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Satellite Laser Ranging in the 1990s

Report of the 1994 Belmont Workshop

Proceedings of a workshop held at
the Belmont Conference Center
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PREFACE

Satellite Laser Ranging (SLR) was initiated by NASA in 1964 with the launch of Explorer 22. Since that time ranging precision, spurred by scientific requirements, has improved by three orders of magnitude: from a few meters to a few millimeters. Similarly, the network of stations has grown from a few experimental and development sites to a global network of 43 stations in 30 countries. Most of these stations (33) are funded by organizations other than NASA.

During the past three decades, the global SLR network has evolved into a powerful source of data for studies of the solid Earth including:

- Detection and monitoring of tectonic plate motion, crustal deformation, Earth rotation and polar motion;
- Modeling of the spatial and temporal variations of the Earth's gravity field;
- Determination of Earth and ocean tides;
- Monitoring of variations in the center of mass of the total Earth system (solid Earth-atmosphere-oceans);
- Establishment and maintenance of the International Terrestrial Reference System (ITRS); and
- Detection and monitoring of vertical motions produced by post-glacial rebound, subsidence, and atmosphere and ocean loading.

In addition, SLR provides precise orbit determination for spaceborne altimeter and radar measurements: 1) of the ocean surface (which are used to model global ocean circulation); 2) for mapping volumetric changes in ice masses; and 3) for land topography. It also provides a means for subnanosecond global time transfer, and a basis for special tests of the Theory of General Relativity.

As the SLR "optical" technique has grown and matured so have "radio" techniques like: Very Long Baseline Interferometry (VLBI), the Global Positioning System (GPS), and more recently DORIS and PRARE. Many of the geophysical properties that SLR measures are analogous to those measured by the radio techniques, however, SLR provides unique strength in the vertical where ranges are measured directly without the corruptive influence of atmospheric water vapor, the ionosphere, or other external influences. On the other hand, the radio techniques provide, in some cases, higher spatial or temporal resolution at lower cost.

At a time of severely constrained financial resources an assessment of the contributions of SLR, particularly areas of uniqueness, and evaluations of opportunities for improved cost effectiveness is essential to assuring the effective use of those resources in achieving the best scientific return.

To aid in this assessment and to define future roles and directions for SLR, the Goddard Space Flight Center (GSFC) Laboratory for Terrestrial Physics convened a two-day workshop at the Belmont Conference Center, Elkridge, Maryland, in early February 1994. The invited participants (Appendix A) were drawn from NASA-sponsored SLR operations and analysis activities as well as representatives from the VLBI and GPS community.

This report summarizes the discussions, conclusion, and recommendations of the 1994 Belmont SLR Workshop. The papers in Sections III and IV of this report were provided by Workshop presenters.

SATELLITE LASER RANGING IN THE 1990s

I. CONCLUSIONS AND RECOMMENDATIONS

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A. CONCLUSIONS

1. SLR is a proven geodetic technique with significant potential for continued substantive contributions to studies of the Earth-atmosphere-oceans system.

2. SLR's ability to measure the temporal variations in the Earth's gravity field and to monitor motion of the SLR station network with respect to the geocenter, together with the capability to monitor vertical motion in an absolute system, makes it unique for modeling and evaluating long-term climate change by:

   a. Providing an absolute reference system for measurements of post-glacial rebound, sea level variations, and ice volume changes;

   b. Determining the temporal mass exchange between the solid Earth, oceans, and atmosphere; and

   c. Monitoring the response of the atmosphere to seasonal variations in solar heating.

3. SLR is the most accurate technique currently available to determine the geocentric position of an Earth satellite, allowing for the precise calibration of radar altimeters and separation of long-term instrumentation drift from secular changes in ocean topography.

4. SLR has proven to be a cost-effective means of evaluating, calibrating, and providing failsafe redundancy to spaceborne radiometric tracking systems such as GPS, PRARE, and DORIS.

5. SLR provides an unique capability for the experimental verification of special predictions of the Theory of General Relativity.

6. The cost effectiveness of SLR operations will improve through increased standardization, configuration control, and automation.

B. RECOMMENDATIONS

1. NASA should maintain a set of SLR stations which will contribute to the global fiducial SLR network.

2. Global SLR operations should make a transition to fixed fiducial stations with densified local measurements assumed by GPS and other techniques. NASA should maintain at least one transportable system for collocation and special purpose studies.

3. **NASA should vigorously pursue the development of SLR 2000, a fully automated, standardized, stand-alone, low-cost, sub-centimeter SLR system.**

II. SUMMARY

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A. CRITICAL SCIENCE ELEMENTS

Planet Earth can be envisioned as a system comprised of a solid body covered in part by water in liquid and solid form and enveloped by a gaseous atmosphere. Within this system, the solid, liquid, and gaseous components interact with each other on a global scale through exchange of angular momentum and mass redistribution.

Mass is redistributed within the Earth system on a variety of spatial and temporal scales. These variations occur at tidal frequencies, as well as in concert with non-tidal changes in the system. The amplitude of these variations can vary from year-to-year depending on the amount of incoming solar radiation, atmospheric chemistry (ozone, etc.), precipitation, ocean circulation, and a variety of other parameters affecting global climate. The measurement of these variations can provide important constraints and tests for global climate models, as well as a monitoring capability for detecting changes, either natural or man-made, in the mass distribution of the Earth system. In addition, redistribution of the Earth's mass also introduces changes in its rotation, which can also reflect changes in climate.

Redistribution of mass within the Earth system changes its gravitational field, and thus changes the orbits of Earth satellites. Sensing such variations through their effect on a satellite orbit requires that difficult-to-model non-gravitational forces such as drag and solar radiation pressure be reduced as much as possible. While the effects of mass variations on satellite orbits are small, the ability of SLR to track targets specifically designed for this purpose (ie; passive, spherical objects with low area to mass ratios) makes it uniquely able to observe these constraints on global mass exchange at their broadest spatial scales (currently >10,000 Km). Although satellites sense only the combined variation in the Earth system, modeling of the different components using geophysical data has led to detection of long-wavelength variations in the distribution of atmospheric mass, detection of changes in the amplitudes of atmospheric and oceanic tides, and detection of secular variations caused by the post-glacial adjustment of the Earth's crust. The unambiguous detection of ocean mass redistribution by SLR has not been verified due largely to inadequacies in current ocean models.

The scale inherent in laser ranging observations to stable high-altitude satellites enables us to determine accurate geocentric height at the observatories. This is important, since the location of the solid Earth on which tracking sites are located with respect to the center of mass about which altimetric satellites orbit is required to observe sea level variations at the millimeter per year level associated with global climate change. The unique capability to monitor secular vertical motion in an absolute system also contributes to improved models of post-glacial rebound and atmospheric pressure loading.

SLR tracking of Lageos and Starlette extends back to the mid 1970s, and the continued tracking of these spacecraft provides a baseline from which to measure sudden, possibly unexpected, changes in the Earth system's mass distribution. The addition of SLR tracking of Ajisai (1985), Lageos-2 (1992), and Stella (1993) provides much improved spatial and temporal resolution over what could be obtained with Lageos and Starlette alone. Short of a dedicated mission to measure the gravity field, no other currently available technology can provide this capability, since these satellites are specifically designed to minimize the size of non-gravitational forces and maximize their modelability.

Therefore, the continued tracking of these satellites using SLR will provide an important and unique contribution to NASA's Global Change Program, both as a constraint for global models of the atmosphere, oceans, and solid Earth, as well as a means of monitoring a fundamental variable of the total Earth system.

B. SCIENTIFIC SUPPORT

1. Precision Orbit Determination

The significance of SLR tracking in the production of precise orbits which are centered in an accurate terrestrial reference frame has been well established. This allows altimetric satellites to provide absolute subcentimeter global sea level measurements and makes it possible to link other altimetry measurement systems for long-term sea level studies. It was for this reason that SLR was selected as the primary tracking system for TOPEX/Poseidon and for ERS-1 orbit determination. The current radial orbit accuracy for the SLR-tracked TOPEX/Poseidon mission is estimated to be 3-4 cm, with geographically correlated orbit error of about 2 cm.

The calibration of radar altimeters is increasingly more critical to the overall success of altimeter missions. Accurate absolute calibration is essential to separate possible sensor drift from long-period phenomena in the measured ocean topography. Constant offsets in the radar range measurements are troublesome, but are less troubling than bias drift, which differentially affects ocean topography measurements. These differential changes, if undetected, obscure the monitoring of long period and secular changes in global sea level.

Since SLR is the most accurate absolute-ranging instrument available, a direct overflight experiment is the best means to produce an accurate orbit-independent instrument calibration. This simplified, geometric calibration approach can, in principle, produce results at the subcentimeter level. Calibration of the altimeter instrument at this level will enable the synoptic altimeter mapping of the ocean surface to produce an unambiguous measure of the change in global sea level.

SLR has demonstrated the capability to provide additional support in the detection of systematic errors and in the resolution of possible ambiguities in other tracking systems, such as DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite) and the GPS receiver on TOPEX/Poseidon. Examples include the verification of the time bias offset in the DORIS tracking system, the center-of-mass correction offset in the GPS tracking system, and other ambiguities such as the geocentric positioning offset along the Earth's spin axis which have been obtained by some radiometric tracking systems.

SLR tracking has also proven to be invaluable in the event of failure of the primary radiometric tracking system as in the case of ERS-1 where, without the SLR tracking, the failure of the PRARE (Precise Range and Range rate Experiment) system would have severely degraded the scientific return of the mission. The current ERS-1 radial orbit accuracy achieved using SLR tracking is below the 15-cm level. The SLR system can also serve as a complement to other tracking systems, especially during data outages. For example, in the case of TOPEX/Poseidon, both DORIS data outages and loss of GPS data due to Anti-Spoofing (AS) have occurred and SLR was able to provide few centimeter orbits totally on its own.

2. Earth Rotation And Reference Frames

Since the beginning of regular space geodetic measurements of Earth Orientation Parameters (EOP) in 1980, SLR has routinely provided polar motion and length of day (or high frequency UT1) solutions to the International Earth Rotation Service (IERS). SLR observations provide the scale for the International Terrestrial Reference System (ITRS) and helps to define the Earth's polar motion in this system. In the following decade, SLR and VLBI (with contributions to UT1 from LLR) became the only techniques used by the IERS in providing the international standard series of EOP. As the decade of the 1990s began, the development of GPS as a tool for studying EOP variation accelerated and during the GIG campaign in 1991 the technique produced polar motion results competitive with SLR and VLBI. At the current time, GPS regularly produces daily polar motion solutions with 0.4 mas accuracy, equivalent to that of the routine 1-day VLBI experiments and SLR solutions using 3 days of Lageos-1 data. The VLBI EOP results are unique because of the technique's inherent ability to access the Celestial Reference Frame (CRF), realized by the positions of distant quasars, with respect to the Terrestrial Reference Frame (TRF) defined by the positions of the radio telescopes. Conversely, the satellite based techniques (GPS and SLR) can access the CRF only to the accuracy of the dynamic models that predict the satellite's motion in the CRF. Errors in the dynamic models for GPS satellites and for Lageos preclude meaningful estimates of precession and nutation and degrade the long term stability of the UT1 estimates.

An ideal reference system for Earth orientation and station positioning would combine the scale from the SLR network with the inertial frame definition of the VLBI stations and densification provided by GPS observations.

3. Relativity Experiments

While General Relativity has been adopted as the standard relativity theory, there are alternative theories, with important implications for gravitational physics, which can only be discounted with tests of sufficient accuracy. In addition to its contributions to lunar and solar system dynamics, Lunar Laser Ranging (LLR), in combination with other solar system data, continues to refine some important limits. SLR tracking to geodetic satellites can provide similar tests, but the accuracy is usually limited by our ability to model the variety of gravitational and non-gravitational perturbations. One important exception is the proposed Lageos-III mission, which would provide a measurement of the Lense-Thirring precession. Using a pair of high-density, high-altitude satellites in orbits with supplementary inclinations, the existence of the gravito-magnetic effect could be confirmed at the few percent level, providing experimental support for the general relativistic formulation of the Mach Principle. With the dual satellite configuration in place, there may be other relativistic and geophysical experiments possible that have not yet been imagined. SLR tracking of Lageos has also provided the most accurate determination 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. In addition, the Lageos SLR analysis has demonstrated the need for considering additional relativistic geopotential effects in the solar system barycentric model for near-Earth applications. SLR is also being used to study relativistic effects associated with transfer of time from GPS and GLONASS satellites to the ground observer through the comparison of the optical range with the radiometric pseudo range. The precise determination of absolute distance is a primary reason for the sensitivity of SLR to relativistic effects. Continued improvement in SLR accuracy will improve the determination of these effects.

C. FUTURE OF SLR

1. Near-Term

The current trend in SLR is away from localized network measurements, and more toward fixed fiducial sites with a global distribution and long term occupations to provide orbital coverage for specialized projects. The localized networks should be transitioning to GPS in a systematic manner, with SLR contributing to global geodetic control.

SLR data and data processing are also in a state of change. Field Generated Normal Points, available within 24-36 hours of acquisition, are rapidly becoming the standard data product, superseding full-rate data that was taking up to six months or more for full availability. Data processing and assessment are rapidly being automated to speed up feedback to the field stations, both NASA and foreign.

Efforts are underway to automate and consolidate activity in the field and at supporting facilities to reduce manpower requirements and to improve the performance and reliability of field stations. Since a significant portion of the global SLR data are provided by stations operated by other countries, it is important that NASA continue to assist these stations by providing operational support, configuration control, standardized software, and calibration standards.

2. SLR 2000

Almost all of the SLR stations currently in use were built 15 to 20 years ago and only the ranging subsystem represents state-of-the-art technology. New capabilities are possible due to recent developments such as: simple, compact microlasers with very short pulse widths; narrowband filters for improved signal-to-noise discrimination; more sensitive CCD cameras; high-speed, highly sensitive detectors; expanded computer capabilities; and faster, more compact electronics.

With these new capabilities, a totally automated, standardized, and easily replicated SLR design would lead to significant reductions in manpower and other operating costs. Equally important is the cost avoidance (both at NASA and the participating international institutions) associated with the increasingly expensive task of maintaining systems based on rapidly aging hardware and difficult or impossible component replacement.

SLR 2000 makes use of this new technology. It is conceived as a totally automated, subcentimeter SLR system which could cost a few hundred thousand dollars each, would be distributed globally at fixed sites, and possibly funded or supported by host countries. Operations control and data transmission would be by two-way communications with central facilities via the NASA Science Internet network.

With adequate funding, a prototype system could be developed and installed at the Goddard Geophysical and Astronomical Observatory by 1998, with the initial deployment of other stations by the year 2000.

3. Long-Term Goals

As a precursor to evolving a SLR Program Plan for the 1990s, a series of eight long-term goals are proposed. These goals assume that:

- 0 GPS will completely take over regional deformation work from SLR and VLBI mobile systems;
- 0 One roving NASA transportable is needed in North America for station backup, system collocations, and special science studies such as post-glacial rebound in Canada, TOPEX/Poseidon calibration, etc;
- 0 A global network of well-distributed SLR stations will be needed to support terrestrial reference frame, gravity field and geoid studies, precise orbit determination, technique intercomparisons, and special science missions; and
- 0 The operational cost will be substantially reduced through increased system standardization and automation.

In keeping with these objectives, NASA should dedicate itself, in the 1990s, to achieving the programmatic and technical goals outlined below.

a. Standardize the performance of the global SLR network.

b. Improve the geographic distribution of stations.

c. Reduce the costs of field operations and data processing.

d. Expand the 24 hour temporal coverage to better serve the growing constellation of satellites.

e. Improve the absolute range accuracy to 2 mm at key stations.

f. Improve satellite force, radiative propagation, and station motion models and investigate alternative geodetic analysis techniques.

g. Support technique intercomparisons and the Terrestrial reference Frame through global collocations.

h. Investigate potential synergisms between GPS and SLR.

