Journal of Geodesy (2019) 93:2181–2194
https://doi.org/10.1007/s00190-019-01228-y

ORIGINAL ARTICLE

Laser geodetic satellites: a high-accuracy scientific tool

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Received: 4 June 2018 / Accepted: 29 December 2018 / Published online: 12 February 2019

Abstract

Satellite Laser Ranging (SLR) began in the mid-1960s on satellites of opportunity with retro-reflectors intended as a part of intercomparison tests of satellite tracking techniques. Shortly thereafter, data from these satellites began to work their way into geodetic solutions and dedicated geodesy experiments. By early 1970s when future requirements for centimeter accuracy were envisioned, planning began for dedicated, spherical retro-reflector geodetic satellites. Built with high mass-to-area ratios, these satellites would have important applications in gravity field modeling, station geolocation and fiducial reference systems, Earth rotation, and fundamental physics. Early geodetic satellites were Starlette, launched in 1975 by Centre National d'Etudes Spatiales (CNES), and LAGEOS in 1976 by the National Aeronautics and Space Administration (NASA). Recent geodetic satellites include LARES, launched in 2012, and LARES-2 under development, both by the Italian Space Agency (ASI). Today, a complex of these 'geodetic satellites' from low to high altitude Earth orbits supports many space geodesy requirements. This paper will discuss the evolution of the geodetic satellites from the early days, through current programs and out to future needs as we approach our goal for millimeter accuracy.

Keywords LAGEOS · Etalon · Starlette · Stella · GFZ-1 · Ajisai · BLITS · LARES · SLR

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1 The early years

The first successful launches of satellites with retro-reflectors were Beacon-B (1964), Beacon-C (1965), and GEOS-1 (1965) by NASA and Diademe-D1C and D1D (1967) by CNES (see Fig. 1). These satellites also carried different combinations of flashing lights, Doppler, S-band, C-band, and Goddard Range and Range-Rate and were tracked by optical and radio techniques which were then inter-compared in order to understand system performance and systematic errors. The optical systems, based originally on cameras (Baker-Nunn, BC-4, PC 1000, MOTS, AFU 75, etc.), provided angular satellite positions that were essentially bias free, but were subject to photographic limitations of 1–2 arcsec and were vulnerable to weather conditions. Satellite observations with ten-meter accuracy were considered as state of the art. By the late 1960s and early 1970s, Satellite Laser Ranging (SLR) data began to appear in the geodetic solutions on the size and shape of the Earth; SLR overcame many of the photographic constraints; limitations were now imposed by laser pulse width, detector rise-time and stability, epoch timing accuracy, and atmospheric propagation modeling. Early systems demonstrated meter accuracy.

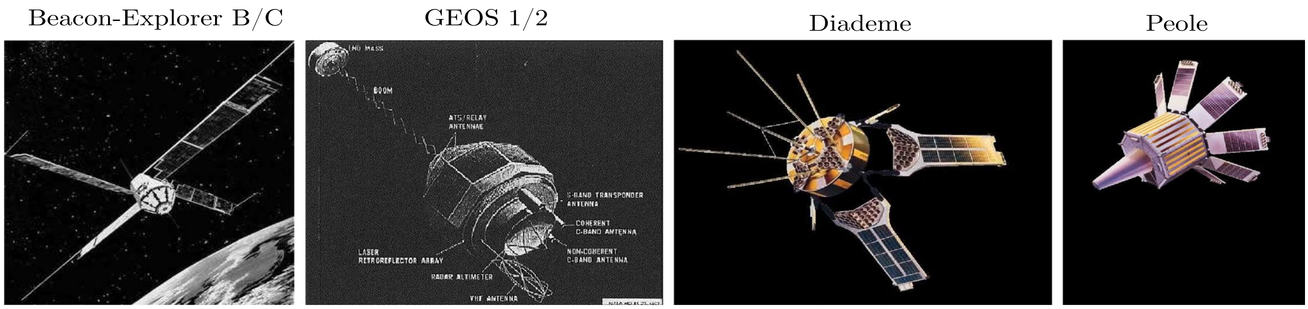

Fig. 1 Satellites with retro-reflectors launched in the early years

In 1971, the Peole satellite was launched by CNES into the first low inclination orbit. Major scientific contributions from the period were documented as a part of the US National Geodetic Satellite Program–NGSP in (Henriksen 1977). Most important are early models of the Earth's gravitational field from satellite tracking and surface gravimeter data; early geoid models suitable for geodetic, tectonic, and altimetry data analysis. Included were also the first positioning results for globally distributed tracking stations to an accuracy of 5–10 m leading to the interconnection of local geodetic datums. In addition, work began on the observation of the Earth and ocean tidal perturbations of satellites (Gaposchkin and Lambeck 1971; Smith et al. 1973a, b).

In 1975, NASA launched the GEOS-3 satellite with several of the radio tracking techniques, an SLR retro-reflector array and a radar altimeter, which provided the first satellite derived global ocean surface topography map. With narrower pulsed Q-switched lasers, improved detectors and discriminators, the introduction of pulse processing techniques, and modeling of the offset between satellite center of mass and the retro-reflector array reflection point, ranging capability now approached the decimeter level, and began playing a key role in orbit determination and instrument validation.

This group of satellites continued to play a role in space geodesy programs for many years, even as other SLR-dedicated satellites were launched; in particular, tracking of Beacon-Explorer C continues until today for measurements of the time-varying gravity field.

2 Current geodetic satellites

Interest in very dense, spherical satellites for geodetic applications emerged at the time of the Williamstown Conference (Kaula 1969), with the recognition that SLR, although still in its infancy, had the potential of centimeter accuracy ranging. Heavy, passive satellites, covered with cube corners could sense conservative gravitational forces reflecting the Earth's structure and yet minimize the effect of non-conservative forces, which could be highly variable and difficult to model. These satellites would act as probes of Earth's gravitational field, and therefore their orbital motion would reflect the distribution of mass inside Earth and in its fluid envelope. The Earth is a viscoelastic body with solid and fluid envelopes that are deformed by the gravitational attraction of the Moon and Sun with a phase lag between their action and the induced deformation. Satellite motion would also be influenced by forces due to the gravitational attraction of the Sun, the Moon and other bodies in the solar system, which would allow us to study these more complex systems. The analysis of orbits of many satellites over long time spans would provide us with a very powerful tool to study tidal phenomena over a wide range of frequencies.

The passive nature of these 'geodetic' satellites and their spherical shape would significantly reduce the spacecraft complexity including the need for stabilization and therefore power, so that missions lasting many decades or even generations could be realized. Its spherical shape would also provide very uniform satellite center-of-mass corrections for accurate interpretation of the ranging data. These satellites would become the basis for SLR network positioning, gravity field modeling, tide studies, lunar-solar interaction modeling, etc., and eventually the SLR contribution to the International Terrestrial Reference Frame (ITRF) and the estimation of fundamental constants (see relevant articles in this issue).

Over time, as SLR tracking accuracy continued to improve, analysis of geodetic satellite data would also reveal information about the non-gravitational forces due to atmospheric drag from the upper terrestrial atmosphere as well as radiation pressure having solar or terrestrial origin, or from thermal emission from the satellite surface itself (Rubincam 1987; Vokrouhlicky and Farinella 1997, 1998). To address this host of applications, we would need long-term SLR tracking on a stable complex of geodetic satellites, at both high and low altitudes. The optical cross section of these satellites should be as homogeneous as possible with cube corners covering the surface in a uniform pattern. The configuration should be very efficient, reasonably economical to fabricate, and observable over very long periods of time. A well-manufactured sphere would have a well-determined center-of-mass for accurate determination of its motion.

Over time, the complex of geodetic satellites would materialize (see Fig. 1).

3 Starlette and Stella satellites

The first dedicated geodetic satellite, Starlette, was launched by CNES in 1975 to measure and interpret long period perturbations in the gravity field, determine precise geodetic positions, measure perturbations in Earth rotation, and eventually to study non-conservative effects. An essentially identical follow-on satellite, Stella, was launched by CNES in 1993. Starlette, along with NASA's LAGEOS satellite launched one year later (1976), helped separate components of the Earth's gravity field and enhance temporal coverage on the Earth's surface. Characteristics are given in Table 1. Some historical details can also be found on the launch of Starlette (Barlier and Lefebvre 2001), especially regarding the close cooperation between CNES and the Smithsonian Astrophysical Observatory (SAO), whose Baker-Nunn Camera Network provided the optical acquisition after launch.

