The Impact of SLR Technology Innovations on Modern Science

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Abstract. We briefly review the technology innovations that allowed SLR range precision to evolve from about 3 meters in 1964 to a few mm today. We then summarize the impact of this increased precision, either by itself or collocated with other instrumentation, on Earth science and fundamental physics and how the technology is , or will be, utilized in related instrumentation, such as laser altimeters, global time transfer, 3D imaging lidars, and interplanetary transponders.

Introduction

Over almost five decades since the first successful satellite laser ranging (SLR) experiments in 1964, system range precision has improved about three orders of magnitude, from 3 m to 3 mm . During the first three decades, the increase in range precision was fueled by the introduction of picosecond pulse modelocked laser transmitters, fast detectors (either MicroChannel Plate PhotoMultiplier Tubes or Compensated Single Photon Avalanche Diodes), and picosecond resolution Time Interval Units (TIUs) Over the past two decades, the exponential increase in the number of satellites (and operating costs) shifted the technology focus from increased precision to increased automation or remote operations, and several SLR groups have since moved from traditional, low repetition rate (5 to 20 pps) , multiphoton systems to few kilohertz , single photon sensitive SLR systems. To cope with large numbers of pulses simultaneously in flight, conventional single stop TIUs were necessarily replaced by Event Timers (ETs), capable of timetagging individual photon "events" over long periods of time. The higher sensitivity and kHz sampling rates allowed the tracking of individual retroreflectors within a satellite array as well as the monitoring of satellite rotation rates. Single photon SLR technology has since been applied to high resolution 3D imaging lidars operating at several megapixels per second and also has application to ranging, global time transfer, and high bandwidth communications over interplanetary distances.

In parallel with the technology innovations, the international network has grown from 5 to approximately 40 stations and roughly 73 satellites have been tracked by laser during this period. The satellites in the SLR constellation fall into four major categories – geodetic (16), earth sensing (27), navigation (11), and space science (19). Each of these categories satisfy a particular science or engineering need as will be described in subsequent sections.

Terrestrial Reference Frame

Of the various space geodetic systems (SLR, VLBI, GNSS, and DORIS), SLR provides the best location of the Earth Center-of-Mass (CoM) and Scale Factor or GM, where G is the Earth Gravitational Constant and M is the Earth Mass. Seasonal and other temporal variations in the CoM, or geocenter, can be monitored by SLR, relative to the global station distribution, at the mm level using geodetic satellites. Geodetic satellites are configured as spheres studded by optical retroreflectors such that they can be viewed from any orientation without introducing significant spreading of the laser pulse and introducing range bias. High altitude satellites, such as LAGEOS 1 and 2 at 6000 km, are especially good targets since their motions are relatively unaffected by atmospheric drag or high order components of the Earth's gravitational field.

Earth Orientation Parameters (EOP)

The Earth Orientation Parameters (EOP) define the spin axis of the Earth and its time-dependent orientation and speed of rotation within the Celestial Reference Frame or star field. EOP includes polar motion (Chandler Wobble), Length of Day (LOD), and Universal Time (UT1). While Very Long Baseline Interferometry (VLBI), which makes its space geodetic measurements using a network of large microwave antennas and a reference frame defined by distant quasars at the edges of the known universe (~15 billion light years), is the most accurate long term source of EOP, SLR has been used for decades to temporally interpolate the results between coordinated VLBI sessions.

Solid Earth Physics

LAGEOS 1 and 2 provide a stable inertial reference frame that allow us to see changes in relative positions of the SLR stations that track them and thereby monitor global tectonic plate motion. During the Crustal Dynamics Project, small highly transportable laser stations, developed in the US and Europe, were joined on opposite sides of the Atlantic to perform regional crustal deformation measurements near tectonic plate boundaries. In alternate years, these stations were positioned near the North American-Pacific plate boundary in the Western US or in the Mediterranean region where the Eurasian, African, and Arabian plates interact.

Earth Gravity Field

The movement of satellites is governed primarily by the Earth's gravity field or geopotential. Conversely, the ability to precisely measure the movement of a satellite relative to a well distributed set of ground stations allows an accurate measurement of the geopotential, which is mathematically expressed by analysts as a sum of spherical harmonics. As one progresses from determining the coefficients of low order to high order harmonics, the spatial distribution of the geopotential becomes increasingly detailed. Furthermore, low satellites are more sensitive to higher order harmonics than high satellites. Over the last five decades, the wide range of altitudes (300 km to 20,000 km) and orbital planes occupied by the SLR constellation, combined with orbits of satellites tracked by microwave techniques, have provided an abundance of data with which to build an increasingly accurate geopotential model. With a good geopotential, some analysts have also been able to develop working models for a number of non-conservative forces acting on the satellites, such as atmospheric drag, radiation pressure, thermal emission, etc.

