012 [10], it is expected to reach an accuracy at the level of 1% [11], [12] in a time span of about seven years after launch. This long period of time is required to average out some periodical orbital perturbations unrelated to relativity. From preliminary

data analysis it was observed that LARES behaves as the best test particle ever put in orbit. This, as will be shown later, is an important characteristic not only for fundamental physics but also in geodesy and geodynamics. A quantitative estimation of the actual contribution of Satellite Laser Ranging (SLR) and in particular of LARES to geodesy and geodynamics is not easy yet. In fact the solution for Earth science applications uses a combination of data not only from several different satellites but also from other geodetic space techniques such as, Very Long Baseline Interferometry (VLBI), the Global Navigation Satellite System (GNSS) constellations and the French system DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite). The preliminary results reported in [13] are quite remarkable, indicating the inclusion of LARES data in purely SLR-ONLY solution results in an improvement of more than 20% in the station positions with an improvement on their stability of near 30%. A similar improvement in Earth Orientation Parameters (EOP) and estimates of the low-degree gravitational harmonics has also been observed. Contributions from several fields: geodesy, geodynamics, geophysics, meteorology and oceanography are necessary to obtain meaningful results and to break the correlations of various small systematic errors that are always present in each of the observational geodetic techniques. Each component of the Earth System acts in different time-scales and periodicities. EOP for example is affected by surface rearrangement of masses in the atmosphere, ocean and hydrological environment, but it is also affected at much longer time-scales by redistribution of masses inside Earth. As mentioned in [14] the effects of the atmosphere on the EOP can be done either by evaluating the torques applied by the atmosphere to the Earth [15] or by evaluating the variations of the atmospheric angular momentum on polar motion and on the Length Of Day (LOD) [16]. The importance of EOP in global environmental monitoring is addressed by several papers such as in [17] just to mention one. Correlations between EOP and global climate variability has been studied in [18]. In [14] the effects of the atmosphere on polar motion and LOD is considered. There are obvious difficulties in separating the effects of the atmosphere from those due to the

oceans, hydrology and internal mass redistribution. However the effect of the atmosphere seems to be prevalent. Similarly the fluctuations in LOD are due not only to angular momentum variation on the atmosphere, but also to ocean etc

## II. LARES SYSTEM

When the qualification launch of VEGA was announced, LARES was first accepted on board. Later the educational program of ESA involved seven Cubesats. These are standard cube-shaped nanosatellites of 10 cm edge-size and a mass of about 1 kg. A microsatellite, ALMASat, from the University of Bologna was also added to the mission. All these payloads were fit on the VEGA payload attachment system called LARES system where central role had LARES, as shown in Fig. 1.

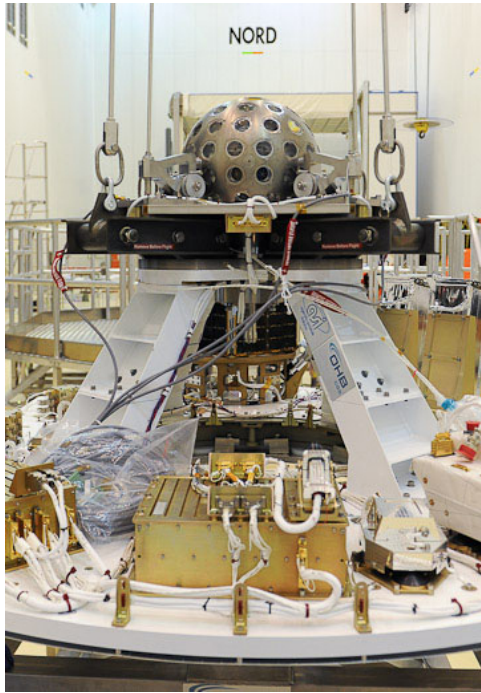


Fig. 1. LARES System. (Credits ESA, CNES, Arianespace, Optique video du CSG, L. Mira)