Starlette and Stella were designed for maximum mass-to-area ratio by using a core made from an alloy of depleted Uranium 238, formed as icosahedrons with 20 triangular planes. Each triangle formed the base for a spherical aluminum cap with three embedded retroreflectors (see Fig. 2). The satellites provided very stable orbits for data interpretation and ease of SLR tracking. Both satellites were launched from the Kourou Launch Center in French Guiana. The orbital parameters for Starlette were chosen in large part based on rocket capability and sensitivity of the orbit to as many tidal waves as possible, and, for Stella, to take advantage of a piggyback opportunity.

Over time, these satellites have been valuable tools for:

– Determining low-degree/order static and time-varying components of the Earth gravity field (Biancale et al.

Fig. 2 The Starlette/Stella satellites

Table 1 Characteristics of past and future geodetic satellites

	Starlette/Stella	LAGEOS-1/2	GFZ-1	Etalon-1/2	WESTPAC	Larets	LARES-1/2*	Ajisai
Launch								
Year of launch	1975/1993	1976/1992	1995	1989	1998	2003	2012/2019	1986
Tracking ceased			1999		2002			
Agency	CNES/CNES	NASA/ASI	GFZ	RSA	EOS/RSA	IPIE	ASI	JAXA
COSPAR ID	7501001/ 9306102	7603901/ 9207002	8601795	8900103/ 8903903	9804301	0304206	1200601/ –	8606101
Satellite								
Diameter (cm)	24.0/24.0	60.0	21.6	129.0	24.0	24.0	36.4/40.4	215.0
Mass (kg)	47.3/48.0	411.0	20.6	1415.0	23.0	23.3	386.8/285.0	685
Number of cubes	60/60	426	60	2146	60	60	92/303	1440
Back coating	Yes/yes	No	Yes	Yes	Yes	Yes	No/no	No
CoM (mm)	75.0/75.0	242.0–256.0	58.0	552.0–613.0	63.4–64.1	56.2	133.0/165.0	1010.0
Cross-sect. (mm^2)	0.65	7.0	0.20	60.0	0.03	0.16	3.3/3.9	12.0
Orbit								
Altitude (km)	790-1100/810	5860/5620	400	19120	835	691	1450/5900	1500
Eccentricity (–)	0.021/0.001	0.004/0.014	0.001	0.001/0.002	0.001	0.002	0.001/0.001	0.002
Inclination (°)	49.8/98.6	109.9/52.7	51.6	64.9/65.5	98.0	98.2	69.5/70.1	50.0

*Parameters of LARES-2 according to the present design (Jan 2018)

2000), including seasonal annual variation in low degree zonal harmonics (Schutz et al. 1993; Cheng and Tapley 2001; Moore et al. 2005; Bloßfeld et al. 2015),
- Determining the impact of the secular gravity field variations on the inference of mantle rheology and lithospheric thickness (Devoti et al. 2001),
- Determining laser station coordinates (Lejba et al. 2007; Sośnica et al. 2014),
- Determining ocean and terrestrial tides and the inferred tidal deceleration in the lunar mean motion (Cazenave and Daillet 1981; Eanes et al. 1983; Rutkowska and Jagoda 2012),
- Measuring Earth rotation (He et al. 1982; Williamson et al. 1985; Schutz et al. 1989),
- Calibrating the Jason-1 altimeter (Exertier et al. 2004),
- Studying the effects of the thermosphere total density on low orbiting satellite (Willis et al. 2005),
- Determining the evolution of the satellite spin axis inferred by torques caused by the Earth's magnetic and gravitational fields (Kucharski et al. 2014).

Starlette and Stella continue to play a role in the refinement of the long wavelength components of the gravity field and the Earth's dynamical flattening. Both satellites have a long history of continuous, heavy tracking by the International Laser Ranging Service (ILRS) network (Pearlman et al. 2002).

4 LAGEOS satellites

One of the principal recommendations of the Williamstown study on Solid-Earth and Ocean Physics (Kaula 1969) was that NASA should develop techniques for ranging to satellites to an accuracy of ± 2 cm. Range measurements at this level of accuracy would allow us to measure tectonic plate motion ("continental drift", as it was called at the time), rotational variations and the wobble of Earth's axis, terrestrial body tides, etc. These objectives could be addressed by measuring time-varying positions of ground stations in a global network of fiducial points on the Earth's surface; the station positions with respect to the Earth's center of mass; and the network with respect to an inertial reference (realized by the orbit). Variations in these positions were known to have time scales ranging from a day (e.g., body tides) to millennia (tectonic motion).

To observe these effects, it would be necessary to perform very accurate measurements on a global scale; each station position would have to be related to all others; global sets of observations would have to be obtained in less than a day; and continuity of observations would have to be maintained over very long time spans. The conclusion was that SLR on a passive, very dense, spherical satellite, uniformly covered with retro-reflectors and in a high-inclination orbit, would be the appropriate choice. The passive nature of the satellite (no radio emissions or power needs) would minimize electromagnetic drag, and selection of an orbit that avoided gravitational resonances would simplify orbit determination.

The first serious concept considered was the 'Cannonball Satellite', a 3500 kg spherical satellite, made from uranium 238 (Weiffenbach and Hoffman 1970). It was conceived as a back-up payload for the emergency launch vehicle for Skylab, which was to be on the pad, ready to go in case it was needed. Cannonball, a relatively inexpensive, passive payload, could be quickly loaded and launched by the already fueled vehicle if it was not needed for Skylab. Ultimately, the decision was made not deploy the backup vehicle, and a dedicated launch was sought. NASA decided that the Cannonball Satellite was not required. However, the concept was strongly endorsed by the science community, so NASA approved the mission, albeit in a smaller version, since it had to be launched on a Delta rocket.

The mission was named LAGEOS (LAser GEOdynamics Satellite), approved by NASA in 1974; it was launched in May 1976 (see Table 1). Orbital acquisition was provided by the Smithsonian Astrophysical Observatory (SAO) network of NASA-supported Baker-Nunn Cameras. The LAGEOS satellite, built at NASA Marshall Space Center, was fabricated from a central brass cube core covered with two aluminum alloy caps providing the outer spherical shape. The surface finish was diffuse (chemically cleaned) to provide a good target for optical tracking acquisition. The retro-reflector array geometry limited the variation in single point range correction to an estimated 3 mm, mainly due to interfering returns from multiple cubes. LAGEOS is equipped with 422 uncoated corner cubes made of fused silica and, at the request of Prof. Charles Townes, four germanium corner cubes for measurements at infrared wavelengths as well. Because of the high index of refraction of germanium, four cubes give coverage at all incidence angles. Initial optical response characterization of the spacecraft was performed at NASA Goddard Space Flight Center (GSFC). LAGEOS carries a small plaque designed by Dr. Carl Sagan containing some binary arithmetic and some temporal maps and information about Earth tectonic evolution that might be interpreted some time in the future when and if the spacecraft is recovered.

The report 'LAGEOS Orbital Analysis in Support of Validation' (Gaposchkin 1979) concluded that the LAGEOS satellite has an extraordinarily stable orbit and the objectives for its use could certainly be fulfilled.

LAGEOS-2 was a joint ASI/NASA mission built by Alenia Spazio of Turin, Italy, for the Agenzia Spaziale Italiana (ASI) and deployed from the Space Shuttle Columbia in

Fig. 3 LAGEOS satellites

October 1992 using the new Italian Research Interim Stage (IRIS) deployment mechanism. The mechanical design of LAGEOS-2 is nearly identical to LAGEOS (see Fig. 3). Extensive prelaunch testing of the response of LAGEOS-2 to short optical pulses was performed at GSFC (Minott et al. 1993).

The lower inclination was chosen to provide more opportunities for simultaneous SLR ground station observations and to provide the differential node rates to observe the physics goals of the mission. The combination of the two LAGEOS satellites greatly enhanced station sky coverage and provided the foundation for the SLR contribution to ITRF. Today, two LAGEOS satellites constitute the most important targets for providing SLR-based operational products such as station coordinates, polar motion and excess length of day (see relevant ILRS papers in this issue, e.g., Luceri et al. 2019).