III. ROLE OF SLR IN THE EARTH SCIENCES

N95- 14275

A. SCIENTIFIC ANALYSIS OF SATELLITE RANGING DATA

D.E. Smith

INTRODUCTION

During the last decade, a network of SLR tracking systems with continuously improving accuracy has challenged the modelling capabilities of analysis groups in institutions throughout the world. A variety of techniques of data analysis have yielded many advances in the development of orbit, instrument and Earth models. The direct measurement of the distance to the satellite provided by the laser ranges has given us a simple metric which links the results obtained by diverse approaches. The different groups have used the SLR data, often in combination with observations from other space geodetic techniques to improve models of the static geopotential, the solid-Earth and ocean tides, and atmospheric drag models for low Earth satellites. Models of radiation pressure and other non-conservative forces for satellites which orbit above the atmosphere have been developed to help us exploit the full accuracy of the latest SLR instruments. These developments have helped static positioning accuracy to reach below one centimeter in all three components of geocentric location and kinematic precision is as low as one or two millimeters/year for stations with long tracking histories. SLR is the baseline tracking system for the altimeter missions TOPEX/Poseidon and ERS-1, and will therefore play an important role in providing the reference frame for locating the geocentric position of the ocean surface at any time, in providing an unchanging range standard for altimeter calibration, and for improving the geoid models to separate gravitational from ocean circulation signals seen in the sea surface. However, even with the many improvements in the models used to support the orbital analysis of laser observations, there remain systematic effects which limit the full exploitation of SLR accuracy today.

SLR OBSERVATION ACCURACY

Laser systems are currently the most accurate and advanced means of satellite tracking and the precision of existing SLR measurements is better than a centimeter for the latest instruments. The process of forming laser normal points, a type of compressed data, eliminates spurious observational noise in the current measurements and can reduce the precision as measured by the noise level to a few millimeters. Systematic errors which are not eliminated in the normal point computation process must be carefully calibrated [see Betti et al., 1987]. The effects of atmospheric propagation, especially horizontal gradients in the atmosphere which are not detectable by the surface meteorological measurements made at the laser sites, can amount to a centimeter [Abshire and Gardner, 1985], although they average out over a period of a few days. Electronic errors, non-linearities in the tracking electronics as a function of signal strength, and errors in the distance to the calibration targets can now be reduced to give ranging systems of subcentimeter absolute accuracy [Degnan, 1985, 1993], with further improvements in tracking hardware in progress.

SLR ANALYSIS METHODS

Data Analysis Centers throughout the world, and particularly in countries which support SLR Observatories conduct their own individual analyses of the observations. Each technique is different and can be interpreted as a combination of geometric and dynamic methods. The dynamic method requires an accurate computation of Earth orientation and orbit perturbations. The quality of the fit of the data to a computed orbit depends on the length of the arc over which the orbit state vector is estimated, because errors in the force model build up with increasing arc length. The GSFC SLR Analysis Group favors arc lengths of a few weeks for high altitude satellites such as Lageos and ETALON, and of a few days for lower orbiting spacecraft, and this is a common approach for the other groups. The CSR team may fit an arc of many years in length to the SLR data to study long term evolution of orbital elements, which is achieved with special orbit analysis techniques by other groups, or by considering parameters which infer orbit behavior. For example, the eccentricity excitation vector [Tapley et al., 1993] which describes the Lageos-1 anomaly which first appeared in 1989 can also be represented by an along-track acceleration which repeats every revolution [for example, see Dunn et al., 1993]. The geometric approach to data analysis, in which the satellite orbit simply interpolates in range observations taken at different stations, can be considered a special case of the dynamic method with very short arc length [Grafarend et al., 1985; Hauck, 1987; Milani et al., 1989]. Although most analysis groups have applied them to special cases, such as collocated systems and stations providing concentrated tracking data in a region, the practical use of purely geometric techniques is limited by requirements for mutual station visibility [Pavlis, 1985; Moore, 1986; Sasaki et al., 1989; Sinclair et al., 1993; Zerbini, 1993]. As SLR systems become more automated and versatile, geometric applications will enable the accurate measurements to be analyzed with very efficient computer resources [see Robbins et al., 1994].

SLR ORBIT ANALYSIS

Since the launch of Lageos, the gravity model has been improved through the analysis of millions of laser ranges acquired on satellites which span a wide range of orbital inclinations. Knowledge of the geopotential field has improved in accuracy by an order of magnitude or more, especially for the longest wavelength portion of the field. Advanced solid Earth and ocean tidal models [Christodoulidis et al., 1988; Dow et al., 1991; Tapley et al., 1993], descriptions of site motion due to various sources of loading, and improved realization of a geocentrically referenced Conventional Terrestrial Reference System [Dow et al., 1986; Himwich et al., 1993] all played an important role in the more accurate representation of SLR data in the orbit determination process. The impact of the precise SLR data on geopotential improvement was demonstrated when Lageos observations were first included in the gravity models [Lerch et al., 1982; Reigber et al., 1985]. Complex non-conservative orbital perturbations are also seen on the Lageos orbit leading to numerous important studies, including those by Rubincam et al. [1987, 1988, 1989]; Afonso et al. [1985, 1989]; Barlier et al. [1986]; Bertotti and Iess [1991]; and Scharroo et al. [1991]. These forces are smaller than the non-conservative effects on lower orbiting satellites. For example, Starlette, like Lageos, is a small dense sphere, but at its 800-1200 Km altitude, it experiences atmospheric drag perturbations in the along track direction which are two orders of magnitude larger than the along track force on Lageos, which includes thermal, neutral density and charged particle drag.

GRAVITY MODELLING

The Lageos range measurements are the most precise satellite observations used to define the long wavelength terms in the Earth's gravity model and improvements are directly attributable to Lageos' contribution. The GEM-T2 solution [Marsh et al., 1990] was developed to meet the stringent requirements of the TOPEX/Poseidon mission and contained over two million observations from 31 satellite orbits, including third generation SLR observations from Starlette, Ajisai, Lageos, BE-C, GEOS-1 and GEOS-3. Gravity signals were still required from some second generation data sets including SEASAT and GEOS-2 as well as the early laser data taken on BE-B, D1-C, D1-D and PEOLE. The truncation limits of the satellite solution was extended to degree 50 for certain resonance and zonal orders. The GEM-T3 solution [Lerch et al., 1992], which combined satellite models with surface gravimetry and satellite altimetry from GEOS-3, SEASAT and GEOSAT, provided the first robust treatment of these diverse data sets within the GEM models. The latest advance in gravity model development is JGM-3 [Tapley et al., in press], and includes information from laser, DORIS, and GPS tracking of TOPEX/Poseidon, as well as additional SLR data from both Lageos-1 and -2 and the recently launched Stella satellite. By increasing the number of harmonic coefficients in both the static and tidal gravity models, the truncation effect on low orbiting satellites is reduced. For example, based on the evaluation of the TOPEX orbit by Casotto [1989], the ocean tide model required for TOPEX to reduce omission effects below the one centimeter radial error requires ocean tide models containing more than 7000 terms spanning 96 discrete tidal lines. The secularly varying component of the gravity field has helped improve our knowledge of Earth processes such as post-glacial rebound through the study of the change in the Earth's second zonal harmonic [Yoder et al., 1983; Rubincam, 1984; Peltier, 1985]. Shorter term variations in both the second and third zonals have shown a relationship with mass balance in the atmosphere and oceans [Nerem et al., 1993; Gegout et al., 1993].

POSITIONING WITH SLR OBSERVATIONS

The time resolution of the positioning parameters from SLR stations has improved with developments in force modelling as well as with engineering advances in the instruments [Wakker et al., 1985; Dietrich et al., 1987; Dow et al., 1986, 1991; Smith et al., 1990; Biancale et al., 1991; Gegout et al., 1991; Murata et al., 1993; Reigber et al., 1993]. For example, the annual solutions for Lageos station positions first provided by the GSFC Analysis Group have been reduced to regular monthly estimates of three-dimensional location, and the SLR observations now provide the scale for the International Terrestrial Reference System and help to define the Earth's polar motion in this system, at times with sub-daily resolution [Gross et al., 1985; Dow et al., 1986; Caporali et al., 1990]. The effects of semi-diurnal and diurnal ocean tides have been detected by several analysis groups on both the Earth orientation and geocenter motion of the Global Laser Tracking Network.

The SLR-defined global and regional kinematic velocity models have suggested that the relative velocities of SLR stations on the stable interiors of tectonic plates were about five percent slower than those expected from the NUVEL-1 geophysical model [Smith et al., 1990]. The recently-revised NUVEL-1A velocities are in better agreement with space techniques, which will simplify the inclusion of contemporary measurements in geophysical models. Notable contributions to regional deformation studies have been made by the transportable SLR campaigns in the Mediterranean organized by the WEGENER group [Wilson et al., 1993]. The extension in the Aegean has been measured and the behavior of deformation in the Eastern Mediterranean is undergoing reassessment [Noomen et al., 1993; Cenci et al., 1993]. The SLR geodynamic observations can now be combined with earthquake moment tensors for regional seismic risk assessment [Jackson et al., 1994]. The direction of the motion of SLR observatories located behind island arcs in Simosato, Japan and in Arequipa, Peru is the same as that of the subducting plate, and a model for this motion is yet to be developed [Robaudo et al., 1993].

It has been shown that SLR, VLBI and GPS systems agree at the level of a few centimeters in position and a few mm/year in horizontal velocity if a transformation is applied to align and scale the reference systems [Ray et al., 1991; Watkins et al., 1994]. A combined solution of all space geodetic measurement types would provide the best reference frame for rigorous kinematics, but until that is achieved, the velocity fields defined by SLR, VLBI and GPS systems can be run together to extend global coverage, and long histories of VLBI and SLR observations can be used to underly the regional detail provided by GPS. An ideal reference system for Earth Orientation and station positioning would combine the scale from the SLR network with the inertial frame definition of the VLBI stations and densification provided by GPS observations.

The ranging accuracy of a modern laser system provides a unique scaling capability to determine the height of the station as the distance from the geocenter [Dunn et al., 1993]. The largest error source in SLR station height determination has been the uncertainty in the orbit of Lageos-1, and this can now be reduced by using the extra tracking geometry of Lageos-2. Vertical signals at current SLR stations show systematic variation at the level of a few millimeters expected from deficiencies in Earth and ocean loading models, which occur at known frequencies, as well as from atmospheric pressure loading. Meteorological observations are available to model this effect, and any remaining seasonal variations will not contaminate any estimate of long-term tectonic uplift or subsidence if a well-sampled series of measurements is collected over a long enough time span.

ALTIMETER MISSION SUPPORT

Satellite Laser Ranging is widely used in oceanographic science through the tracking support provided on satellite altimeter missions [Wagner et al., 1989]. Both TOPEX/Poseidon (launched in August 1992) and ERS-1 (launched in July 1991) depend on SLR data for precise orbit determination. The accuracy of the orbital reference allows us to monitor the ocean surface over the time needed for studying global ocean circulation. The analysis of climatological models suggests that the sea surface departs significantly from the geoid, and is offset in its center of figure with respect to the Earth's center of gravity at the decimeter level. The absence of perfect symmetry in the dynamic height field with respect to the geocenter gives non-zero degree one terms in the spherical harmonic expansion of the ocean topographic field which describe the east-to-west slope of the ocean topography across the major ocean basins and have implications for seasonal thermal expansion of the oceans. The values for the first degree terms from climatology imply that on average during this century, the southern oceans are more dense than their northern counterparts, and that the western portion of the major gyres are more energetic than that of the east. It is important to verify that these terms are accurately determined within the satellite analyses. The best standard for precise ranging is provided by SLR, and when altimeter satellites overfly ocean oil platforms, simultaneous tracking from the SLR and altimeter systems can be used to position the satellite with respect to the platform location using GPS ties. Through tide gauges on the platform, the satellite altimeter can be accurately located with respect to the instantaneous ocean surface and the altimeter range calibrated for instrument drift.

SUMMARY

The development of models which support millimeter level ranging will require further advances in the understanding of the geophysical response of the Earth. There are a number of environmental sources of mass redistribution arising from meteorological sources, such as variations of the atmospheric pressure field [Chao and Au, 1991] and continental water storage [Chao and O'Connor, 1988] which require further attention in current orbit determination processes. Nerem et al. [1993] show significant changes in the Lageos sensed zonal harmonics of the gravitational field related to atmospheric mass redistribution, and this effect must be accommodated if we are to monitor changes in the geopotential field due to post-glacial rebound, tectonic movement, and the motion of the core. Although our ability to model the range data to Lageos and other satellites has greatly improved, the accuracy of SLR systems are yet to be fully exploited in current solutions, and geodetic signals at the centimeter level are difficult to detect. We should focus on developing the underlying geophysical models, as well as improving data treatment and the incorporation of databases to help model short-term and erratic meteorological sources of mass transport in geodetic investigations. The tracking support for altimeter missions provides a further example of our use of these accurate measurements to better understand the Earth's climatological system and ocean circulation in a reference system tied through the SLR scale to the solid Earth.

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B. GLOBAL REFERENCE FRAME: INTERCOMPARISON OF RESULTS (SLR, VLBI, GPS)

107862
350027
6p

C. Ma, M.M. Watkins, and M. Heflin

The terrestrial reference frame (TRF) is realized by a set of positions and velocities derived from a combination of the three space geodetic techniques, SLR, VLBI and GPS. The standard International Terrestrial Reference Frame (ITRF) is constructed by the International Earth Rotation Service (IERS) in such a way that it is stable with time and the addition of new data. An adopted model for overall plate motion, NUVEL-1 NNR, defines the conceptual reference frame in which all the plates are moving. In addition to the measurements made between reference points within the space geodetic instruments, it is essential to have accurate, documented eccentricity measurements from the instrument reference points to ground monuments. Proper local surveys between the set of ground monuments at a site are also critical for the use of the space geodetic results. Eccentricities and local surveys are, in fact, the most common and vexing sources of error in the use of the TRF for such activities as collocation and intercomparison.

The global SLR and VLBI TRFs each consist of more than 100 sites occupied since the 1970s. Each technique is currently active at over 30 sites distributed globally although much more limited in the southern hemisphere. SLR stations operate independently and can potentially observe continuously, but weather and budget both limit actual observing in an unpredictable way. VLBI sessions must necessarily involve a network of stations observing simultaneously. VLBI observations are scheduled on a weekly basis on the NEOS (National Earth Orientation Service) network of five stations to monitor EOP (Earth Orientation Parameters).

With other geodetic observing programs coordinated by NASA, USNO, NOAA, IfAG, and GSI, there was on average during 1993 one 24-hour session every other day as well as a 1-hour session every non-NEOS day to monitor UT1. The fact that many SLR and VLBI sites are no longer active means, however, that the current realization of the TRF at these sites is gradually degraded as the mean epoch of observation recedes into the past and the current position is derived using velocities with finite or even unknown errors. The GPS TRF consists of over 40 IGS (International GPS Service) sites, some beginning as early as 1991, with permanent, continuously operating receivers. Like SLR and VLBI, the number of southern hemisphere sites is limited. The GPS data are retrieved remotely daily and the analysis products, orbits and EOP, derived by several analysis centers are distributed promptly to various data centers via Internet.

Table 1 shows, in round numbers, the contribution of each technique to the most recent ITRF realization, ITRF92. The WRMS is the scatter of the results from a particular technique from

ITRF92, which incorporated all the techniques using results from several analysis centers for each technique. No GPS velocities were included because of the limited GPS time interval when the results entering ITRF92 were generated in early 1993. It can be seen that the scatters are similar. The CSR-University of Texas SLR results were used to set the scale and origin of ITRF92.

TABLE 1

Contributions to ITRF92 from SLR, VLBI and GPS

WRMS scatter

		Position (mm)		Velocity (mm/yr)	
	Sites	horiz	vert	horiz	vert
SLR	110	15	20		
	45			1.5	3.0
VLBI	110	5	10		
	60			0.6	1.0
GPS	45	10	15		

The different Celestial Reference Frames (CRF) used by the different techniques have a direct bearing on the complexity of analysis and the stability and accuracy of the TRF parameters that can be estimated. VLBI uses 130 extragalactic radio sources that constitute a nearly inertial CRF. The technique is geometric with no ties to the geocenter but can measure the complete orientation of the Earth accurately over the long term. SLR uses the orbits of 5 satellites specifically designed for geodetic ranging. While the orbits can be integrated for up to a few weeks, there exist unmodelable drifts in the orbit node that preclude the long-term measure of UT1. However, the determination of the geocenter is strong. GPS uses the orbits of 25 complicated, actively maneuvered, distant satellites, so that both the orbit stability and the tie to the geocenter are weak. However, the quantity of data acquired from continuous observing as well as considerable mutual visibility of the satellites from different sites provide strong daily solutions for station and pole positions.

