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Current Trends in Satellite Laser Ranging

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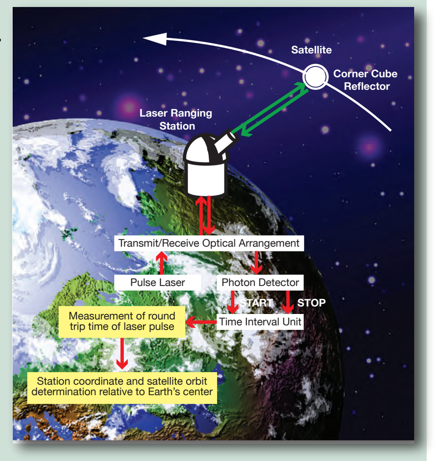
Abstract

Satellite Laser Ranging (SLR) techniques are used to accurately measure the distance from ground stations to retroreflectors on satellites and the moon. SLR is one of the fundamental techniques that define the International Terrestrial Reference Frame (ITRF), which is the basis upon which we measure many aspects of global change over space, time, and evolving technology. It is one of the fundamental techniques that define at a level of precision of a few mm the origin and scale of the ITRF. Laser Ranging provides precision orbit determination and instrument calibration/validation for satellite-borne altimeters for the better understanding of sea level change, ocean dynamics, ice budget, and terrestrial topography. Laser ranging is also a tool to study the dynamics of the Moon and fundamental constants. Many of the GNSS satellites now carry retro-reflectors for improved orbit determination, harmonization of reference frames, and in-orbit co-location and system performance validation. The GNSS Constellations will be the means of making the reference frame available to worldwide users. Data and products from these measurements support key aspects of the GEOSS 10-Year Implementation Plan adopted on February 16, 2005. The ITRF has been identified as a key contribution of the IAG to GEOSS and the ILRS makes a major contribution for its development since its foundation. The ILRS delivers weekly additional realizations that are accumulated sequentially to extend the ITRF and the Earth Orientation Parameter (EOP) series with a daily resolution. Additional products are currently under development such as precise orbits of satellites, EOP with daily availability, low-degree gravitational harmonics for studies of Earth dynamics and kinematics, etc. SLR technology continues to evolve toward the next generation laser ranging systems as programmatic requirements become more stringent. Ranging accuracy is improving as higher repetition rate, narrower pulse lasers and faster detectors are implemented. Automation and pass interleaving at some stations is already expanding temporal coverage. Web-based safety keys are allowing the SLR network stations to range to optically vulnerable satellites. Some stations are experimenting with two-wavelength operation as a means of better understanding the atmospheric refraction and with very low power laser to improve eye-safety conditions. New retroreflector designs are improving the signal link and enable daylight ranging. Dramatic improvements have also been made with lunar ranging with the new APOLLO Site in New Mexico, USA and the upgraded lunar station "MEO" in Grasse, France. We will discuss many of these laser ranging activities and some of the current challenges that the SLR network currently faces.

The Laser Ranging Technique and Science/Applications of SLR

The laser ranging technique consists of a precise range measurement between an SLR ground station and a retroreflector-equipped satellite using ultrashort laser pulses corrected for refraction, satellite center of mass, and the internal delay of the ranging machine. The global network of SLR stations has supported more than sixty space missions supported since 1970; five of these missions have been rescued in the last decade by laser ranging measurements.

Concept:
- Simple measurement of range from accurate time interval counters
- Space segment is passive
- Accurate atmospheric delay correction (independent of water vapor)
- Night/Day Operation
- Near real-time global data availability
- Satellite altitudes from below 300 km to synchronous satellites, and the Moon
- Unambiguous centimeter accuracy orbits
- Long-term stable time series of positions, low degree spherical harmonics, orbital elements, and others



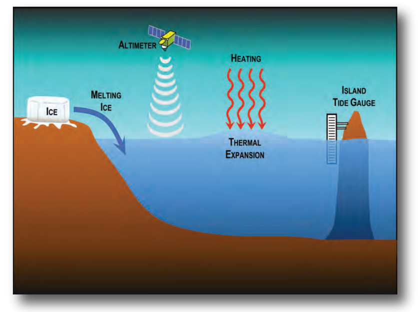
Measurements:
- Precision Orbit Determination (POD)
- Time history of station positions and motions
- Low degree gravitational harmonics and GM
- Tidal harmonics, planetary Love numbers, etc.

