THIRTY YEARS OF SATELLITE LASER RANGING

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ABSTRACT

Laser ranging to an artificial satellite equipped with retroreflectors (Beacon Explorer B) was first successfully demonstrated by a team of engineers and scientists from the NASA Goddard Space Flight Center (GSFC) in 1964. Compared to the 50 or more meter accuracy of microwave radars of the period, the 2 to 3 meter accuracies of these early experiments represented a quantum leap in capability for precise orbit determination. The author, who was a junior member of the GSFC team in 1964, provides a retrospective of those early NASA experiments with an emphasis on the key people, hardware, and early data. This is followed by a decadal review of the key scientific, technologic, and programmatic milestones in the history of SLR.

Over the past three decades, SLR has contributed to an ever expanding set of science and engineering applications as system precisions have dramatically improved from a few meters to a few millimeters. Counting both fixed and mobile sites, SLR contributes well over 100 sites, whose locations are known with centimeter accuracy and whose velocities have been established with mm/yr precision, to the International Terrestrial Reference Frame (TRF) and, uniquely among the space geodetic techniques, SLR defines the frame origin (Earth center of mass) with subcentimeter accuracy. SLR provides the longest (17 years), high accuracy (submilliarcsecond) record of the orientation of the Earth's spin axis as well as periodic and secular variations in its spin rate. Changes in spin axis orientation and rotation rate can be associated with the exchange of angular momentum or the movement of mass between or within the solid, liquid, or gaseous components of the Earth making SLR highly relevant to studies of global change. SLR data is predominant in the determination of the static long wavelength components of the Earth's gravity field as well as temporal variations. In addition to providing basic reference frame and gravity (geoid) information, SLR further supports oceanographic and ice missions, such as TOPEX/Poseidon and ERS-1, through precise determination of the satellite orbit in a geocentric reference frame and periodic calibration of onboard microwave altimeters.

Along with Very Long Baseline Interferometry (VLBI), SLR has successfully verified that the Earth's tectonic plates are in constant motion and that contemporary plate velocities are within a few percent of the long term average motion inferred from the geologic record. Complicated motions resulting from deformations occurring at plate boundaries have been observed in the Southwest United States and Mexico, in Southern Europe, and the Far East. SLR has also found a role in subnanosecond intercontinental time transfer, the measurement of fundamental physical constants, and studies of general relativity.

Today, the capability of SLR in precise orbit determination and some areas of geophysics is being augmented by several new and relatively inexpensive radionavigation systems. SLR has provided the "ground truth" against which these emerging systems (such as GPS, GLONASS, TDRSS, DORIS, and PRARE) have been compared and calibrated. Despite the formidable cost competition from radio techniques, several important applications remain, at least for the foreseeable future, which are squarely within the sole dominion of SLR. Furthermore, the presence of several orbiting satellites having both retroreflectors and one or more radionavigation transmitters/receivers presents a unique opportunity for the synergistic combination of laser and radiowave datasets to achieve an absolute accuracy, unification of terrestrial frames, and densification of data which could not be achieved by a single technique.

1. INTRODUCTION

The first ruby laser was invented by Thomas Maiman of Hughes Aircraft Laboratories in 1960. Only four years later, in 1964, NASA scientists and engineers successfully used a ruby laser to range with few meter precision to an artificial satellite, and the field of Satellite Laser Ranging (SLR) was born. It is doubtful anyone could have predicted in 1964 how rapidly the technology and international involvement would evolve and how widespread and interdisciplinary the science applications would become. Yet, as we convene in this Ninth Workshop on Laser Ranging Instrumentation in Canberra, one has to look back and marvel at what has been accomplished by the international community in the fields of geodynamics, gravity, oceanography, relativity, fundamental physics, lunar science, etc. in their pursuit to understand the "signal" content in these very precise range measurements.

I was surprised and honored when the Workshop Program Committee asked me to deliver the keynote address on this thirtieth anniversary of SLR. Apparently, my principal claim to this distinction is extreme longevity in the field. I participated as a junior member of the NASA SLR team in 1964 and am again very active in the field today thanks to my appointments as Deputy Manager for the NASA Crustal Dynamics Project in 1989 and as CSTG SLR Subcommission Chairman in 1992. However, during the intervening 25 years, I had been only occasionally and peripherally involved in the international SLR program, largely through my engineering activities at NASA which often meandered between laser ranging, communications, and remote sensing. I contributed to the 1978 Third International Workshop in Greece "in absentia" (i.e. Tom McGunigal read my papers) but finally, in 1981, I was able to participate fully in the Fourth Workshop in Austin, Texas (the first held in the United States). As a result, there may be large temporal gaps in my memory of key events (especially those which are international in nature). I trust the reader will forgive me if the upcoming brief history of the international SLR program is not totally accurate or if I have unwittingly failed to give appropriate credit to key individuals and/or institutions. However, in an attempt to keep these omissions at a minimum, I solicited and received information from several SLR pioneers in the international community in preparing the synopsis on the 30 year history of SLR. These individuals are listed in the Acknowledgements section.