Tables 2 and 3 from Watkins, Eanes and Ma (GRL in press) shows the most recent comparison between SLR and VLBI for position at 1988.0 and velocity. While the number of sites with both position and velocity estimated from both techniques is limited, they are globally distributed. The common sites are, unfortunately, among the weaker sites for both techniques. The agreement is better than 10 mm WRMS for the horizontal components and 20 mm in the vertical. The WRMS agreement in horizontal velocity is ~2 mm/yr.

Table 2
Position Comparison - GLB886a/CSR93L01

Sites	Differences After Fit (mm)						Uncertainties (mm)		
	X	Y	Z	East	North	Vert.	σ_E	σ_N	σ_V
Tidbinbilla	-34	2	-29	16	-6	42	14	21	19
Greenbelt	6	-29	9	12	10	-27	6	4	9
Ft. Davis (N)	3	-21	8	8	-3	21	7	8	11
Ft. Davis (O)	-2	12	11	-5	15	-4	8	10	14
Mon. Peak	6	3	-7	4	-3	-8	5	4	8
Plattevile	-2	-1	-2	-2	-2	0	8	7	17
Quincy	-4	-1	3	-3	-3	1	4	4	8
Shanghai	-20	87	95	-28	37	122	41	36	56
Wettzell	18	-17	25	-19	6	28	9	11	16
Matera	-13	-20	6	-15	16	-10	12	14	20
Weighted rms	9	15	10	9	7	19			

Table 3
Velocity Comparison - GLB886a/CSR93L01

Sites	Differences After Fit (mm)					Uncertainties (mm)	
	X	Y	Z	East	North	σ_{VE}	σ_{VN}
Tidbinbilla	5.2	-8.7	-2.9	4.8	-7.3	2.2	2.4
Greenbelt	-2.2	-1.4	-2.3	-2.4	-2.3	1.4	1.1
Ft. Davis (N)	-1.8	-1.9	3.1	-1.3	1.5	1.6	1.6
Ft. Davis (O)	-2.0	-2.4	2.1	-1.3	0.3	2.4	2.2
Mon. Peak	1.3	0.6	1.7	0.9	2.0	1.0	1.0
Plattevile	0.4	1.4	1.2	0.0	1.9	2.1	2.0
Quincy	0.5	-0.4	-0.2	0.6	-0.2	1.0	1.1
Shanghai	-7.7	-8.7	-5.8	11.1	6.7	11.4	9.9
Wettzell	0.3	-1.0	2.9	-1.0	1.8	2.2	2.3
Matera	-0.6	-3.6	5.0	-3.3	4.8	2.5	2.6
Weighted rms	4.5	4.3	2.8	1.8	2.5		

Tables 4 and 5 show the comparison between GPS and VLBI at 1992.5. The GPS sites have data spanning up to three years. It can be seen that the position comparison is slightly worse than SLR-VLBI while the velocity comparison is considerably worse. There are some sites that have such large discrepancies in velocity that they are excluded from the comparison. Generally these are in the southern hemisphere, where coverage is weak.

The unique contributions of each technique are summarized as follows:

Contributions to the TRF

SLR:

- center of mass
- longest pole and LOD series
- scale

VLBI:

- tie to inertial frame
- stable pole, UT1, nutation series
- precision/accuracy
- site velocities

GPS:

- daily measurements of position
- pole densification

Table 4

GPS-VLBI Position Differences After Transformation - mm

	Up	East	North	Magnitude
ALGOPARK	-37	-7	0	38
DSS45	-54	24	6	60
DSS65	34	10	-16	39
GILCREEK	-5	-8	1	10
HARTRAO	5	-6	22	24
JPL MV1	-44	-12	8	46
KAUAI	24	-2	-3	24
MATERA	4	11	-5	13
METSHOVI	-28	0	-27	39
MOJAVE12	-7	0	-14	15
NL-VLBA	-20	-3	-4	21
ONSALA60	3	7	-14	16
PENTICTN	-67	-5	-2	68
PIETOWN	3	-1	-9	10
PINFLATS	3	-6	-4	8
RICHMOND	-26	-9	11	30
SANTIA12	55	12	8	58
TROMSONO	2	-42	3	42
VNDNBERG	0	-10	-6	12
WETTZELL	3	1	-4	5
YELLOWKN	50	0	0	50
Weighted RMS	31	13	11	

Table 5

GPS-VLBI Rate Differences After Rotation - mm/yr
(x-not included in rotation or statistics)

		Up	East	North
	ALGOPARK	-2.9	4.1	-2.1
	DSS45	-2.3	-14.8	-2.2
	DSS65	7.3	5.2	-1.4
	GILCREEK	9.6	6.4	-4.2
X	HARTRAO	4.0	29.1	1.7
X	HOBART26	1.5	-22.4	-3.9
X	JPL MV1	-22.5	-3.8	6.2
	KAUAI	0.4	5.8	0.4
	MATERA	-9.5	6.5	-0.3
	METSHOVI	-6.8	-1.3	1.1
	MOJAVE12	-0.9	-4.9	-3.1
	NL-VLBA	5.5	1.8	7.4
	ONSALA60	0.0	4.1	1.2
X	PENTICTN	-26.9	0.6	-1.7
	PIETOWN	-0.8	-1.3	9.2
	PINFLATS	-5.5	-1.1	2.0
	RICHMOND	10.8	2.8	-0.9
X	SANTIA12	-59.2	23.5	-23.3
	TROMSONO	-4.0	-13.9	1.3
	VNDNBERG	5.6	-8.3	1.8
	WETTZELL	-7.8	5.3	-4.0
	YELLOWKN	-3.0	1.7	-4.3
	RMS	5.9	6.5	3.6

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C. MEASURING TEMPORAL GRAVITATIONAL VARIATIONS USING SLR DATA

107863
350009 6p

R.S. Nerem

Mass is redistributed within the solid Earth-ocean-atmosphere system on a variety of spatial and temporal scales. These variations occur at tidal frequencies, as well as in concert with non-tidal changes in the system. They are caused by a variety of complex phenomena including luni-solar tides, atmospheric and oceanic mass redistribution, variations in groundwater storage and snow cover/ice thickness, earthquakes, post-glacial rebound in the Earth's mantle, long-term mantle convection and core activities, and other geophysical phenomena. The amplitude of these variations can vary from year-to-year depending on the amount of incoming solar radiation, atmospheric chemistry (ozone, etc.), precipitation, ocean circulation variations, and a variety of other parameters affecting global climate. It is important to understand these variations because of the implications they have for understanding and monitoring global climatic and geophysical changes, Earth rotation, and synoptic sea level changes. The measurement of these variations can provide important constraints for global climate models, as well as a monitoring capability for detecting changes, either natural or man-made, in the mass distribution of the Earth system. In addition, redistribution of the Earth's mass also introduces changes in its rotation, which can also reflect changes in climate.

Redistribution of mass within the Earth system changes its gravitational field, and thus changes the orbits of Earth satellites. While these variations are small, Satellite Laser Ranging (SLR) to precise geodetic satellites such as Lageos-1, Lageos-2, Starlette, Ajisai, and Stella can detect these changes at their broadest spatial scales (currently >10,000 km). The satellites sense only the combined variation in the solid Earth-ocean-atmosphere system; however, modeling of these different components has led to detection of long-wavelength variations in the distribution of atmospheric mass, changes in the amplitudes of atmospheric and oceanic tides, and secular variations caused by the post-glacial adjustment of the Earth's crust. The unambiguous detection of ocean mass redistribution by SLR has not been verified due largely to inadequacies in current ocean models.

Great progress has been made in recent years in the determination of luni-solar tides and the braking they induce in the Earth-Moon-Sun system (leading to secular changes in the length-of-day and lengthening of the lunar orbit period) using a wide variety of techniques including ocean tide gauges, satellite altimetry, Lunar Laser Ranging, and near-Earth satellite orbit modeling. Recent investigations of the more complex and less predictable non-tidal temporal variations in the gravity field have generally proceeded along two fronts: 1) the determination of long-wavelength variations in the gravity field through the changing perturbations seen in the orbits of near-Earth satellites, and 2) the prediction of temporal variations in gravity using geophysical, atmospheric, and oceanic models. A convergence of these efforts is sought to better understand the source of observed changes in the Earth's gravitational field.

Both approaches to studying non-gravitational changes have been utilized within the last several years with great success. Variations in the long wavelengths of the Earth's gravitational field have been measured using precise tracking of artificial Earth satellites. SLR tracking of Lageos over the last 15+ years has produced measurements of monthly variations in the J_2 and J_3 harmonics of the gravity field [Nerem et al., 1993a: Gegout and Cazenave, 1993]. In addition, Chao and Eanes [1993] have analyzed 5 day variations in the nodal longitude of the orbit of Lageos, which are a function of the variations in the even degree zonal gravitational coefficients. Gravitational variations caused by redistribution of atmospheric mass can be predicted by analyzing pressure fields output from global atmospheric models, such as those provided by the European Center for Medium Range Weather Forecasts (ECMWF) [Chao and Au, 1991]. Through comparisons to gravitational variations computed from the atmospheric models, each of the aforementioned Lageos studies have concluded that much of the variation observed in J_2 can be explained by the redistribution of atmospheric mass (Figure 1) on both seasonal and sub-seasonal time scales. These studies have also been applied to study the ocean's response to atmospheric pressure loading (the inverted barometer effect). A higher correlation of measured and model-predicted J_2 estimates has been found when the inverted barometer effect is included with the atmospheric model [Nerem, et al., 1993a], as well as in the atmospheric excitation of polar motion and length-of-day. However, while such modeling is better than ignoring the inverted barometer effect, the true response of the ocean is probably somewhere in between.

Measured secular variations in J_2 [Yoder et al., 1983] are difficult to separate from very long period tides (e.g. the 18.6 year lunar tide [Eanes et al., 1993]) because they both cause long period changes in the orbit longitude. Under the assumption that the 18.6 year tide is in equilibrium, the measured secular rate of J_2 is consistent with models of post-glacial rebound of the Earth's mantle.

Variations in J_3 determined using Lageos SLR data are not well predicted by the models of atmospheric mass redistribution [Nerem et al., 1993a; Gegout and Cazenave, 1993]. Recent results attribute this difference to large annual variations in J_3 caused by mass redistribution in the ocean [Marshall and Pavlis, 1993] and variations caused by diurnal radiationally-forced atmospheric tides [Nerem et al., 1993b]. Figure 2 shows a time history of along-track once per revolution accelerations on Lageos estimated using SLR data. The large peaks in 1989 and 1991-92 are especially interesting. A spectral analysis of these variations shows that they predominantly occur at annual and 560 day periods. The 560 day period is thought to be caused by the radiationally-forced S_1 atmospheric tide, whose amplitude varies with time depending on the amount of incoming solar radiation and the response of the atmosphere to that radiation. The larger peaks in 1989 and 1991-92 may be associated with the peak in the 11 year solar cycle at about the same time, which may modulate the 560 day S_1 effect on Lageos. If this explanation is confirmed, SLR data could provide an important capability for monitoring the response of the atmosphere to solar radiation. The annual variation is believed to be due to variations in J_3 caused by ocean mass redistribution. Undoubtedly, ocean mass redistribution is a significant source of non-tidal temporal gravitational variations. The development of realistic multi-layer eddy-resolving ocean models forced by real wind fields will be an important resource over the next few years for determining the role played by the atmosphere and oceans in the excitation of the Earth's gravitational and rotational variations.

SLR tracking of Lageos and Starlette extends back to the mid 1970s, thus the continued tracking of these spacecraft provides a baseline from which to measure sudden, possibly unexpected, changes in the Earth's mass distribution. The addition of SLR tracking of Ajisai (1985), Lageos-2 (1992), and Stella (1993) provides much improved spatial and temporal resolution over what could be obtained with Lageos and Starlette alone. Short of a dedicated mission to measure the gravity field, no other currently available technology can provide this capability, since these satellites are specifically designed to minimize the size of non-gravitational forces and maximize their modelability. Therefore, the continued tracking of these satellites using SLR will provide an important and unique contribution to NASA's Global Change Program, both as a constraint for global models of the atmosphere, oceans, and solid Earth, as well as a means of monitoring a fundamental variable of the total Earth system.

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Measured and Predicted Temporal Variations in the J_2 Gravitational Coefficient

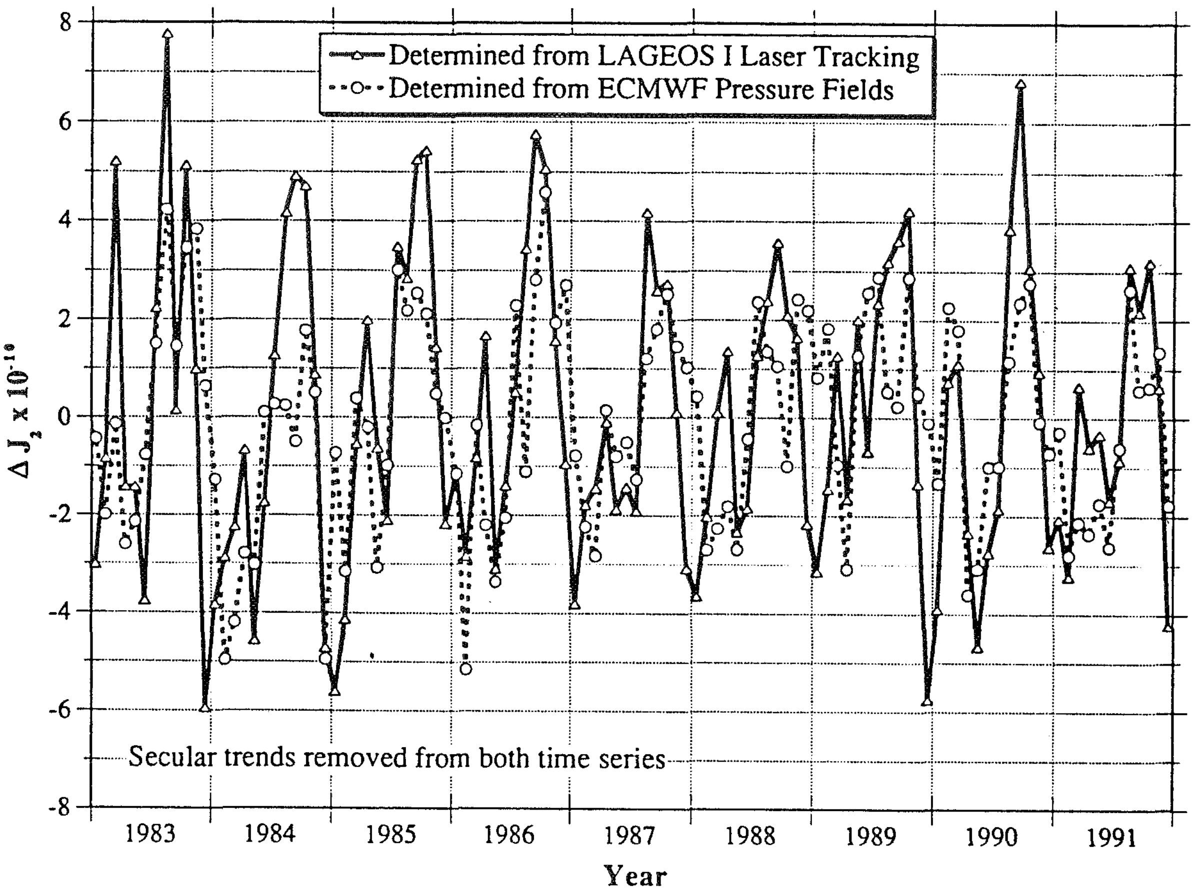

Figure 1. Time variations of the J_2 Earth gravitational coefficient, which describes the oblateness of the Earth, from 1983 to 1991. Two estimates of the variations in J_2 are shown; measured values using Lageos satellite laser ranging (SLR) data and predicted values from the European Center for Medium Range Weather Forecasts (ECMWF) atmospheric pressure fields. The J_2 estimates from Lageos are determined by analyzing the orbit perturbations seen in the SLR tracking data. The atmospheric predicted J_2 estimates, which described mass redistribution in the atmosphere, were computed from global gridded values of surface atmospheric pressure created by an atmosphere model ingesting real meteorological data. No inverted barometer correction was applied to the atmospheric-derived J_2 estimates.