SLR/LLR products contributing to:
- Terrestrial reference frame (Center of mass and scale)
- Plate tectonics and crustal deformation
- Static and time-varying gravity field
- Earth orientation and rotation (polar motion, length of day)
- Orbits and calibration of altimetry missions (oceans, ice)
- Total Earth mass distribution
- Space science (tether dynamics, etc.)
- Relativity measurements and lunar science

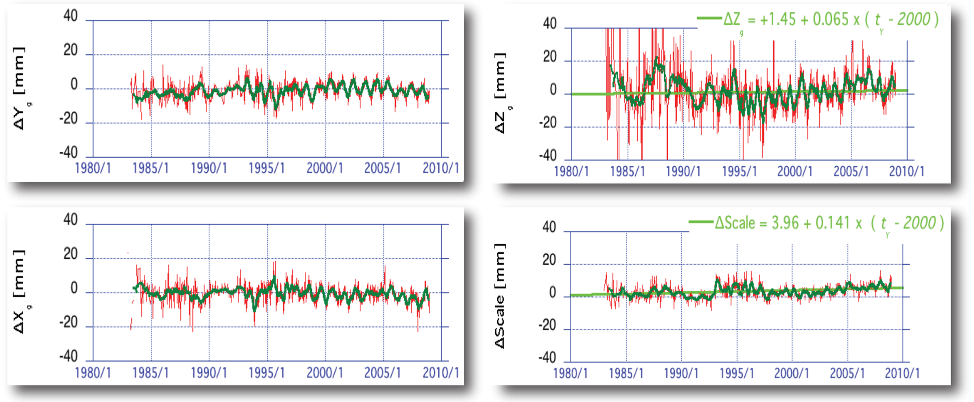

TerraSAR-X and TanDEM-X: SLR provides calibration and validation of onboard systems and supports POD

SLR and the Terrestrial Reference Frame

- SLR is one of the key space technologies that contribute to the development of the ITRF:
  - An accurate, stable set of station positions and velocities.
- The unique contribution of SLR to ITRF is the link of its origin to the center of mass of the Earth system
- SLR contributes also in maintaining a stable scale for the ITRF, in equal parts with VLBI
- The ITRF Requirements of GGOS are:
  - <1 mm reference frame accuracy
  - < 0.1 mm/yr stability
- The primary science driver is the measurement of sea level change
- The GGOS goal requires a factor of 10-20 improvement over current ITRF performance demonstrated below for ITRF2008



ITRF2008 Origin and Scale Variations from SLR



Need for SLR measurements on the GNSS Constellations

Geoscience
- Improve the Terrestrial Reference Frame (co-location of techniques in space)
- Improve LEO POD based on GNSS tracking of SLR-calibrated GNSS orbits

GNSS World
- Provide independent quality assurance:
  - GNSS orbit accuracy cannot be directly validated from the GNSS data itself
- Assure interoperability amongst GPS, GLONASS, Galileo, COMPASS, QZSS, etc.
- Ensure realization of constellation-dependent reference frames (WGS84, GTRF, etc.) are consistent with ITRF

The International Laser Ranging Service and its Support of Missions through Laser Ranging

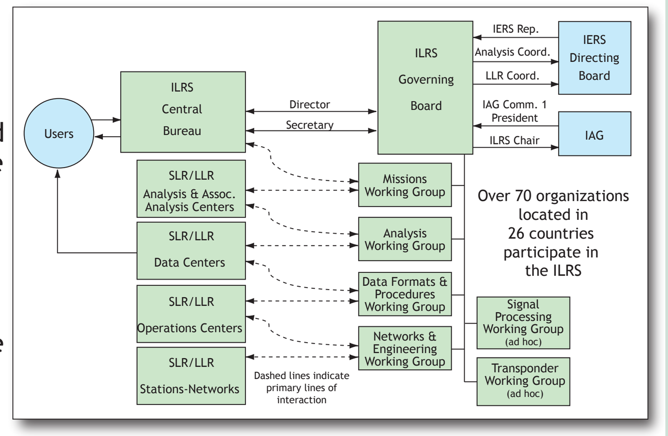
The International Laser Ranging Service (ILRS), founded by the International Association of Geodesy (IAG) in 1998, organizes and coordinates Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) to support programs in geodetic, geophysical, and lunar research and provides the International Earth Rotation and Reference Frame Service (IERS) with products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF).