Deviations of the satellite motion from that predicted by the geopotential model are described as *gravity anomalies* and can be plotted on a global map. A location with a positive anomaly exhibits more gravity than predicted, while a negative anomaly exhibits a lower value than predicted. Positive anomalies are often associated with mountain ranges or subsurface mass concentrations ("mascons") that create highly localized gravitational pulls on the satellite.

In an effort to further refine the gravity field and how it changes with time, the Gravity Recovery and Climate Experiment (GRACE) was launched in 2002. The experiment consists of two identical satellites (GRACE A&B) in tandem polar orbits at 500 km altitude and separated by 220 km. The two satellites are tracked by both SLR and GPS, with their separation monitored by a K-band microwave link. Observed changes in that separation provide high spatial frequency components of the gravity field as well as their temporal dependence which might be due to: (1) surface and deep currents in the oceans; (2) runoff and ground water storage on land masses; (3) mass exchanges between ice sheets or glaciers with the oceans; and (4) variations of mass distribution within the

Earth. A future GRACE 2 mission is expected to have both a smaller separation (100 km) as well as a laser-based interferometric link, which would be more accurate due to its shorter wavelength.

Ocean Science

Sea Surface Topography (SST) is defined as the height difference between the sea surface and the geoid. In the Northern Hemisphere, currents flow clockwise around topographic highs in the oceans and counterclockwise around topographic lows. The reverse is true in the Southern Hemisphere. Furthermore, the height is proportional to the speed of the currents. Over the past few decades, microwave radar altimeters have been flown on a number of SLR-tracked satellites such as GeoSat, ERS-1, TOPEX/Poseidon, ERS-2, GFO, and JASON. SLR provides: (1) the location of the stations relative to the geocenter; (2) the moderate to long wavelength geoid surface relative to the geocenter; and (3) the satellite position relative to the geocenter. Since the radar measures the distance from the satellite to the sea surface, the SST can be computed via the relation SST = Satellite position – geoid – microwave range. Thus, the combination of SLR with microwave altimetry permits the monitoring of global currents and their velocities as well as spatially resolved mean sea level (MSL) rise. Globally, MSL has risen 70mm during the period from 1992 to 2013, corresponding to an average rate of 3.2 ± 0.4 mm/year. Contributors to sea level change include: (1) variations in sea water temperature and salinity at all depths; (2) tectonic changes to the water basin "shape"; and (3) change of the total ocean mass resulting from exchanges of water with the other surface reservoirs (atmosphere, continental waters, glaciers and ice sheets).

Since underwater sea mounts create gravity anomalies that cause the surface water to mimic the topographic variations in the sea floor with about a 1000 to 1 ratio (e.g., a 1 km high sea mount creates a nominal 1 m "bump" in sea level) , researchers have been able to use precision sea surface altimetry data to develop global maps of the sea floor.

Spaceborne Laser Altimeters

Compared to microwave altimeters, lasers have two orders of magnitude (10 m vs 1000 m) better horizontal spatial resolution from orbit and range precisions of roughly one cm. However, all spaceborne laser altimeters flown to date have been largely based on 1970's SLR technology. Nevertheless, laser altimeters have successfully mapped the Earth (ICESat-1/GLAS), Moon (Apollo, Clementine, Selene/LALT, and LRO/LOLA), Mars (MGS/MOLA), Mercury (Messenger/MLA), and two asteroids, Eros (NEAR/NLR) and Itokawa (Hayabusa). In addition, two Earth-orbiting laser altimeters, ICESat-1/GLAS and CALIPSO/CALIOP, have successfully mapped global cloud heights and aerosols. When combined with "free air" gravity data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, the billion plus surface measurements obtained by LRO/LOLA allow the gravity anomalies associated with lunar topography to be separated from those caused by subsurface density variations ("mascons") underlying large impact basins. This residual field is referred to as a "Bouguer gravity map".

At least three other spaceborne laser altimeters are currently in development including: (1) the ATLAS lidar on ICESat-2 (NASA, 2016); (2) the Bepi-Colombo Altimeter on the Mercury Planetary Orbiter (ESA/JAXA, 2022); and (3) the OSIRIS-Rex Laser Altimeter (OLA) on Origins Spectral Interpretation Resource Identification Security Regolith Explorer (Univ. of Arizona, CSA/NASA). Both ATLAS and Bepi-Colombo will incorporate some 5^{th} generation SLR photon-counting technology. ATLAS has 6 beams operating at 10 kHz yielding surface measurement rates up to 60 kHz, but future spaceborne systems will have orders of magnitude higher surface measurement rates (~1 Million pixels per sec) and correspondingly higher horizontal resolution.