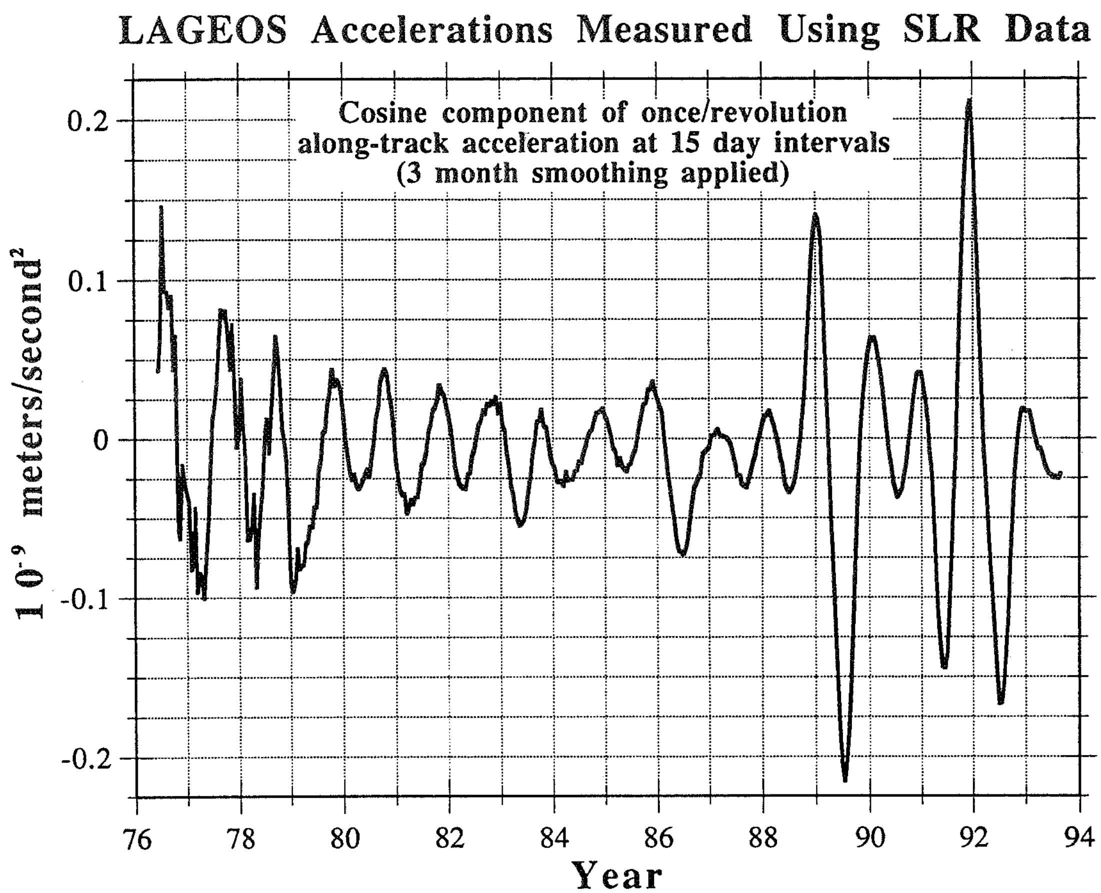

Figure 2. Cosine component of the estimated once/revolution along-track acceleration on Lageos determined using SLR tracking data from 1976 to 1993. The time series is dominated by annual and 560 day variations. The annual variation is probably caused by a real variation in J_3, possibly due to redistribution of ocean mass. The 560 day variation is caused by the S_1 atmospheric tide. The peaks in 1989 and 1991-92 may be caused by an amplification of the 560 day variation during the peak of the 11 year solar cycle.

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D. GLOBAL AND REGIONAL KINEMATICS FROM SLR STATIONS

P.J. Dunn

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The launch of Lageos-1 in May 1976 was the event which first enabled the stations of the Global Laser Tracking Network to significantly contribute to the measurement of plate kinematics. Until then, positioning accuracy was limited by errors in the orbits of the low-Earth satellite targets which were available at the time. The expanding network of progressively improving instruments clearly demonstrated the systems' centimeter positioning accuracy in the MERIT campaign of 1983. Since that time, several different SLR analysis groups have adopted a variety of techniques to distill geodynamic information from the Lageos observations using orbital arc lengths from an hour to a decade. SLR observations now provide the scale for the International Terrestrial Reference System and help to define the Earth's polar motion in this system.

The SLR-defined global and regional kinematic velocity models have made some unique contributions to geophysics. In their review of Global Tectonics and Space Geodesy, Gordon and Stein [1992] noted that the relative velocities of SLR stations on the stable interiors of tectonic plates are about five percent slower than those expected from long-term plate motion models (Figure 1). This observation supports the recent revision of the Potassium/Argon-defined paleomagnetic time scale based on astro-geochronology [Hilgen, 1991). The adoption of the revised scale will now allow the direct inclusion of contemporary measurements in the geophysical models. The successful deployment of transportable systems with the WEGENER campaign in the Mediterranean has confirmed the expected extension in the Aegean (Figure 2), and the SLR geodynamic observations can now be combined with earthquake moment tensors for regional seismic risk assessment [Jackson et al., 1994]. The direction of the motion of SLR observatories located behind island arcs in Simosato, Japan and at Arequipa, Peru (Figure 3) is aligned with that of the subducting plate; Robaudo and Harrison [1993] have concluded that strain expected to be relieved at the trench is carried over onto the over-riding plate, to be compensated by a mechanism for which a model has yet to be developed.

Agreement between positions separately determined with SLR, VLBI and GPS systems has been established at the level of a few centimeters in position and a few mm per year in horizontal velocity [Ma et al., this meeting], as long as a seven parameter transformation is applied to align and scale the reference systems until a simultaneous reduction of the measurement types can be accomplished. Velocity fields defined by SLR and VLBI systems have been successfully combined by Robbins et al. [1993] to extend global coverage, as well as to strengthen the calibration of the paleomagnetic time scale and the regional model in Japan. The elaboration of velocity models using GPS networks in the vicinity of SLR and VLBI stations, which have a long history of observations, is underway in the Western US, the Mediterranean and Australia. An ideal reference system for Earth orientation and station positioning would combine the scale from the SLR network with the inertial frame definition of the VLBI stations and densification provided by GPS observations.

The positioning accuracy of the SLR systems has progressively improved as the instruments were upgraded and the network expanded. This progress will continue with the deployment of advanced stations (MLRO, TIGO, SALRO, SLR-2000) and positioning capability can be further enhanced by measurements to new, stable satellite targets with improved gravity models such as JGM-3, and more refined non-conservative perturbation models based on Lageos-2 and ETALON observations. The contribution of Lageos-2 will be particularly helpful in the definition of the vertical component of station position, by reducing the influence of orbit force model errors on a station's height estimate, as the second satellite improves the tracking geometry.

The definition of horizontal position and velocity is more forgiving than that of the vertical component because tracking geometry is strong enough that the effects of orbital and instrumental errors on station latitude and longitude largely cancel over the time span of the orbital arc. A modern laser system can be calibrated to a ranging accuracy of a few millimeters [Degnan, 1993]. This unique scaling capability, which can be confirmed by collocation techniques, eliminates the influence of instrument error on the height measurement. System height eccentricity errors are more manageable in a properly calibrated SLR instrument than for a large VLBI antenna or a GPS receiver with an uncertain phase center, and atmospheric refraction errors are much lower for the optical measurements. Until recently, the largest error source in SLR station height determination has been the uncertainty in the orbit of Lageos-1; Lageos-2 observations provide firstly a calibration of the Lageos-1 results, and then an improvement through the two-satellite solution.

Recent studies of the effects of post-glacial rebound expected at SLR sites from the melting of continental ice sheets since the last Ice Age have shown little correlation with model predictions. The analysis described by Dunn et al. [1993] employed Lageos-1 observations from the GLTN starting in 1984, but upgrades in the systems have improved their ranging accuracy since that time. The installation of short pulse lasers, advanced receivers and stable calibration targets now enables us to measure the vertical position of strategically located stations much better than before. The geophysical model by Peltier [1988] suggests subsidence of about 2 millimeters per year at Greenbelt in the zone of forebulge collapse, but predicts less than a millimeter per year motion at the present locations of the other SLR stations. James and Morgan [1990] have indicated that horizontal motions due to post-glacial rebound in North America and Fennoscandia can amount to 4 millimeters per year from plausible models. This movement is predicted in the Hudson Bay region where vertical movement can amount to over 10 millimeters per year, and both components are clearly within the resolution capability of a good SLR system occupying this region in an extended campaign.

The vertical resolution of a modern SLR station can be seen in the plots of height values determined in monthly arcs of Lageos-1 and -2 data (Figure 4). The agreement in monthly height values for independent solutions for the Yarragadee laser in western Australia using observations from each satellite leads to uncertainty estimates of less than ten millimeters. Formal errors for a simultaneous solution from both satellites' data are as low as one or two millimeters for strong cases. The total spread of heights determined in the two-satellite solution is about twenty millimeters, but the systematic nature of the height variation suggests that this spread is not a good three sigma error estimate. The vertical signal is smooth at the three millimeter level and we should assign this value to it's uncertainty and seek geophysical sources for the systematic variation. These would include errors in Earth and ocean loading models, which occur at known tidal frequencies, and atmospheric pressure loading, which is seasonal and is driven by the regional field. For suitably located sites, meteorological observations are available to model this loading, but a rough indication of its form and magnitude is given by the pattern of average values of pass-by pass pressure measurements which are collected at each site for atmospheric refraction correction to the ranging observations. A simple model based on these local approximations to the regional pressure field suggests that loading could contribute up to one half of the twenty millimeter spread in the height signature. Even if the seasonal variation is not adequately modelled, it will not contaminate any estimate of long-term tectonic uplift or subsidence if a well sampled series of measurements is collected over a long enough time span.

Millimeter level height accuracy using SLR observations can currently only be achieved over averaging intervals of several days. However, the response with which a geodynamic measurement can be reduced from the SLR tracking data is only limited by the speed of the analysis procedure. This is a matter of minutes, as the ranging observations require no further processing after a pass of data is taken by a modern SLR system. Whatever the averaging time for the geodynamic measurement, the results can be immediately distributed to the scientific community. Daily estimates of Yarragadee's height, which can be made as soon as the last pass has been taken, are seen to lie within a spread of about 45 mm during a fine weather period in January 1994 (Figure 5). The variation appears to be random, and probably represents a fair three-sigma measure of height precision, so daily monitoring of the vertical to 15 millimeter precision may be the current limit for a good SLR station, but this will improve when other stable targets become available.

Notwithstanding the rapid response time possible from the GLTN, the long-term stability of the SLR reference frame leads to arguably the strongest potential positioning application for the network. The rate of sea level rise caused by global warming is currently measured over decade time scales with tide gauges which provide observations relative to the Earth's surface. The scale inherent in laser ranging observations to stable high-altitude satellites enables us to determine accurate geocentric height at the observatories. The resulting unique capability to monitor secular vertical motion in an absolute system, as well as seasonal and annual variations, will contribute to improved models of post-glacial rebound and atmospheric pressure loading. This advancement in our knowledge of Earth processes will allow estimates of sea level variation to be improved by tide gauge observations in high latitude regions currently excluded due to contamination of the measurement by tectonic signals. The connection of the SLR station heights to the coasts can also be made by GPS networks in many regions. This technique would accurately monitor the solid Earth's contribution to sea level variations and allow the tide gauges to provide timely input to the policy-making process.

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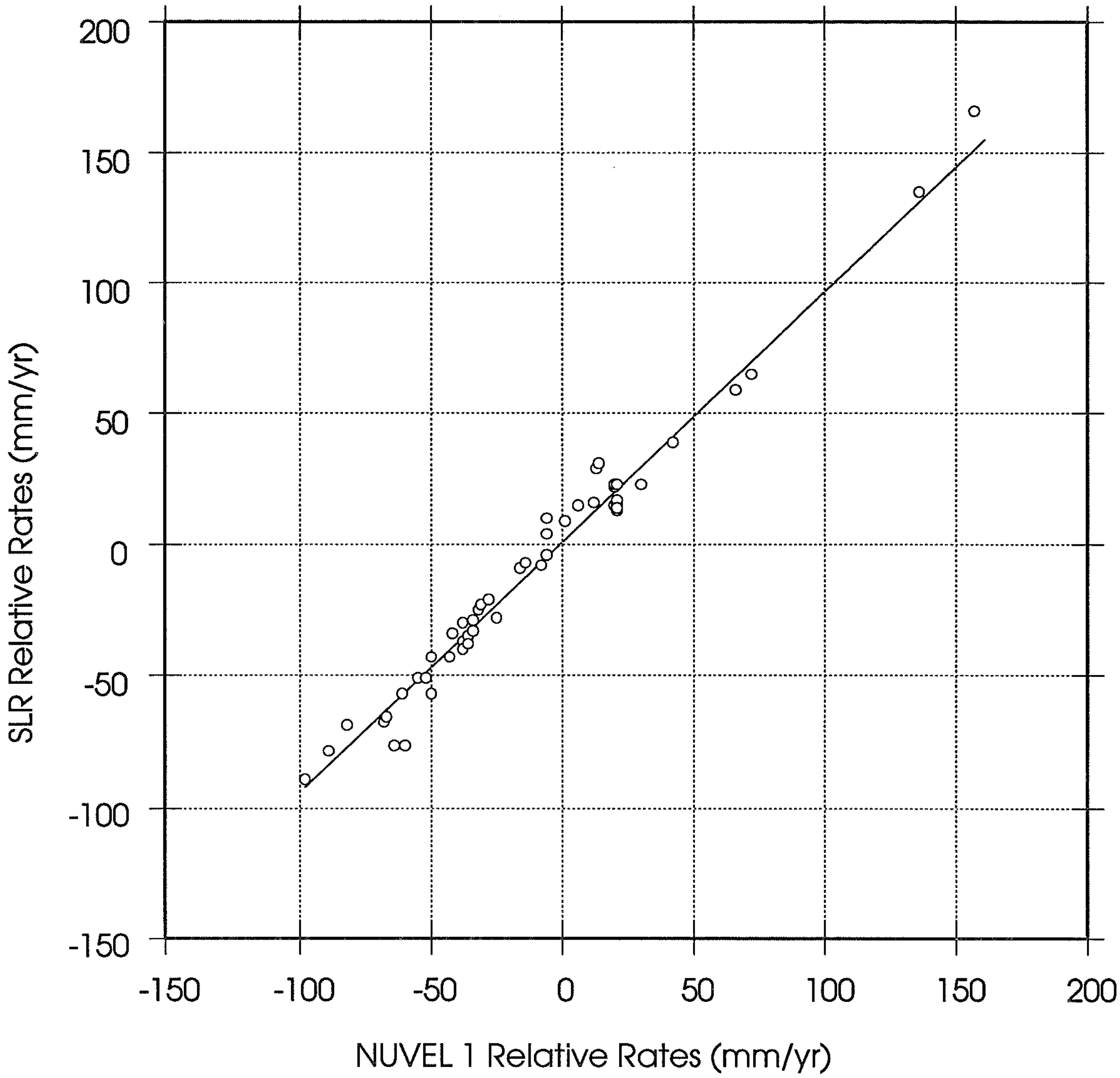

Fig. 1 Geodesic rates between SLR stations move more slowly than is predicted by NUVEL-1: the slope of the line is 0.95. The geophysical model assumed a paleomagnetic time scale which has recently been revised to reduce this discrepancy.