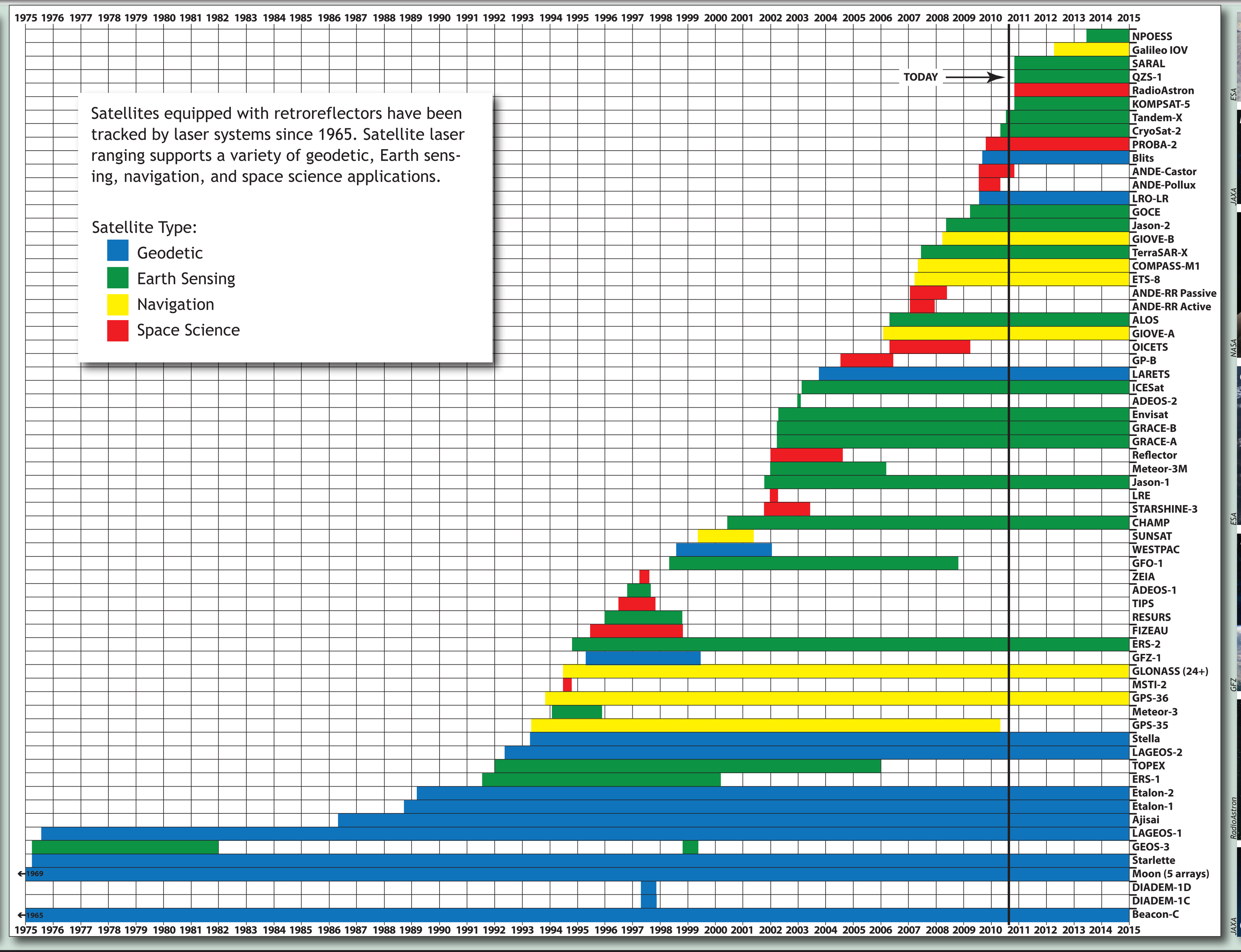
The ILRS produces quality-assured scientific results from the SLR and LLR data including:

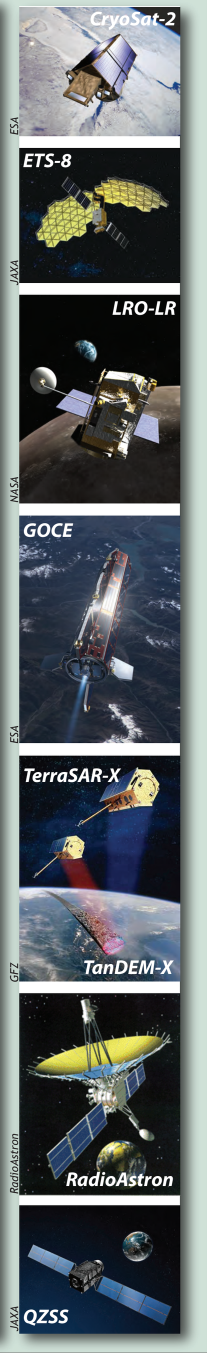
- Satellite ephemerides
- Earth orientation parameters
- Position and velocity of the ILRS tracking stations
- Time-varying geocenter coordinates
- Static and time-varying coefficients of the Earth's gravity field
- Fundamental physical constants
- Lunar ephemerides and librations
- Lunar orientation parameters

The ILRS accomplishes its mission through the following components:

- Tracking Stations and Subnetworks — range to the approved constellation of artificial satellites and the moon
- Operations Centers — collect, QC, merge data from tracking sites and transmit to data centers
- Data Centers — archive laser ranging data and products
- Analysis and Associate Analysis Centers — produce official ILRS products (station coordinates and EOP) as well as special products
- Working Groups — provide expertise to make technical decisions and plan programmatic courses of action
- Central Bureau — coordination and management of ILRS activities
- Governing Board — responsible for general direction of service and defines official ILRS policy



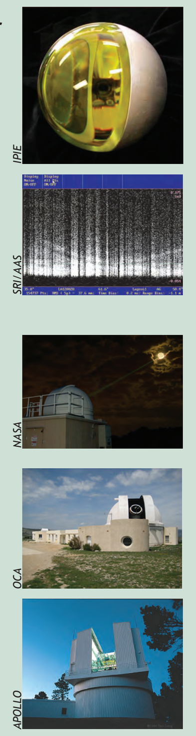




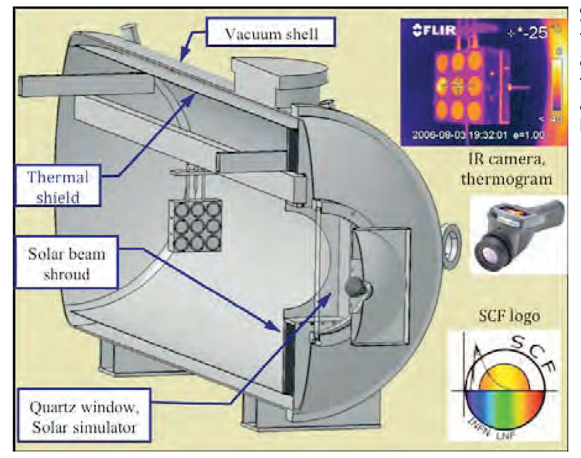
Current SLR/LLR Network

New Technology and Developments

- The Russian Blits satellite with a novel Luneberg Lens, a single corner cube reflector whose center of mass correction can be very accurately computed independent of aspect angle resulting in very precise ranging measurements.
- Stations with kHz repetition laser systems provide ranging measurements that show details of retroreflector geometry and can measure spin rate on spherical geodetic satellites. At this time, four stations in the ILRS network operate at kHz rates.
- NASA supports the development of the Next Generation SLR (NGSLR) system, a prototype automated SLR system for replication and deployment as part of the future GGOS network.
- New French MEO system at Grasse built for both satellite and lunar ranging. The MLRO system in Matera Italy has recently revived its lunar capabilities.
- New high performance Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) measures the round-trip travel time of laser pulses to the lunar retroreflectors to a precision of a few picoseconds, corresponding to about one mm of precision in range to the Moon. These data will be used to gauge the relative acceleration of the Earth and Moon toward the sun in order to ascertain the free-fall properties of Earth's gravitational self-energy.