In this paper, I briefly describe the earliest SLR experiments and campaigns and review, decade by decade, the key technological, scientific, and programmatic events that shaped the development of the SLR technique and the supporting international network. I then provide a summary of the scientific applications to date and discuss some future directions of SLR. More detailed descriptions can be found in a recently published series of AGU monographs [Smith and Turcotte, 1993] and in the report of the 1994 Belmont Workshop [Degnan, 1994], which was convened by NASA to plan its SLR program for the 1990's.

2. THE FIRST SLR EXPERIMENT

The first SLR satellite, Explorer 22/Beacon Explorer-B, was launched by NASA on October 9, 1964. The satellite entered into an orbit with an inclination of 79.7°, an apogee of 1100 Km, and a perigee of 939 Km. The spacecraft attitude was magnetically stabilized, presenting its panels of fused quartz optical retroreflectors only to observers in the Northern Hemi sphere. The array had an optical radar cross-section of approximately 5 million square meters.

A few weeks later, at 10:26 GMT on the morning of 31 October 1964 , a team of engineers and scientists at NASA's Goddard Space Flight Center (GSFC) recorded the first weak laser echoes from Explorer 22 BE-B [Plotkin et al, 1965]. In these first experiments, the output of the 9558A photomultiplier tube was recorded on an oscilloscope, and only four verifiable returns were recorded in approximately 200 oscilloscope traces. In subsequent experiments, the laser returns were also recorded on photographic film and as actual range measurements.

The telescope for the GODLAS system, short for Goddard Laser, was pointed by a modified Nike-Ajax missile tracking mount controlled by two operators guiding on the sunlit satellite under joystick control.

One operator controlled azimuth and the other controlled elevation. The receive telescope had a 16 inch diameter primary and a 300 inch focal length. Background noise was reduced by a 10 Angstrom bandpass filter. The ruby laser transmitter, built by General Electric, was air-cooled and utilized a rotating prism Q-switch to generate an approximate 20 nanosecond pulsewidth. The laser operated at a 1 Hz rate with a single pulse output energy of 0.8 Joules.

The NASA SLR team in 1964 was led by Dr. Henry Plotkin, then Head of the Optical Systems Branch (Code 524) at GSFC. The other NASA team members were Thomas Johnson , Paul Spadin, John Moye, Walter Carrion, Nelson McAvoy, Howard Genatt, Louis Caudill, John Degnan, Edward Reid, and Charles Peruso. In 1965, an SAO team, also using a laser provided by General Electric Corporation, received its first laser returns from Explorer 22 BE-B at its optical tracking site at Organ Pass, New Mexico.

3. A BRIEF HISTORICAL OVERVIEW

The first international SLR measurement campaign, in support of the National Geodetic Satellite Program (NGSP), took place in the Spring of 1967. By this time, six retroreflector-equipped satellites had been launched - four of the NASA Explorer series (22, 27, 29, and 36) and the French Diadem 1 and 2 satellites. During this first campaign, the Centre National d'Etudes Spatiales (CNES) in France operated three laser sites in Haute Provence (France), Colomb-Bechir (Algeria), and Stephanion (Greece). NASA operated its station in Greenbelt, Maryland [Johnson et al, 1967]and SAO operated a fifth site in Organ Pass, New Mexico. The campaign resulted in formal position errors of 5 meters at the laser sites. This represented approximately a factor of four better precision than that obtained from the more conventional Baker-Nunn optical observations which were carried out concurrently with the laser measurements. The laser and other optical data taken during this campaign resulted in a gravity model, the SAO Standard Earth Model, which was completed to degree and order 16 and included 14 pairs of higher degree coefficients. The development of this model was an important milestone in the burgeoning, yet infant, science of satellite geodesy.

A year later, in 1968, SAO sponsored another major campaign centered around the GEOS-2 satellite which had been launched as a test platform for comparing the performance of contemporary radars, lasers, and conventional optical tracking techniques. In the same year, the SAO network prototype laser was installed at the Mt. Hopkins Observatory, and the original Organ Pass system was moved to Mt. Haleakala on the island of Maui in Hawaii. In 1969, NASA/GSFC reported the first daylight laser ranging [Premo and O'Neill, 1969].