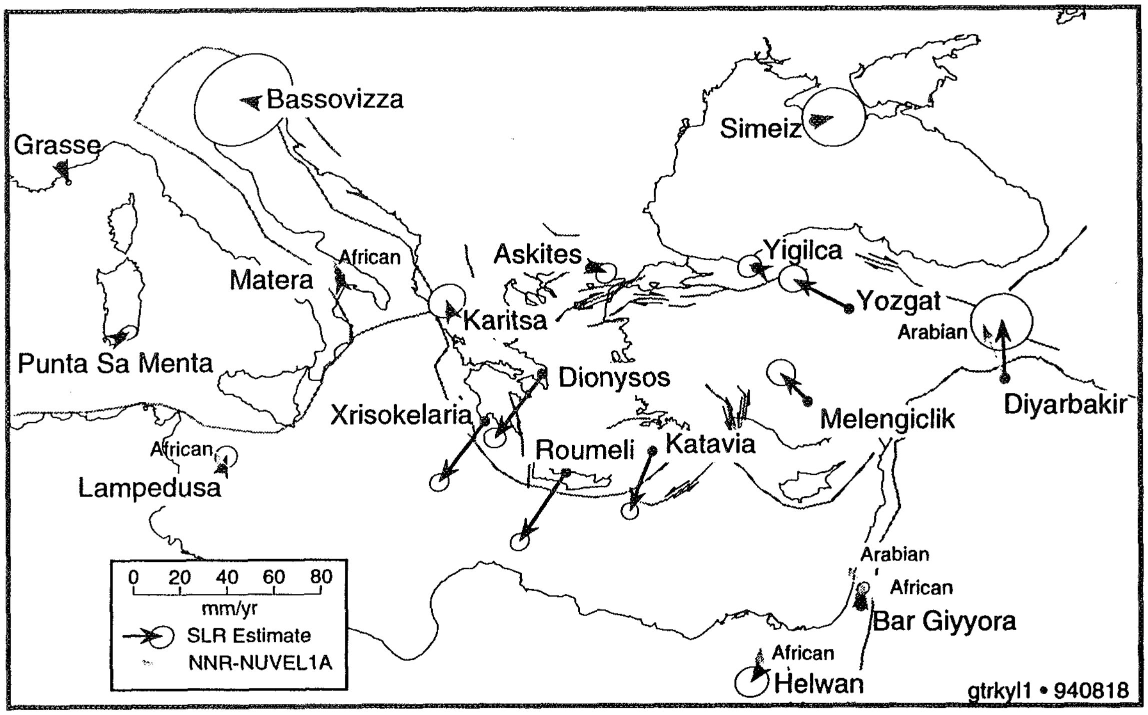

Fig. 2 Horizontal motion vectors in the Mediterranean relative to northern Europe support some of the extension in the Aegean expected from seismic data analysis. The deformation in NW Greece and SE Aegean cannot be accounted for by slip in earthquakes this century.

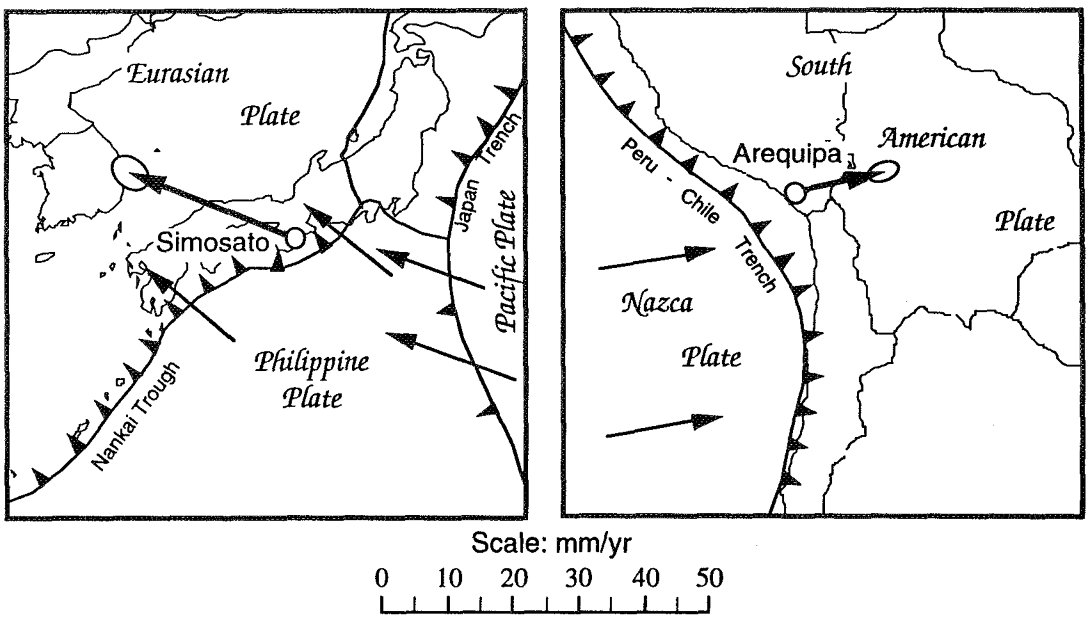

Fig. 3 Vector differences between SLR and NUVEL-1 show that Simosato and Arequipa both move at a rate carried over from the oceanic plate, and this provides a new measure of deformation occurring behind island arcs. Thinner arrows show the subduction relative to the overriding plate.

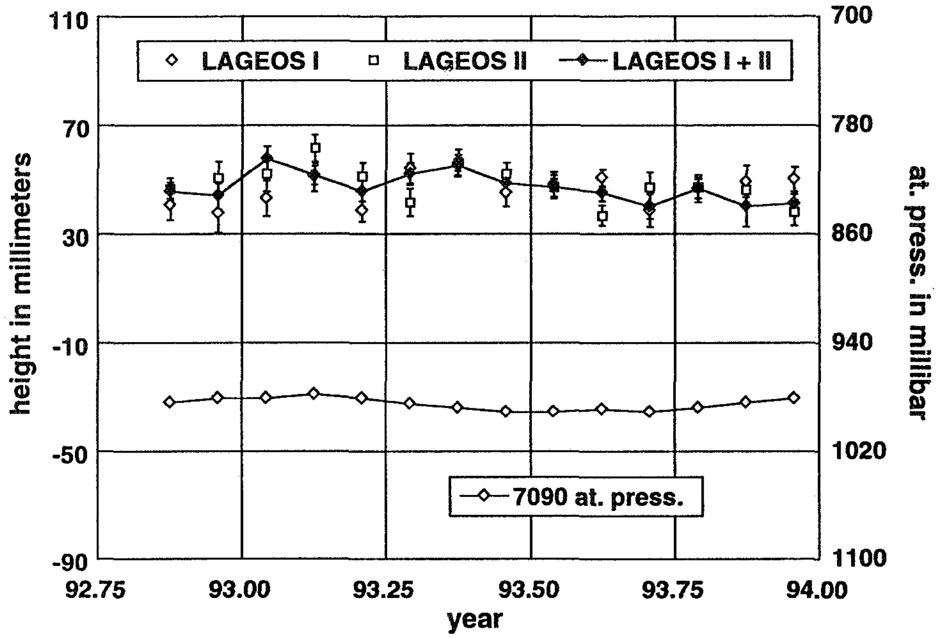

Fig. 4 LAGEOS II provides independence from force model error and helps to improve the accuracy of Yarragadee's height estimated from LAGEOS I data alone. The vertical signal from the two-satellite solution is smooth to a few millimeters and includes the effect of atmospheric pressure loading averaged over a month.

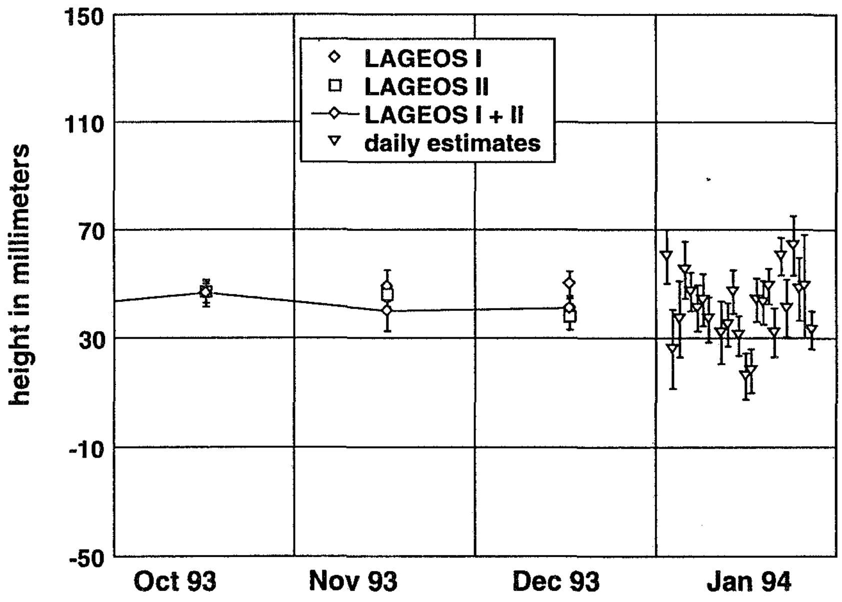

Fig. 5. The value of Yarragadee's height can be resolved within minutes of the end of the data span; daily estimates are currently good to about 15 mm., but a monthly average gives a formal error of just a few millimeters.

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E. GLOBAL AND REGIONAL KINEMATICS WITH GPS

R.W. King

INTRODUCTION

The inherent precision of the doubly differenced phase measurement and the low cost of instrumentation made GPS the space geodetic technique of choice for regional surveys as soon as the constellation reached acceptable geometry in the area of interest: 1985 in western North America, the early 1990s in most of the world. Instrument and site-related errors for horizontal positioning are usually less than 3 mm, so that the dominant source of error is uncertainty in the reference frame defined by the satellites orbits and the tracking stations used to determine them. Prior to about 1992, when the tracking network for most experiments was globally sparse, the number of fiducial sites or the level at which they could be tied to an SLR or VLBI reference frame usually set the accuracy limit [e.g., Feigl et al., 1993]. More recently, with a global network of over 30 stations, the limit is set more often by deficiencies in our models for non-gravitational forces acting on the satellites. For regional networks in the northern hemisphere, reference frame errors (or uncertainties) are currently about 3 parts per billion (ppb) in horizontal position, allowing centimeter-level accuracies over intercontinental distances (Figure 1) and less than 1 mm for a 100 km baseline (Figure 2).

The accuracy of GPS measurements for monitoring height variations is generally 2-3 times worse than for horizontal motions. As for VLBI, the primary source of error is unmodeled fluctuations in atmospheric water vapor, but both reference frame uncertainties and some instrumental errors are more serious for vertical than horizontal measurements. Under good conditions, daily repeatabilities at the level of 10 mm rms have been achieved (Figure 3), leading to the hope that with frequent or continuous measurements, long-term monitoring of geophysical changes in station heights can be accomplished at the millimeter level.

This paper will attempt to summarize the current accuracy of GPS measurements and their implication for the use of SLR to study regional kinematics. Readers not familiar with the fundamentals of GPS surveying, both field work and analysis, are referred to the recent reviews by Dixon [1991], King and Blewitt [1990], and Hager et al. [1991].

NON-ORBITAL ERRORS IN POSITIONING

There are four primary sources of GPS measurement error that are not related to the accuracy or stability of the reference frame: 1) operator setup error; 2) signal multipathing; 3) deficiencies in modeling the atmosphere; and 4) error or uncertainty in relating the effective phase center of the antenna to the ground mark. For horizontal measurements, each of these sources usually contributes between about 0.5 and 2 mm, so that the aggregate effect varies between 1 mm and 5 mm, with 2-3 mm typical. For vertical measurements, atmospheric effects dominate, at 10-50 mm, except on very short (<2 km) baselines.

Operator setup errors can be limited to about 1 mm in both horizontal and vertical with sufficient care by the field operator. Miscalibrated tribrachs, poor lighting, high wind, and poorly defined center points on the ground monuments can degrade the quality of the setup, but it would be unusual for the total error to exceed 2 mm. For permanent sites with antennas mechanically fixed to a ground mark, there is no significant setup error contributing to measurements of the *change* in position.

Multipath errors are strongly dependent on the environment of the site and the type of antenna used. They are also among the most difficult to assess since they tend to repeat from day to day and alias with atmospheric effects for low elevations. Often the most obvious multipath signature - high amplitude and frequency in the phase residuals - has minimal effect on position estimates, but the invisible low-frequency component may be introducing significant error. I know of no systematic study that quantitatively and reliably relates identifiable multipath to errors in horizontal or vertical position. Crude numerical experiments carried out at MIT, in which spans of high multipath are deleted from the analysis and the elevation cutoff varied, suggest that even several centimeters of high-frequency multipath usually affects horizontal position estimates at the level of only 1-3 mm. Since multipath is frequency dependent (dispersive), its effect is amplified when the ionosphere-free linear combination (LC or L_3) of the two GPS signals (L_1 and L_2) is formed; thus, it will introduce less error into the measurement of very short (<5 km) baselines for which the L_1 (and/or L_2) signal can be used directly.

Atmospheric errors are most serious in estimates of vertical position but can affect estimates of the horizontal if there are azimuthal asymmetries in either the atmospheric delay or the geometry of the satellite constellation. As for VLBI, both water-vapor radiometer measurements and stochastic estimation techniques have proven successful in improving estimates of vertical position [Tralli and Lichten, 1990], but the low elevation (<15 degrees) observations used with fixed VLBI antennas to separate atmospheric and height parameters are not as effective since GPS antennas are omnidirectional and thus subject to significant signal multipathing. To the advantage of GPS, however, are the larger number of "sources" to be observed and the low cost of frequent measurements. Since atmospheric errors for many (though not all) sites are nearly random, the accuracy can be improved by averaging over a large number of observations. This strategy is most easily followed with permanent tracking sites, which can observe continuously for months or years [Bock and Shimada, 1990].

The phase centers of all commonly used GPS antennas have elevation-dependent variations of 10 mm in the LC observable, and some are as large as 50 mm. These variations cancel when matched antennas are used over regional baselines, for which the elevation angle of the satellites from both sites is nearly the same. Alternatively, they can be modeled using anechoic chamber measurements of the antennas [Schupler et al., 1992]. The most serious problem occurs when antennas of different types are used in a survey [Braun et al., 1993; Mireault et al., 1993]. For the commonly used combination of Rogue (Dorne-Margolin with JPL choke ring) and Trimble antennas, horizontal errors of about 2 mm and vertical errors of about 4 mm remain even after modeling the variations [S. McClusky, personal communication, 1994]. Modeling also becomes more important for long baselines since the elevation angle of the satellites will be different for each station. For example, introducing a phase-center model to our analysis of 23 global sites with matched Rogue antennas from the 1991 "GIG" experiment changed estimated heights by 20-30 mm.

STABILITY OF THE GLOBAL REFERENCE FRAME FOR REGIONAL SURVEYS

With the current (43-station) tracking network of the International GPS Geodynamics Service (IGS) there may still be non-negligible reference-frame (baseline-length dependent) errors for regional surveys. The dense northern hemisphere network provides reference-frame control at the level of 1-4 ppb for horizontal, and 2-8 ppb for vertical positions [Blewitt et al., 1992; Heflin et al., 1992]. For the southern hemisphere, however, the density of tracking stations may not be sufficient to reach this level of stability. Analysis of the 1991 GIG experiment, which included 5 southern hemisphere stations, resulted in repeatabilities of 5-10 ppb for baselines between northern and southern hemisphere stations, and 15 ppb for southern hemisphere baselines [Heflin et al., 1992]. The current IGS network includes nine southern hemisphere sites (soon to expand by another five), and there is clear evidence that the stability of the reference frame has shown marked improvement [Heflin et al., 1993].

Although the GPS orbits are dynamically tied to the Earth's center of mass, their high altitude and perturbations by non-gravitational forces result in a significantly weaker tie than for lower laser geodetic satellites such as Lageos. While SLR currently provides a determination of the center of mass at the level of about one centimeter for monthly averages, the GPS estimate is no better than a decimeter [M.G. Heflin and T.A. Herring, personal communications, 1994]. By constraining the motion of the center of mass, however, a few ppb stability can be achieved without applying any further constraint in position or velocity from SLR or VLBI measurements.