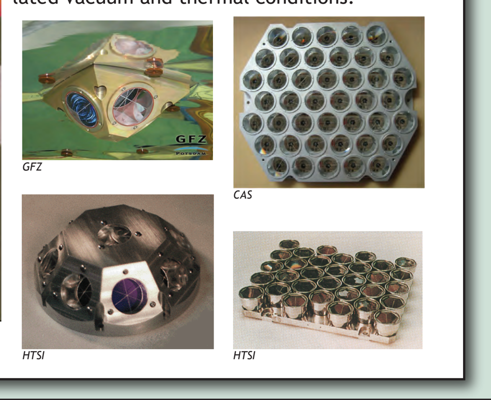


Test Facility for Laser Retroreflector Arrays



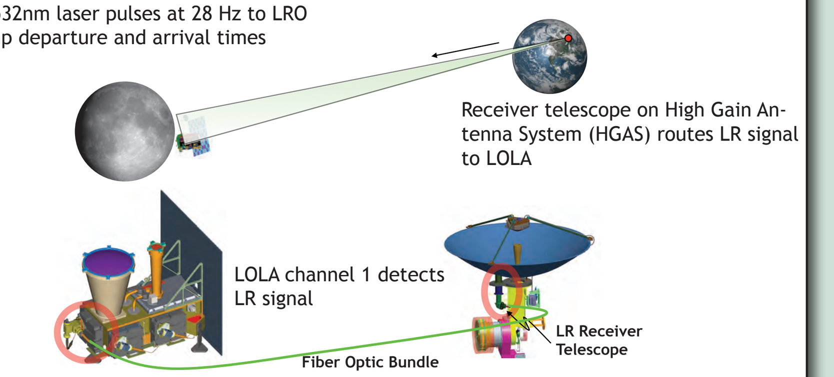
Courtesy of: Simone Dell'Agnello
Istituto Nazionale di Fisica Nucleare (INFN), Rome, Italy

Schematic of facility developed at the Laboratori Nazionali di Frascati to test, characterize and validate the performance of laser retroreflector arrays (S. Dell'Agnello et al.). The array allows performance testing under space simulated vacuum and thermal conditions.



LRO Laser Ranging (LRO-LR)

Transmit 532nm laser pulses at 28 Hz to LRO
Time stamp departure and arrival times

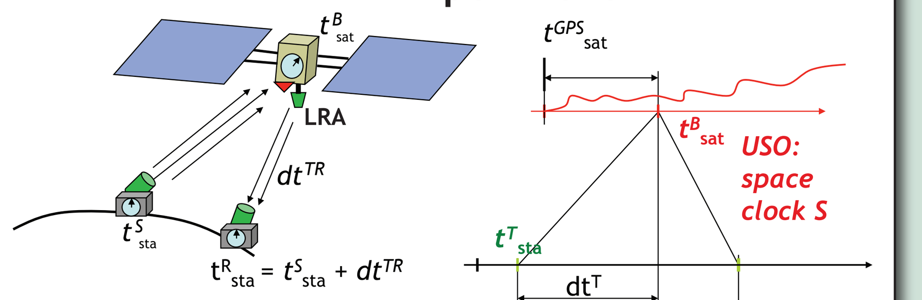


One-way Laser Ranging data from the international SLR network is being used to determine LRO spacecraft clock drift and to "transfer" time and will also be used to improve orbit determination in support of gravity modeling and precise positioning.

Approximately 450 hours of successful LRO Laser Ranging data has been collected since launch in both synchronous (28 Hz) and asynchronous modes by stations in the ILRS network.

Reference:
Zuber, M., D. Smith, R. Zellar, G. Neumann, X. Sun, J. Connelly, A. Matuszeski, J. McGarry, M. Ott, L. Ramos-Izquierdo, D. Rowlands, M. Torrence, T. Zagwodzki, "The Lunar Reconnaissance Orbiter Laser Ranging Investigation", Space Science Reviews, Volume 150, Issue 1-4, 2010.

T2L2 Experiment



$t^{R}_{sta} = t^{S}_{sta} + dt^{TR}$

t^{S}_{sta}, dt^{TR}, t^{B}_{sat} : measured quantities = « triplet »

(dt^{T} is computed from dt^{TR})

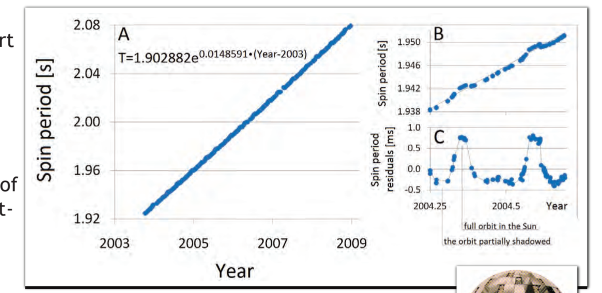
$$X_A = \frac{t_S + t_R}{2} - t_B + \tau_{Relativity} + \tau_{Atmosphere} + \tau_{Instrument}$$