In July 1969, the Apollo 11 spacecraft carried the first laser retroreflector array to the moon. In competition with other groups around the world, the Lunar Ranging Experiment (LURE) team, working at the 2.7 meter telescope at the McDonald Observatory at the University of Texas, were the first to successfully record signals from the Apollo 11 retroreflector, and, for the next 15 years, McDonald would provide virtually all of the operational data to the growing lunar laser ranging community. Within a few years, four additional arrays would be placed on the lunar surface by the manned NASA Apollo 14 and 15 missions and by the unmanned Soviet Lunakhod I and II missions carrying French-built reflector panels. An updated 25 year history of the LLR program is provided by Dr. Carroll Alley of the original LURE team in a second invited talk and hopefully a companion article in these Proceedings [Alley, 1994].

In August 1969, NASA organized a major international conference in Williamstown, Massachusetts to formulate a long range plan for the application of space techniques, including SLR, to the improved understanding of solid Earth dynamics. It was at this conference, chaired by William Kaula, that the requirement for one centimeter accuracy laser ranging was first specified [Kaula, 1969].

During the period October 1969 to January 1970, the NASA MOBLAS-1 system participated in the first SLR collocation with an SAO system at the Mount Hopkins Observatory in Arizona. Range biases of 1 to 2 meters were observed, and the bias changed sign several times during collocation.

Following the launch of the PEOLE satellite by France in late 1970, SAO and CNES continued to organize a series of international measurement campaigns to further develop the geodetic reference frame and improve the gravity models. The most important of these was the International Satellite Geodesy Experiment (ISAGEX) in 1971. With NASA support, SAO deployed several submeter-quality SLR systems [Pearlman et al, 1975] at its existing Baker-Nunn camera sites in Arequipa (Peru), Natal (Brazil), and Olifantstein (South Africa). By 1973, following the assimilation of these data, the goals of the NGSP program, i.e. a unified global datum with ± 5 meter accuracy, had been met. After SAO published its final Standard Earth Model, SE-III, which was the first gravity model to use significant amounts of laser data, gravity model work in the United States was turned over to the NASA Goddard Space Flight Center.

In 1972, the first of the INTERKOSMOS network stations began successful operations in Ondrejov, Czechoslovakia under the technical leadership of the Czech Technical University in Prague [Masevitsch and Hamal, 1975]. First generation stations were later deployed internationally at several Soviet AFU 75 optical camera sites, including sites in Poland, Latvia, Bolivia, Cuba, and India. Under a joint program between SAO, the Technical University of Prague, the Soviet Academy of Sciences , and the Helwan Institute for Astronomy and Geophysics , an SLR station was established in Helwan, Egypt, which has since been upgraded to subcentimeter status by Dr. Hamal. European interest in SLR was strong in these early years, and the first three International Workshops on Laser Ranging Instrumentation were held in Lagonissi, Greece in May 1973, Prague , Czechoslovakia in August 1975, and Athens, Greece in July 1978

In 1975, CNES in France launched the first satellite dedicated solely to laser ranging , Starlette., to further improve the gravity field and improve station position estimates. NASA also launched GEOS-3, the first operational radar altimeter satellite equipped with retroreflectors and reported the first SLR system to achieve a precision better than ten cms[McGunigal et al, 1975]. Laser tracking of GEOS-3 was augmented by U.S. Navy Doppler and C-band radar. International tracking campaigns were organized for the two satellites and led to a much refined geoid. Initial acquisition of the two satellites was obtained optically using the international network of Baker-Nunn cameras. During this same time period, the SAO station in Olifantstein, South Africa was relocated to the Orroral Valley in Australia at a site not far from the current observatory.