SUMMARY AND IMPLICATIONS FOR SLR RESOURCES

For densification of regional networks less than 1000 km in extent, there is little question that GPS measurements equal or exceed the horizontal accuracy available from mobile VLBI or SLR and at a fraction of the cost. For large-scale regional and global kinematics, GPS seems poised also to supplant the older techniques, due principally to the relative economy of fixed, continuously tracking stations. There are some regions of the world for which the longer span of SLR plate motion measurements may warrant their continuation at one or two sites for a few more years [see, e.g., Oral, 1994]. These measurements are most valuable if they provide velocity constraints for the region at the level of a few mm/year.

The jury is still out on the ultimate accuracy and role of GPS in monitoring height variations. Like SLR and (at least mobile) VLBI, GPS seems stuck at the 10 mm level, which may not be sufficient for studying vertical tectonic motions and changes in global sea level. Among the most important experiments that can be carried out over the next few years are rigorous intercomparison of vertical measurements using the three techniques together with efforts to improve the accuracy of each.

ACKNOWLEDGEMENTS

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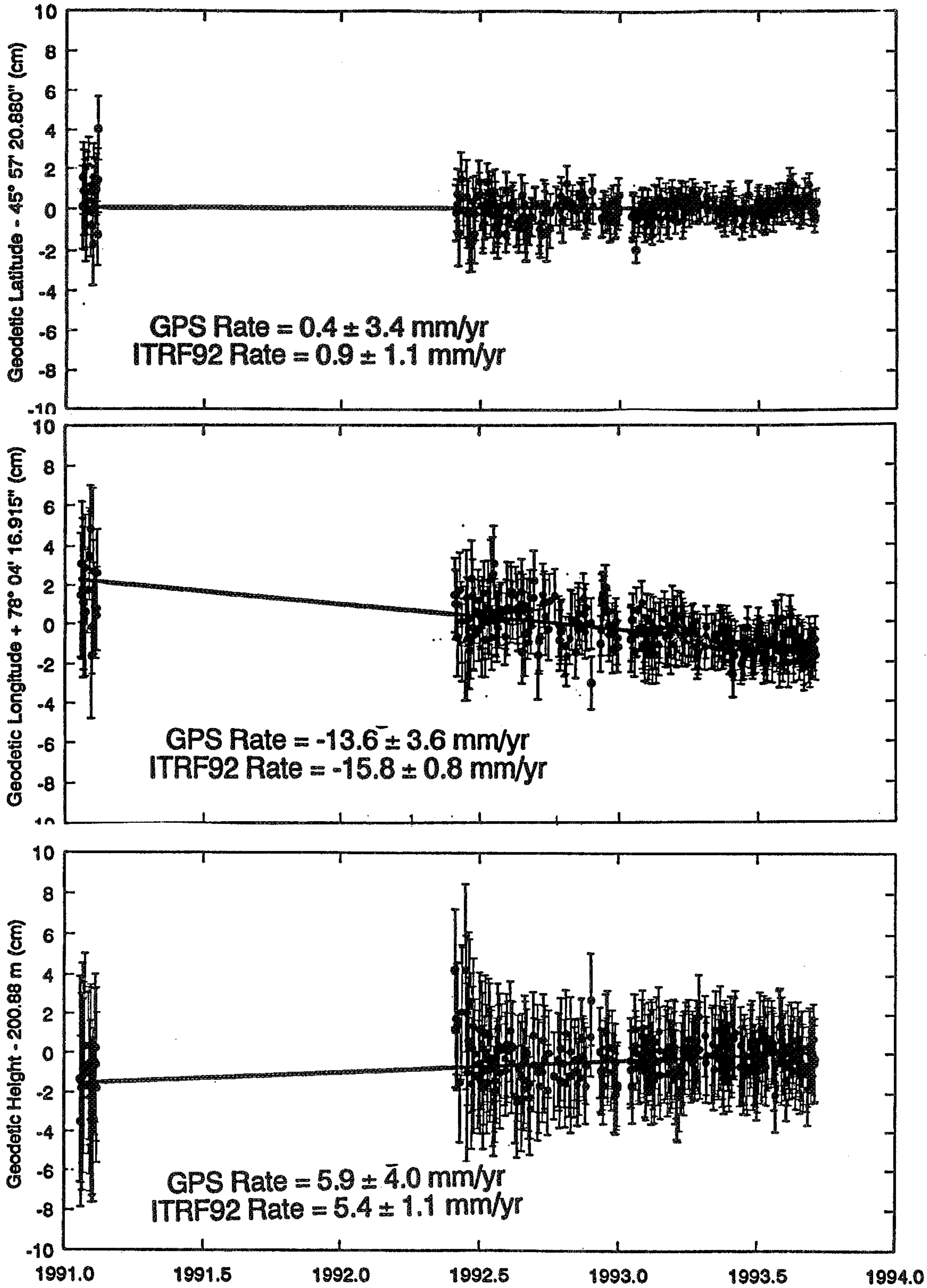

Figure 1. Time evolution of the north, east, and height of Algonquin from GPS estimates in GIG '91 and 1992–93 [*Heflin et al.*, 1993]. The reference frame is defined solely by the global network of GPS tracking stations.

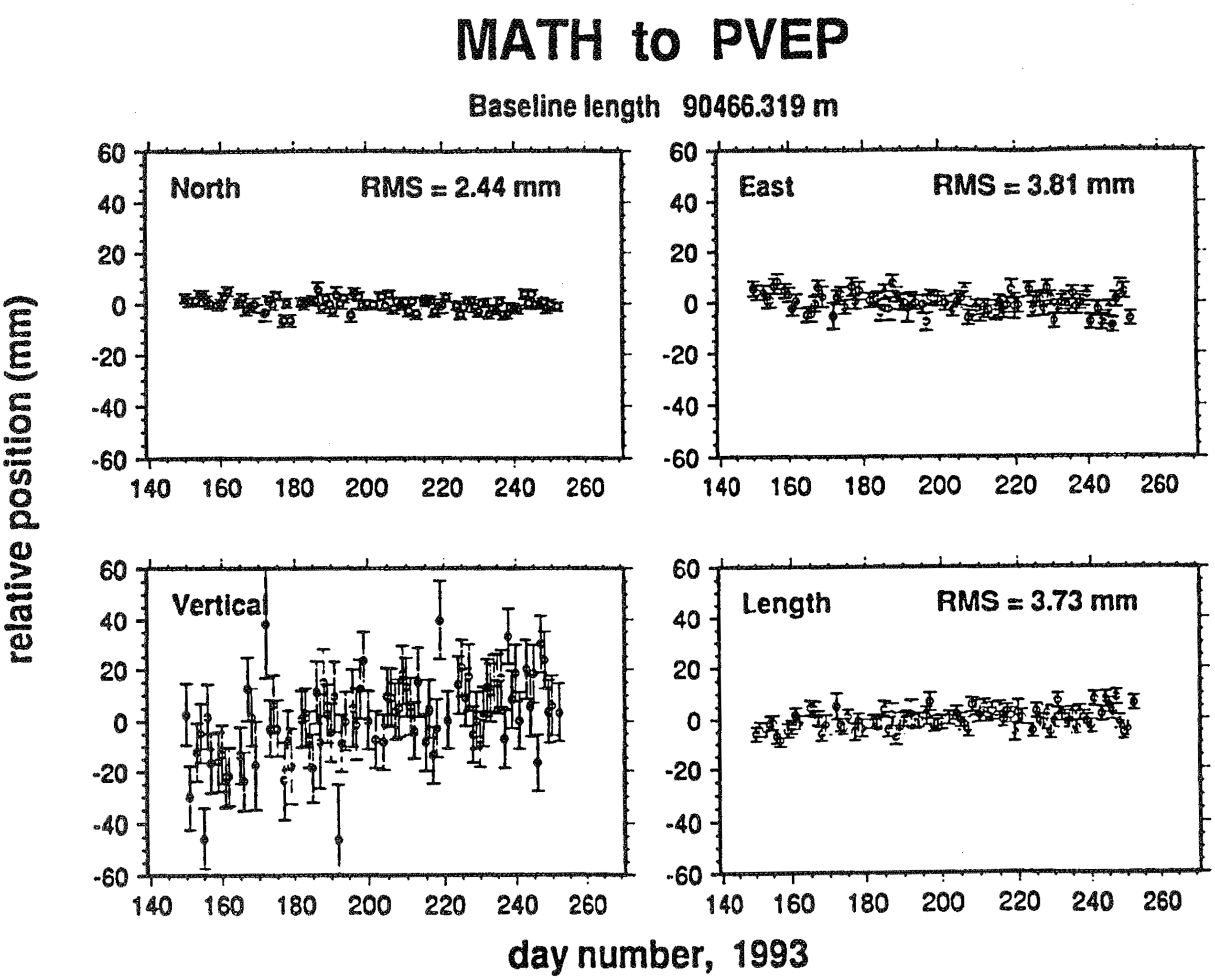

Figure 2. Daily baseline estimates for the relative position of PGGA sites at Lake Mathews (MATH) and Palos Verdes (PVER), June–September, 1993. A comparison of solutions using simultaneously estimated and extrapolated orbits indicates no significant contribution of orbital error for this 90-km baseline [*Bock*, 1993].

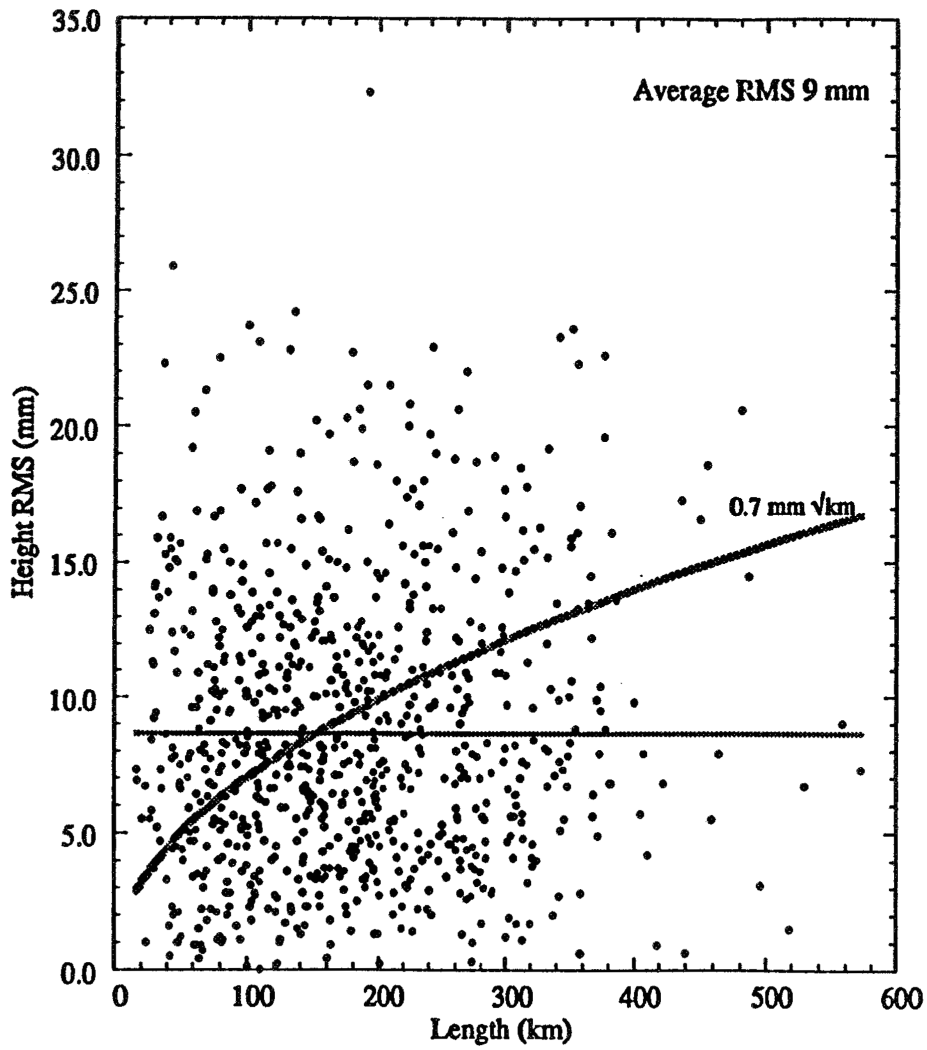

Figure 3. Vertical repeatabilities over 3 days for baselines in a 87-station network in Kazakhstan surveyed in July, 1993. The horizontal gray line gives the average value of the rms, and the lighter, curved line shows the expected error of first-order leveling. There is a large amount of (expected) scatter in the rms values since each is based on only 3 determinations. [T. A. Herring, personal communication, 1993].

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F. GLOBAL AND REGIONAL KINEMATICS WITH VLBI

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C. Ma

The measurement of global and regional kinematics using VLBI begins with the definition of an observing program but does not end with the selection of the most appropriate analysis. Since a VLBI station cannot operate in isolation and since simultaneous operation of the entire VLBI network is impractical, it is necessary to design observing programs with periodic observing sessions using networks of 3-7 stations that, when treated together, will have the necessary interstation data and network overlaps to determine the desired rates of change. Thus there has been a mix of global, intercontinental, transcontinental, and regional networks to make measurements ranging from plate motions to deformation over a few hundred km. Over time, even the networks focusing on regional deformation using mobile VLBI included large stations removed by several thousand km to increase sensitivity, determine EOP more accurately, and provide better ties to the terrestrial reference frame (TRF). Analysis products have also evolved, beginning with baseline lengths, then broadening to the transverse and vertical baseline components, and then to full three-dimensional site velocities in a global TRF.

The type of analysis that simultaneously estimates site positions and velocities along with EOP values, thereby defining a TRF, has a number of variations. The Goddard Mark III Data Analysis System allows all the stations to move uniformly or any subset to move in a piecewise-linear, continuous fashion, to have a break such as caused by coseismic motion ("episodic motion"), to have step-wise positions (effectively averaging over some time interval), or to be unconstrained between sessions. The uniform velocity mode gives the most precise long-term answer while the other methods allow finer temporal resolution. The conceptual basis of this type of analysis is that there are enough sites moving in a simple manner to permit the definition of a TRF.

Another approach is to estimate the site positions and baseline components independently for each day and study the evolution of individual baselines and sites by plotting the time series. This approach provides the greatest detail in examining the data, and the baseline lengths are independent of the TRF. The scatter of baseline lengths about their best fit lines as a function of baseline length is 5 mm+2 ppb for all baselines and 1.2 mm+0.5 ppb for the best observing program. The transverse and vertical baseline components and site positions, whether Cartesian or topocentric, are strongly dependent on accurate EOP values, which in practice are derived from VLBI TRF solutions. The typical 1-sigma formal errors in EOP from the weekly NEOS-A network are 0.1 mas in pole component and 0.004 ms in UT1, while the best Space Geodesy Program errors are 0.05 mas in pole and 0.002 ms in UT1. Since VLBI fundamentally measures baseline vectors, some arbitrary definition is required to map the interstation vectors to site positions. The Mark III Data Analysis System has two options: to fix the position of one station in the network (used in the Goddard VLBI annual reports) or to minimize the sites' position residuals each day from a specified TRF (which gives minimal position scatter).

Figure 1 shows the horizontal site velocities around the Atlantic in the No-Net-Rotation (NNR) NUVEL-1 TRF. The 3-sigma error ellipses are drawn at the head of the measured vector, and the NNR NUVEL-1 vectors are also shown. Several points should be noted. Some of the error ellipses cannot be seen, being less than 1 mm/yr for some stations. Second, the stations at Fortaleza, Brazil and O'Higgins, Antarctica, have less than a year of data. Their errors are large but the values are interesting. Third, there are significant deviations from NNR NUVEL-1 such as Hartebeesthoek, South Africa; the Italian stations at Noto, Matera and Medicina; and Santiago, Chile.

