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LARES Mission Operations

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Abstract—LAsER Relativity Satellite (LARES) is an Italian Space Agency mission that started operations on February 2012 after a successful launch on ESA’s VEGA qualification flight. The satellite is covered with retroreflectors that allow accurate laser ranging tracking from the stations of the International Laser Ranging Service. Data of laser ranged satellites are publicly available for scientific analysis and in the case of LARES are being used mainly for testing general relativity and in particular the Lense-Thirring effect due to the rotation of Earth. Although designed for fundamental physics, the LARES mission is also very useful for geodesy and geodynamics and it will provide, among other things, improvement of the International Terrestrial Reference Frame. After a description of the scientific objectives and of the satellite, the paper will focus on the operations required to run the mission.

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1. INTRODUCTION

The accurate tracking of the LARES satellite is a fundamental key to the success of the mission [1] because orbital deviations from classical Galilei-Newton mechanics are very small when the mass and velocity involved are those typically present in the solar system [2]. Larger effects can be observed around spinning black holes [3] where the spacetime warp is more pronounced. In fact, according to the theory of general relativity, a current of mass-energy and, in particular, the rotation of a mass produces an additional contribution to the gravitational field called, in a weak field and slow motion approximation, the gravitomagnetic field [4]. In principle, around a rotating black hole it might be possible to travel to the past (for cosmological models that would in principle allow such a time travel see [5]; for other time puzzles due to a rotating body see [6,7]). The gravitomagnetic field causes frame dragging [8] and laser ranging is a technique that is a precious means for detecting it [9], although more complex experiments have been performed for the measurement [10] and others have been proposed on the ground [11]. The idea

of using two laser ranged satellites for testing general relativity and frame-dragging was proposed in [12]. Frame-dragging on an orbiting object produces a shift of the orbital nodal line (intersection of the equatorial plane with the orbital plane). This shift is called Lense-Thirring Effect (LTE) named after the two Austrian physicists that derived it from general relativity in 1918 [15]. This orbital node shift, produced by the gravitomagnetic field, in the case of LARES, amounts to about 118-milliarsecond/year [16]. After the launch of the LAGEOS 2 satellite by NASA and ASI in 1992, it was possible to obtain the first rough measurement of the LTE [13]. Later thanks to the availability of a more accurate gravitational field of Earth the measurement was refined [14]. Further confirmation of LTE at the level of 10% was obtained in several publications [17-19] where different orbital determination programs and updated Earth gravitational fields with increasing accuracies were used. In [20] a new approach was proposed to improve the accuracy of the LTE measurement using three or more laser ranged satellites even if the best results would have been obtained with two satellites in supplementary orbits. For this reason in 1998 a new mission, LARES, was proposed to the Italian Space Agency, which was supposed to put in supplementary orbit with respect to LAGEOS, a new laser ranged satellite [21-23]. In that proposal also a small orbital eccentricity was proposed with the objective of performing not only the LTE measurement but also several more general relativity tests. This was indeed a revisiting of the previous proposal [12] of LAGEOS 3. The difficulty in finding a launch up to 6000km altitude (the same altitude as the two LAGEOS satellites) forced us to use the approach proposed in [20] where the satellite orbits did not have specific requirements. A new version of the LARES mission was therefore proposed that could use any launcher for any altitude and inclination away from equatorial and non polar [24]. On February 13, 2012 LARES was finally successfully inserted in orbit with the inaugural flight of the new ESA launcher VEGA [25, 26].

2. MAIN ASPECTS OF LARES MISSION

LARES mission objective is to measure the LTE with an accuracy of about 1% which is an improvement of one order of magnitude better than the previous measurements. It is worth noting that the objectives are not limited to testing general relativity [27,28] because LARES will give

significant contributions to geodesy and geodynamics as well [29].

Combination of satellites for LTE measurement

In theory the perfect knowledge of the gravitational field of Earth would allow the LTE measurement just with one satellite. However in spite of the fact that the knowledge of the gravitational field of Earth is very accurate, still the uncertainties of the first two even zonal harmonics, known as J_2 (mathematical expression that accounts for the oblateness of the Earth) and J_4 are too high for allowing an accurate determination of the LTE. In fact the even zonal harmonics of the Earth produce on a satellite orbit the same effect on the node motion but million times bigger. In particular, the uncertainty on the value of J_2 produces an uncertainty in the motion of LAGEOS 1 node of about 160% of the LTE while for J_4 is instead about 6%. Likely, as demonstrated in [22], the contemporary use of N laser ranged satellites allows the elimination of the effects of the first $(N-1)$ even zonal harmonics on the node motion of the satellite. This property allowed the first measurement of the LTE [13,14] by combining the residuals of the two LAGEOS satellites. Indeed this combination allowed the elimination of the uncertainty of J_2 . To go down to 1% accuracy the effect of the uncertainty of J_4 need to be eliminated with the addition of a third satellite: LARES [57,58]. Data analysis is now in progress and the preliminary results have shown that indeed the motion of the satellite approaches the theoretical geodesic of spacetime better than any other satellite [59-61].