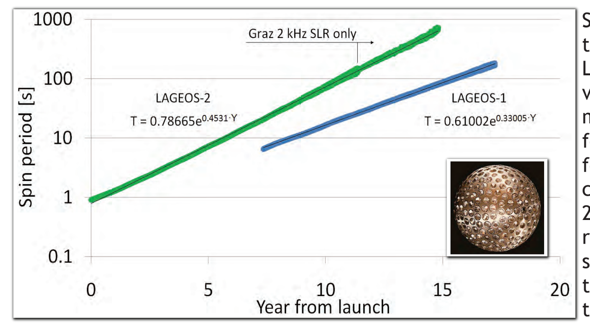
The T2L2 experiment on Jason-2 uses an event timer, photo detection modules, and ultra-stable quartz oscillator and a laser retroreflector array to implement a two way time transfer system to synchronize clocks on the ground and on the satellite. It is anticipated that time transfer among participating SLR ground stations will reach the 100 ps level once the current modeling activities are completed.

Reference:
Samain, E., Ph. Guillemot, P. Exertier, D. Albanese, P. Berio, O. Laurain, F. Para, J. Paris, J.-M. Torre, H. Viot, P. Vrancken, I. Petitbon, S. Leon. "Time Transfer by Laser Link - T2L2: First Data", Proc. 16th International Workshop on Laser Ranging, Poznan, Poland, Oct. 13-17, 2008.

Spin Rate Measurements

Graz kHz SLR station measures the spin period of Ajisai with accuracy of 80µs. Chart A shows the spin period measurements of Ajisai (years 2003.8-2009). Chart B shows the spin period change during arbitrary selected 163 days. Chart C shows spin period residuals to the spin period trend function for the selected data set. The distribution of the residuals is correlated with the percentage of the Ajisai orbit illuminated by the Sun. The spin period is increasing faster when the full orbit is exposed to the solar irradiation. The minimum percentage of Ajisai orbit in the Sun is about 75% - this corresponds to the minimum value of the spin period residuals (chart C). The average slowing down rate is 29.7 ms/year.

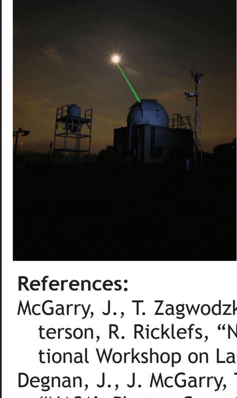




SLR allows for spin period determination of the passive satellites LAGEOS-1 and LAGEOS-2. The chart presents spin period values obtained from all available laser measurements of all SLR stations: 10 years for LAGEOS-1 (10426 values) and 15 years for LAGEOS-2 (15580 values). Due to the increasing spin period of LAGEOS-2, only Graz 2 kHz SLR system - with its high repetition rate and 10 ps pulse width - permitted measurement of the spin period after year 2003; the kHz data also yields an order of magnitude higher accuracy.

Reference:
Kucharski, D., Kirchner, G., Koidl, F., Cristea, E. 10 Years of LAGEOS-1 and 15 Years of LAGEOS-2 Spin Period Determination from SLR Data. Adv. Space Res., vol. 43, no. 12, pp. 1926-1930, doi:10.1016/j.asr.2009.01.019, June 2009.

NASA's Next Generation SLR (NGSLR)



System Capabilities
- Centimeter ranging accuracy
- Two-way ranging to satellites up to 22,000 km altitude
- Automated
- No ocular, chemical, or electrical hazards (system with microJoule laser is eye-safe)
- Small, compact, low maintenance
- Lower replication/operating costs

System Characteristics:
- Telescope: 40 cm off-axis parabola
- Mount: Arc-second precision tracking
- Detector: MCP PMT 4-quadrant
- Laser: < 100 microJoules per pulse at 2 KHz
- Outgoing beam divergence: ~ 4 arcsec FWHM
- Pointing accuracy: 2-3 arcseconds

References:
McGarry, J., T. Zagwodzki, T. Varghese, J. Degnan, J. Cheek, C. Clarke, P. Dunn, A. Mallama, A. Mann, D. Patterson, R. Ricklefs, "NGSLR: Sharing Eye-safe Kilohertz SLR with Transponder Ranging", Proc. 16th International Workshop on Laser Ranging, Poznan, Poland, Oct. 13-17, 2008.
Degnan, J., J. McGarry, T. Zagwodzki, H. Donovan, D. Patterson, C. Steggerda, A. Mallama, and J. Cheek, "NASA's Photon-Counting SLR2000 Satellite Laser Ranging System: Progress and Applications", Proc. AMOS 2003 Technical Conference, Maui, HA, Sept. 8-13, 2003.