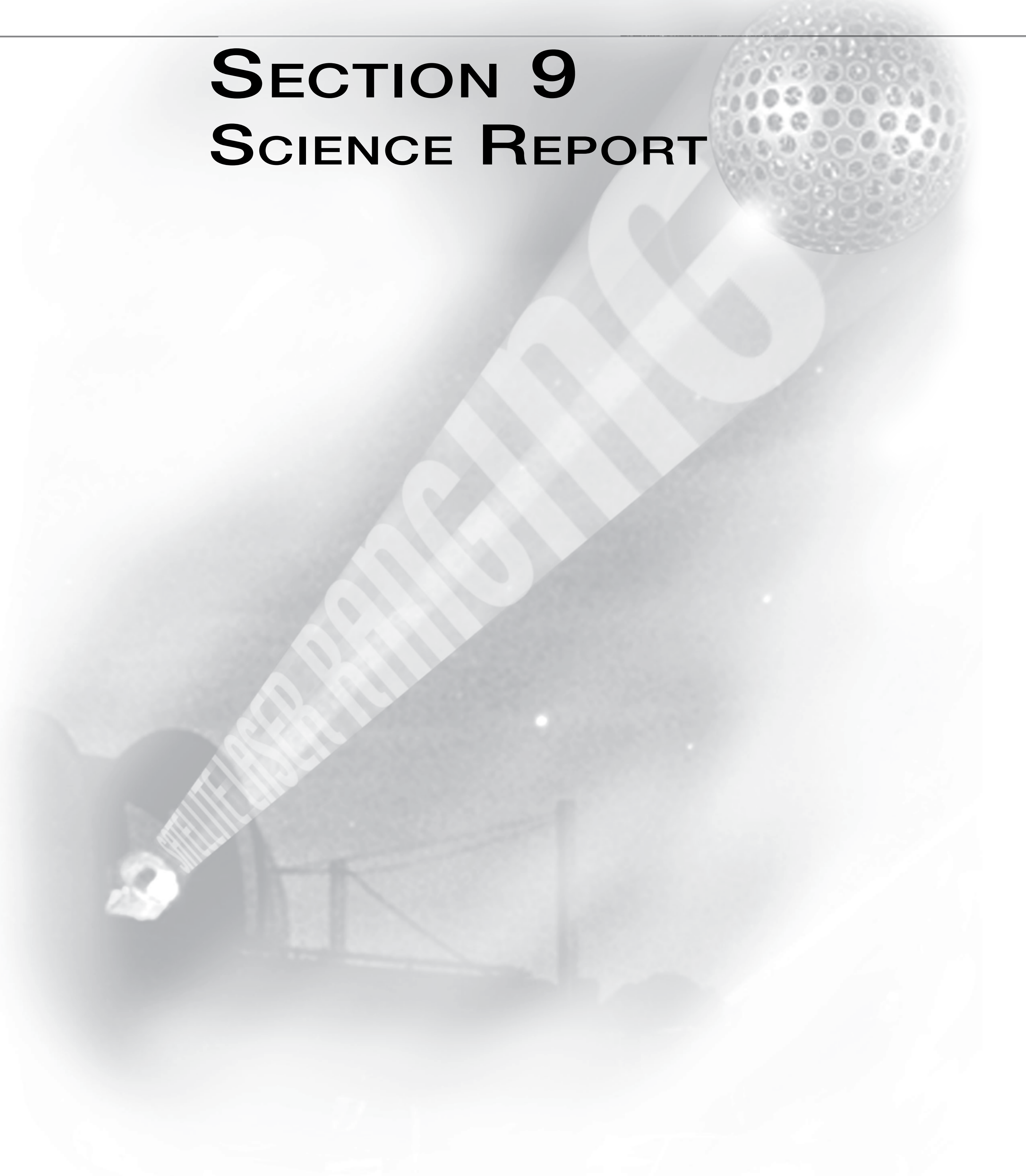
SECTION 9
SCIENCE REPORT



SECTION 9

SCIENCE REPORT

Steve Klosko/SGT

Introduction

Satellite Laser Ranging began tracking near-Earth satellites over 40 years ago with stations in Maryland and North Carolina tracking the Beacon Explorer satellites. From the beginning, the range accuracy delivered by laser systems far surpassed the absolute accuracy delivered by other tracking technologies, a fact that has remained unchanged to the present. With a focus on continually improving the range accuracy that SLR systems can deliver, and improving the analysis techniques that employ SLR, laser tracking has continued to be an important contributor to precision orbit determination and the generations of science products of a geophysical nature.