3. LARES DESIGN HIGHLIGHTS

To reach the objective of improving by one order of magnitude the determination of the LTE with respect to the values already obtained by using the combined data of the LAGEOS 1 and LAGEOS 2 satellites [14] and by the Gravity Probe B mission [10], an innovative design of the LARES satellite has been performed. This design minimizes the effects of non-gravitational perturbations. That means the satellite basically moves only under the effect of gravity thus allowing us to study the gravitational laws of physics as well as the terrestrial gravity field that is very important for geodesy and geodynamics. That has been achieved by designing the spherical satellite in one single piece with 92 cavities for hosting the Cube Corner Reflectors (CCRs) [30-33]. The small circles, visible in Figures 1 and 2 are the front faces of the CCRs. Figure 2 shows a photograph of the flight unit of LARES mounted on the separation system. The material chosen for the satellite was a tungsten alloy characterized by a very high density: 18000kg/m^3 . The tungsten alloy, never used for structural components of a satellite, makes LARES the densest orbiting object in the solar system but above all this characteristics makes LARES the artificial orbiting object with the smallest surface-to-mass ratio. This quantity is proportional to the acceleration

produced on the satellite by the non gravitational perturbations acting on the surface of the satellite. Shortly LARES, thanks to this design choice is the best test particle ever manufactured and inserted in orbit [44-47].

Technical challenges

The choice of using a tungsten alloy resulted in several manufacturing challenges: maintaining strict mechanical tolerances, typically used for aluminum alloy (density of 2700kg/m^3). manufacturing the screws of the CCR mounting system and manufacturing the hemispherical cavities to interface the separation system, to mention just a few [38-43]. In Figure 1, labeled with “CCR-Assy”, one can see the CCR and CCR mounting system with the three tungsten alloy screws. In the bottom part, labeled with “SEP - interface hole”, is one of the four hemispherical cavities mentioned above that will be engaged by the separation system brackets (see Figure 2). The other four equatorial cavities are threaded holes used for handling and are labeled “EHH”, these are closed with “EHH - Caps” after final assembling before the launch.

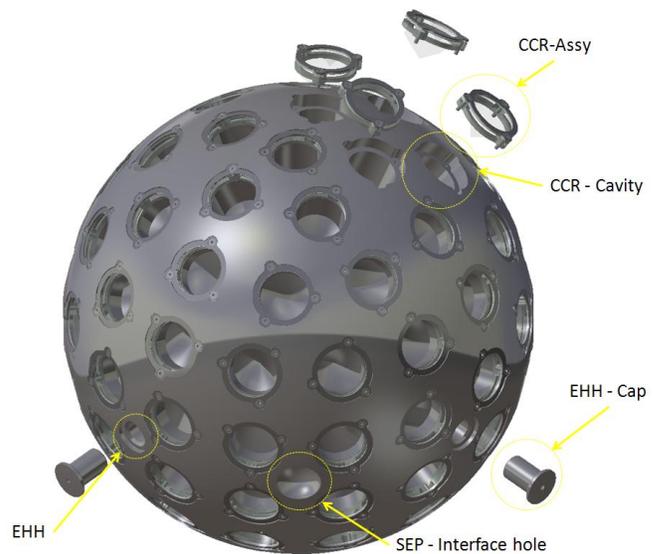


Figure 1 - Rendered drawing of LARES satellite taken from ref. [31].

The satellite is manufactured out of a single piece of tungsten alloy. With conventional casting technique is not possible to manufacture a sphere without defects. The material provider has used liquid phase sintering in which small particles of tungsten are surrounded by 5% of Ni-Cu matrix. The tungsten particles were so evenly distributed that the center of mass of the satellite was within 0.2 mm from the geometric center of the satellite [32]. The separation system was designed specifically for LARES [34,35] and special tests were devised for testing the interface and the separation [36-38]. Of special relevance was the accuracy required to machine the hemispherical cavities. In fact the separation system brackets pushed on the cavity with about 27000N and the pressures developed

at the contact area approached the admissible strength of the material. No minimum defects were acceptable and very tight tolerances were required.

Also a tiny but sensible perturbation, the thermal thrust, was considered very seriously by first conceiving a LARES design different from the one typically adopted for laser ranged satellites [54,55]. That design, specifically suggested for minimization of the thermal thrust, were not appropriate for minimization of other perturbations acting on the surface of the satellite; consequently, a single-piece design for the satellite body was finally adopted. This single piece design in fact reduced thermal thrust of the satellite body. Also, the optical design was such that the contribution of the CCRs to thermal thrust was reduced [50,56]. The satellite has a mass of about 387 kg with a diameter of 364 mm.



Figure 2- LARES satellite on the separation system

3. OPERATIONS

Few months before the launch of LARES, and after a request of the owner or Principal Investigator team containing all the mission details, the International Laser Ranging Service (ILRS) started planning the satellite tracking operations. Operations associated with each mission are the responsibility of the satellite owner or scientific mission project office. The main operations performed for the LARES mission are the orbital predictions and the ranging measurements. The orbital predictions are performed by accredited centers that are in charge of providing the ILRS with the position of the satellite as a function of time. In the case of the LARES satellite, the International Space Time Analysis Research Center (ISTARC), located in Sapienza University of Rome (1) generates tracking predictions that are delivered to the ILRS Operations Center and (2) performs a precise data analysis for orbital determination of LARES using the data collected from the entire network. This second point is not strictly related to satellite operations

but is more relevant to the scientific exploitation and will not be treated in this paper.