Lunar Laser Ranging (LLR)

Beginning in 1969, a total of five retroreflector arrays have been placed on the Moon by three NASA manned missions (Apollo 11, 14, and 15) and two Soviet unmanned Lunakhod missions. Of the five arrays, the Apollo 15 array, with 300 corner cubes, has the largest optical cross-section. For over 30 years, the LLR data set was provided by three sites: MLRS at the McDonald Observatory in Texas, USA; CERGA LLR at Grasse, France; and Mt. Haleakala in Hawaii, USA (decommissioned in 1992). Two new LLR systems have since come online – the Matera Laser Ranging Observatory (MLRO) in Matera, Italy and the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) in Apache Point, New Mexico, USA. APOLLO is the first LLR system capable of multi-photon returns (due primarily to its large, 3.5 m receive aperture) and has greatly enhanced the quantity of LLR data while improving LLR precision from about 2 cm to a few mm since starting operations late in the last decade.

Science applications of LLR data have included:

- Lunar Physics
  - Centimeter accuracy lunar ephemerides
  - Lunar librations (variations from uniform rotation)
  - Lunar tidal displacements
  - Lunar mass distribution
  - Secular deceleration due to tidal dissipation in Earth's oceans
  - Measurement of $G(M_E + M_M)$
- Solar System Reference Frame (LLR)
  - Dynamic equinox
  - Obliquity of the Ecliptic
  - Precession constant
- General Relativity/Fundamental Physics
  - Test/evaluate competing gravitational and relativistic theories
  - LLR validates Strong Equivalence Principle (SEP), which states that an object's movement in a gravitational field does not depend on its mass or composition.
  - Constrain β parameter in the Robertson-Walker Metric
  - Constrain time rate of change in G (G-dot)

Laser Time Transfer (LTT)

One of the earliest demonstrations of LTT occurred in 1975 when Professor Carroll Alley and his students at the University of Maryland transferred time continuously between two ensembles of atomic clocks via a laser link. The two ensembles were synchronized on the ground prior to one ensemble being placed on an aircraft and flown in a racetrack pattern for 15 hours around a trailer containing the second ensemble. The trailer also contained a ground-based laser (100 psec @ 30 Hz) and telescope pointed at the aircraft by an operator via a joystick controller. The time at which the laser pulse exited the station, or "start pulse", was recorded by the ground ensemble. An airborne detector recorded the pulse time of arrival at the aircraft, as measured by the airborne clock ensemble, and a retroreflector on the aircraft fuselage reflected the pulse to the ground telescope and ground-based detector, which measured the "stop pulse" via the ground ensemble. Since the pulse time of arrival at the satellite necessarily coincided with the midpoint of the recorded ground start and stop times, any time offset Δt between the two clock ensembles resulting from relativistic gravity and velocity effects could be continuously monitored. Over the approximate 15 hour flight period, a total offset of 47.1 nsec (~3.14 nsec/hr) was accumulated between the two clock ensembles, with 52.8 nsec attributable to Einstein's "gravitational redshift" and – 5.7 nsec to velocity-induced "time dilation". Furthermore, as fuel consumption allowed the aircraft to climb to higher altitudes, the lower gravity field seen by the airborne ensemble caused the differential rate between the ensembles to visibly increase.

Active global Laser Time Transfer (LTT) experiments – which currently include L2T2 (France), Compass (China), ELT/ACES (ESA), and SOTA (Japan) - all use the same basic approach to transfer time between widely separated ground stations via an intermediate and highly precise spaceborne clock. An onboard detector sequentially records the arrival times of pulses from participating ground stations while a retroreflector array provides a stop pulse to each of the stations. Since the midpoint of each "start-stop" pulse pair can be compared to the corresponding arrival time of that station's pulse at the satellite, the time offset between the spacecraft and station clock can be determined, as in the Maryland experiment. Furthermore, since the time offset between the spaceborne clock and each of the ground clocks is now known, one can combine the station information and accurately compute the time offset between any two station clocks.

Interplanetary Transponders

Given the current difficulty of laser ranging to passive reflectors on the Moon due to the R^{-4} signal loss, conventional single-ended ranging to passive reflectors at the planets is unrealistic. However, since double-ended laser transponders have active transmitters on both ends of the link, signal strength falls off only as R^{-2} and interplanetary ranging becomes possible. There are two types of two-way transponders – "echo" and "asynchronous".