### A. The LARES satellite payload

The LARES satellite is a sphere with a radius of 182 mm (top in 1) covered with 92 Cube Corner Retroreflectors (CCRs) [19]. It is manufactured from a single piece of tungsten alloy [20]. It is totally passive i.e., there is no attitude control, power supply, antennas, active thermal control, propulsion, or telecommanding involved. The presence of CCRs allow the measurement of the distance from laser ground stations. The overall weight of the satellite is 386.8 kg with a mean density of about  $15000 \text{ kg/m}^3$  that makes LARES the densest orbiting object in the solar system. But the most important property is the surface-to-mass ratio that is also the smallest among all artificial Earth-orbiting objects. This parameter is proportional to the acceleration induced on the satellite by the action of the non-gravitational perturbations. The design

of LARES was performed minimizing this value and thus obtaining an object with an orbit that best approximates the geodesic in spacetime [21]. The choice of using a single piece of tungsten alloy for the satellite body had a further beneficial effect on reducing thermal thrust, a tiny but measureable non-gravitational perturbation [22] that has been observed on the other cannoball satellites. An alternative design for reducing this perturbation was proposed in [23] but that design was not as good for the minimization of the other non-gravitational perturbations.

### B. The separation and support system

The LARES separation system, visible in Fig. 1 just below the satellite, has been specifically designed for LARES. The main requirement, besides that concerning the structural integrity of the satellite and the separation system during launch, was to avoid the need of protruding parts on the satellite at the interface points. The solution adopted was to rely on the force (about 17000 N) exerted by each one of the four hemispherical pins on the corresponding four hemispherical equatorial cavities. The pressure at the contact point was close to the admissible limit of the satellite tungsten alloy. It was therefore required to check experimentally if this separation system design was feasible [24]. The final separation test demonstrated the validity of the design [25].

## III. SATELLITE LASER RANGING

Satellite Laser Ranging (SLR) was first tried and successfully tested at NASA Goddard Space Flight Center on October 31, 1964, shortly after the invention of lasers. Since then the technology has evolved tremendously and has enabled ranging to the Moon and to transponders on spacecraft orbiting other planets (e.g. Mars). The key technology for laser ranging is provided by an international network of ground stations coordinated by the International Laser Ranging Service (ILRS) [26]. The current network comprises about 60 stations distributed all over the world Fig. (2), however, there are only about 40 active stations and of these 50% are the ones providing the bulk of the tracking data routinely.

Extremely short ( $\sim 10\text{-}300 \text{ ps}$ ) laser pulses are transmitted at various rates (10 Hz to 10 kHz) through a telescope toward the targets. An extremely accurate counter or an event timer allows to measure the round-trip time of flight with extreme accuracy thus providing single-shot distance measurements with an accuracy of a few millimeters. Laser ranging data acquired at each station are initially preprocessed locally at the stations, forming the so-called Normal Points (NPs), by averaging the data over pre-specified time intervals determined on the basis of the altitude of the targets, to suppress random noise while preserving any dynamic signals. The process reduces by several orders of magnitude the number of data to be analyzed later on, and improves the precision of the NPs to about 1 mm or less. The SLR data collected by the ILRS network are subsequently used by analysis groups for precision orbit determination (POD), geophysical parameter estimation, experimental tests, the study of satellite dynamics, etc. The data and products of these analyses are distributed to researchers through the two data centers shown in Tab. 1. The main products are full rate data, i.e. the single laser pulse time