The launch of the second dedicated SLR satellite, LAGEOS, by NASA in 1976 further fanned international interest in the SLR technique by providing a stable, high altitude, low drag inertial platform which lent itself extremely well to still more precise geodetic and gravity field studies. Starlette and LAGEOS would serve as the primary tools of the SLR community for well over a decade. The STALAS (for Standard Laser) system at GSFC set a new performance standard in 1976 by achieving single shot precisions of about 7 cm with the first use of a modelocked Nd:YAG laser. The laser was engineered by Bud Erickson of the Sylvania Corporation and integrated into the STALAS system by John Degnan and H. Edward Rowe of GSFC. The rather complex transmitter consisted of a CW-pumped acousto-optically modelocked oscillator, followed by an electro-optic switch, a multipass regenerative amplifier, three single pass amplifiers, and a doubling crystal [Johnson et al, 1978]. An identical laser was later installed in Wettzell, Germany. At about the same time, as part of the Earth and Oceans Dynamics Applications Program (EODAP), NASA built five new SLR systems (MOBLAS 4 through 8) to provide precise orbit determination support to the SEASAT ocean altimeter mission. Although SEASAT failed prematurely in October 1978 after only three months of operation, the data retrieved during that brief period kept analysts occupied for years. The five systems were later turned over in 1979 to NASA's fledgling Crustal Dynamics Project (CDP) under the direction of Dr. Robert Coates at the Goddard Space Flight Center.

In 1981, at the request of Chris Stephanides, SLR Manager for the CDP, a NASA engineering team, led by the author, was tasked to upgrade the MOBLAS-4 system at GSFC. The team installed a custom-built passively modelocked Quantel laser and a prototype microchannel plate photomultiplier (QE= 5%) built by ITT, raised the repetition rate from 1 Hz to 5 Hz, and demonstrated both an unprecedented single shot precision of 1.5 cm and a greatly increased data set [Degnan and Adelman, 1981; Degnan et al, 1984]. The team further recommended that the CDP, as part of a general NASA network upgrade, install a new Tennelec discriminator and a new Hewlett Packard time interval unit because these devices had yielded subcentimeter results in earlier ground tests. By the mid-to-late 80's, the upgraded hardware was implemented throughout the NASA SLR network, along with some additional improvements developed by Dr. Thomas Varghese and his Bendix Field Engineering Corporation (BFEC) team, and was routinely recording subcentimeter precision satellite data [Varghese and Heinick, 1986]. By the end of the decade, the Prague group had developed an alternative approach to subcentimeter ranging which made use of ultrashort pulse lasers and Single Photon Avalanche Photodiodes, or SPAD's, which did not require the use of a discriminator [Prochazka et al, 1990].

Also in the early 1980's, Dr. Eric Silverberg and his team at the University of Texas had developed the first highly transportable SLR station, TLRS-1, which was totally housed within a camping van [Silverberg and Byrd, 1981]. In a parallel development, GSFC's Thomas Johnson and his development team were conducting field tests of the TLRS-2 system which was designed to be shipped to remote sites like Easter Island in standard aircraft containers. The latter system was later upgraded by the author in 1985. By 1981, the number of international SLR geodetic sites had grown markedly, due largely to the mobile operations of the NASA MOBLAS systems and the new transportables TLRS-1 and 2, but also augmented by a growing network of fixed stations, including sites in Australia (Yarragadee and Orroral), Africa (the Czech Helwan station), and Asia (Tokyo).

By the end of the 1980's, seven transportables were operating successfully - four by NASA (TLRS-1 through 4), one by Germany (MTLRS-1), one by the Netherlands (MTLRS-2), and one by Japan (HTLRS). The MTLRS-1 system, in particular, routinely demonstrated high efficiency in data gathering, even in daylight. NASA "parked" its larger MOBLAS systems at fixed sites and turned over regional measurements to the more nimble transportables. The American and European transportables participated in cooperative and very successful campaigns to measure the complex tectonics in Southern Europe (as part of the WEGENER/MEDLAS program) and to better understand the spreading of the Gulf of California through occupations in the Southwest U.S. and Mexico. The European studies were augmented by a sizable increase in the number of fixed national stations in Europe. The Japanese HTLRS system concentrated on geodetic mapping of farflung Japanese islands.

During the same decade, major SLR developments were occurring in the former USSR. Three Soviet "Crimea" stations, under the leadership of Dr. Yuri Kokurin of the Lebedev Institute in Moscow, became part of the international SLR network and were operating in the Ukraine at Simeiz and Katzively and in Latvia at Riga under the auspices of the Soviet Academy of Science. As part of a massive national geodetics and space navigation program, the USSR launched several series of retroreflector-equipped satellites including GEOICA, GLONASS, and ETALON. These national satellites were supported by a vast ground network of 25 mobile and 5 permanent SLR stations distributed across the USSR.

The 1980's also saw the development of two new lunar stations at Grasse in France and Mt. Haleakala on the island of Maui in Hawaii. By the mid-80's, the CERGA lunar station at Grasse had surpassed MLRS as the dominant provider of lunar laser ranging data.

