Dr Graham Appleby
Dr Andreja Susnik
NERC Space Geodesy Facility, Herstmonceux

New geodetic satellite LARES-2 joins the laser-tracked constellation

The team at the BGS Space Geodesy Facility, Herstmonceux (SGF), was excited to follow the launch of a new geodetic satellite in July 2022. The very prolific and mm-accurate laser ranging station, part of the International Laser Ranging Service (ILRS), a Service of the International Association of Geodesy, immediately made plans to track the satellite, called LARES-2. The SGF ILRS Analysis Centre (AC) recognised the launch as a major new opportunity to strengthen its work on computing accurate global reference frames and components of the Earth's gravity field.

The determination of the Earth's gravity field using space geodesy techniques has continued with constant improvements in accuracy and spatial resolution from the late 1950s when UK scientists from the Royal Aircraft Establishment, Farnborough measured [1] the polar flattening using visual observations of the first Earth-orbiting satellites, including Sputnik-1. Results, based on this determination of the flattening, showed that the polar diameter of the Earth is ~40km less than the equatorial one, improving the estimate previously made from many years of dedicated ground-based surveying. This space-based value was retrieved from the satellite observations by means of orbit determination, where solutions included estimates of the rate of the linear motion of the node of the satellite's orbital plane along the celestial equator. This linear motion is primarily driven by the so-called second-degree, zero-order C_{20} term in the spherical harmonic expansion of the Earth's gravitational potential, from which the flattening can be derived.

Three decades later, laser ranging observations with centimetre-level accuracy from the emerging global network of tracking stations to the geodetic spherical satellite LAGEOS, a sphere with a diameter of 60cm, mass of 400kg and which is encrusted with 426 corner-cube reflectors, were used [2] to measure the tiny *acceleration* in its orbital node. Results showed that the flattening was slowly decreasing, providing the evidence for the now well-known and accepted Glacial Isostatic Adjustment (GIA) - also directly measured by Global Navigation Satellite System (GNSS). This Glacial Isostatic Adjustment is a direct result of the ongoing retreat of the ice sheets over much of the northern hemisphere happening since the last glacial maximum ~21,000 years ago. This means that, for instance, Scotland is 'bouncing back' by 10-15mm per year, while lower latitude regions (or sites), including SGF at Herstmonceux are 'sinking' by about 0.4mm per year as the crust 'creeps' towards the north.

Because of the high-precision inherent in laser ranging observations and the low area-to-mass ratio of the geodetic satellites, they are also attractive 'probes' for testing some of the predictions of General Relativity (GR). Relativistic frame-dragging, or Lense-Thirring precession, predicts that the plane of the orbit of a satellite will rotate by the tiny amount of 30 milli-arcsecond per year.

To separate out this predicted relativistic effect on the orbital plane motion from the larger effect coming from the much improved, but still imperfectly known, Earth's gravity field (especially the long-wavelength terms relating to the polar flattening), ideally one would use two satellites whose orbital inclinations are such that the gravity-induced effects would cancel out, leaving the GR frame-dragging effect exposed. Simple perturbed orbital theory shows that the C_{20}-induced orbit plane motion is related to the cosine of the orbital inclination *I;* hence two satellites whose orbital inclinations are supplements of each other would meet the required criteria. For that reason, the LAGEOS-2 satellite was launched by the National Aeronautics and Space Administration (NASA) and the Italian Space Agency (*Agenzia Spaziale Italiana*; ASI) in 1998. However, due to launch restrictions and the fact that its primary mission was to strengthen efforts to determine (together with LAGEOS observations) the terrestrial reference frame, the satellite was placed into its orbital position with far-from-ideal inclination. Nonetheless, an estimate of the Lense-Thirring effect was made, with an estimated uncertainty of 10%. A later effort, using observations from the LARES (Laser Relativity Satellite) satellite launched in 2012, but again in a non-optimum orbit, reduce the level of uncertainty to 2% [3].