The ILRS provides a forum for laser practitioners to discuss the science investigations they are pursuing and to better understand the technology advancements that underpin their efforts.

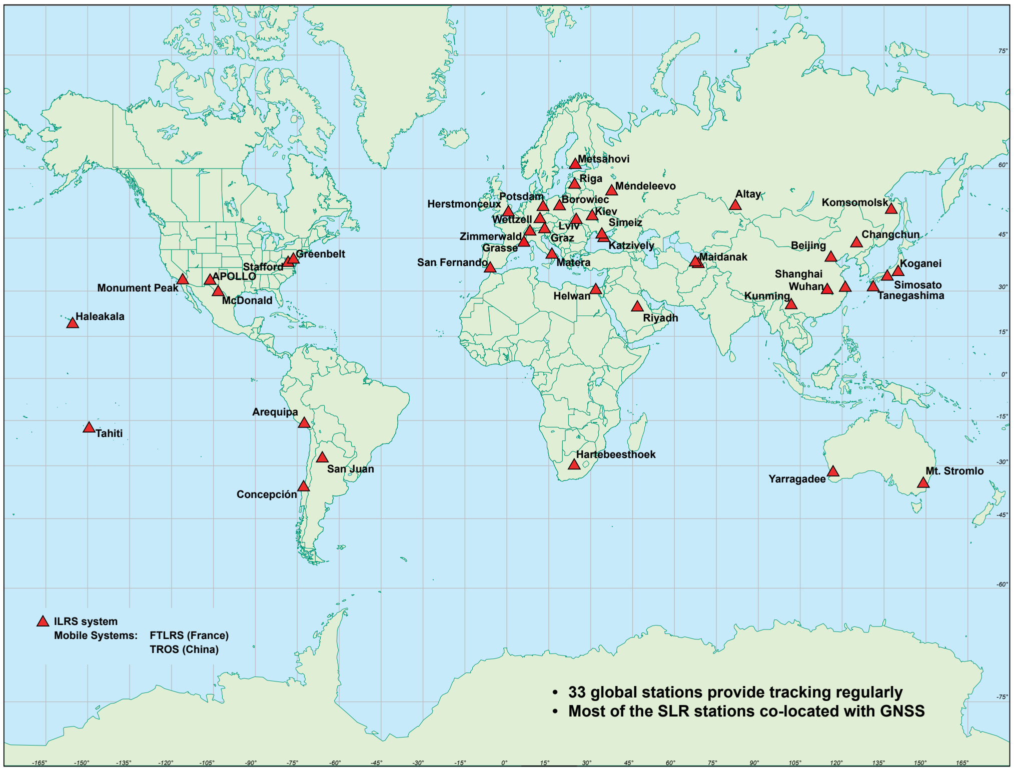


Figure 9-1. The current ILRS network

Under the auspices of the ILRS, today's laser network finds more than thirty active stations (Figure 9-1) with an ever-increasing number of targets to support. For example, the ILRS Board recently approved tracking of Cryosat-2 and RadioAstron which brings to a total of 44 the number of current and future satellites tracked or to be tracked by the laser network.

The new missions that will be supported in 2009 are shown in Figure 9-2 below. Advances in technology and in data processing methodologies have improved the accuracy of the SLR science products. Important technical advances that contribute to improvements in the science delivered include: new kilohertz systems, systems which operate at dual wavelengths, improved orbiting reflector targets, and improved orbit force and measurement modeling. This summary will address these developments and describe the current state of the SLR science and mission support that is being delivered.

Figure 9-2. Proposed missions supported by the ILRS for 2009.