As we entered the decade of the 1990's, SLR began to see intense competition from radio techiques such as the American Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the French Doppler Orbitography in Space (DORIS) system, and most recently the German Precise Range and Range-rate Equipment (PRARE). As GPS demonstrated a capability to perform regional crustal deformation measurements in a more cost effective manner and with accuracies comparable to SLR and VLBI, NASA began to restrict the mobility of its TLRS systems.

Despite the new competition, international interest in SLR has remained high as evidenced by several developments. . By 1994, the number of SLR systems had grown to approximately 45, with both Russia and China expanding the size of their scientific networks. Additional stations are currently being developed by Germany, Russia, China, France, Japan, Poland, and Saudi Arabia. Over the past decade, the number of satellites routinely supported by SLR has grown dramatically from only two (LAGEOS and Starlette) in 1984 to thirteen in 1994 and is expected to grow to over twenty satellites by 1996. The first half of the decade has seen the launch of two new dedicated geodetic satellites (LAGEOS 2 and Stella) and two high precision altimetric missions (ERS-1 and TOPEX/POSEIDON) which rely heavily on SLR. Several additional missions are anticipated in the next two years (e.g. GFZ-1, ERS-2, ADEOS, GFO-1, etc.). The growth in the SLR constellation has been matched by a corresponding growth in the data yield from the international SLR network which has also benefited from more shift hours (largely due to the additional support provided by the TOPEX/POSEIDON mission) as well as increased automation and operational efficiency at many sites .

4. SCIENCE APPLICATIONS OF SLR

The two to three meter precisions of the earliest SLR systems represented a better than order of magnitude improvement over the conventional microwave radars of the day. The potential role of SLR in providing precise orbits and geodetic positioning of stations and their subsequent impact on our knowledge of the gravity field was rapidly recognized by the science community following the early international campaigns and the NGSP was established to exploit these technological developments. In 1969, the proceedings of a conference held in Williamstown, Massachusetts, laid out many of the scientific objectives which would ultimately be achieved over the next two decades [Kaula, 1969]. As the precision of the SLR technique improved from a few meters to a few millimeters at the approximate rate of an order of magnitude per decade, many new scientific opportunities presented themselves.

The earliest plate motion experiment was the San Andreas Fault Experiment (SAFE) in which NASA placed two SLR stations on opposite sides of the fault in California and measured the relative rate of motion through laser tracking of the Beacon Explorer-C satellite. The launch of LAGEOS in 1976 provided an ultra-stable inertial platform which enabled highly accurate geodetic measurements of the three-dimensional station positions and site motions, Earth orientation parameters such as polar motion and length of day (LOD), and the Earth's gravity field. Centimeter precision positioning was rapidly achieved using LAGEOS and confirmed the earlier SAFE results. Tectonophysicists and geophysicists were soon puzzling over the so-called "San Andreas Anomaly" [Minster and Jordan, 1978], i.e. a baseline rate half as large as anticipated from rigid plate models, and this led to increased scientific interest in the study of regional crustal deformation near plate boundaries.

The formation of NASA's Crustal Dynamics Project (CDP) in 1979 provided a programmatic focus for the international Earth science community and harnessed the necessary financial, facilities, and manpower resources to enable the first study of contemporary tectonic plate motion on a global scale. For the next twelve years, the CDP pursued its stated science goals with its international partners using the two most accurate space geodetic technologies of the day - Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI)[Bosworth et al, 1994]. The CDP goals included contemporary measurements of:

1) Global tectonic plate motion
2) Regional crustal deformation
3) Earth gravity field and
4) Earth orientation parameters (EOP)

Following termination of the CDP in December 1991, the measurements continued under the NASA Dynamics of the Solid Earth (DOSE) Program and an expanded WEGENER program supporting a more detailed study of European/ Mediterranean tectonic processes using the three primary space geodetic techniques, i.e. VLBI, SLR, and GPS.

Along with VLBI, SLR successfully demonstrated that the Earth's tectonic plates exhibit steady state motion and that contemporary plate velocities are typically within a few percent of their long term average motion as determined by geological evidence averaged over the last three million years. The velocities for all of the major plates were determined, and together the two techniques defined the Terrestrial Reference Frame (TRF) which is maintained by the International Earth Rotation Service (IERS) in Paris, France.[1] By itself, SLR has contributed over 100 site positions to the TRF, has established well-resolved kinematic motion at over 50 sites, and uniquely provides the frame origin (Earth center of mass) with subcentimeter accuracy relative to the global SLR network. In a highly successful collaboration of CDP with the WEGENER/MEDLAS consortium in Europe, detailed studies of regional crustal deformation in the Mediterranean countries of southern Europe (notably Italy, Greece, and Turkey) were determined by the three SLR transportables, TLRS-1, MTLRS-1, and MTLRS-2 working together with several fixed SLR stations in the region. Similar studies were carried out jointly in the southwest United States and Mexico.