The most important contributions from the LAGEOS satellites include:

– Determining laser station coordinates and tectonic plate motions (Smith et al. 1985; Christodoulidis et al. 1985; Tapley et al. 1985; Smith et al. 1990),
– Determining very low degree static and time-varying components of the Earth gravity field (Lerch et al. 1985; Reigber et al. 1985), including in particular variation in the the Earth's oblateness term C_{20} (Yoder et al. 1983; Cox and Chao 2002; Dickey et al. 2002; Cheng et al. 2013), the coefficients related to pole excitation functions C_{21}, S_{21} (Chen and Wilson 2008; Cheng et al. 2011) and Chandler wobble parameters (Nastula and Gross 2015),
– Determining geocenter motion (Chen et al. 1999; Pavlis 1999; Pavlis and Kuźmicz-Cieślak 2009),
– Defining the origin and scale of the ITRF (Pavlis 2002; Altamimi et al. 2016; Appleby et al. 2016) and the scale transfer to GNSS (Thaller et al. 2015),
– Determining the most accurate Earth's gravitational product GM (Ries et al. 1992; Dunn et al. 1999),
– Verifying the effects of general relativity, including the frame-dragging effect (Ciufolini et al. 1998; Ciufolini and Pavlis 2004; Ciufolini et al. 2016),
– Observing the postglacial rebound (Rubincam 1984) and constraining the mantle viscosity (Peltier 1983),
– Determining Love and Shida numbers describing Earth's elasticity (Rutkowska and Jagoda 2010),
– Determining Earth's polar motion and length-of-day (Tapley et al. 1985; Dow and Agrotis 1986; Pavlis 1994; Bourda 2008; Sośnica et al. 2018; Bloßfeld et al. 2014),
– Determining changes in global geodetic parameters due to ocean and atmospheric mass redistribution (Gutierrez and Wilson 1987; Chao and Eanes 1995; Sośnica et al. 2013),
– Confirming the Yarkovsky effect and other minor effects perturbing satellite orbits (Rubincam 1987, 1990; Vokrouhlicky and Farinella 1997, 1998).

5 Etalon satellites

Etalon-1 and Etalon-2 were designed and launched to investigate satellite orbit dynamics of the Russian 'GLObalnaja NAvigazionnaja Sputnikowaja Sistema' (GLONASS) constellation and tailor the geopotential model to these orbits (see Table 1). The goal of these satellites was to model the Earth's gravity field to support the GLONASS program and at the same time, support international space geodesy programs, including improvements in the terrestrial reference frame, Earth rotation parameters, gravity field modeling, the gravitational constant GM, and the improvement of the selenocentric gravitational constant (Dick et al. 1993). At the initial altitude of 19130 km, the orbit was not in resonance and hence provided unique targets for these applications.

The Etalon satellites were designed and manufactured by the organization now known as the 'Academician M. F. Reshetnev Information Satellite Systems'. Each of the satellites has a heavy spherical metal body covered with 304 arrays of 7 fused-silica CCR's each and 2 arrays with 6 CCR's each (for a total of 2140 CCRs) and 6 germanium, aluminum-coated retro-reflectors (see Fig. 4). The diffusely reflecting metal surface between the reflectors permits observation of the satellites in reflected sunlight. The distribution of corner cubes over the satellite surface is not uniform for technical reasons, because some space was needed for the holders and separation devices (Krebs 2017).

The spherical shape of Etalon satellite, the large mass-to-area ratio, and the large number of corner cubes resulted in a reasonably good design. Etalons therefore allow for an accurate calculation of all non-gravitational forces affecting the satellite motion and hence the satellite is a good tool for

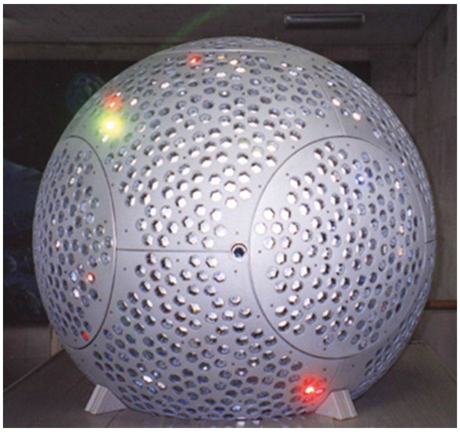

Fig. 4 Etalon satellites

Fig. 5 GFZ-1 satellite

the recovery of the lowest degree gravity field harmonics. The satellites are regularly observed by the ILRS tracking network and along with the LAGEOS satellites they are used for scientific research, including the definition of the ITRF and Earth rotation parameters (Torrence et al. 1995; Appleby 1998).

6 GFZ-1 satellite

The GFZ-1 mission was conceived at GeoForschungsZentrum Potsdam (GFZ) in early 1994 as a low-cost, fast realization project for improving the knowledge of the Earth's gravity field (see Table 1). Its basic design followed the well-proven concept of the passive, spherical satellite configuration, but its main emphasis was put on an orbit of considerably lower altitude than e.g. LAGEOS. The prime contractor, the Kayser-Threde company in Munich, subcontracted the Russian Institute for Space Device Engineering (RNIIKP) for the design, construction and testing of the satellite and the Russian Space Corporation RKK Energia to provide the launch. Within a year, the satellite was launched from the MIR Russian space station using a spring-loaded ejection mechanism from the airlock. This separation technique provided a low-eccentricity, well-predicted orbit, which made it possible for the SLR stations within the ILRS network to acquire GFZ-1 shortly after launch.

The technical parameters of GFZ-1 were restricted by the 30 cm diameter of the MIR airlock and weight restriction necessary to keep launch costs low. The satellite consisted of a bronze spherical body with retro-reflectors distributed equally over its surface (see Fig. 5). The velocity aberration correction was provided with a cornercube design featuring a two-spot far field diffraction pattern for a single prism. These cornercubes were arranged in sets of three cubes with each cube contributing 2 of the 6 spots forming a hexagon of spots for each triad, covering all possible orientations between GFZ-1 and the SLR ground stations for the full range of velocity aberration values between 4.9 and 10.5 arc-sec.

Both the non-polar orbit and the considerably high air drag at this low altitude introduced orbit acceleration, which had to be separated from the gravity signals. This limited the impact of GFZ-1 data on the global gravity field modeling effort. However, the mission made unique contributions to the gravity field model as the decaying orbit passed through resonances around the harmonic coefficients of orders 16, 31, 46, 62 and 77.

The global satellite-only gravity field model GRIM4-S4G, which included 30 months of GFZ-1 laser data, provided a spherical harmonics spectral representation up to degree/order 60 with higher-degree zonal terms (König et al. 1999). A total of 33 SLR stations worldwide contributed to the laser tracking of this mission until its decay on June 23, 1999.

GFZ-1 data are still used for orbit adjustment tests as a validation tool for some gravity field model development (Förste et al. 2009) and for surface force parameterization for low-orbiting satellites (König et al. 1997). GFZ-1 was the lowest SLR satellite at its time and thus provided a challenge for the SLR ground stations. It provided the opportunity for the network to develop tracking techniques that would be essential for tracking future low-orbiting LEO missions such as CHAMP, GRACE, ANDE and GOCE.

7 WESTPAC satellite

At the Western Pacific Laser Tracking Network (WPLTN) Executive meeting in Moscow on December 2, 1995, it was announced that Electro Optic Systems (EOS) had entered into a joint project with the Russian Space Agency (RSA) to construct and launch a new SLR satellite (WESTPAC, formerly known as WPLTN-1), designed to overcome the limitations introduced by multi-cube illumination on all of the other geodetic satellites, an obstacle to millimeter geodesy (Burmistrov et al. 1998). The satellite had a very similar design to GFZ-1 (see Table 1).

The main purpose of the satellite was to provide the best possible target for the WPLTN stations and, by implication, the Keystone Project constructed by the Communications Research Laboratory (CRL) of the Japanese Ministry of Posts and Telecommunications (Burmistrov et al. 1998). A second goal was to test the concept for general use. The WESTPAC design was an engineering test of a concept to reduce the centre-of-mass (CoM) correction uncertainty by making only one cube corner reflector (CCR) visible when ranging at any moment. The satellite was covered with retro-reflectors of the Russian Fizeau design with a conical shade hood to permit only one retro-reflector to contribute to the return. On average, 0.7 corner cubes contributed to the return, and therefore the return signal faded in and out as different reflectors came into view. The satellite was also well suited for advanced two color-ranging experiments.