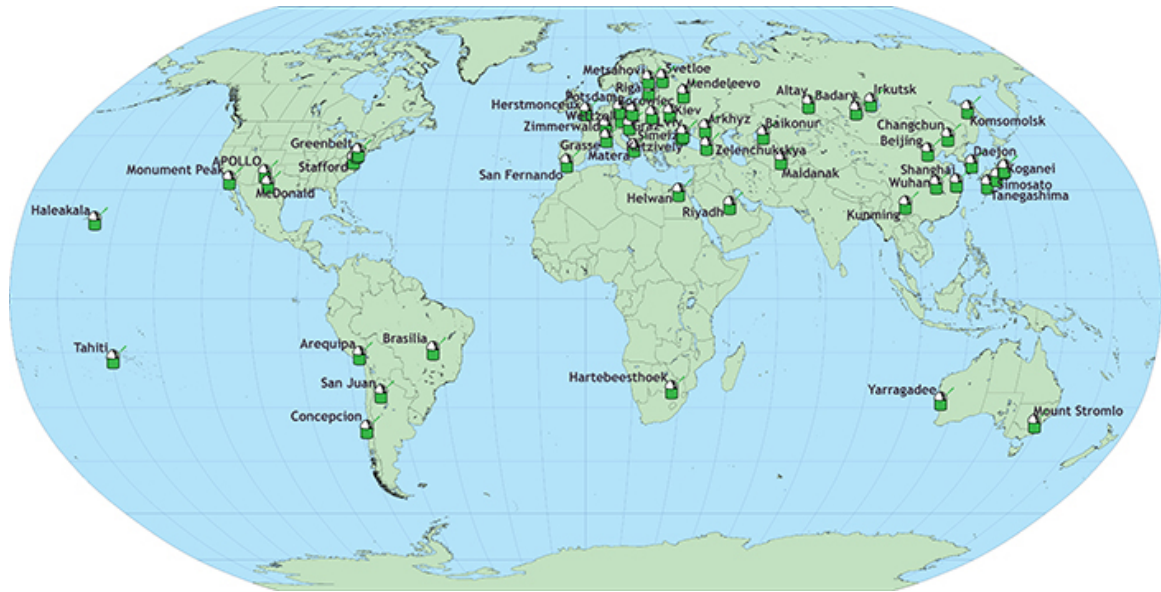


Fig. 2. The International Laser Ranging Service Tracking Network.

of flight, and the NPs. The latter are the most commonly used by scientists.

#### IV. ENVIROMENTAL MONITORING WITH GEODETIC SATELLITES

Related to this paper topic, NPs are used to measure the kinematics and long-term dynamics of the solid Earth, oceans and atmosphere through the estimation of EOP, gravity model parameters, station positions and velocities, etc. Figure 3 illustrates the daily differences of the polar motion and LOD series obtained using the data from the LAGEOS satellites with respect to the official IERS series derived primarily from GPS data. In Fig. 4 and Fig. 5 the graphs show the weekly variations of the instantaneous Earth center of mass with respect to the conventional origin of the tracking network and the weekly variation in scale, all being the result of analyses of the LAGEOS satellites SLR data.

TABLE I. DATA CENTERS

Data Center	Acronym	Location	Web site
Crustal Dynamics Data Information Center	CDDIS	NASA GSFC	<a href="http://cddis.nasa.gov/">http://cddis.nasa.gov/</a>
Eurolas Data Center	EDC	DGFI in Munich	<a href="http://edc.dgfi.badw.de/en/">http://edc.dgfi.badw.de/en/</a>

The time series of the Earth center of mass (geocenter) are dominated by a strong annual signal that is climate driven, the change of seasons between the two hemispheres. There is also a much smaller semiannual and seasonal (quadrennial) signal. The annual amplitude for the X and Y components is about 3 mm, while the much more strongly affected Z component is closer to 5 mm. In addition to these periodic signals, transients at various times are the effect of other environmental phenomena such as El Niño/La Niña events, excessive melting of icecaps over the Arctic Ocean, Antarctica and Greenland, etc. The same phenomena are also responsible for apparent scale variations as noted in Fig. 5.

The addition of the LARES data to those from the two LAGEOS will improve the overall accuracy, resolution and

reliability of these time series. Preliminary analyses indicate that one can expect an improvement on the order of 20–30% depending on the estimated parameter [13].

The initial reduction of the LARES NP data along with those from LAGEOS 1 & 2 gave us a pretty clear picture of what we can expect in terms of accuracy improvement in the resulting station positions and EOP series. Figure 6 shows the percent improvement in the calibrated standard deviation of each Cartesian coordinate component for all the stations tracking all three satellites vs. the same quantities when the coordinates were obtained on the basis of the data from the two LAGEOS alone. On average, from only three years of LARES data we see an improvement of 20%. You can observe some very impressive improvements in the case of a couple of stations which had very little tracking data from LAGEOS 1 & 2 alone, indicating the crucial role of LARES in such cases. From the same analysis, we can also infer the percent improvement in the error estimates for the daily EOP time series from the two solutions. In Fig. 7 we see the percentage of improvement for each individual daily estimate of the polar motion coordinates  $X_p$  and  $Y_p$ , as well as that in LOD. Again, on average, the improvement is at about 20%. The addition of the lower altitude LARES data will also allow us to estimate improved low degree spherical harmonics for Earths gravitational field over weekly intervals to help monitor large-scale mass redistribution in Earths fluid envelope. By forward modeling the effect of the atmospheric and oceanic circulation based on dedicated space missions, the combination of SLR-derived low degree harmonic variations and those from missions like GRACE, GRACE-FO, etc. for the higher degree terms, help monitor the largely otherwise unobserved hydrological cycle on Earths surface. Finally, the improved ITRF from the addition of the LARES data to those from the two LAGEOS, will help generate improved accuracy and stability GNSS orbits that in turn will result in far more accurate positioning, navigation, and timing applications for the huge international user community.