Because of its unique access to the Celestial Reference Frame (CRF) defined by the distant quasars, VLBI provides the only long term tie between the celestial and terrestrial reference frames through its regular monitoring of the full suite of Earth Orientation Parameters (EOP), i.e. precession, nutation, polar motion, and Universal Time (UT1). However, because of the temporal gaps between routine VLBI operations, the centimeter accuracy measurement of SLR site positions would not have been possible without simultaneously solving for the short term effects of polar motion as well as variations in the Earth rotation rate (or length of day). Thus, beginning with the MERIT campaign in 1980, short term EOP parameters became natural and important byproducts of the SLR geodynamics analysis. Consequently, LAGEOS is today the most rapid source of polar motion and length of day (LOD) data and has provided the longest-running record of high frequency polar motion and UT1. However, the ability of SLR to sustain UT1 over long periods, without periodic updates by VLBI, is limited by errors in the LAGEOS dynamic models [Eanes, 1994].

The pole orientation and rotation rate of the solid Earth varies due to exchanges of angular momentum with the sun, moon, atmospheres, and oceans and the effects of mass redistribution on the Earth moment-of-inertia tensor. Mass redistribution also changes the Earth's gravity field. The physical mechanisms by which mass is redistributed are many and include: tidal forcing caused by the gravitational attraction of the sun and moon, variations in oceanic and atmospheric circulation , the melting of polar and glacial ice, precipitation, earthquakes and other tectonic movements, post-glacial rebound of the Earth's crust , redistribution of ground waters , and long term mantle convection and core activities. While tidal and seasonal effects are periodic with well-defined frequencies, others such as postglacial rebound introduce long term secular changes in both the LOD and the gravity field.

For over 15 years, high frequency variations in the length of day, as determined from LAGEOS ranging, have shown excellent correlation with seasonal and subseasonal variations in the global atmospheric angular momentum. Short term variations are largely explained by exchanges of angular momentum between the solid Earth and atmosphere and by tidal processes. Long term decadal signals have been attributed to angular momentum coupling at the core-mantle boundary and to the effects of postglacial uplift. Ocean circulation models are now being analyzed as possible sources of the residual signals.

Our knowledge of the long wavelength components of the Earth's gravity field improved dramatically over the past three decades as new and better satellites were launched into a wide variety of orbital planes and altitudes and the distribution and precision of SLR systems continued to improve. SLR tracking of LAGEOS had the greatest impact on gravity modeling improvements in the first half of the 1980's [Lerch et al, 1982; Reigber et al, 1985] and, in the second half, led to a better understanding of nonconservative forces acting on the satellite, such as thermal, neutral density, and charged particle drag and the effects of solar and Earth radiation pressure [Rubincam, 1990; Marshall et al, 1995]. In the early 1990's, the inclusion of data from surface gravimetry and earlier altimetric satellites produced a series of Goddard Earth Models (e.g. GEM-T2, GEM-T3) and the Joint Gravity Model JGM-1, produced jointly by GSFC and the University of Texas Center for Space Research in anticipation of the TOPEX/POSEIDON oceanographic mission. The most recent model, JGM-3, takes into account SLR data from the recently

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[1] GPS was added to the TRF in 1992 and DORIS petitioned for inclusion in 1994.

launched LAGEOS-2 and Stella satellites in addition to SLR, GPS, and DORIS tracking of TOPEX/POSEIDON and its high accuracy altimetry data [Tapley et al, 1994].

Temporal variations in the low order zonal harmonics of the Earth's gravity field (e.g. J_2, J_3, and J_4) have been monitored monthly for over 15 years through SLR tracking of LAGEOS and are attributable to movements of mass within the closed solid Earth-oceans-atmosphere system over large spatial scales on the order of 10,000 Km. The short term seasonal and subseasonal variations in J_2 are well-correlated with the distribution of atmospheric mass as determined independently by global measurements of the pressure field as provided, for example, by the European Center for Medium Range Weather Forecasts (ECMWF) [Chou and Au, 1991]. The model agreement is improved by including the displacement of the ocean surface by the atmospheric pressure ("inverse barometer effect") but the true response of the oceans is somewhere in between [Nerem et al, 1993a]. However , atmospheric pressure models alone cannot account for the observed temporal variations in J_3. Large annual residuals in the latter zonal have been attributed to variations in the ocean mass distribution [Marshall and Pavlis, 1993] while other signals appear to be associated with radiationally-forced atmospheric tides, such as the S_1 tide with an approximate 560 day cycle [Nerem et al, 1993b]. If these explanations are confirmed, SLR may provide an important means of monitoring the response of the atmosphere to solar radiation and of testing and discriminating between multilayer ocean circulation models. Furthermore, accurate zonal rates are essential in constraining post-glacial rebound models [Miltrovica and Peltier, 1993] and ice mass balance models [Trupin, 1993].