Conical shades (see Fig. 6) limited the access angle of every single CCR to 13°. The clear aperture of a CCR was limited to 20 mm (at zero incidence angle) by the shade-opening diameter. As a result of this design, the maximum variation in the CoM correction value for WESTPAC was only slightly more than 0.5 mm. However, vignetting of the laser beam by the shades at nonzero incidence further increased the optical loss introduced by the shades, making the WESTPAC cross-section average value as low as 3×10^4 m^2. After separation from the carrier spacecraft, WESTPAC did not achieve the intended spin rate (6 rpm); the actual spin rate was too slow for proper averaging of the measurement results obtained during the normal point period (30 s). Over time in orbit, the spin rate decreased due to eddy currents induced in the satellite metal body moving in the Earth's magnetic field. The reduced spin rate caused significant outages at the ground stations due to time gaps between CCR illuminations.

WESTPAC provided a very important test bed for the engineering concept, but the combination of data outages, poor data averaging, and low return signal strength made WESTPAC a difficult target for operational data to support geodetic applications and routine SLR tracking was discontinued in early 2002.

8 Larets satellite

Larets was designed and built by the Institute of Precision Instrument Engineering in Moscow, Russia for scientific and applied research in geodesy and geodynamics and launched by the Russian Space Agency (see Table 1). It was planned as the next stage in the development of low-target signature SLR, and it is a modified version of GFZ-1 and WESTPAC satellites. The spacecraft has a spherical brass body covered with retro-reflectors (see Fig. 7). The corner cubes are recessed into the brass body to limit the acceptance at the satellite to a single cornercube (instead of using external baffles, as on WESTPAC). The technique was adopted to increase the target cross-section and eliminate the dead spaces between cubes, which had led to ranging outages in the case of WESTPAC. Larets has a much higher rotation rate than WESTPAC resulting in better data averaging.

The RMS target error of Larets (about 1.5 mm) is only slightly more than that of WESTPAC, while the

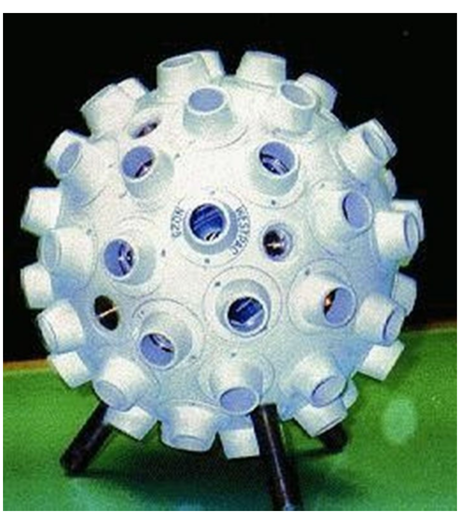

Fig. 6 WESTPAC satellite

Fig. 7 Larets satellite

cross-section is approximately one-fourth that of Stella and Starlette, but much higher than that of WESTPAC. The SLR data yield for Larets is, however, still lower when compared to Starlette or Stella.

Currently, Larets is the lowest orbiting spherical satellite. Thus, it is helpful in recovering medium wavelength gravity field coefficients. However, the sun-synchronous and near-polar orbit limits the number of observations and makes the satellite very sensitive to resonances with diurnal and semi-diurnal tidal constituents. As a result, Larets typically is not used alone but along with other geodetic satellites for the recovery of the Earth's gravity field (Bloßfeld et al. 2015; Sośnica et al. 2015).

9 LARES satellites

The LAser RElativity Satellite (LARES), of the Italian Space Agency (ASI), was launched on February 13, 2012, using the new ESA launch vehicle VEGA. The primary purpose of the mission is the support of relativity experiments and Space Geodesy programs (Ciufolini et al. 2016). In particular, LARES observations combined with data from LAGEOS and LAGEOS-2, and the GRACE gravity field models, are being used to measure the Earth's gravitomagnetic field and the frame-dragging effect with an accuracy intended to reach the few percent level. Gravitomagnetic and frame-dragging phenomena are predicted by the theory of General Relativity (see Ciufolini and Wheeler 1995; Ciufolini 2007), and have been called gravitomagnetic because of a formal analogy of Einstein's gravitational theory with electrodynamics.

A measurement of frame-dragging (Ciufolini and Pavlis 2004) was already obtained using SLR data and the early GRACE Earth gravity field models. The method to get this measurement was to use the observables provided by the nodes of the two LAGEOS satellites. LARES was proposed to improve this by about an order of magnitude, using the three observables provided by the nodes of the three satellites, to eliminate the influence of the uncertainty in the first two even zonal harmonics, C_{20} and C_{40} and to allow the measurement of Earth gravitomagnetism with an accuracy of a few percent. The same data were used in exploratory solutions for station coordinates and Earth rotation parameters, indicating the significant contribution of LARES, 10% to 80% depending on the estimated parameter (Bloßfeld et al. 2018).

The LARES orbit, with nearly zero eccentricity, was chosen to minimize the uncertainty due to the non-gravitational orbital perturbations, whereas the altitude was the maximum achievable with the first flight of VEGA (see Table 1). An accurate measurement of frame-dragging with a few percent uncertainty was recently obtained using LARES (Ciufolini et al. 2016).

LARES is a passive spherical satellite (see Fig. 8) covered with 92 fused silica retro-reflectors (Paolozzi et al. 2015). The satellite is made of a high-density solid tungsten alloy that was chosen to minimize the non-gravitational perturbations and to make LARES, as nearly as possible, a test-particle freely falling in Earth's gravitational field. The corner cubes are arranged in the form of 10 rings around the polar axis of the body (Kucharski et al. 2012). Unlike the other geodetic satellites, LARES consists of only a solid metal body, without a separate inner core. The highest mass-to-area ratio, and the orbital parameters of LARES, make it an important addition to the constellation of satellites being used for the development of the ITRF, GM, and the determination of the Earth rotation parameters. Moreover, the high-accuracy LARES observations are very useful for the recovery and decorrelation of low-degree gravity field parameters, e.g., the C_{30} and C_{50} terms. Therefore, LARES will be included in the operational solutions as the fifth satellite, together with LAGEOS/LAGEOS-2 and Etalon-1/2, in generating the official ILRS products, such as station coordinates, Earth rotation parameters and low-degree gravitational harmonics (see relevant papers in this issue).

ASI has approved the development of another satellite, LARES-2, to go into a supplementary to LAGEOS orbit to support the LARES objectives, including the improvement of the ITRF (Paolozzi 2019). This satellite will have a construction similar to that of LARES, but it will be larger in diameter and will use smaller Commercial Off The Shelf (COTS) CCRs to permit a more densely packed array to reduce ranging discontinuities between adjacent cubes, thus improving ranging accuracy. The smaller 1-inch cubes planned for LARES-2 will provide a broader diffraction pattern to avoid the need for CCRs with costly dihedral angle offsets. Since thermal effects in the CCRs are the primary source of uncertainty and variation in the range correction

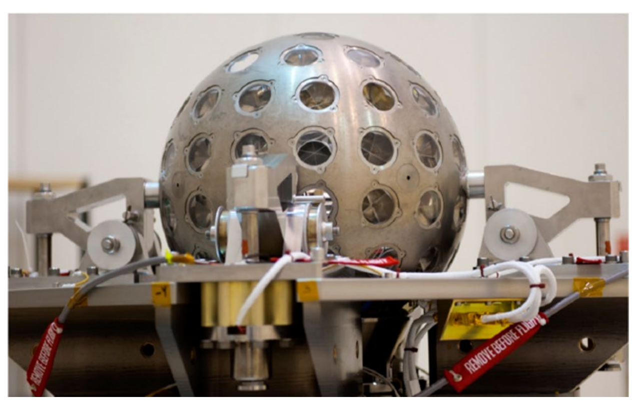

Fig. 8 LARES satellite

in the space environment, the design of LARES-2 uses the 1-inch cubes, significantly smaller than in the 1.5-inch cubes used on LARES to minimize thermal effects. LARES-2 will be the first geodetic satellite where the effect of thermal variations will be within the one millimeter range accuracy goal (Ciufolini et al. 2017a, b).