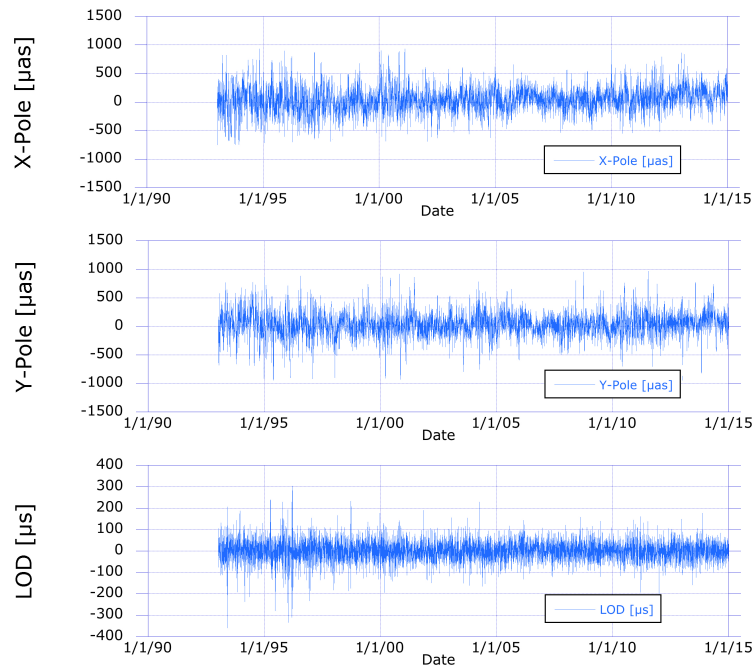


Fig. 3. Daily EOP differences of the SLR-derived series from the official IERS series over the past two decades.

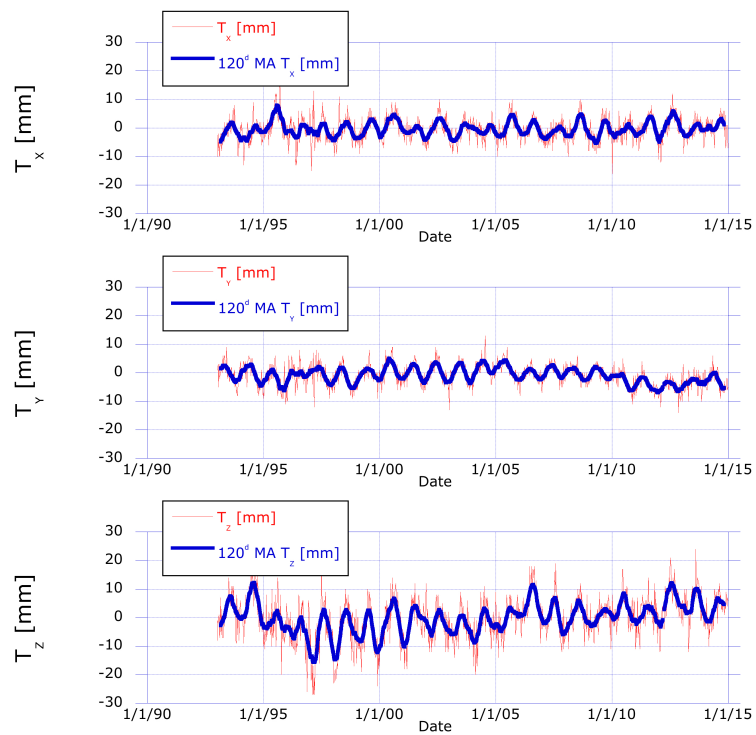


Fig. 4. Weekly SLR-derived series of the coordinates of Earth's center of mass over the past two decades.