Laser ranging technique

Laser ranging is the most accurate technique to measure distances. There are about forty targets orbiting Earth that are tracked by the forty-six laser ranging stations on the ground. Those targets are mainly geodetic satellites (such as LARES and LAGEOS) remote sensing satellites (such as ERS) and navigation satellites (such as GPS and Galileo), not to mention the lunar CCR arrays. Each of those satellite carries retroreflectors that can be solid CCRs, hollow CCR and spherical retroreflectors. The most commonly used are the solid CCRs because of their strong geometrical stability with respect to the hollow CCR. These CCRs sometimes are called mirrors but this is not correct. In fact a mirror send back the signal towards the same direction only with 90 degree incidence angle, while for a retroreflector any incidence angle (within a relatively wide angle intervals) would work. Indeed hollow CCRs are basically manufactured by gluing three mirrors together with a mutual angle of 90 degrees. Solid CCRs rely instead on three reflections off the back surfaces (Figure 3). To guarantee that a laser pulse is reflected in the direction of the emitting station one has to take into account the satellite motion. For LARES and LAGEOS CCRs this is accomplished by increasing the dihedral angle by a nominal amount of 1.5 and 1.25 arcseconds respectively. In particular, very important for the satellite operations were the surface properties of the satellite [48, 49]. In fact it has been estimated, based on the experimental values of emissivity and absorptivity, that the CCR temperature gradients would induce a deformation of the dihedral angle such that the reflected signal could not hit the ground station. The optical tests [51-53] performed in the simulated space environment of the thermovacuum lab, demonstrated that the CCRs would perform correctly , under all the possible operational conditions.

Orbit reconstruction

Soon after separation the initial conditions of the satellite were provided by the launcher and later by the radar data from NORAD (NORTH American Aerospace Defense Command) whose accuracy is not adequate to laser ranging. In fact only few days after the launch it was possible to get the first laser return. After that first event the ephemeris were refined and after just one day five more stations started tracking LARES. The availability of data from many stations allows the orbit determination of the target satellites with very high accuracy. The underlying principle is very simple, being based on a tridimensional triangulation. In practice, the situation is more complicated because the ranging data from different stations generally are not simultaneous and there may be times in which ranging data are missing because of low tracking priority, bad weather condition, presence of aircrafts in the line of the laser beam, and other issues mainly related to safety.

Ranging data

The ILRS tracks [62], using its international network of fifty-six operating ground stations (Figure 3), the passive satellites such as LARES, LAGEOS, ETALON, etc., and makes the data available publically for scientific analyses.

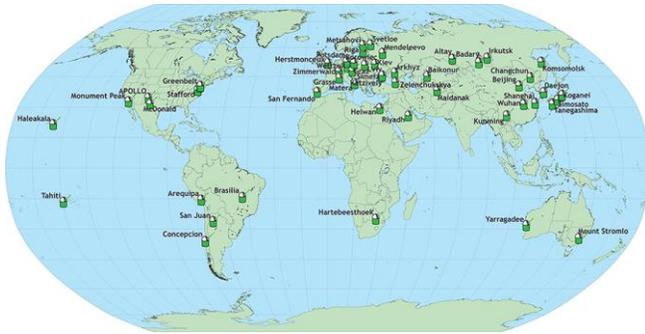


Figure 3 - International Laser Ranging Service Stations (Courtesy of ILRS) [63].

The operations of the ILRS network is governed by the ILRS Central Bureau, and nowadays many stations are operating in a semi-automated fashion. The laser stations operate according to a priority list among the many missions they support (over 70 at present), which takes into account several factors such as the most recent launch date of the satellite in the list, the orbit altitude of the satellite, and above all, the scientific significance of the tracking for each mission. Although ILRS uses eye-safe systems, stations operate a ground-radar or equivalently use the real-time information on the position of aircraft in the vicinity of the station to maintain safe operations. Laser beams, in fact, represent a potential hazard for the eyes of pilots or passengers passing through the line of sight between the station and the target. Also, concerns arise about optical instrumentation on board other satellites that may occasionally be in the line of site mentioned. In another experiment [64,65], where it was necessary to point a laser beam towards the International Space Station with the aim of improving the resolution of ground-based photographs of the spacecraft, a complicated procedure was set, including requesting, for any programmed laser ranging, authorization from the Federal Aviation Authority and the Air Force. All the ranging information is acquired as (1) full-rate data i.e., the collection of time of flight (return trip time) from which distance is evaluated and corrected for effects induced, for instance, by the atmosphere, the calibration of the ground station, etc. and (2) Normal Points (NP) that are preprocessed locally to produce a reduced set of data. Due to the importance of NP in what follows a more detailed description will be given. In Table 1 are compared the total number of observations and satellite passes acquired as full-rate data for LARES. The fourth column reports the number of observations in the first year while the fifth column the number of observations in almost three years. From a rapid analysis one can observe that six (underlined and in italic) out of nineteen stations increased the number of LARES

full-rate data acquisitions. Particularly relevant the increase in the following stations: Herstmonceux (United Kingdom) three times more data than expected from the first year number of data; Changchun (China) twice; Zimmerwald (Switzerland), twice, All the stations reported in the table, with the exclusion of Changchun provide also normal points. Seventeen more stations for a total of thirtyfive are providing normal points for LARES.