Figure 2 shows the topocentric coordinates of Gilmore Creek, Alaska in two-month windows. The vertical wrms scatter is 10 mm and there is a roughly annual variation. The wrms scatter of the horizontal values is 3 mm. Gilmore Creek is now the most often used station with a session every 2.7 days on average in 1993. However, even the horizontal WRMS scatter at Santiago, with about 5 sessions in each 2-month window, is not worse than 9 mm.

Figure 3 shows the evolution of the Gilmore Creek to Yellowknife, Northwest Territories baseline components. The dashed line shows the expected rates for a rigid North American plate. There appears to be a significant upward motion of Yellowknife with respect to the other end, which is also seen in other Yellowknife baselines. The inferred site vertical rate at Yellowknife is in excess of 15 mm/yr with a 3-sigma error of 10 mm/yr.

VLBI measurements of global and regional kinematics have made major contributions to geophysics, demonstrating and quantifying the reality of present day plate motions and the complex regional deformations in Alaska, California, and the Mediterranean. While regional measurements with mobile VLBI are now history, there is an active program to extend accurate measurements to Australia, South America, and interior Eurasia using existing and recently constructed or equipped stations.

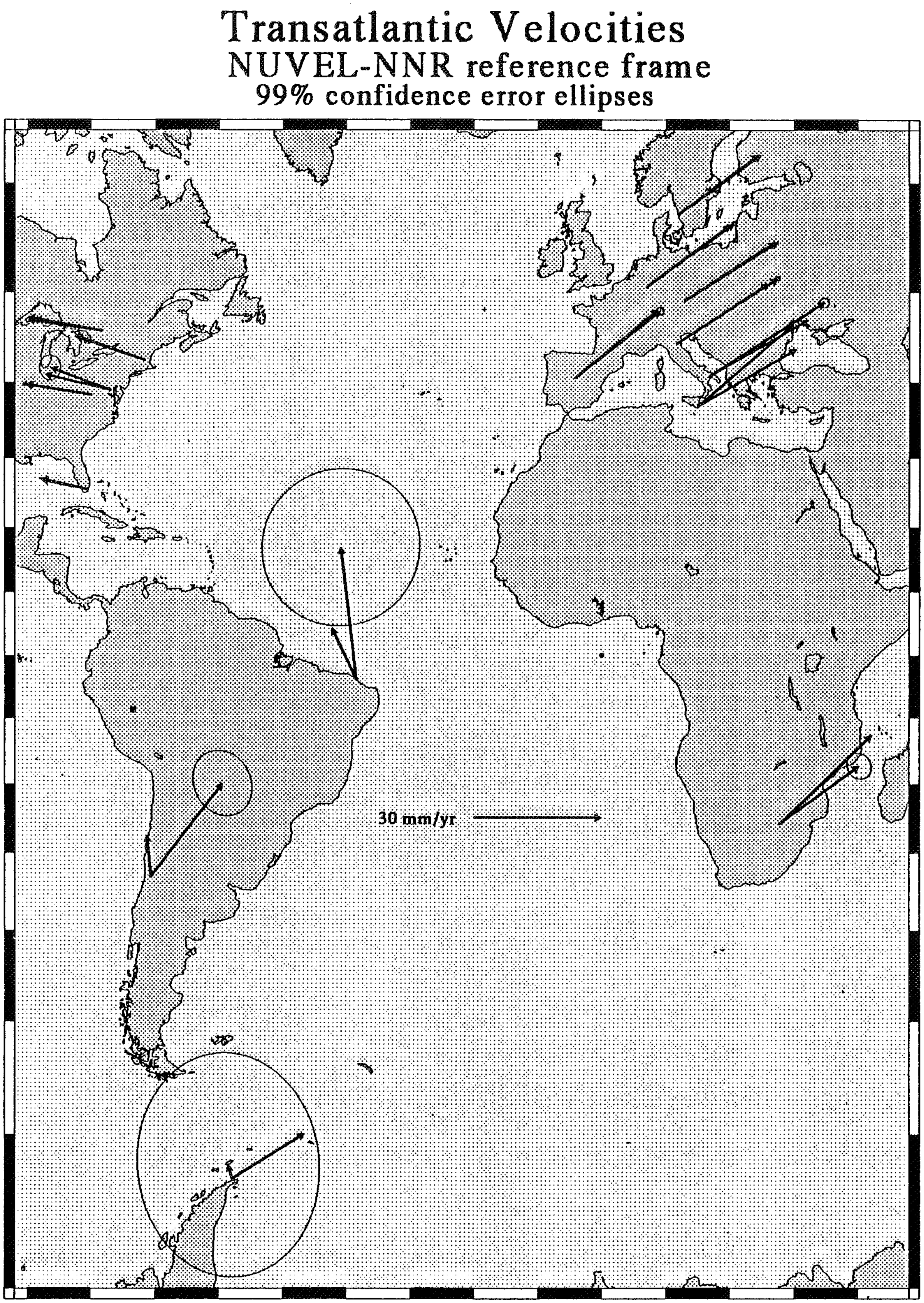
Transatlantic Velocities
NUVEL-NNR reference frame
99% confidence error ellipses
30 mm/yr

Figure 1.

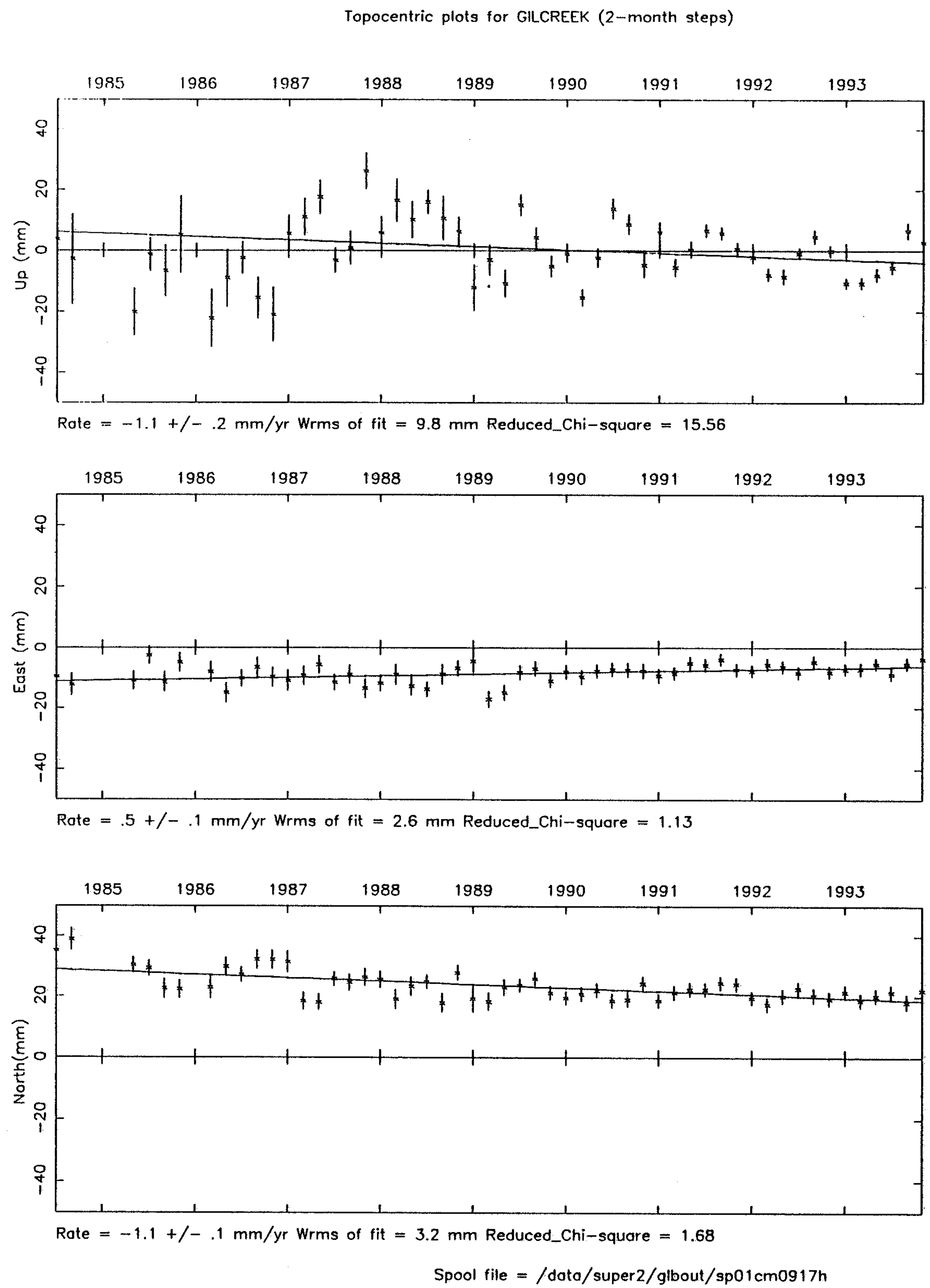
Topocentric plots for GILCREEK (2-month steps)
1985 1986 1987 1988 1989 1990 1991 1992 1993
Up (mm)
40 20 0 -20 -40
Rate = -1.1 +/- .2 mm/yr Wrms of fit = 9.8 mm Reduced_Chi-square = 15.56
1985 1986 1987 1988 1989 1990 1991 1992 1993
East (mm)
40 20 0 -20 -40
Rate = .5 +/- .1 mm/yr Wrms of fit = 2.6 mm Reduced_Chi-square = 1.13
1985 1986 1987 1988 1989 1990 1991 1992 1993
North(mm)
40 20 0 -20 -40
Rate = -1.1 +/- .1 mm/yr Wrms of fit = 3.2 mm Reduced_Chi-square = 1.68
Spool file = /data/super2/glbout/sp01cm0917h

Figure 2.

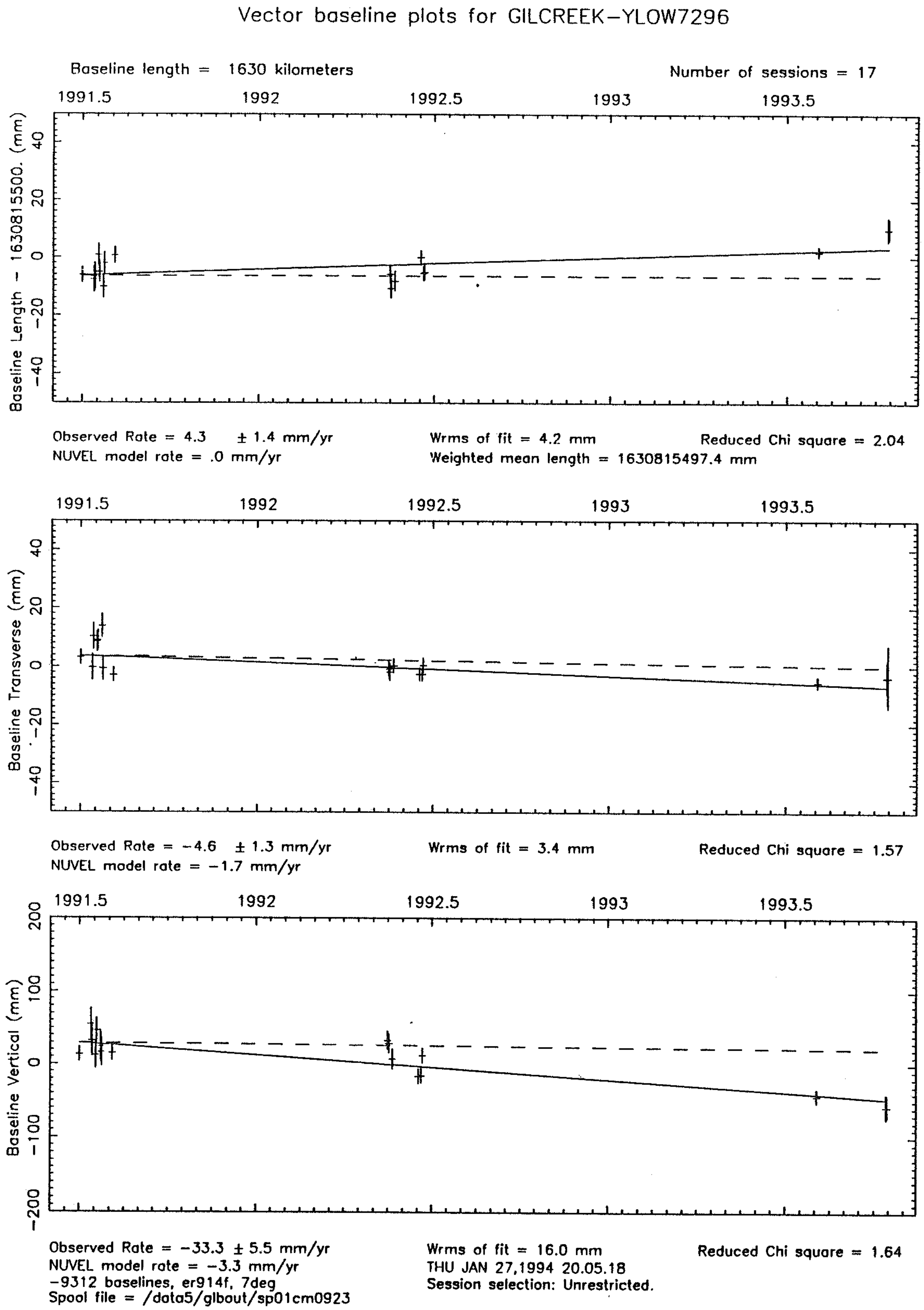
Vector baseline plots for GILCREEK–YLOW7296
Baseline length = 1630 kilometers
Number of sessions = 17
1991.5
1992
1992.5
1993
1993.5
Baseline Length – 1630815500. (mm)
40
20
0
–20
–40
Observed Rate = 4.3 ± 1.4 mm/yr
NUVEL model rate = .0 mm/yr
Wrms of fit = 4.2 mm
Weighted mean length = 1630815497.4 mm
Reduced Chi square = 2.04
Baseline Transverse (mm)
Observed Rate = –4.6 ± 1.3 mm/yr
NUVEL model rate = –1.7 mm/yr
Wrms of fit = 3.4 mm
Reduced Chi square = 1.57
Baseline Vertical (mm)
200
100
0
–100
–200
Observed Rate = –33.3 ± 5.5 mm/yr
NUVEL model rate = –3.3 mm/yr
–9312 baselines, er914f, 7deg
Spool file = /data5/glbout/sp01cm0923
Wrms of fit = 16.0 mm
THU JAN 27,1994 20.05.18
Session selection: Unrestricted.
Reduced Chi square = 1.64

Figure 3.

N95-14281

G. EARTH ORIENTATION PARAMETERS

107867 4p
350016

R.J. Eanes

Since the beginning of regular space geodetic measurements of EOP marked by the beginning of the MERIT short campaign in 1980, SLR has routinely provided polar motion and length of day (or high frequency UT1) solutions to the IERS. In the following decade SLR and VLBI (with contributions to UT1 from LLR) became the only techniques used by the IERS in providing the international standard series of EOP. As the decade of the 1990s began the development of GPS as a tool for studying EOP variation accelerated and by the time of the GIG campaign in 1991 the technique produced polar motion results competitive with SLR and VLBI. See Eubanks [1993] for an excellent review of the scientific importance of monitoring EOP variations as well as a description of each of the techniques discussed here. At the current time, GPS regularly produces daily polar motion solutions with 0.4 mas accuracy, equivalent to that of the routine 1-day VLBI experiments and SLR solutions using 3 days of Lageos-1 data (IERS Bulletin B, March 1994). These high quality GPS solutions should continue indefinitely under the auspices of the International GPS Service (IGS). The rapid progress of the GPS technique forces a review of any resource allocations for VLBI and SLR measurements of EOP.