With an "echo transponder", the spacecraft transponder detects pulses from Earth and fires a reply pulse back to the Earth station, in a manner similar to modern day aircraft transponders. To determine range, the time delay between the arrival of the Earth pulse and the emission of the reply pulse must either be known a priori or measured onboard and communicated back to Earth and then subtracted from the measured round-trip time-of-flight at the Earth station. The "echo" transponder works best on "short" links (e.g. to the Moon) where the round trip transit time is short (~2.5 sec) and the single shot detection probability at both terminals is high. Such a transponder would make LLR accessible to all ILRS ground stations.

With an "asynchronous transponder", transmitters at opposite terminals fire asynchronously (independently). The signal from the opposite terminal must be acquired autonomously via a search in both space and time. The spacecraft transponder measures both the local transmitter time of fire and any received photon "events" (Earth laser signal plus background noise) on its own time scale and transmits the information back to the Earth terminal via the spacecraft communications link. Range and clock offsets can then be computed using any successful pair of opposite links. The asynchronous approach works well on "long" links (e.g., interplanetary) even when the single shot probability of detection is relatively small. In May 2005, a successful two way link was established between the NASA/GSFC 1.2 meter telescope and the MLA instrument on Messenger at a distance of 24 million km. In September 2005, the MOLA altimeter receiver in orbit about Mars successfully detected ~500 pulses from the GSFC station at a distance of 80 million km. Unfortunately, the MOLA laser was inoperable and could not transmit pulses to the Earth station.

A variation is the "one-way transponder", which relies on the synchronization of the Earth and spaceborne clocks to obtain an accurate range measurement. For the last several years, this approach has been used operationally to estimate the range between multiple ILRS stations and the LOLA altimeter on LRO. However, to achieve one cm ranging, the spaceborne and Earth clocks must remain synchronized to within 34 picoseconds. Two-way transponders do not require this level of synchronization.

Transponder applications include but are not limited to:

- **Solar System Science**
  - Solar Physics: gravity field, internal mass distribution and rotation
  - Few mm accuracy lunar ephemerides and librations
    - Improves ranging accuracy and temporal sampling over current lunar laser ranging (LLR) operations to Apollo retroreflectors on the Moon with small, low energy, ground stations
  - Decimeter to mm accuracy planetary ephemerides
  - Mass distribution within the asteroid belt
- **General Relativity**
  - Provides more accurate (2 to 3 orders of magnitude) tests of relativity and constraints on its metrics than LLR or microwave radar ranging to the planets, e.g.
    - Precession of Mercury's perihelion
    - Constraints on the magnitude of G-dot ($1x10^{-12}$ from LLR)
    - Gravitational and velocity effects on spacecraft clocks
    - Shapiro Time Delay
- **Lunar and Planetary Mission Operations**
  - Decimeter to mm accuracy spacecraft ranging
  - Calibration/validation/backup for Deep Space Network (DSN) microwave tracking
  - Subnanosecond transfer of GPS time to interplanetary spacecraft for improved synchronization of Earth/spacecraft operations

Laser Communications

There is a great desire among planetary scientists to use high bandwidth sensors, similar to those currently monitoring the Earth, to study other planets and moons within our solar system. Unfortunately, the microwave communications links typical of NASA's Deep Space Network (DSN) have inadequate data bandwidths to support such sensors. For example, a 100W X-band transmitter, coupled with a rather large 3 m spaceborne antenna and communicating with a 34 m DSN ground antenna, achieves bandwidths measured in tens of kilobits for Jupiter and beyond and only achieves Mbps rates for Mars near PCA with Earth. Like transponders, lasercom signal strength falls as R^{-2}.

Since they are already designed to track satellites at optical wavelengths, SLR stations are uniquely suited to support future space-to-ground and ground-to-space laser communications experiments. Over the past two decades, there have been a few high bandwidth lasercom experiments between Earth-orbiting spacecraft or between spacecraft and a ground station. More such experiments are currently planned by various countries. A low bandwidth link between LOLA/LRO and NGSLR successfully transmitted an image of the Mona Lisa over much longer Earth-Moon distances (385,000 km), but, on 1 October 2013, the Lunar Laser Communications Demonstration (LLCD) experiment on the NASA LADEE lunar mission demonstrated a bandwidth of 622 Mbps.

Summary

For visual images and references related to the aforementioned topics, the reader is referred to the original presentation located elsewhere on the Workshop web site. Comprehensive reviews by the author of SLR/Transponder history, hardware, and theory can be found on the ILRS Web Site.