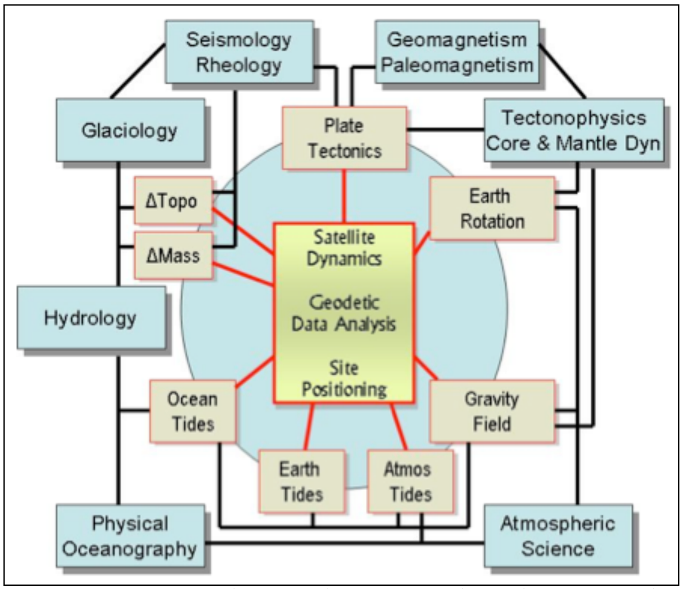


Figure 9-3. SLR data, techniques and products provide a means to measure the manifestation of key geophysical processes.

Figure 9-3 left gives an overview of the role SLR plays within multidisciplinary and interdependent investigations ongoing in the Earth Sciences. The center green box shows the basic analyses that use SLR data. These analyses yield significant products (connected to this center box with red lines), which provide important evidence and constraints in a wide range of science applications and disciplines through direct observation of the temporal behavior of geodynamical processes. The fundamental products delivered by SLR are: highly accurate orbits and improved understanding of the forces at work; accurate station locations and their 3-dimensional movement within a well understood terrestrial frame; Earth center-of-mass and the absolute scale of the terrestrial frame; and the longest continuous history of Earth orientation parameters determined by space geodetic techniques. SLR science investigations have contributed to studying important physical processes related to the state and sustainability of the Earth's environment including the sources and magnitude of mass flux, in defining a stable mm-level reference frame, and in developing an integrated and interdependent understanding of the Earth's system in four dimensions at increasingly detailed scales. SLR has provided precision orbits for the constellation of orbiting laser targets and an independent calibration of precise orbit positioning provided by other tracking systems. By being a dynamic technique, SLR is able to improve the fundamental force modeling needed to produce cm-level orbit accuracy. These force models are science products in their own right.

SLR provides important and in many cases key independent validation capabilities within the GRACE, Envisat, Jason, OSTM and ICESat missions. Herein, SLR complements the set of measurements acquired by these missions. At the same time, dedicated SLR satellite missions like LAGEOS-1 and -2 continue to provide unique long wavelength gravity and decadal time histories of site motions to help establish the geophysical context for many of the phenomena being observed by missions like GRACE. This is especially evident when modeling the Glacial Isostatic Adjustment (GIA) processes dominant over high latitude regions needed to understand contemporary ice sheet mass balance and its contribution to sea level rise. Overall, in each of these missions, and in our attempts to optimally exploit their data, SLR plays an important role.

Below is an overview of current SLR science activities.

Lunar Laser Ranging

Lunar laser ranging has also continued to advance in recent years. The new APOLLO station located at the Apache Point Observatory, New Mexico, has significantly advanced LLR capabilities. With its 3.5 meter telescope and the excellent viewing conditions in the New Mexico desert, the APOLLO station produces multiple photons returned with each laser pulse, yielding mm-level range precision to the Moon.This is a significant gain over earlier deployed LLR capable systems. The data acquired by LLR significantly improves our ability to model and confirm relativistic effects such as the relativistic geodetic precession; and the evolution of the Earth-Moon system.

Gravity Field Determination

The tracking taken on the constellation of SLR satellites continues to improve the recovered time changes in the longest wavelength components of the Earth's gravity field. These SLR results are being used for the calibration/validation of the monthly gravity fields produced from the GRACE intersatellite tracking data, and likely those from GOCE (although at this writing, preliminary GOCE results are awaiting release). In many investigations, the C(2,0) time history produced by SLR is incorporated with or replaces the GRACE-determined time series for this term. One of the most interesting developments in the last 15 years has been our ability to measure the Earth's gravity field to sufficient accuracy and temporal resolution to observe subtle changes in its longest wavelength features (e.g., Cox and Chao, 2002; Cheng, et al,). SLR analyses were the first to observed temporal variations in the gravity field at a variety of tidal and non-tidal frequencies and this was the basis and forerunner of the very successful GRACE mission. SLR remains a key component in validating the changes in the long wavelength gravity field observed from GRACE.