The disadvantage of the 1-inch CCRs is their smaller optical cross-section per unit surface, but you can pack a much higher number of 1-inch CCRs than 1.5-inch CCRs on the same spherical surface. Ultimately, the 1-inch CCR option will reduce the satellite cross-section but not by much. In the case of LARES-2 with about a 0.2 m radius, the average optical cross section is 5.3×10^6 m^2 with 1.5-inch CCRs and $3.9 \cdot 10^6$ m^2 with 1-inch CCRs, while the range variation is 1.8 mm and 0.8 mm, respectively.

10 Ajisai satellite

Ajisai (also known as Experimental Geodetic Payload or Experimental Geodetic Satellite, EGS) was launched on August 12, 1986, by the National Space Development Agency of Japan–(NASDA), later reorganized as Japan Aerospace Exploration Agency–(JAXA). The main objective of the mission was the precise positioning of fiducial reference points on the Japanese Islands and testing NASDA's two-stage launch vehicle.

The satellite is equipped with 1440 1.9-inch (48.5 mm) uncoated fused silica corner cube reflectors, arranged in the form of 15 rings around the symmetry axis (see Fig. 9). Ajisai is also equipped with 318 spherical mirrors used for the optical or CCD observations and for photometric measurements to determine Ajisai's spin rate (Otsubo et al. 1999). The mass of the satellite is 685 kg, and the diameter is 215 cm. The mass-to-area ratio of Ajisai is less favorable in comparison with other geodetic satellites. Ajisai has a considerable sensitivity to non-gravitational forces perturbing its orbit. On the other hand, the layers of aluminum nets and a partly hollow interior minimize the magnetic torques affecting other geodetic satellites made of solid metal. Ajisai is the fastest spinning object among the geodetic satellites. Its specific construction prevents the Earth's magnetic field from inducing eddy currents in the body, hence minimizing the slowdown of its spin and stabilizing the orientation of the spacecraft.

Fig. 9 Ajisai satellite

Ajisai is used along with other spherical satellites for the recovery of Earth's gravity field (Sengoku 1998; Cheng and Tapley 2001) as well as for the determination of station coordinates and Earth rotation parameters (Lejba and Schillak 2011; Sośnica et al. 2014).

High repetition-rate SLR observations offer new possibilities for the post-processing of the range measurements on large-size spacecraft, such as Ajisai, in particular for the isolation of the reflections from individual CCRs in the high-rate data. The large separation of the retro-reflectors and the stable spin rate of Ajisai enable designation of the range measurements to specific retro-reflectors, hence the formation of the normal points which most closely approximate the physical distance between the ground station and the center of mass of Ajisai. The method developed by (Kucharski et al. 2015) eliminates the satellite signature effect from the distribution of the post-fit range residuals and improves the average single-shot RMS per normal point to 3.05 mm and the normal point RMS per pass to 0.06 mm. Such sub-mm distance measurements will be very useful for future geodetic applications as soon as all perturbations affecting Ajisai's orbit are handled in a proper manner and when more SLR stations start providing kHz data.

11 BLITS

The heavy, spherical, passive satellites covered with corner cubes have addressed many of the ranging issues needed to reach sub-cm ranging performance. Careful data averaging can take us a bit farther. However, as we approach millimeter and sub-millimeter requirements, spacecraft signatures will impose limitations.

Spherical satellites are launched with a high spin rate, which provides spatial and temperature averaging over the satellite. Over time, the spin rate slows down, reducing spatial and temperature averaging, which introduces small biases in the range data, and more complicated perturbations in the orbit. In the case of LAGEOS, the original spin pattern has been lost and the motion has become more complicated. The array structure becomes evident in the pattern and must be somehow modeled or filtered in order to extract the highest-accuracy range measurements.

One interesting concept that overcomes the problem with the slowing down of the spin rate and the reflection from multiple cubes is the application of the Luneburg Sphere.

The BLITS (Ball Lens In The Space) satellite was designed by the Federal State Unitary Enterprise - Institute for Precision Instrument Engineering (FSUE-IPIE) in Russia, and launched on September 17, 2009. The main purpose of this satellite was the experimental verification of the Luneburg lens satellite concept. The satellite had a radius of 85.16 mm and a mass of 7.53 kg. The uncertainty of the reflection center relative to the center of mass position was less than 0.1 mm (best defined of all the geodetic satellites). The retro-reflector was freed from the polarization effects, and the Earth magnetic field did not affect the satellite orbit and spin parameters as the satellite was made of glass (Kucharski et al. 2011). Due to the virtually non-existent target error, the RMS of the laser range residuals to BLITS were almost at the same level as to the ground targets. However, the number of SLR observations from BLITS was lower than that for Starlette or Stella, due to reflections from only one satellite hemisphere, declining reflectivity caused by aging, and low optical cross-section of about 0.1 Mm^2.

BLITS consisted of two concentric outer hemispheres(see Fig. 10): the outer made of a low-refraction-index glass, and an inner ball lens made of a high-refraction-index glass. One hemisphere of external surface was aluminum-coated and protected by a varnish layer. Therefore, BLITS demonstrated a new concept of geodetic satellites, which is an alternative for the classical structure of a spherical body equipped with silica or germanium corner cubes. BLITS was launched into a sun-synchronous near-circular orbit with a mean altitude of 832 km and an inclination of 98.8°. On January 22, 2013, BLITS was probably hit and destroyed by a space debris fragment.

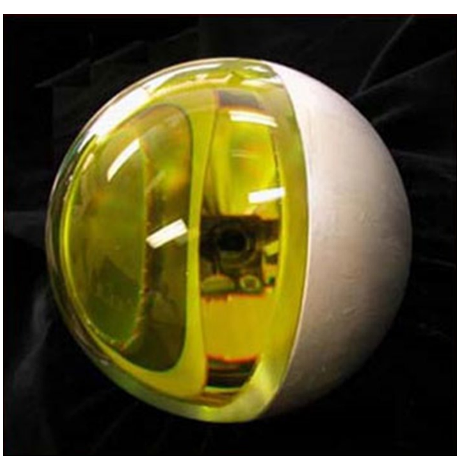

Fig. 10 BLITS satellite

BLITS observations were mostly used for gravity field recovery (Bloßfeld et al. 2015); however, its sun-synchronous orbit and low mass-to-area ratio made the satellite very sensitive to resonances with diurnal tidal constituents and non-gravitational orbit perturbations, all of which limited the accuracy of BLITS products. Moreover, BLITS' low cross-section prevented its use in high-altitude orbits, thence the motivation for a new design of its successor, BLITS-M, to be discussed in the next section.

12 New concepts of geodetic satellites

Several concepts of future geodetic satellites are currently being considered. Such satellites should, on the one hand, maximize the mass-to-area ratio (to minimize the influence of non-gravitational accelerations on the orbit) and, on the other hand, minimize the spacecraft signature effect (to reduce the uncertainty in the range extrapolation to the satellite center of mass).

One of the considered concepts of zero-signature target is the BLITS-M satellite (a spacecraft similar to BLITS, but with increased mass to 17 kg, increased radius to 110 mm and a 2.5 times increased cross-section compared to BLITS. The satellite is made of radiation-resistant glass with high-reflectivity dielectric interference phase-shift coating instead of aluminum coating which was used for BLITS (Sokolov et al. 2016). BLITS-M will be launched into an orbit of 1500 km altitude in 2019.

Another concept is the Geodetic Laser Autonomic Spherical Satellite (GLASS), made of glass to avoid induction of eddy currents and thus preventing the satellite spin slow down (see Fig. 11). GLASS will have a diameter of 210 mm and a mass of 17 kg; it will not be a fully zero-signature target, but the signature effect will be very small, in the range of 0.6–1.0 mm (Sokolov et al. 2016). Further increasing the satellite mass will further reduce the impact of non-gravitational perturbing forces.