Table 1, Full-rate data of LARES since launch date.

STATION	PASSES		OBSERVATIONS	
	29 Dec 2014	Feb 2013	29 Dec 2014	Feb 2013
<i>Golosiv</i>	339	96	<i>19116</i>	5434
Simeiz	342	139	34879	15055
Zelenchukyska	1	---	240	---
Katzively	392	206	42073	32307
<i>Changchun</i>	2149	531	<i>37052268</i>	6314799
Beijing	3	---	15856	---
Koganei	4	---	3106	---
Concepcion (1)	4	4	1267	1267
Concepcion (2)	264	168	232285	143260
San Juan	602	262	80820	46804
<i>Zimmerwald</i>	1404	251	<i>4247197</i>	738479
Shanghai	147	77	2787380	1313631
San Fernando	266	120	49547	21448
<i>Mt Stromlo</i>	1348	387	<i>1199440</i>	338700
<i>Herstmonceux</i>	1018	333	<i>4823942</i>	545381
Potsdam	512	285	6851576	3415830
Grasse	183	111	154030	76735
Matera	1226	468	1086276	468527
<i>Wettzell</i>	1188	319	<i>803290</i>	230112

NP are transmitted to the data centers within an hour or so, so that they can be used almost real time since they are almost always the only data researchers use for their studies. In fact, full rate data are used only for particular purposes such as co-location analysis, Fizeau effect, and center-of-mass algorithm development [66]. The minimum number of data to synthesize a good NP depends on the reliability expected on the CCRs return signals . So a higher number of full rate points is required for high altitude satellites such as the Global Navigation Satellite Systems (GNSS) and for daylight observations. Concerning the repetition rate of the laser stations, obviously the number of full rate points to be used for obtaining the corresponding NP is higher for kHz stations. The time interval during which the full rate data are acquired is called Standard Normal Point Interval (SNPI) and can be from a few seconds to minutes depending on satellite altitude, and all those data will be used to produce a single NP. This last consideration let's understand that the reduction process may concern a large part of the orbit and, therefore, the procedure that provides the NP is rather complicated, because it cannot be a mere interpolation and averaging of the ranging information data. The SNPI can be lowered sensibly when a high repetition rate station is used so that the use of the laser on several targets available at the

same time can be optimized. This is the recently adopted *modus operandi* of the ILRS Network in order to allow pass interleaving for increased data yield and minimization of idle time at the stations.

Orbital predictions

The predictions are distributed to the ILRS tracking stations in order to plan their tracking schedule, knowing where and when the satellite will be and to point their telescopes accordingly. There are 22 accredited prediction providers [66] one of which is the ISTARC mentioned above.

ISTARC is providing at an almost daily basis the orbital prediction for LARES to ILRS. Those predictions are prepared in semi-automatic procedures and are basically obtained by propagating the orbit of LARES starting from initial conditions determined using the actual laser ranging data. The high rate at which those predictions are provided is due to the high pointing accuracy required by the laser stations: the predictions are affected by small modeling errors that introduce small unmodeled accelerations that, after a few days, bring the satellite off the predicted track by few meters (Figure 4). As can be seen, the deviations for LARES are very small; however, the actual deviations are bigger than that reported because, in figure 4, all the modeled effects due to non-gravitational perturbations have been removed. This, together with other preliminary results reported in [67] and references therein, show the very good behavior of LARES as a test particle thus proving the good design of the satellite.

International Laser Ranging Service and provide accurate ranging data as normal points that are readily available to the scientists. In particular, the LAGEOS and LARES data are being processed at the ISTARC in Rome to improve the accuracy of the Lense-Thirring effect predicted by general relativity down to the level of about 1%.

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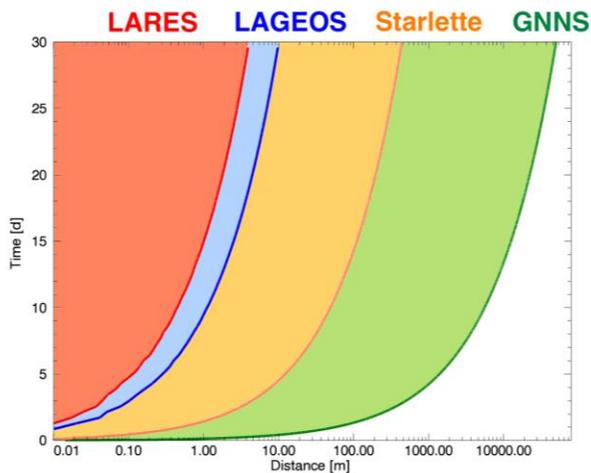


Figure 4 - Estimated deviation of satellite orbit from the ideal behavior of a perfect test particle (vertical axis). The values in the horizontal axis are the along-track deviation from a theoretical geodesic of spacetime.