From these observations of mass redistribution on and within the Earth, significant improvements have been achieved in our understanding of Earth's upper mantle viscosity, the tidal response at different frequencies, and the tidal braking in the Earth/Moon system. The latter of which, given its change in lunar mean motion, is exquisitely confirmed directly through the use of Lunar Laser Ranging.

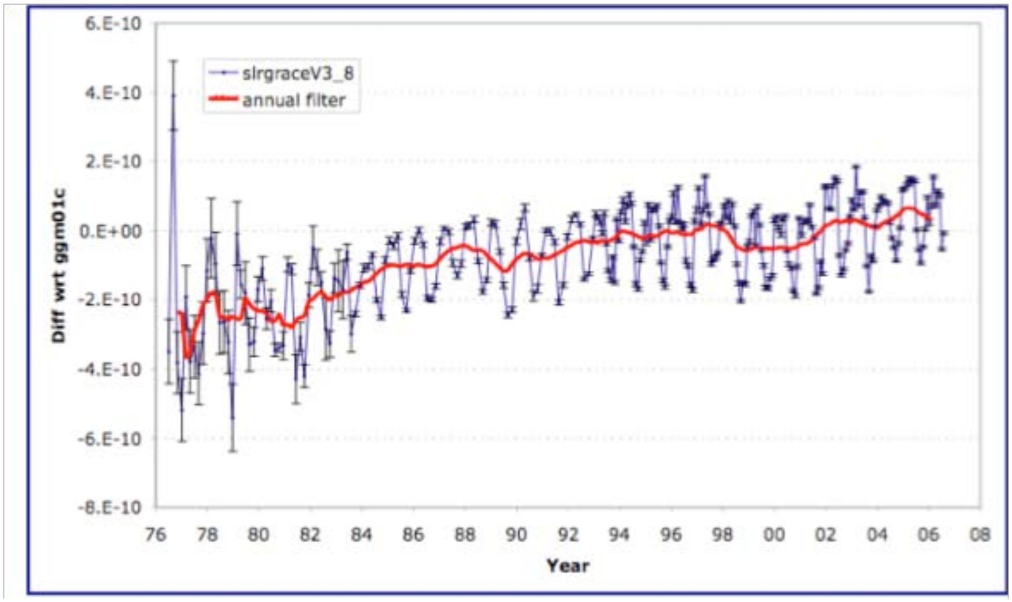


Figure 9-4. Changes in the C(2,0) harmonic over the past three decades obtained from SLR tracking of primarily the LAGEOS satellites (update from Cox and Chao, 2002).

While the GRACE satellites continue to perform nominally and are expected to successfully operate to 2013 and beyond, current plans show an interruption in the time-varying gravity time series awaiting the launch of a GRACE-Follow-On Mission. If this is unchanged, SLR will be a critical resources for the bridging of this time series, at least at its longest wavelengths, and considerable attention will need to be paid in combining SLR with other available tracking data types (e.g., DORIS, GPS, radar and laser altimetry) to deliver the highest quality and best spatially and temporally resolved gravity fields during this period.

Reference Frame

Space geodesy is required to resolve geodynamical signals at mm to sub-mm levels of accuracy on a wide variety of time and spatial scales. To accomplish this goal, an International Terrestrial Reference Frame (ITRF) and the motion of the Earth within both the Inertial and Celestial Systems are required with high temporal resolution and with comparable accuracy. The implementation of the terrestrial reference frame (including its origin and scale) is now being derived by combining results from station coordinate solutions independently being solved and in combination using four space geodetic technologies – SLR, VLBI, GPS and DORIS. Under the auspices of the International Association of Geodesy, the Global Geodetic Observing System (GGOS) is an effort that is underway to produce and maintain an ITRF that has an accuracy for site positioning of 1 mm and 0.1mm/yr for site motions. GGOS is coordinating with a worldwide network of organizations to provide the geodetic infrastructure necessary for detailed monitoring of the Earth system and its global changes at this accuracy level.