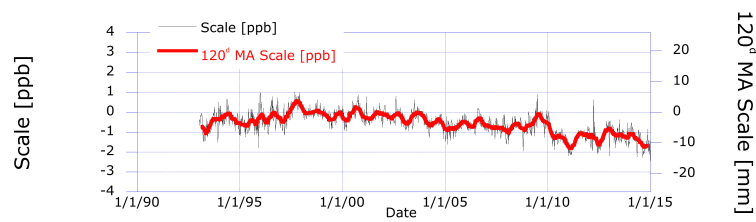


Fig. 5. Weekly SLR-derived series of the network scale over the past two decades.

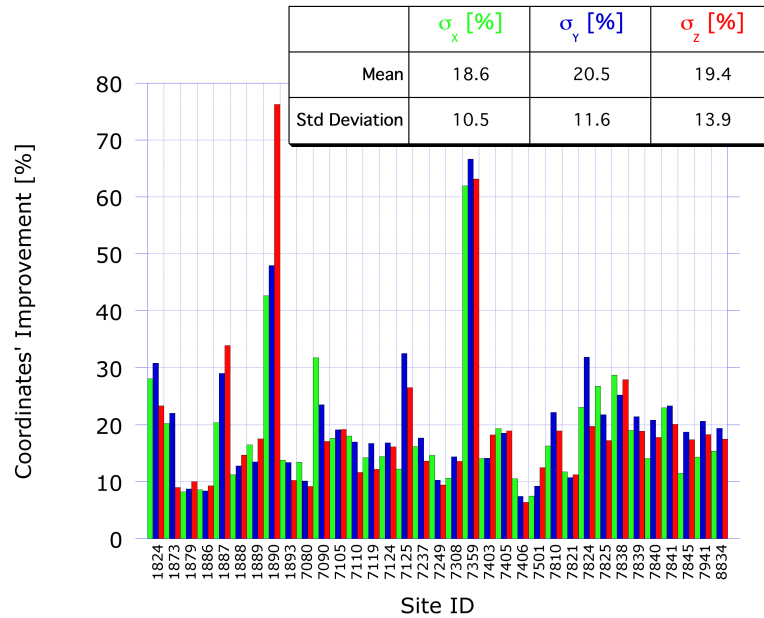


Fig. 6. Percent improvement in the calibrated errors of the three Cartesian components X, Y, Z of station positions derived from a 3-year solution using LAGEOS 1 & 2 alone vs. one with LARES SLR data added.

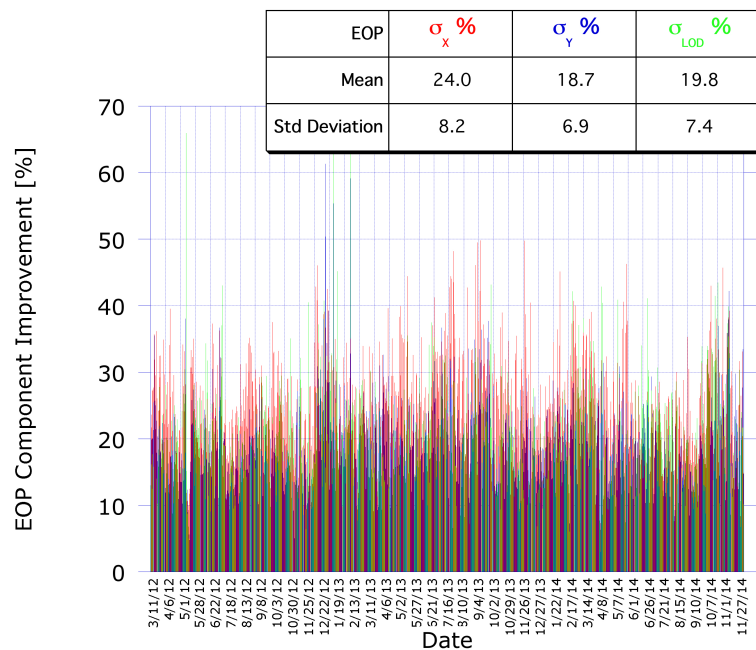


Fig. 7. Percent improvement in the calibrated errors of the Polar Motion ( $X_p$  &  $Y_p$ ) and LOD EOP derived from a 3-year solution using from LAGEOS 1 & 2 alone vs. one with LARES SLR data added.

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