4. CONCLUSIONS

Satellite laser ranging is a very accurate technique of measuring distances of orbiting satellites and the Moon. Fifty-six operating stations are organized under the

REFERENCES

- [1] I. Ciufolini, A. Paolozzi, G. Sindoni, E.C. Pavlis and A. Gabrielli, Scientific aspects of LARES Mission, in: Proceedings of 60th International Astronautical Congress IAC 2009, Daejeon, Republic of Korea, 12-16 Oct. 2009.
- [2] I. Ciufolini, E.C.Pavlis, J.C.Ries, R.Koenig, G.Sindoni, A.Paolozzi and H.Neumayer, Phenomenology of the Lense-Thirring effect in the Solar System: Measurement of frame-dragging with laser ranged satellites, *New Astronomy*, 17, 341 (2012).
- [3] Wei Cui, S. N. Zhang, and Wan Chen, “evidence for frame-dragging around spinning black holes in x-ray binaries” *The Astrophysical Journal*, 492:L53–L57, 1998, January 1
- [4] I. Ciufolini and J.A. Wheeler, “Gravitation and Inertia” (Princeton Univ. Press, Princeton, 1995).
- [5] Godel K. An Example of a New Type of Cosmological Solutions of Einstein’s Field Equations of Gravitation, *Reviews of Modern Physics*, Vol. 21 no.1, July 1949 pp. 447-450.
- [6] I. Ciufolini and F. Ricci, Time delay due to spin inside a rotating shell. *Class. and Quantum Grav.* 19, 3875-3881 (2002).
- [7] I. Ciufolini, F. Ricci, Time delay due to spin and gravitational lensing, *Classical and Quantum Gravity* 19 (15), 3863 (2002).
- [8] I. Ciufolini, “Dragging of inertial frames”, *Nature* vol. 449, 41 (2007).
- [9] I. Ciufolini, Frame-Dragging, Gravitomagnetism and Lunar Laser Ranging, *New Astronomy*, 15 (2010), 332-337.
- [10] Everitt et al. "Gravity Probe B: Final Results of a Space Experiment to Test General Relativity", *Physical Review Letters*, May 11, 2011.
- [11] M. Cerdonio, G.A. Prodi, S. Vitale. Dragging of inertial frames by the rotating Earth: Proposal and feasibility for a ground-based detection. *General Relativity and Gravitation*. Volume 20, Issue 1, January 1988, Pages 83-87.
- [12] I. Ciufolini, Measurement of the Lense–Thirring drag on high-altitude laser-ranged artificial satellites. *Phys. Rev. Lett.* 56, 278–281 (1986).
- [13] I. Ciufolini, E.C.Pavlis, F. Chieppa, E. Fernandes-Vieira and J. Perez-Mercader, 1998 *Science* 279 2100.
- [14] I. Ciufolini and E. C. Pavlis, “A confirmation of the general relativistic prediction of the Lense-Thirring effect”, *Nature* 431, 958–960 (2004).
- [15] J. Lense, H. Thirring, Über den Einfluss der Eigenrotation der Zentralkörper auf die Bewegung der Planeten und Monden nach der Einsteinschen Gravitationstheorie [On the Influence of the Proper Rotation of Central Bodies on the Motions of Planets and Moons According to Einstein's Theory of Gravitation], *Physikalische Zeitschrift* 19(1918)156–163.
- [16] I. Ciufolini, A. Paolozzi, C. Paris, G. Sindoni, “The constellation of LARES and LAGEOS satellites for testing general relativity”, *proc. IEEE Aerospace Conference*, Big Sky, Montana, USA, Mar 7-14, 2015.
- [17] I. Ciufolini, E.C. Pavlis, J. Ries, R. Koenig, G. Sindoni, A. Paolozzi and H. Neumayer, Gravitomagnetism and its Measurement with Laser Ranging to the LAGEOS satellites and GRACE Earth Gravity Models, in *John General Relativity and John Archibald Wheeler* I. Ciufolini and R. Matzner eds., 371-434 (Springer Verlag, 2010).
- [18] J. C. Ries, I. Ciufolini, E. C. Pavlis, A. Paolozzi, R. Koenig, R. A. Matzner, G. Sindoni and H. Neumayer, The Earth's frame dragging via Laser Ranged Satellites: a response to ‘Some considerations on the present-day results for the detection of frame-dragging after the final outcome of GP-B’ by L. Iorio. *European Physics Letters*, 96, 30002 (2011).
- [19] I. Ciufolini, A. Paolozzi, E.C. Pavlis, J. Ries, R. Koenig, R. Matzner, G. Sindoni and H. Neumayer, Testing Gravitational Physics with Satellite Laser Ranging *The European Physical Journal Plus* 126 72 (2011).
- [20] I. Ciufolini, On a new method to measure the gravitomagnetic field using two orbiting satellites. *Nuovo Cimento A* 109, 1709-1720 (1996).
- [21] I. Ciufolini, A. Paolozzi, I. Peroni, A. Gabrielli, A Study for a Laser Ranged Relativity Satellite, in: Proceedings of Sixth Pan American Congress of Applied Mechanics -. PACAM VI and Eighth International Conference on Dynamics Problems in Mechanics - DINAME 99, Rio de Janeiro, Brasil, 4-8 January 1999, PACAM VI/DINAME 99. vol. 6 (1999), pp. 467-470.
- [22] I. Ciufolini, A. Paolozzi, LARES: A New Laser-ranged Satellite for Fundamental Physics and General Relativity, *Actual Problems of Aviation and Aerospace Systems*, vol. 1 (1999), pp. 61-73.
- [23] I. Ciufolini, D.G. Currie, A. Paolozzi, The LARES Mission for Testing the Dynamics of General Relativity, In: Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 5-12 March 2003, Vol. 2, p. 693-703.