The most recent combination of these technologies produced the ITRF2005, which yielded some controversial results (Altamimi, et al., 2007). The scale difference between SLR (ILRS) and VLBI (IVS) was observed for the period of 2002 onward and has been resolved at least in part as an error in the VLBI processing. The SLR community developed a modified ITRF for laser analyses, but at some level this defeats the purpose of having a multi-technology and unified reference frame (Luceri and Bianco, 2007). A significant amount of work is underway to deliver refined and improved SLR contributions to the ITRF2008. These SLR contributions will significantly benefit from force modeling improvements like those developed to support GRACE (e.g. atmospheric and hydrological mass flux) and products coming directly from GRACE like improved mean and time varying comprehensive gravity fields (e.g., Förste et al., 2008; Luthcke et al., 2006; Lemoine et al., 2007).

Another important role for SLR within the ITRF is its applications within the Global Navigation Satellite Systems (GNSS). The GNSS represents the current satellite navigation systems that are capable of providing autonomous geo-spatial positioning with global coverage. SLR is now supporting operations on 7 GNSS satellites (GPS 36; GLONASS 102, 109 and 115; GIOVE –A and – B; and Compass-M1). SLR is uniquely able to independently calibrate and verify the key orbit determination accuracies being achieved for these GNSS satellites and is a means to bridge and assess the interoperability and consistency across GNSS constellations. At the same time SLR is not required for use in routine/operational RF derived orbit and clock products but provides a key monitoring function (Urschl et al., 2007).

Fundamental Physics

As knowledge of the long wavelength gravity field has improved, especially with advances coming from the GRACE mission, further improvements are being made in the estimation of the Lense-Thirring effect, the dragging of inertial frames due to the Earth's angular momentum. SLR pursuits of this science goal will significantly increase with the coming launch of the LARES satellite (Ciufolini et al., 2008).

LARES, a satellite developed by ASI, the Italian space agency, is expected to launch during 2010. The satellite is a dense sphere, completely passive, and is covered with 92 cube corner retroreflectors. LARES will be inserted into a circular 1,400 kilometers at an inclination from 60 to 86 degrees. The main scientific objective of the LARES mission is the measurement of the Lense-Thirring effect, with an accuracy goal of about a few percent as well as providing measurements across the field of geodynamics and space geodesy (Ciufolini et al., 2009).

Satellite Laser Altimetry

Satellite Laser Altimetry is a rapidly advancing form of remote sensing which has yielded extremely interesting results in both Earth and planetary sciences applications. There is a high interest in the SLR community of these developments. Indeed, on the basis of the National Research Council's Decadal Survey, two of the four "Tier 1" missions will fly laser altimeters – ICESat II primarily for ice surface mapping, and DESDynI – for both natural hazard and biospheric/biomass applications.

For interplanetary applications, great strides are being made in our understanding of aspects of planetary geophysics with the successful laser altimeter experiments on Mars Global Surveyor and Near Earth Asteroid Rendezvous missions. Lunar Reconnaissance Orbiter LRO now yields a large data set for lunar studies and future manned landing site locations. Mercury MESSENGER, Dawn, and anticipated missions to the icy moons of Jupiter are all expected to add additional science insights to a wide range of planetary bodies. The LOLA data from LRO has already improved our knowledge of theMoon's surface topography (Smith et al., 2009).

Laser altimetry has also matured from LEO platforms. For example, ICESat has already delivered over 2.1 billion ranges and has produced the first ever direct mapping of the thickness of the Arctic ice sheets. These results have been complementary to the traditional measures of ice extent and have made significant contributions to our understanding of the degradation in ice sheets seen over the past three years (Schutz et al., 2005; Brenner et al., 2007).

SLR systems support the companion efforts using satellite radar altimetry to directly monitor the ocean's circulation and global rate of sea level rise. All state-of-the-art radar altimeter satellites (TOPEX/Poseidon, Jason-1, OSTM, Envisat) fly laser retroreflectors. SLR tracking to these satellites is used to support a wide variety of altimeter range calibration experiments and help to ensure consistent time series spanning these missions (Lemoine et al., 2010; Cerri et al., 2010; Beckley et al., 2007).

Lunar and Planetary Satellite Tracking

As a precursor to interplanetary laser communication applications, during the past few years GSFC demonstrated a one-way laser transmission from Earth to the Mars Global Surveyor satellite orbiting Mars. This range experiment was over a distance of over 80 million kilometers. This exceeded the successful experiment that involved Earth to the MESSENGER satellite transmission and increased the range distance by over a factor of three (Smith et al., 2006; Neumann et al., 2007; Degnan, 2008).