This trend is consistent with LARES-2 that has a predicted signature effect below 1 mm and a mass-to-area ratio second only to LARES; this is due to the material to be used for the LARES-2 body, which, at the time of this writing, will likely be either a nickel or a copper alloy. The accuracy of the CoM correction depends on the uniformity of the distribution of the CCRs on the surface of the satellite. In the case of LARES-2 for instance, a random distribution of CCRs (i.e. a distribution which is not along rows or parallels) resulted in the highest uniformity. Furthermore, the use of smaller CCRs will approximate the spherical surface better than larger CCRs. To eliminate systematic effects on the

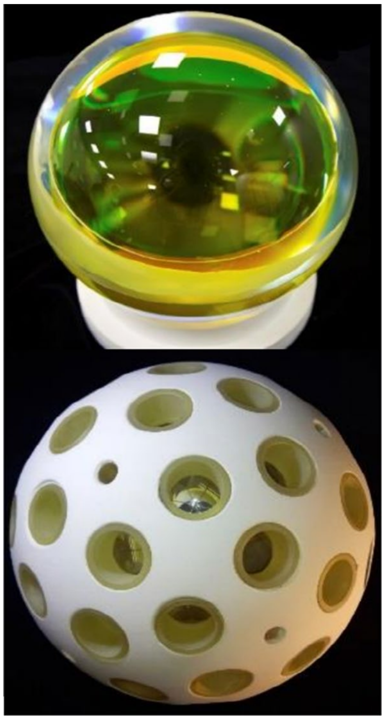

Fig. 11 Concept of BLITS-M (top) and GLASS (bottom)

range correction, the orientation of the CCRs with respect to their axes is randomized.

Degnan (2016) proposed several concepts for future geodetic satellites that meet the high-accuracy requirements. In his reference, future satellites should have a reduced range of accepted incidence angles to limit return signals to single CCRs through the use of hollow retroreflectors or recessed hollow or solid retroreflectors, and should maximize the packing density of retros to achieve the necessary optical cross-section with the maximized mass of the satellite.

13 Summary

SLR tracking of geodetic satellites became an exceptional contributor to science in particular after the launch of the first two satellites specifically designed for geodetic application of SLR, i.e., Starlette in 1975 and the LAGEOS in 1976. SLR to geodetic satellites enabled confirmation of the theory of plate tectonics through the determination of SLR station positions and allowed definition of the precise value of one of the fundamental constants in physics and astronomy, i.e., the standard gravitational parameter of the Earth GM, through the high-accuracy satellite orbit reconstruction. Even today, SLR is indispensable in defining the origin and scale of the global reference frame, determining the Earth's long-wavelength gravitational potential (in particular the oblateness term), and observing Earth rotation parameters. These products are essential in climate change and terrestrial environment studies, that allow us to monitor and better understand the mechanisms of change in the hydrosphere, cryosphere, and above all, mean sea level variations. Even in the era of such dedicated missions as GRACE and GRACE-FO, the SLR products are still considered the standard for the long-wavelength scales. The SLR tracking of geodetic satellites remains fundamental in many fields of space geodesy due to the relatively unperturbed orbits of geodetic satellites and the precision of laser observations at a level of a few millimeters. Thus, SLR plays a fundamental role in establishing global networks and deriving geodetic parameters of superior quality. Finally, the long time series of precise SLR observations allow verification and confirmation of particular aspects of the theory of general relativity, e.g., the Lense-Thirring effect (Ciufolini and Pavlis 2004; Ciufolini 2007).

Acknowledgements The authors acknowledge the ILRS for providing the ground stations and the laser ranging data of all the satellites described in the paper. M.R. Pearlman and D. Arnold acknowledge the support of NASA Grant 80NSSC18K0220. F. Barlier and R. Biancale acknowledge the support of CNES and the Observatoire de la Cte dAzur/GEOAZUR. I. Ciufolini and A. Paolozzi acknowledge the Italian Space Agency for the support of the LARES and LARES 2 space missions under agreements No. 2017-23-H.0 and No. 2015-021-R.0. E. C. Pavlis acknowledges the support of NASA Grant NNX15AT34A.

References

Altamimi Z, Rebischung P, Metivier L, Xavier C (2016) ITRF2014: a new release of the International Terrestrial Reference Frame modeling nonlinear station motions. J. Geophys. Res. Solid Earth 121:6109–6131. https://doi.org/10.1002/2016JB013098

Appleby GM (1998) Long-arc analyses of SLR observations of the Etalon geodetic satellites. J Geod 72(6):333–342. https://doi.org/10.1007/s001900050172

Appleby G, Rodrguez J, Altamimi Z (2016) 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. https://doi.org/10.1007/s00190-016-0929-2

Barlier F, Lefebvre M (2001) A new look at planet Earth: satellite geodesy and geoscience. In: Bleeker JAM, Geiss J, Huber MCE (eds) The century of space science. Springer, Dordrecht, pp 1623–1651. https://doi.org/10.1007/978-94-010-0320-9_66

Biancale R, Balmino G, Lemoine J-M, Marty J-C, Moynot C, Barlier F, Laurain O, Gegout P, Schwintzer P, Reigber C, Bode A, König R, Massmann F-H, Raimondo J-C, Schmidt R, ZhuS Yuan (2000) A new global Earth's gravity field model from satellite orbit perturbations: GRIM5-S1. Geophys Res Lett 27(22):3611–3614. https://doi.org/10.1029/2000GL011721

Bloßfeld M, Müller H, Gerstl M, Štefka V, Bouman J, Göttl F, Horwath M (2015) Second-degree Stokes coefficients from multi-satellite SLR. J Geod 89(9):857–871. https://doi.org/10.1007/s00190-015-0819-z

Bloßfeld M, Gerstl M, Hugentobler U, Angermann D, Müller H (2014) Systematic effects in LOD from SLR observations. Adv Space Res 54:1049–1063. https://doi.org/10.1016/j.asr.2014.06.009

Bloßfeld M, Rudenko S, Kehm A, Panadina N, Müller H, Angermann D, Hugentobler U, Seitz M (2018) Consistent estimation of geodetic parameters from SLR satellite constellation measurements. J Geod 92:1003–1021

Bourda G (2008) Length-of-day and space-geodetic determination of the Earths variable gravity field. J Geod 82(4):295–305. https://doi.org/10.1007/s00190-007-0180-y

Burmistrov V B, Parkhomenko N N, Pliev L F, Shargorodsky V D, Soyuzova N M, Vasiliev V P (1998) The westpac satellite: design features and first results of return signal analysis. In: Procedings of the 11 th international workshop on laser ranging, Deggendorf, Germany, 21–25 Sept, pp 297

Cazenave A, Daillet S (1981) Lunar tidal acceleration from Earth satellite orbit analyses. J Geophys Res 86(B6):1659–1663. https://doi.org/10.1029/JB086iB03p01659

Chao B, Eanes R (1995) Global gravitational changes due to atmospheric mass redistribution as observed by the Lageos nodal residual. Geophys J Int 122:755–764

Chen J, Wilson C (2008) Low degree gravity changes from GRACE, Earth rotation, geophysical models, and satellite laser ranging. J Geophys Res 113:B06402. https://doi.org/10.1029/2007JB005397

Chen J, Wilson C, Eanes R, Nerem R (1999) Geophysical interpretation of observed geocenter variations. J Geophys Res 104:2683–2690

Cheng M, Tapley BD (2001) Seasonal variations in low degree zonal harmonics of the Earth's gravity field from satellite laser ranging observations. J Geophys Res 104(B2):2667–2681. https://doi.org/10.1029/1998JB900036

Cheng M, Ries J, Tapley B (2011) Variations of the Earth's figure axis from satellite laser ranging and GRACE. J Geophys Res 116(B01):409

Cheng M, Tapley B, Ries J (2013) Deceleration in the Earth's oblateness. J Geophys Res 118:740–747. https://doi.org/10.1002/jgrb.50058

Christodoulidis DC, Smith DE, Kolenkiewicz R, Klosko SM, Torrence MH, Dunn PJ (1985) Observing tectonic plate motions and deformations from satellite laser ranging. J Geophys Res 90(B11):9249–9263. https://doi.org/10.1029/JB090iB11p09249

Ciufolini I, Wheeler JA (1995) Gravitation and inertia. Princeton University Press, Princeton. ISBN: 0-691-03323-4