With the launches of ERS-1 by ESA in 1991 and TOPEX/POSEIDON in 1992, SLR again became a major contributor to the study of sea and ice surface topography. Both missions have been a great success - due in no small part to the contributions of SLR. In spite of the unfortunate failure of the onboard PRARE transceiver and a relatively low (800Km) high drag orbit, ERS-1 orbits have been maintained at roughly the 15 cm level radially with the sole support of the international SLR network. Using the combined SLR and DORIS data sets and a much-improved JGM-3 gravity field, the higher (1375 Km) TOPEX/POSEIDON orbits are generally believed to be accurate to 2 to 3 cm radially - significantly surpassing the original mission requirement of 13 cm. Efforts are underway by the TOPEX/POSEIDON POD Team to improve the radial accuracy to between 1 and 2 cm by applying a heavier relative weighting to the SLR data [S. Klosko, private communication].

The goal of oceanographic missions is to measure the sea surface topography defined as the difference between the local sea surface height and the local geoid (reference gravity equipotential surface). From the two-dimensional slope of sea surface topography, one can compute the global ocean circulation. SLR contributes to sea surface topography in several ways.

(1) By tracking LAGEOS 1 and 2, SLR establishes the positions of the tracking stations with centimeter accuracy in a geocentric reference frame.

(2) SLR provides centimeter accuracy range measurements between the satellite and the station.

(3) The combination of site position and accurate range establishes the altimeter orbital ephemerides with respect to the Earth center-of-mass with centimeter accuracy.

(4) The tracking of the full constellation of SLR satellites provides the longer wavelengths of the gravity field and hence the marine geoid. Knowledge of the gravity field assists in space navigation when laser tracking is sparce, and the geoid surface is essential for computing sea surface topography and ocean circulation.

(5) Because of its insensitivity to the two most dynamic components of the atmosphere, i.e. the ionosphere and the "wet" troposphere, SLR is ideally suited to the calibration and correction of the onboard microwave altimeters during periodic overflights. Long term drifts in altimeter bias can be easily mistaken for changes in sea level.

Recent TOPEX results suggest that the mean sea level is rising at a rate of 2.9 ± 0.9 mm/yr [Nerem et al, 1994] in approximate agreement with earlier estimates based on global tide gauge measurements .

For the sake of completeness, one should also mention the use of SLR in global time transfer and relativity experiments and in the measurement of fundamental physical constants. In the LASSO experiment, coordinated by Dr. Christian Veillet of CERGA, successful subnanosecond time transfer experiments were carried out between the French SLR station at Grasse and the American station at McDonald Observatory in Texas using an intermediary detector, clock, retroreflector array, and telemetry system on the METEOSAT-P2 satellite[Veillet and Fridelance, 1993]. Earlier aircraft experiments conducted by Professor Carroll Alley and his students at the University of Maryland in the late 1970's successfully used a laser ranging system to transfer time between a set of atomic clocks on the ground and a set of clocks on an aircraft [Alley, 1983]. During a flight that lasted approximately thirty hours, the airborne clocks ran faster than the ground clocks due to the reduced gravity field (as expected from Einstein's theory of general relativity) and the change of rate with altitude could be easily seen. Similar NASA/SAO experiments will be carried out over longer time intervals in upcoming missions on the Russian MIR spacecraft to test the performance of hydrogen masers in space. LLR experiments have provided tests of competing relativistic theories, verified the strong equivalence principle in Einstein's formulation of General Relativity, and placed an upper limit on the rate of change in the gravitational constant G [Reis, 1994].

5. FUTURE ROLE OF SLR

The precision of the SLR technique has improved by an order of magnitude in each of its three decades of existence. Approximately 30 countries worldwide are presently active in SLR, and the present network of 45 stations continues to expand as does the SLR constellation which is expected to surpass twenty operational satellites by 1996.