An additional activity is underway where the LRO is being tracked by Earth-based SLR systems. The objective of the LRO Laser Ranging (LR) system is to enable LRO to have high quality precision orbits to support the analysis of the laser altimeter experiment, LOLA, flown on the spacecraft. The LR makes one-way range measurements via laser pulse time-of-flight from Earth to LRO, and from these data, enables the position of the spacecraft to be determined at the sub-meter level with respect to Earth and the center of mass of the Moon (Zuber et al., 2009; McGarry et al., 2007).

Ranging occurs whenever LRO is visible in the line of sight from participating Earth ground tracking stations. The first two successful SLR passes between a terrestrial ground station and a spacecraft orbiting the Moon were obtained on July 1 and 2, 2009 between the NGSLR station at Greenbelt, Maryland, USA (shown in Figure 9-5), and the Lunar Reconnaissance Orbiter (LRO). The Lunar Ranging data to LRO are being analyzed and validated and the data flow and system operations for operational ranging to LRO are being tested. The LR system on LRO will supplement the S Band (radio) tracking system for purposes of precision orbit determination and gravity field improvement (Torrence, et al., 2009).

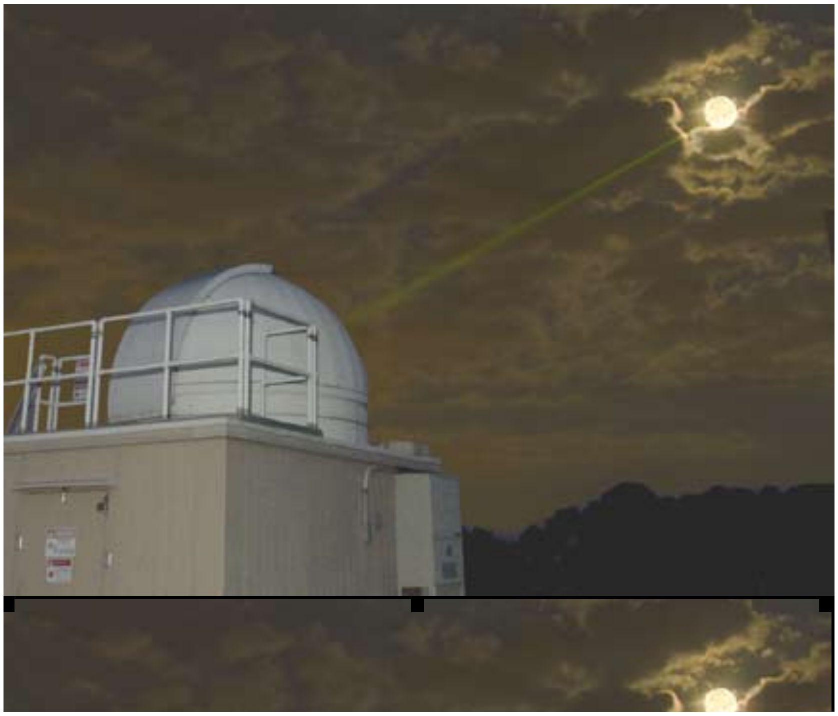


Figure 9-5. NGSLR ranging to LRO orbiting the Moon.

Summary

As for the future, the ongoing trend towards higher accuracy, larger data volumes and the need to support more missions is expected to continue. The SLR community needs to continue striving for an absolute single shot accuracy of one millimeter, a more automated and robust international network, and increased collaboration and contribution to many ongoing and future missions. The unprecedented richness of coincident observations from the international SLR network, offers significant opportunity to improve our understanding of the integrated Earth and planetary systems awaiting further exploration.

References

Altamimi, Z., Collilieux, X., Legrand, J., et al. (2007), ITRF2005, A new release of the International Terrestrial Reference Frame based on time series of station positions and earth orientation parameters. *J. Geophys. Res. 112(B9), B09401.*

Beckley, B.D., Lemoine, F.G., Luthcke S.B., et al. (2007), A reassessment of TOPEX and Jason-1 altimetry based on revised reference frame and orbits, *Geophys. Res. Lett., 34*, L14608, 2007, DOI:10.1029/2007GL030002.

Brenner, A.C., DiMarzio J.R., and Zwally, H.J. (2007), Precision and accuracy of satellite radar and laser altimeter data over the continental ice sheets, IEEE Trans. on Geosci. Remote Sensing, 45(2).