Ciufolini I, Pavlis EC, Chieppa F, Fernandes-Vieira E, Pérez-Mercader J (1998) Test of general relativity and measurement of the lense-thirring effect with two earth satellites. Science 279:2100–2103. https://doi.org/10.1126/science.279.5359.2100

Ciufolini I, Pavlis EC (2004) A confirmation of the general relativistic prediction of the Lense-Thirring effect. Nature 431(7011):958–960. https://doi.org/10.1038/nature03007

Ciufolini I (2007) Dragging of inertial frames. Nature 449(7158):41–47. https://doi.org/10.1038/nature06071

Ciufolini I, Paolozzi A, Pavlis E, König R, Ries J, Gurzadyan V, Penrose R, Sindoni G, Paris C, Khachatryan H, Mirzoyan S (2016) A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model: measurement of Earth's dragging of inertial frames. Eur Phys J C 76:120. https://doi.org/10.1140/epjc/s10052-016-3961-8

Ciufolini I, Paolozzi A, Pavlis EC, Sindoni G, Koenig R, Ries JC, Matzner R, Gurzadyan V, Penrose R, Rubincam D, Paris C (2017a) A new laser-ranged satellite for general relativity and space geodesy: I. An introduction to the LARES2 space experiment. Eur Phys J Plus 132(8):336. https://doi.org/10.1140/epjp/i2017-11635-1

Ciufolini I, Pavlis EC, Sindoni G, Ries JC, Paolozzi A, Matzner R, Koenig R, Paris C (2017b) A new laser-ranged satellite for general relativity and space geodesy: II. Monte Carlo simulations and covariance analyses of the LARES 2 experiment. Eur Phys J Plus 132(8):337. https://doi.org/10.1140/epjp/i2017-11636-0

Cox C, Chao B (2002) Detection of a large scale mass redistribution in the terrestrial system since 1998. Science 297:831–833

Degnan J (2016) Reducing the satellite contribution to range error. In: 20th International workshop on laser ranging, Potsdam, Germany, 2016. https://cddis.nasa.gov/lw20/docs/2016/papers/66-Degnan_paper.pdf

Devoti R, Luceri V, Sciaretta C, Bianco G, Di Donato G, Vermeersen LLA, Sadabini R (2001) The SLR secular gravity variations and their impact on the inference of mantle rheology and lithospheric thickness. Geophys Res Lett 28(5):855–858. https://doi.org/10.1029/2000GL011566

Dick G, Gendt G, Montag H, Nischan T, Sommerfeld W (1993) Results of ETALON data analysis. In: Montag H, Reigber C (eds) Geodesy and physics of the Earth: geodetic contributions to geodynamics. Springer, Berlin, pp 315–318. https://doi.org/10.1007/978-3-642-78149-0_73

Dickey J, Marcus S, de Viron O, Fukumori I (2002) Recent Earth's oblateness variations: unraveling climate and postglacial rebound effects. Science 298:1975–1977. https://doi.org/10.1126/science.1077777

Dow J, Agrotis L (1986) Polar motion and Earth rotation series from LAGEOS. Adv Space Res 6:17–21

Dunn P, Torrence M, Kolenkiewicz R, Smith D (1999) Earth scale defined by modern satellite ranging observations. Geophys Res Lett 26(10):1489–1492

Eanes RJ, Schutz BE, Tapley BD (1983) Earth and ocean tide effects on LAGEOS and Starlette. Proceedings ninth international symposium earth tides. E. Schweinzerbert'she Verlagbuchhandlong, Stiuggart, pp 236–249

Exertier P, Nicolas N, Berio P, Coulot D, Bonnefond P, Laurain O (2004) The Role of laser ranging for calibrating Jason-1: the Corsica tracking campaign. Mar Geod 27(1–2):333–340. https://doi.org/10.1080/01490410490476272

Förste C, Stubenvoll R, König R, Raimondo J-C, Barthelmes F, Kusche J, Dahle C, Neumayer H, Biancale R, Lemoine J-M, Bruinsma S (2009) Evaluation of EGM2008 by comparison with other recent global gravity field models. Newton's Bull 4:26–37

Gaposchkin EM, Lambeck K (1971) Earth's gravity field to the sixteenth degree and station coordinates from satellite and terrestrial data. J Geophys Res 76(29):4855–4883. https://doi.org/10.1029/JB076i020p04855

Gaposchkin EM (1979) Lageos orbital analysis in support of validation. Smithsonian astrophysics observatory (SAO), Grant NSG 5261, final report. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790015288.pdf

Gutierrez R, Wilson C (1987) Seasonal air and water redistribution effects on the Lageos and Starlette. Geophys Res Lett 14(9):929–932

He M, Tapley BD, Eanes RJ (1982) Earth rotation parameters deduced from Starlette laser ranging. Sci Sir Ser A Eng Trans 25(10):1090–1098. https://doi.org/10.1360/ya1982-25-10-1090

Henriksen SW (ed) (1977) National Geodetic Satellite Program, Part 1 and 2, NASA-SP-365-PT-1/2, 19780003602/78N11545. NASA, Washington, DC, United States

Kaula W M (1969) The terrestrial environment: solid—Earth and ocean physics, report of a study at Williamstown, Massachusetts, sponsored by NASA-Electronics Research Center and MIT Measurement Systems Laboratory

Krebs G (2017) Gunter's space page. Etalon 1, 2. http://space.skyrocket.de/doc_sdat/etalon.htm

König R, Bode A, Chen Z, Reigber C (1997) Surface forces parameterization of GFZ-1 orbits and gravity field recovery. Adv Space Res