- [24] A. Paolozzi, LARES: a New Laser Ranged Satellite for Testing General Relativity. In: Proceedings of the Ninth Marcel Grossmann Meeting on General Relativity, Rome, Italy, 2-8 July, 2000. vol. part C, p. 1766-1770. World Scientific, London, 2002.
- [25] I. Ciufolini, A. Paolozzi, E. Pavlis, J. Ries, R. Koenig, R. Matzner, G. Sindoni. The LARES Space Experiment: LARES Orbit, Error Analysis and Satellite Structure. In: General Relativity and John Archibald Wheeler. I. Ciufolini and R. Matzner eds., 467-492 (Springer, 2010).
- [26] A. Paolozzi, I. Ciufolini. LARES successfully launched in orbit: satellite and mission description. *Acta Astronautica*, Volume 91, October–November 2013, Pages 313–321.
- [27] A. Paolozzi, I. Ciufolini, E. Flamini, A. Gabrielli, S. Pirrotta, E. Mangraviti, A. Bursi. LARES in orbit: Some aspects of the mission. Proceedings of the International Astronautical Congress, IAC, Volume 6, 2012, Pages 4468-4474. 63rd International Astronautical Congress 2012, IAC 2012; Naples; Italy; 1 October 2012 through 5 October 2012; Code 98825.
- [28] I. Ciufolini, A. Paolozzi, G. Sindoni, E. Pavlis, A. Gabrielli, S. Pirrotta, D. Barbagallo, E. Mangraviti, Objective of LARES Satellite, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June - 3 July, 2009.
- [29] E.C. Pavlis, “The contribution of LARES in future ITRF developments”, 2nd International LARES Science Workshop, Accademia dei Lincei, Roma, Italy, 17-19 September 2012 pag. 28, available at http://www.lares-mission.com/ILSW2012/talks_2012/ILSW2012_Pavlis.pdf
- [30] A. Paolozzi, I. Ciufolini and C. Vendittozzi, Engineering and scientific aspects of LARES satellite, *Acta Astronautica*, vol. 69 (2011), pp. 127-134.
- [31] A. Paolozzi, I. Ciufolini, C. Vendittozzi and I. Peroni, Mechanical design of LARES Satellite, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June - 3 July, 2009.
- [32] A. Paolozzi, I. Ciufolini, C. Vendittozzi and A. Bursi, Cost Effective Center of Mass Determination of LARES Satellite, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June - 3 July, 2009.
- [33] A. Paolozzi, I. Ciufolini, S. Dell'Agnello, I. Peroni, F. Graziani, G. Sindoni, C. Paris, C. Vendittozzi, P. Ialongo, C. Cerruti, A. Lucantoni, A. Boni, C. Cantone, G. Delle Monache, A. Franceschi, T. Napolitano, N. Intaglietta, M. Martini, M. Garattini, G. Bollettini, R. Tauraso, L. Caputo, F. Passeggio, F. Longobardo, E. Pavlis, R. Matzner, D. P. Rubincam, D. Currie, V. J. Slabinski, D.A. Arnold, The design of LARES: a satellite for testing General Relativity. In: Proceedings of 58th International Astronautical Congress IAC 2007, Hyderabad, India, 24-28 Sep. 2007. Paper: IAC-07-B4.2.07.
- [34] A. Paolozzi, I. Ciufolini, C. Paris, G. Sindoni, M. Ramiconi, F. M. Onorati and L. Scolamiero, Design of LARES Separation System, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June - 3 July, 2009.
- [35] A. Paolozzi, I. Ciufolini, I. Peroni, F. M. Onorati, L. Acquaroli, L. Scolamiero, G. Sindoni, C. Paris, C. Vendittozzi, M. Ramiconi, N. Preli, A. Lucantoni, F. Passeggio and S. Berardis, Fibre optic sensors for the validation of the numerical simulation on the breadboard of the LARES Separation System, in: Proceedings of 59th International Astronautical Congress - IAC 2008, Glasgow, Scotland, 29 Sep. - 3 Oct. 2008. Paper: IAC-08.C2.I.7.
- [36] A. Paolozzi, I. Ciufolini, C. Paris, L. Acquaroli, P. Piersigilli, A. Gabrielli, Tests on LARES separation system components using fiber optic sensors, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June–3 July, 2009.
- [37] A. Paolozzi, I. Ciufolini, I. Peroni, C. Paris, M. Ramiconi, F. M. Onorati and L. Acquaroli, Testing the LARES Separation System breadboards, in: Proceedings of 60th International Astronautical Congress - IAC 2009, Daejeon, Republic of Korea, 12-16 Oct. 2009. Paper: IAC-09.D5.1.9.
- [38] A. Paolozzi, I. Ciufolini and C. Paris, Contribution of strain measurements to the LARES satellite mission, in: Proceedings of ICEDyn 2011, Tavira, Portugal, 20-22 June 2011.
- [39] A. Paolozzi, I. Ciufolini, G. Caputo, L. Caputo, F. Passeggio, F. Onorati, C. Paris, A. Chiodo, LARES satellite and separation system, in: Proceedings of 63rd International Astronautical Congress IAC 2012, Naples, Italy, 1-5 Oct. 2012. Paper: IAC-12- C2.9.5.x15247.
- [40] A. Paolozzi, I. Ciufolini, F. Felli, A. Brotzu, D. Pilone. Issues on LARES satellite material. 60th International Astronautical Congress, IAC 2009; Daejeon, Korea; 12-16 October 2009.