After many years of simulations and funding applications, the Italian Space Agency achieved the launch of LARES-2 (LAser RElativity Satellite 2) from the European Space Agency (ESA) spaceport in Kourou on 13 July 2022 using a European Vega C rocket [5], placing it into an orbital altitude very close to LAGEOS at 5,890km above the Earth. The inclination of LAGEOS's orbit is 109.84 degrees, with cos(I) = -0.3394, whereas the inclination of LARES-2's orbit is by design 70.16 degrees, with cos(I) = +0.3394, demonstrating a spectacularly good orbit placement of the 'new kid on the block'. This will provide an excellent opportunity to perform simultaneous analyses of observations coming from both satellites, thus enabling mitigation of the residual orbit-plane error due to the inevitably incomplete gravity field model and hence giving an opportunity to test the GR theory to very high precision [4].

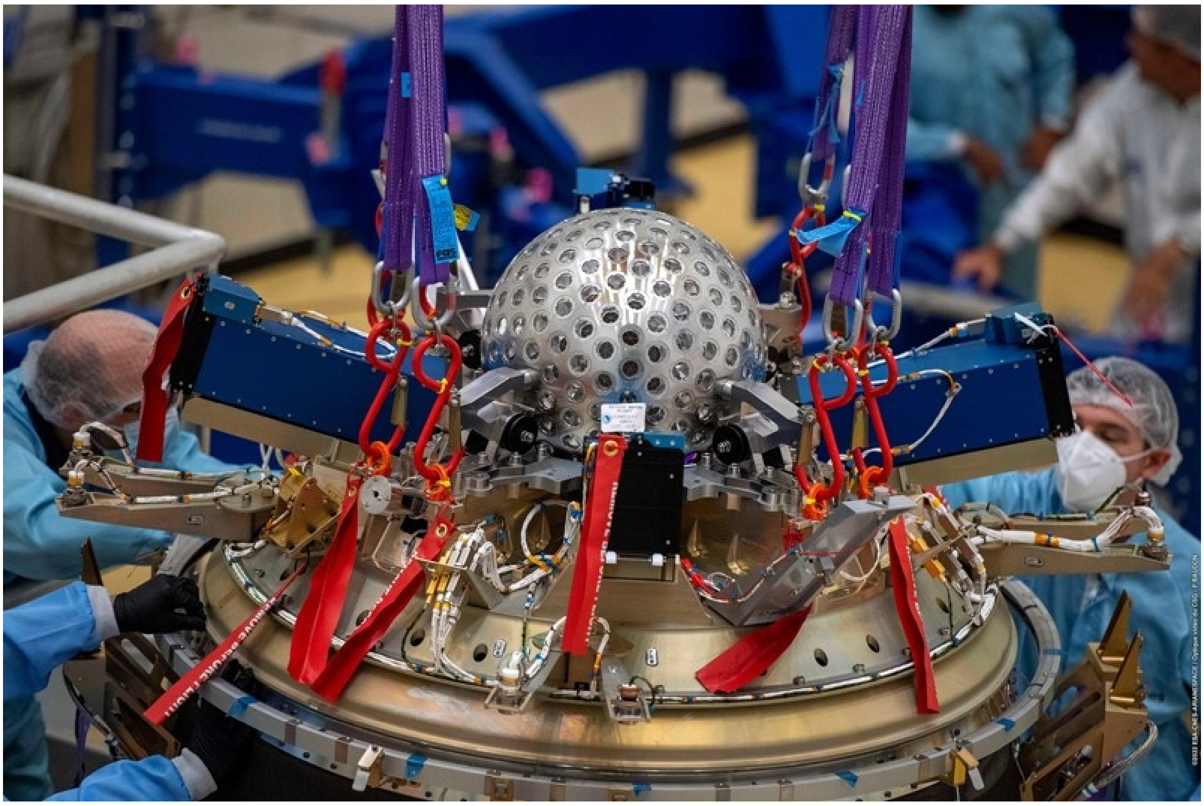
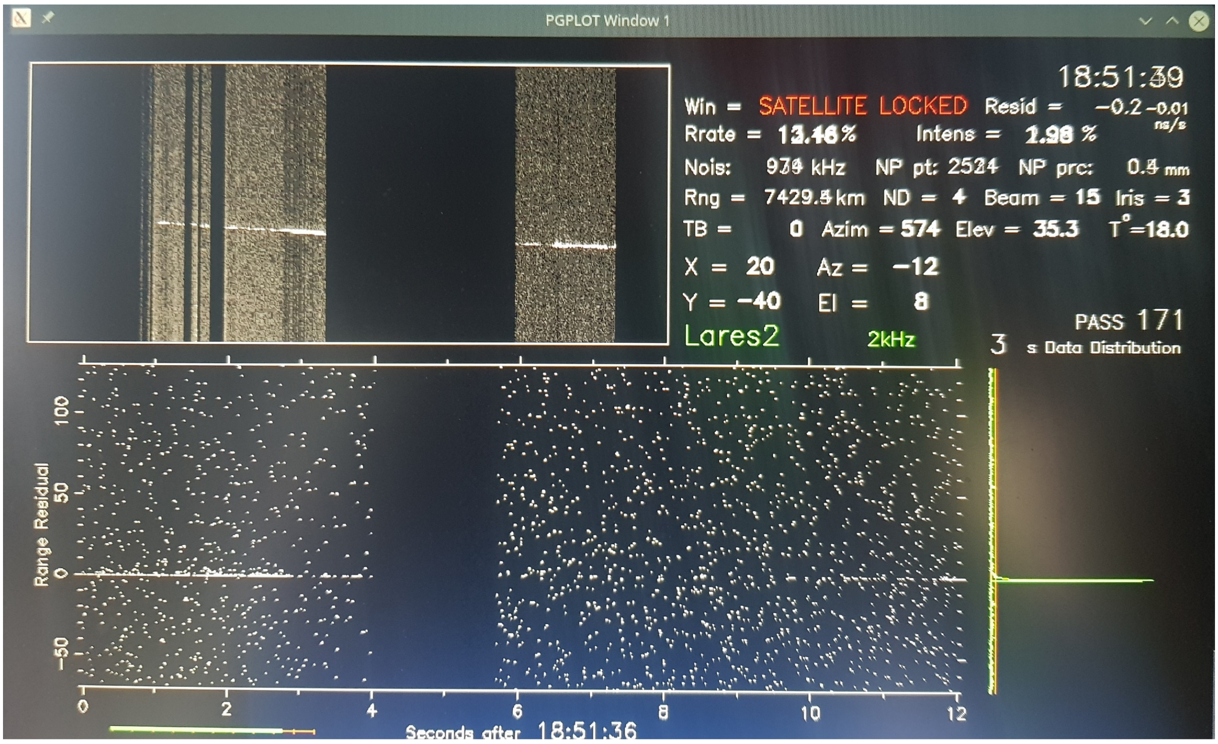