SLR remains crucial to the maintenance of the Terrestrial Reference Frame through its unique subcentimeter determination of the Earth center-of-mass and orbital scale. Laser tracking of LAGEOS has provided the most accurate measurement of the Earth's gravitational coefficient (GM) and has demonstrated the importance of considering the relativistic consequences of the definition of time in the various reference frames {Reis, 1994]. The accurate determination of GM is critical in determining the absolute scale of the geocentric reference frame and affects the intercomparisons of site locations determined independently by SLR and VLBI and the determination of absolute ocean height using altimetric satellites. This has important implications in science applications which have a need for absolute vertical height information such as mean sea level, ice mass monitoring, postglacial uplift, tide gauge monitoring, etc.

Because it uses relatively "clean" cannonball satellites, SLR is presently the best technique for separating conservative from non-conservative forces acting on near-Earth satellites and is presently the only source of information on the time varying gravity field which has potentially major implications for ocean and atmospheric modeling ice mass balance, and other Global Change related science. SLR continues to make unique and important contributions to all elements of Earth science including the solid Earth, oceans, cryosphere, atmosphere, and Earth-lunar dynamics.

The demonstrated capability of SLR to transfer time over global distances with an accuracy measured in tens of picoseconds could have significant scientific and engineering impacts in the not too distant future. In addition to the LASSO experiment discussed previously, SLR tracking of the GPS and GLONASS satellites is presently being used to test the performance of the onboard atomic clocks and to verify the proper handling of certain relativistic effects in ground operations. Over the next few years, spacecraft experiments plan to use SLR to monitor the performance of hydrogen masers in space and to study longterm relativistic effects on spaceborne clocks. There may be commercial applications of time transfer as well. As larger datasets are merged and transmitted electronically around the globe via groundbased optical fibres or wideband communication satellites, the need for improved absolute timing at the sending and receiving stations will grow proportionately.

Today, the traditional role of SLR in precise orbit determination and some areas of geophysics is being challenged by several new and relatively inexpensive radionavigation systems. Because of its simple and unambiguous range observable and its insensitivity to the dynamic ionosphere and "wet" troposphere, SLR has provided the "ground truth" against which these emerging systems (such as GPS, GLONASS, TDRSS, DORIS, and PRARE) have been compared and calibrated. Despite the formidable competition from radio techniques, several important applications remain, at least for the foreseeable future, which are squarely within the sole dominion of SLR. Nevertheless, SLR must continue to improve its data product , both in accuracy and timeliness, and to move rapidly toward automated field stations and data processing centers in order to be competitive with low cost radio systems.

The presence of several orbiting satellites having both retroreflectors and one or more radionavigation transmitters/receivers presents a unique opportunity for the synergistic combination of laser and radiowave datasets to achieve an absolute accuracy and densification of data which could not be achieved by one technique alone. For example, it is likely that continued SLR tracking of the GPS-35 and GPS-36 satellites will isolate the source of observed biases, ultimately improve the modeling of the onboard atomic clocks as well as the nonconservative forces acting on the GPS spacecraft, and lead to improved accuracy in future GPS measurements. Furthermore, SLR's totally passive space segment provides fail-safe redundancy in high profile altimetric or other spacecraft missions.

In the 1994 Belmont Workshop report [Degnan, 1994], NASA proposed eight programmatic goals which should be pursued by the agency and its international partners over the remainder of this decade. These were:

1) Standardize the performance of the global network.
2) Improve the geographic distribution of SLR stations
3) Reduce the cost of field and data operations through increased standardization and automation
4) Expand the temporal coverage to better serve the growing satellite constellation
5) Improve the absolute accuracy to 2 mm at key sites via two color techniques
6) Continue to improve the satellite force, station motion, and atmospheric propagation modelling
7)Support technique intercomparisons and the Terrestrial Reference Frame through global collocations
8) Investigate potential synergisms between GPS and SLR

In summary, the international SLR community can be justifiably proud of its many technological and scientific accomplishments over the past three decades. The high precisions achieved at several stations have resulted in many new and exciting science applications. However, we must work as a community to proliferate these existing capabilities to other stations which have fallen behind technologically and to establish new stations outside our national borders where they are desperately needed. In an era of falling science budgets and increased competition from the radio techniques in performing traditional SLR tasks, we must continue to improve the quality and timely delivery of the range observable and make it more cost effective through increased automation. With picosecond resolution two color satellite ranging becoming a reality at several stations [Zagwodzki et al., 1994], subpicosecond lasers and streak camera detectors already demonstrated in the laboratory, and new millimeter satellite array designs on the drawing boards [Degnan, 1993], there is no reason to believe that the next order of magnitude improvement in range accuracy and precision is beyond our grasp.

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