- [41] C. Vendittozzi, F. Felli, A. Paolozzi and I. Ciufolini, Material and manufacturing issues of a laser ranged satellite, in: Proceedings of 9th Youth Symposium on Experimental Solid Mechanics (Gruppo Italiano Frattura), July 7-10, 2010, Trieste, Italy, pp. 78-82.
- [42] A. Paolozzi, I. Ciufolini, F. Felli, A. Brotzu, D. Pilone, C. Vendittozzi and F. Passeggio, Material and manufacturing of LARES Satellite, in: Proceedings of XX Congresso Nazionale AIDAA, Milano, Italy, 29 June - 3 July, 2009.
- [43] A. Paolozzi, I. Ciufolini, C. Vendittozzi, F. Passeggio, L. Caputo, G. Caputo. Technological challenges for manufacturing lares satellite. 60th International Astronautical Congress, IAC 2009; 12-16 October 2009.
- [44] A. Paolozzi, I. Ciufolini, G. Sindoni, C. Paris, "LARES Satellite: the best test particle for testing General Relativity", Proceedings of XXII Congresso Nazionale AIDAA, Napoli, Italy, 9-12 Sept. 2013.
- [45] I. Ciufolini, A. Paolozzi, R. König, E. C. Pavlis, J. Ries, R. Matzner, V. Gurzadyan, R. Penrose, G. Sindoni, C. Paris (2013). Fundamental Physics and General Relativity with the LARES and LAGEOS satellites. Nuclear Physics B - Proceedings Supplements, 243-244, 180-193.
- [46] I. Ciufolini, A. Paolozzi, E. Pavlis, J. Ries, V. Gurzadyan, R. Koenig, R. Matzner, R. Penrose, G. Sindoni, "Testing General Relativity and gravitational physics using the LARES satellite", Eur. Phys. J. Plus (2012) 127: 133.
- [47] I. Ciufolini, V. G. Gurzadyan, R. Penrose and A. Paolozzi, Geodesic motion in general relativity: LARES in Earth's gravity, in: V. G. Gurzadyan, A. Klümper, A. G. Sedrakyan (Eds.), Low Dimensional Physics and Gauge Principles (Matinyan Festschrift), World Scientific Publishing co., Singapore, 2013.
- [48] A. Paolozzi, I. Ciufolini, C. Vendittozzi, F. Felli. Material and surface properties of lares satellite (conference paper). Proceedings of the International Astronautical Congress, IAC. Volume 8, 2012, Pages 6559-6565. 63rd International Astronautical Congress 2012, IAC 2012; Naples; Italy; 1 October 2012 through 5 October 2012; Code 98825.
- [49] A. Paolozzi, I. Ciufolini, G. Caputo, L. Caputo, F. Passeggio, E. Visca, F. Felli, "Surface Treatment on Breadboards of LARES Satellite", ASST 2012.
- [50] A. Paolozzi, I. Ciufolini, A. Lucantoni, D. Arnold (2009). Optical Design of LARES Satellite. Proceedings of XX AIDAA Congress. Milano, Italy, June 29-July 3, 2009.
- [51] A. Paolozzi, I. Ciufolini, L. Schirone, I. Peroni, C. Paris, D. Spano, G. Sindoni, C. Vendittozzi, G. Battaglia, M. Ramiconi. Tests of LARES Cube Corner Reflectors in Simulated Space Environment (preliminary results). 61st International Astronautical Congress, Prague, CZ, 27 September – 1 October 2010.
- [52] A. Paolozzi, I. Ciufolini, C. Paris, D. Spano, G. Battaglia, N. Reinhart. Thermal tests on LARES satellite components. Proceedings of 63rd International Astronautical Congress. Naples, Italy, 1-5 October, 2012. IAC 8, pp. 6653-6657.
- [53] A. Paolozzi, I. Ciufolini, C. Paris, G. Sindoni, D. Spano. Qualification tests on the optical retro-reflectors of LARES satellite. Proceedings of 63rd International Astronautical Congress. Naples, Italy, 1-5 October, 2012. IAC 8, pp. 6280-6286.
- [54] A. Bosco, C. Cantone, S. Dell'agnello, G.O. Delle Monache, M. A. Franceschi, M. Garattini, T. Napolitano, I. Ciufolini, A. Agneni, F. Graziani, P. Ialongo, A. Lucantoni, A. Paolozzi, I. Peroni, G. Sindoni G. Bellettini, R. Tauraso, E. C. Pavlis, D.G. Currie, D.P. Rubincam, D. A. Arnold, R. Matzner, V. J. Slabinski, Probing gravity in NEO with high-accuracy laser-ranged test masses. International Journal of Modern Physics D, vol. 16, p. 2271-2285, 2007.
- [55] D. Arnold, G. Bellettini, A. Boni, C. Cantone, I. Ciufolini, D. G. Currie, S. Dell'Agnello, G. O. Delle Monache, M. A. Franceschi, M. Garattini, N. Intaglietta, A. Lucantoni, M. Martini, T. Napolitano, A. Paolozzi, R. Tauraso, and R. Vittori (2008) The INFN-LNF Space Climatic Facility. Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications: pp. 842-846. Proceedings of the 10th Conference, Villa Olmo, Como, Italy, 8 – 12 October 2007.
- [56] I. Ciufolini, A. Paolozzi, C. Paris, G. Sindoni, "The LARES satellite and its minimization of the thermal forces", Metrology for Aerospace (MetroAeroSpace), IEEE DOI: 10.1109/MetroAeroSpace.2014.6865938, presented in Benevento Italy 29-30 May 2014.
- [57] I. Ciufolini, A. Paolozzi, E. C. Pavlis, J. C. Ries, R. Koenig, R. A. Matzner, G. Sindoni, H. Neumayer. Towards a One Percent Measurement of Frame Dragging by Spin with Satellite Laser Ranging to LAGEOS, LAGEOS 2 and LARES and GRACE Gravity Models. Space Science Reviews, December 2009, Volume 148, Issue 1-4, pp 71-104.
- [58] I. Ciufolini, A. Paolozzi, C. Paris. Overview of the LARES Mission: orbit, error analysis and technological aspects. Journal of Physics, Conference Series, vol. 354, p. 1-9. 2012.