Figure 1: Installation of LARES-2 into the Vega C launcher. The surface of the satellite is covered in 303 reflectors that will reflect laser pulses sent out by a global network of laser-ranging stations. Credit: CNES/ESA/Arianespace/Optique Vidéo CSG/P. Baudon

SGF interest and involvement

An initial priority at SGF following the launch of LARES-2 was to obtain ranging data as soon as possible. The difficultly at this post-launch stage is very high due to the lack of the accurate predictions that are required to aid acquisition. Nevertheless within a few days SGF was one of 5 stations that had managed to obtain precise data to the new satellite, using publicly available radar-based predictions with km-level accuracy. To enable the rest of the global network to join in making routine observations, especially during daytime, regular accurate predictions are required, based on recent data. Without this service the science benefits of the new target cannot be unlocked.

The SGF Analysis Centre has a long-term commitment to the global community to compute predictions for the geodetic spherical satellites and using this first data obtained after the launch, provided the *first very accurate predictions* for LARES-2. To date, the SGF is the *only provider* of such predictions which are successfully being used by many stations of the global laser ranging network. The predictions, which are generated automatically every day, are based on fits to four days of range measurements to determine accurate orbital elements, which are then propagated a few days into the future. The high level of prediction accuracy that is achieved is shown in this screenshot made during an observation of a daytime pass at Herstmonceux, where the solid white lines in the centre of the plot windows show multiple range measurements from the satellite, amongst many sky-noise events. The mean value of this O-C measurement time series, an estimate of prediction error, is a very modest +1m.