Cerri, L., Mercier, F., Berthias, *J*.P., et al. (2010), Precision orbit determination standards for the Jason series of altimeter missions, *Marine Geodesy special issue on the Jason-1/Jason-2 mission calibration and tandem mission*, Manuscript in revision.

Ciufolini, I., A. Paolozzi, E. Pavlis (2008), “Status of the LARES Experiment for Accurate Measurements of Earth Gravitomagnetism”, 16th International Workshop On Laser Ranging, Poznan, Poland, Oct. 13-17, 2008.

Ciufolini, I., Paolozzi, A., Pavlis, E.C., et al. (2009), Towards a one percent measurement of frame dragging by spin with satellite laser ranging to LAGEOS, LAGEOS-2 and LARES and GRACE gravity models, Space Sci. Reviews, 148(1-4), 71-104.

Cox, C.M, and B.F. Chao (2002), Detection of a large-scale mass redistribution in the Earth system, Science, 297,831-833.

Degnan, J. (2008), Laser transponders for high-accuracy interplanetary laser ranging and time transfer, *Lasers, Colocks and Drag-Free Control*, Astrophysics and Space Science Library, Vol. 349, Springer Verlag, Berlin.

Förste, C., Schmidt, R., Stubenvoll, R., et al. (2008), The GeoForschnungsZentrum Potsdam/Groupe de Recherche de Géodésie Spatiale satellite-only and combined gravity field models, EIGEN-GL04S1 and EIGEN-GL04C, *J. Geod., 82(6), pp*. 331-346.

Lemoine, J.M., Bruinsma S., Loyer S., et al. (2007), Temporal gravity fields inferred from GRACE data, Adv. Space Res., 39,1620-1629.

Lemoine, F.G., Zelensky N.P. Chinn, D.S., et al. (2010), Towards development of a consistent orbit series for TOPEX/Poseidon, Jason-1 and Jason-2, *Adv. Space Res.*, DORIS Special Issue, In review.

Luceri, V., Bianco, G. (2007), The temporary ILRS reference frame: SLRF2005, International Laser Ranging Service Fall Meeting, 24-28 Sept., 2007, Grasse, France, URL: *http://www.oca.eu/gemini/ecoles_colloq/colloques/ilrs2007/articles.php?lng=en&pg=98*

Luthcke, S.B., Rowlands, D.D., Lemoine, F.G., et al. (2006), Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone, *Geophys. Res. Lett., 33(2)*, art. L02402, DOI:10.1029/2005Gl024846.

McGarry J., T. Zagwodzki, R. Ricklefs, et al. (2007), "An Update on Laser Ranging to LRO", Fall 2007 ILRS Workshop, Grasse France, Sept. 25-28, 2007.

Neumann, G., Cavanaugh, J., Coyle, B., McGarry, J., Smith, D., Sun, X. Zagwodzki, T., Zuber, M. (2006), Laser Ranging at Interplanetary Distances, 15th International Workshop on Laser Ranging, Canberra, Australia, Oct 15-20, 2006. URL: *http://cddis.gsfc.nasa.gov/lw15/*

Schutz, B.E., Zwally H.J., Shuman, C.A., et al. (2005), Overview of the ICESAT Mission, Geophys. Res. Lett, 32(21), L21S01.

Smith, D.E., Zuber, M.T., Neumann, G.A., et al. (2009), Early results from the Lunar Orbiter Laser Altimeter on LRO, Eos, Trans. AGU 90(52), Fall Meet. Suppl., Abstract U21C-05.

Smith, D.E., Zuber, M.T., Sun, X., Neumann, G.A., Cavanaugh, J.F., McGarry, J. F., Zagwodzki, T.W. (2006), Two-way laser link over interplanetary distance, Science, 311, pp. 53.

Torrence, M.H., Zuber, M.T., Smith, D.E., et al. (2009), Initial results from the Lunar Reconnaissacne Orbiter Laser Ranging investigation, Eos, Trans. AGU, 90(52), Fall Meet. Suppl., Abstract U31A-0005.

Urschl, C., Beutler, G., Gurtner, W., et al. (2007), Contribution of SLR tracking data to GNSS orbit determination, Adv. Space Res., 39(10), 1515-1523.

Zuber, M.T., Smith, D.E., Zellar, R.S., et al. (2009), The Lunar Reconnaissance Orbiter laser ranging investigation, Space Sci. Reviews, DOI: 10.1007/s11214-009-9511-z.