- [59] I.Ciufolini, A.Paolozzi, V. Gurzadyan, E.C. Pavlis, R.Koenig, J. Ries, R. Matzner, R. Penrose, G. Sindoni, C. Paris, Dragging of inertial frames, fundamental physics, and satellite laser ranging, *Frontiers in Relativistic Celestial Mechanics*, Volume 2, Applications and Experiments, Ed. by Kopeikin, Sergei M., Series:De Gruyter Studies in Mathematical Physics 22, Publisher: De Gruyter. August 2014, ISBN: 978-3-11-034566-7.
- [60] I. Ciufolini, A. Paolozzi, E.C.Pavlis, J.Ries, V. Gurzadyan, R. Koenig, R. Matzner, R. Penrose, G. Sindoni, "Testing General Relativity and gravitational physics using the LARES satellite", *Eur. Phys. J. Plus* (2012) 127: 133 pp.1-7.
- [61] I. Ciufolini, A. Paolozzi, E.C. Pavlis, R. Koenig, J. Ries, R. Matzner, V. Gurzadyan, G. Sindoni, C. Paris, A. Gabrielli, "Preliminary results of the LARES mission to test general relativity", 65th International Astronautical Congress, Toronto, Canada, IAC-14-B6.2.11, pp.1-11.
- [62] M.R. Pearlman, J. J. Degnan, J. M. Bosworth, The international laser ranging service, *Adv. Space Res.*, 30(2002)135–143
- [63]http://ilrs.gsfc.nasa.gov/network/stations/ILRS_Stations_Map.html
- [64] F. Graziani, A. Paolozzi, D.G. Currie, M. Porfilio, R.F. Dantowitz, F. Passetto, R. Fortezza, M. J. Kozubal, R. Iorio, G. Sindoni, F. Felli, A. Brotzu, A.L R. Hajian, M.A.Caponero, R. Baiocchi (2005). Improving the imaging of the ISS through the SPQR Experiment, in: *Proceedings of 56th International Astronautical Congress IAC 2005*, Fukuoka, Japan, 17-21 Oct. 2005. Paper: IAC-05-B4.4.01.
- [65] A. Paolozzi, M. Porfilio, D. G. Currie, R. F. Dantowitz, The SPQR experiment: detecting damage to orbiting spacecraft with ground-based telescopes, *Microgravity Science and Technology*, XIX-2 (2007), pp. 45-49. [67] http://ilrs.gsfc.nasa.gov/data_and_products/data/frt/index.html
- [66]http://ilrs.gsfc.nasa.gov/data_and_products/predictions/prediction_centers.html
- [67] I. Ciufolini, A. Paolozzi, E.C. Pavlis, R. Koenig, J. Ries, R. Matzner, V. Gurzadyan, G. Sindoni, C. Paris, A. Gabrielli, "Preliminary results of the LARES mission to test general relativity", 65th International Astronautical Congress, Toronto, Canada, IAC-14-B6.2.11, pp.1-11.

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