The SGF AC, in addition to providing predictions, is also one of the eight appointed ILRS Analysis Centres committed to use laser range observations of the two LAGEOS and two Etalon geodetic satellites to contribute to efforts for realisation of high precision global reference frames by computing station coordinates on a weekly basis and daily Earth Orientation Parameters (namely polar motion and length-of-day). The origin of the frame, the geocentre, is determined with respect to the Earth's crust solely by the SLR technique, while the scale is defined together by SLR and Very Long Baseline Interferometry (VLBI). The most recent realisation of the frame, the International Terrestrial Reference Frame 2020, was published in 2022 [5] and gives the coordinates and velocities of more than 500 geodetic sites worldwide ranging from single automatic GNSS receivers, to major geodetic observatories operating all four of the techniques, to more modest stations such as SGF with SLR and GNSS along with a very valuable absolute gravity capability [6].

The primary value to the SGF AC of the new satellite is that its observations from Herstmonceux and the global network will strengthen reference frame solutions through the addition of more data from a different orbital regime. An urgent task necessary to exploit fully the data from LARES-2 is the computation of station dependent corrections that accurately refer range measurements to the centre of mass of the LARES-2 sphere; the SGF AC has considerable experience in this work, having carried out such modelling for the LAGEOS and other geodetic satellites [8]. Future analysis plans include using the observations from the full constellation of geodetic satellites to improve the quality of low degree and order coefficients in the model of the Earth's gravity field, which, despite recent dedicated gravity missions such as GOCE and Grace-FO, are still determined more accurately using laser range measurements to the geodetic satellites. There is also the possibility of using a multi-satellite technique to determine *GM*, the product of the universal gravitational coefficient with the mass of the Earth. Our previous attempts [7, 8] to retrieve *GM* merely suggested that the currently adopted value is not significantly in error.

The new LARES-2 satellite is now observed routinely day and night at SGF and globally thanks to the predictions provided by our AC service. Fully supporting such a target requires considerable tracking time due to the nature of the orbit, but the potential benefits to the core geodetic products, reference frame and of course the Lense-Thirring relativity determination mean this is time very well spent.

References

1 King-Hele, D., Merson, R. A New Value for the Earth's Flattening, derived from Measurements of Satellite Orbits. *Nature* **183,** 881–882 (1959). https://doi.org/10.1038/183881a0

2 Yoder, C.F., Williams, J.G., Dickey, J.O., Schutz, B.E., Eanes, R.J., and Tapley, B.D., "Secular Variation of Earth's Gravitational Harmonic J2 Coefficient from LAGEOS and Nontidal Acceleration of Earth Rotation", Nature, V.303, pp. 757-762, 1983.

3 Ciufolini, I. & Pavlis, E. C. *Nature* **431**, 958–960 (2004).

4 Ciufolini, I, et al, 2022. Disco-ball satellite will put Einstein's theory to strictest test yet. https://www.nature.com/articles/d41586-022-02034-x

5 Altamimi, Z. ITRF2020: https://itrf.ign.fr/en/solutions/ITRF2020

6 Smith, V.A., Appleby, G., Ziebart, M., Rodriguez, J. (2021). Twelve Years of High Frequency Absolute Gravity Measurements at the UK's Space Geodesy Facility: Systematic Signals and Comparison with SLR Heights. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2021_129

7 Appleby, G., Rodríguez, J. & Altamimi, Z. Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993–2014. *J Geod* 90, 1371–1388 (2016). https://doi.org/10.1007/s00190-016-0929-2

8 Rodríguez, J., Appleby, G. & Otsubo, T. Upgraded modelling for the determination of centre of mass corrections of geodetic SLR satellites: impact on key parameters of the terrestrial reference frame. *J Geod* 93, 2553–2568 (2019). https://doi.org/10.1007/s00190-019-01315-0