19(11):1677–1680. https://doi.org/10.1016/S0273-1177(97)00324-4
König R, Chen Z, Reigber C, Schwintzer P (1999) Improvement in global gravity field recovery using GFZ-1 satellite laser tracking data. J Geodesy 73(8):398–406. https://doi.org/10.1007/s001900050259
Kucharski D, Lim H, Kirchner G, Koidl F (2014) Spin parameters of low earth orbiting satellites Larets and Stella determined from satellite laser ranging data. Adv Space Res 53(1):90–96
Kucharski D, Kirchner G, Lim H, Koidl F (2011) Optical response of nanosatellite BLITS measured by the Graz 2 kHz SLR system. Adv Space Res 48(8):1335–1340. https://doi.org/10.1016/j.asr.2011.06.016
Kucharski D, Otsubo T, Kirchner G, Bianco G (2012) Spin rate and spin axis orientation of LARES spectrally determined from satellite laser ranging data. Adv Space Res 50(11):473–477
Kucharski D, Kirchner G, Otsubo T, Koidl F (2015) A method to calculate zero-signature satellite laser ranging normal points for millimeter geodesy–a case study with Ajisai. Earth Planets Space 67:34. https://doi.org/10.1186/s40623-015-0204-4
Lejba P, Schillak S, Wnuck E (2007) Determination of orbits and SLR stations coordinates on the basis laser observations of the satellites Starlette and Stella. Adv Space Res 40(1):143–149. https://doi.org/10.1016/j.asr.2007.01.067
Lejba P, Schillak S (2011) Determination of station positions and velocities from laser ranging observations to Ajisai, Starlette and Stella satellites. Adv Space Res 47(4):654–662. https://doi.org/10.1016/j.asr.2010.10.013
Lerch F, Klosko S, Patel G, Wagner C (1985) A gravity model for crustal dynamics (GEML2). J Geophys Res 90(B11):9301–9311. https://doi.org/10.1029/JB090iB11p09301
Luceri V, Pavlis E C, Kuzmicz-Cieslak M, Evans K, Pirri M, Bianco G (2019) The contribution of satellite laser ranging to the development of the ITRF2014. J Geod (**submitted**)
Minott P O, Zagwodzki T Q, Varghese T, Seldon M (1993) Prelaunch optical characterization of the laser geodynamic satellite (LAGEOS 2), NASA technical paper 3400
Moore P, Zhang Q, Alothman A (2005) Annual and semiannual variations of the Earth's gravitational field from satellite laser ranging and CHAMP. J Geophys Res. https://doi.org/10.1029/2004JB003448
Nastula J, Gross R (2015) Chandler wobble parameters from SLR and GRACE. J Geophys Res Solid Earth 120:4474–4483. https://doi.org/10.1002/2014JB01182
Otsubo T, Amagai J, Kunimori H (1999) The center-of-mass correction of the geodetic satellite AJISAI for single-photon laser ranging. IEEE Trans Geosci Remote Sens 37(4):2011–2018
Paolozzi A, Ciufolini I, Paris C, Sindoni G (2015) LARES: a new satellite specifically designed for testing general relativity. Int J Aerosp Eng 2015:9. https://doi.org/10.1155/2015/341384
Paolozzi A (2019) Studies on the materials of LARES 2 satellite. J Geod (**submitted**)
Pavlis E C (1994) High resolution earth orientation parameters from LAGEOS SLR data analysis at GSFC. In: IERS technical note 16, 1994
Pavlis E C (1999) Fortnightly resolution geocenter series: a combined analysis of LAGEOS 1 and 2 SLR data (1993–96). In: IERS technical note 25, Observatoire de Paris, April 1999
Pavlis EC (2002) Dynamical determination of origin and scale in the earth system from satellite laser ranging, in vistas for geodesy in the new millennium. In: Adam J, Schwarz K-P (eds) Proceedings of the 2001 international association of geodesy scientific assembly, Budapest, Hungary, 2–7 Sept 2001, pp 36–41. Springer-Verlag, New York. https://doi.org/10.1007/978-3-662-04709-5_7
Pavlis E C, Kuźmicz-Cieślak M (2009) Geocenter motion: causes and modeling approaches. In: Schillak S (ed) Proceedings of 16th international laser workshop, pp 16–26. Space Research Center, Polish Academy of Sciences, Warszawa, Poland
Pearlman M, Degnan J, Bosworth J (2002) The international laser ranging service. Adv Space Res 30(2):135–143. https://doi.org/10.1016/S0273-1177(02)00277-6
Peltier WR (1983) Constraint on deep mantle viscosity from LAGEOS acceleration data. Nature 304:434–436
Reigber C, Balmino G, Mller H, Bosch W, Moynot B (1985) GRIM gravity model improvement using LAGEOS (GRIM31). J Geophys Res 90(B11):9285–9299. https://doi.org/10.1029/JB090iB11p09285
Ries JC, Eanes RJ, Shum CK, Watkins MM (1992) Progress in the determination of the gravitational coefficient of the Earth. Geophys Res Lett 19(6):529–531. https://doi.org/10.1029/92GL00259
Rubincam DP (1987) LAGEOS orbit decay due to infrared radiation from Earth. J Geophys Res 92(B2):1287–1294. https://doi.org/10.1029/JB092iB02p01287
Rubincam D (1984) Postglacial rebound observed by LAGEOS and the effective viscosity of the lower mantle. J Geophys Res 89:1077–1088
Rubincam D (1990) Drag on the LAGEOS satellite. J Geophys Res 95:4881–4886
Rutkowska M, Jagoda M (2010) Estimation of the elastic earth parameters using the SLR LAGEOS 1 and LAGEOS 2 data. Acta Geophys 58:705. https://doi.org/10.2478/s11600-009-0062-1
Rutkowska M, Jagoda M (2012) Estimation of the elastic earth parameters using slr data for the low satellites STARLETTE and STELLA. Acta Geophys 60(4):1213–1223. https://doi.org/10.2478/s11600-012-0045-5
Schutz B E, Cheng M K, Shum C K, Eanes R J, Tapley B D (1989) Analysis of earth rotation solution from Starlette. J Geophys Res. https://doi.org/10.1029/JB094iB08p10167
Schutz BE, Cheng MK, Eanes RJ, Shum CK, Tapley BD (1993) Geodynamic results from starlette orbit analysis. In: Smith DE, Turcotte DL (eds) Contributions of space geodesy to geodynamics: Earth dynamics, vol 24. AGU, Washington, pp 175–190. https://doi.org/10.1029/GD024p0175
Sengoku A (1998) A plate motion study using Ajisai. Earth Planet Space 50:611. https://doi.org/10.1186/BF03352156
Smith DE, Kolenkiewicz R, Dunn PJ (1973a) A determination of the earth tidal amplitude and phase from the orbital perturbations of the Beacon Explorer C spacecraft. NASA GSFC No. 19730020633
Smith DE, Lerch FJ, Wagner C A (1973b) A gravitational field model for the Earth. Space research XIII. In: Proceedings of the fifteenth plenary meeting, Madrid, Spain, 10–24 May 1972, vol 1, pp 11–20, (A73-41325 21-13) Berlin, East Germany, Akademie-Verlag GmbH
Smith DE, Christodoulidis DC, Kolenkiewicz R, Dunn PJ, Klosko SM, Torrence MH, Fricke S, Blackwell S (1985) A global geodetic reference frame from LAGEOS ranging (SL5.1AP). J Geophys Res 90(B11):9221–9233. https://doi.org/10.1029/JB090iB11p09221
Smith D, Kolenkiewicz R, Dunn P, Robbins J, Torrence M, Klosko S, Williamson R, Pavlis E, Douglas N, Fricke S (1990) Tectonic motion and deformation from satellite laser ranging to LAGEOS. J Geophys Res 95:22013–22041
Sokolov A, Sadovnikov M, Shargorodskiy V, Vasiliev V (2016) SC BLITS-M. In: Presented at the ILRS missions standing committee, October 2016, Potsdam, Germany
Sośnica K, Thaller D, Dach R, Jäggi A, Beutler G (2013) Impact of loading displacements on SLR-derived parameters and on the consistency between GNSS and SLR results. J Geod 87(8):751–769. https://doi.org/10.1007/s00190-013-0644-1

Sośnica K, Jäggi A, Thaller D, Dach R, Beutler G (2014) Contribution of Starlette Stella and AJISAI to the SLR-derived global reference frame. J Geod 88(8):789–804. https://doi.org/10.1007/s00190-014-0722-z

Sośnica K, Jäggi A, Meyer U, Thaller D, Beutler G, Arnold D, Dach R (2015) Time variable Earths gravity field from SLR satellites. J Geod 89(10):945–960. https://doi.org/10.1007/s00190-015-0825-1

Sośnica K, Bury G, Zajdel R (2018) Contribution of multi-GNSS constellation to SLR-derived terrestrial reference frame. Geophys Res Lett. https://doi.org/10.1002/2017GL076850J

Tapley B, Schutz B, Eanes R (1985) Station coordinates, baselines, and earth rotation from LAGEOS laser ranging: 1976–1984. J Geophys Res 90:9235–9248

Thaller D, Sośnica K, Steigenberger P, Roggenbuck O, Dach R (2015) Pre-combined GNSS-SLR Solutions: What Could be the Benefit for the ITRF? In: International association of geodesy symposia, Springer Berlin Heidelberg. https://doi.org/10.1007/1345_2015_215

Torrence M, Dunn P, Kolenkiewicz R (1995) Characteristics of the LAGEOS and ETALON Satellites Orbits. Adv Space Res 16(12):21–24

Vokrouhlicky D, Farinella P (1997) Thermal force effects on slowly rotating, spherical artificial satellitesII. Earth infrared heating. Planet Space Sci 45:419–425. https://doi.org/10.1016/S0032-0633(96)00147-X

Vokrouhlicky D, Farinella P (1998) The Yarkovsky seasonal effect on asteroidal fragments: a nonlinearized theory for the plane-parallel case. Astronom J 116(4):2032

Weiffenbach G C, Hoffman TE (1970) A passive stable satellite for earth-physics applications (cannonball a satellite for accurate laser ranging). Smithsonian Astrophysical Observatory (SAO), special report no. 329,

Williamson RG, Marsh JG (1985) Starlette geodynamics: the Earth's tidal response. J Geophys Res. https://doi.org/10.1029/JB090iB11p09346

Willis P, Deleflie F, Barlier F, Bar-Sever YE, Romans LJ (2005) Effects of thermosphere total density perturbations on LEO orbits during severe geomagnetic conditions (Oct-Nov 2003) using DORIS and SLR data. Adv Space Res 36(3):522–533. https://doi.org/10.1016/j.asr.2005.03.029

Yoder C, Williams J, Dickey J, Schutz B, Eanes R, Tapley B (1983) Secular variations of Earth's gravitational harmonic J_2 coefficient from Lageos and nontidal acceleration of Earth rotation. Nature 303:757–762