The VLBI EOP results are unique because of the technique's inherent ability to access the Celestial Reference Frame (CRF), realized by the positions of distant quasars, with respect to the Terrestrial Reference Frame (TRF) defined by the positions of the radio telescopes. This allows VLBI to determine all of the parameters describing the orientation of the CRF and TRF, namely precession, nutation, polar motion and universal time (UT1). Conversely, the satellite based techniques (GPS and SLR) can access the CRF only to the accuracy of the dynamical models that predict the satellite's motion in the CRF. Errors in the dynamical models for GPS satellites and for Lageos prevent getting meaningful estimates of precession and nutation and degrade the long term stability of the UT1 estimates. The model's ability to predict the motion of the longitude of the ascending node of the satellite's orbit determines how rapidly the UT1 product will degrade. For Lageos-1 SLR the error in UT1 grows at an RMS rate of 0.02 millisecond per day. The error growth in GPS UT1 results is not clear at the present time, but is thought to be more rapid than that of Lageos-1 due to the much larger errors in the models of the non-gravitational accelerations on the GPS spacecraft.

As long as regular VLBI observations are continued with experiments scheduled every few days, and especially if the short duration daily IRIS intensive series is continued, then adequate resolution of high frequency UT1 variations (few day periods) can be maintained. If, on the other hand, VLBI is cut back to a weekly or longer rhythm then either GPS or SLR must fill in the missing high frequency measurements. If the GPS derived UT1 product's drift is larger than that of Lageos-1 SLR then Lageos-1 SLR must be maintained to retain adequate UT1 accuracy at all frequencies. The drift rate quoted above for SLR is from the single satellite results from Lageos-1. Switching to a dual satellite SLR EOP analysis using Lageos-1 and Lageos-2 will reduce the UT1 drift rate somewhat. If a Lageos-3 target in supplementary orbit to either Lageos-1 or Lageos-2 is added the SLR UT1 drift rate will be reduced substantially.

A relatively recent thrust of research in EOP analysis is toward determining the high frequency fluctuations in the EOP and in the geocenter caused by diurnal and semidiurnal tides. The SLR, VLBI and GPS techniques are all sensitive to these small, but significant fluctuations. The results obtained to date are being compared between techniques and to predictions from existing tidal models [Lichten et al., 1992, Sovers et al., 1993, Herring and Dong 1994, Watkins and Eanes 1994]. Currently, the space geodesy results agree better with each other than they do to the tide models indicating that the observations can provide useful constraints that can be used to test for improvements in the tide models.

In summary, if regular daily IRIS intensive observations continue, then the combination of VLBI and GPS will be adequate to provide EOP with sufficient accuracy for all uses. If VLBI cutbacks eliminate the daily measurements then Lageos SLR may be required to adequately interpolate UT1 between weekly VLBI sessions. All three techniques should be continued for a few more years in order to provide independent measurements of rapid changes in EOP including diurnal and semi-diurnal tidal fluctuations.

References:

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Lichten, S.M., S.L. Marcus, and J.O. Dickey, *Sub-daily resolution of Earth rotation variations with Global Positioning System measurements,* Geophys.Res.Lett.,19,537, 1992.

Sovers, O.J., C.S. Jacobs, and R.S. Gross, *Measuring rapid ocean tidal Earth orientation variations with VLBI*, J.Geophys.Res., 1993.

Watkins, M.M., and R.J. Eanes, *Diurnal and semidiurnal variations in Earth orientation determined from Lageos laser ranging*, J.Geophys.Res., In press, 1994.

H. PRECISION ORBIT DETERMINATION OF ALTIMETRIC SATELLITES

C.K. Shum, J.C. Ries, and B.D. Tapley

The ability to determine accurate global sea level variations is an important contributor to both the detection and understanding of changes in the climate patterns. Sea level variability occurs over a wide spectrum of both temporal and spatial scales, and precise global measurements are only recently possible with the advent of spaceborne satellite radar altimetry missions. One of the inherent requirements for the accurate determination of absolute sea surface topography is that the altimetric satellite orbits be computed with sub-decimeter accuracy within an accurately defined terrestrial reference frame. The significance of SLR tracking in support of precision orbit determination (POD) of altimetric satellites has been well established. Recent examples are the use of SLR as the primary tracking systems for TOPEX/Poseidon and for ERS-1 precision orbit determination. The current radial orbit accuracy for TOPEX/Poseidon is estimated to be around 3-4 cm, with geographically correlated orbit errors around 2 cm [Tapley et al., 1994]. The significance of the SLR tracking system is its ability to allow altimetric satellites to obtain absolute sea level measurements and thereby provide a link to other altimetry measurement systems for long-term sea level studies. SLR tracking allows the production of precise orbits which are well centered in an accurate terrestrial reference frame. With proper calibration of the radar altimeter instrument, these precise orbits, along with the altimetric measurements, provide long-term absolute sea level measurements. As an example, the U.S. Navy's Geosat mission is equipped with only Doppler beacons and without laser retroreflectors. The orbits computed using a decimated Tranet and Opnet tracking network have a reported radial accuracy of 20-40 cm [Shum et al., 1990; Haines et al., 1993]. However, these orbits, and even the Geosat orbits computed using the available full 40-station Tranet tracking network, yield orbits with significant north-south shifts with respect to the IERS terrestrial reference frame. The resulting Geosat sea surface topography will be tilted accordingly, making interpretation of long-term sea level variability studies difficult. Figure 1 shows two cases of altimeter residuals, or inverse sea levels, displayed geographically for Geosat orbits computed with and without the additional use of direct altimeter data (top and bottom pictures, respectively) in orbit determination. A significant north-south tilt (+/-50 cm) of the sea surface is observed for the orbit computed without using the direct altimeter to constrain the z-component of the orbit [Kozel, 1992]. However, the use of direct altimeter data for orbit determination has the potential to alias oceanographic features into the orbit and should be avoided, if possible. Without the benefit of global laser tracking, the use of Geosat measurements for the study of long-term or broad-scale sea level variations should be done with caution.

SLR is the most accurate absolute-ranging instrument among existing tracking systems. Because of this, SLR has demonstrated the capability to provide additional support in the verification of possible ambiguities in other tracking systems, such as DORIS and the GPS receiver on TOPEX/Poseidon. Examples include the verification of the time bias offset in the DORIS tracking system, the center-of-mass correction offset in the GPS tracking system, and other ambiguities such as the geocentric positioning offset along the Earth's spin axis which have been obtained by some radiometric tracking systems. Figure 2 shows the time history of DORIS measurement time tag bias compared to SLR for Cycles 1-9 of TOPEX/Poseidon. The large offsets seen in the original analysis were corrected and considerably reduced in a subsequent re-release of the DORIS data. Thus, SLR provides an independent verification tool for calibration of a radiometric tracking system.

Figure 3 shows a comparison between TOPEX/Poseidon Cycle 10 orbits computed using SLR tracking data and using GPS tracking data by JPL. A significant radial offset on the order of 6 cm was observed initially during the verification time period of the TOPEX/Poseidon GPS Demo experiment. This offset appears to have been caused by an error in the correction of the GPS receiver phase center to the center of mass of the TOPEX/Poseidon spacecraft. This offset is now routinely estimated as part of the GPS orbit solution, so it is no longer a problem. Without SLR tracking, the GPS tracking system would not have the benefit of an independent calibration device to achieve absolute ranging accuracy. Results of detailed comparisons between the SLR/DORIS orbits and the GPS reduced-dynamic orbits for TOPEX/Poseidon indicate that there is a z-axis offset on the order of 2-3 cm [Tapley et al., 1994]. The cause of this offset is still under investigation. The advantage of the SLR tracking system enhances the ability to identify and correct ambiguities of tracking systems.

The SLR tracking system has also proven to be invaluable in the event of failure of the primary radiometric tracking system, as in the case of ERS-1. Without the SLR tracking, the failure of the PRARE system would have severely degraded the scientific return of the mission. The current ERS-1 radial orbit accuracy achieved using SLR tracking is below the 15-cm level [Shum et al., 1993]. The SLR system can also serve as a complement to other tracking systems, especially during data outages. In the case of TOPEX/Poseidon, DORIS data outages and loss of GPS data due to anti-spoofing or other system problems may occur.

References:

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Shum, C.K., B.D. Tapley, B.J. Kozel, P. Visser, J.C. Ries, and J. Seago, *Precise orbit analysis and global verification results from ERS-1 altimetry,* Proc. 2nd ERS-1 Symposium, Hamburg, Germany, October 1993.

Tapley, B.D., J.C. Ries, G.W. Davis, R.J. Eanes, B.E. Schutz, C.K. Shum, M.M. Watkins, J.A. Marshall, R.S. Nerem, B.H. Putney, S.M. Klosko, S.B. Luthcke, D.Pavlis, R.G. Williamson, and N.P. Zelensky, *Precision orbit determination for TOPEX/Poseidon*, J.Geophys.Res., accepted for publication, 1994.

Fig. 1. GEOSAT Altimeter Residuals from Orbits Computed With and Without Direct Altimeter Data

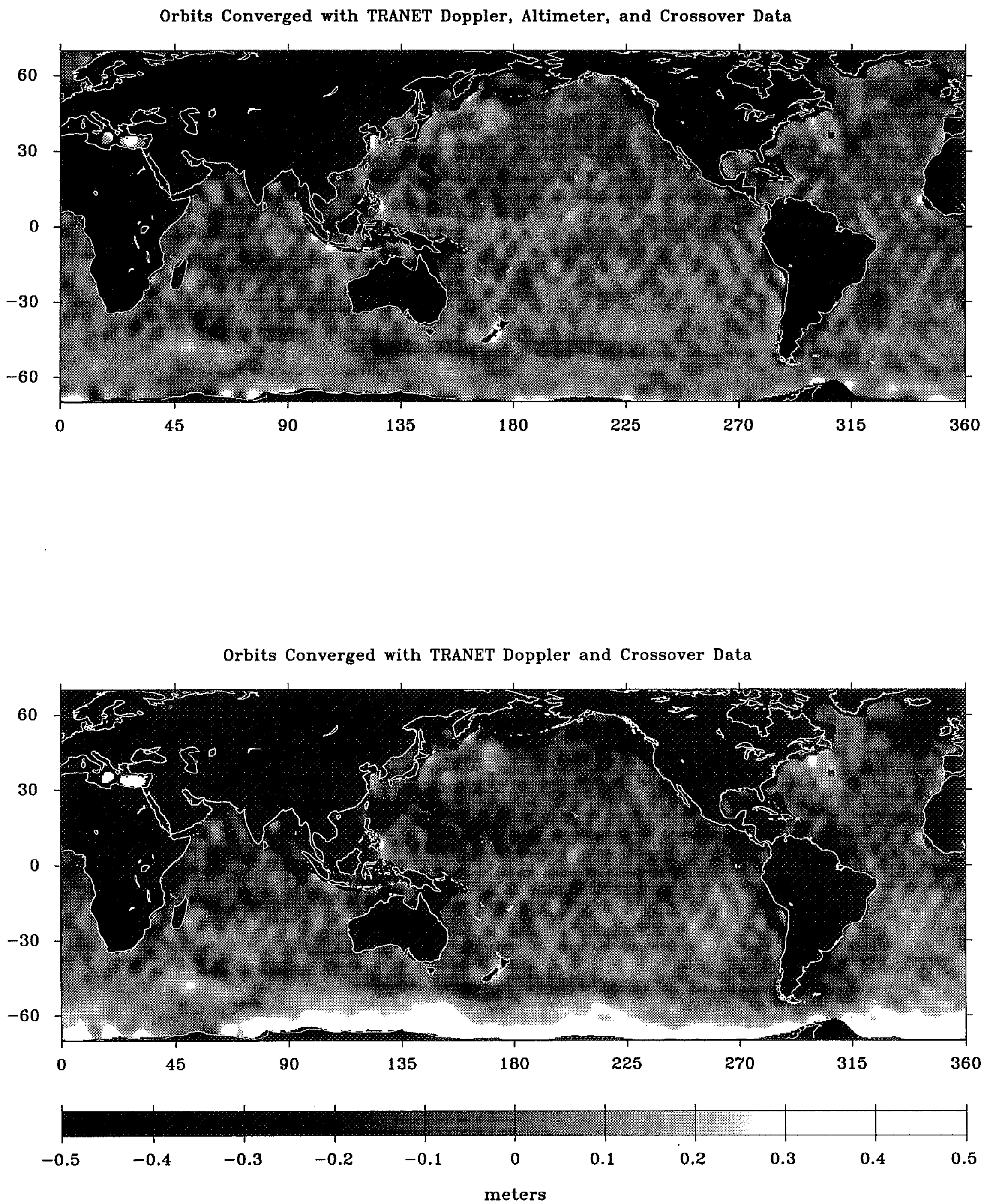


Figure 2. DORIS/SLR Time Bias vs. Time for Cycles 1–9

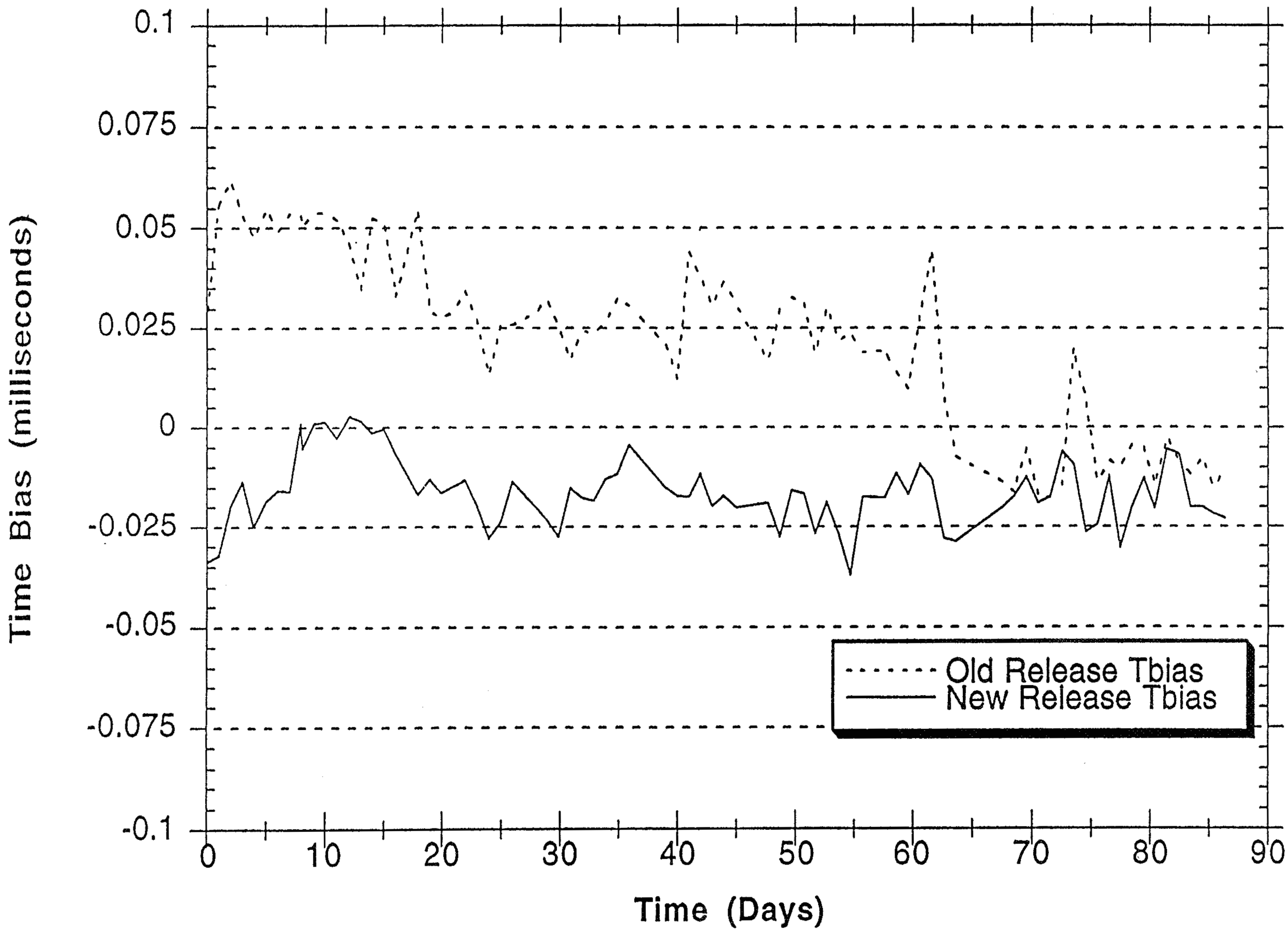
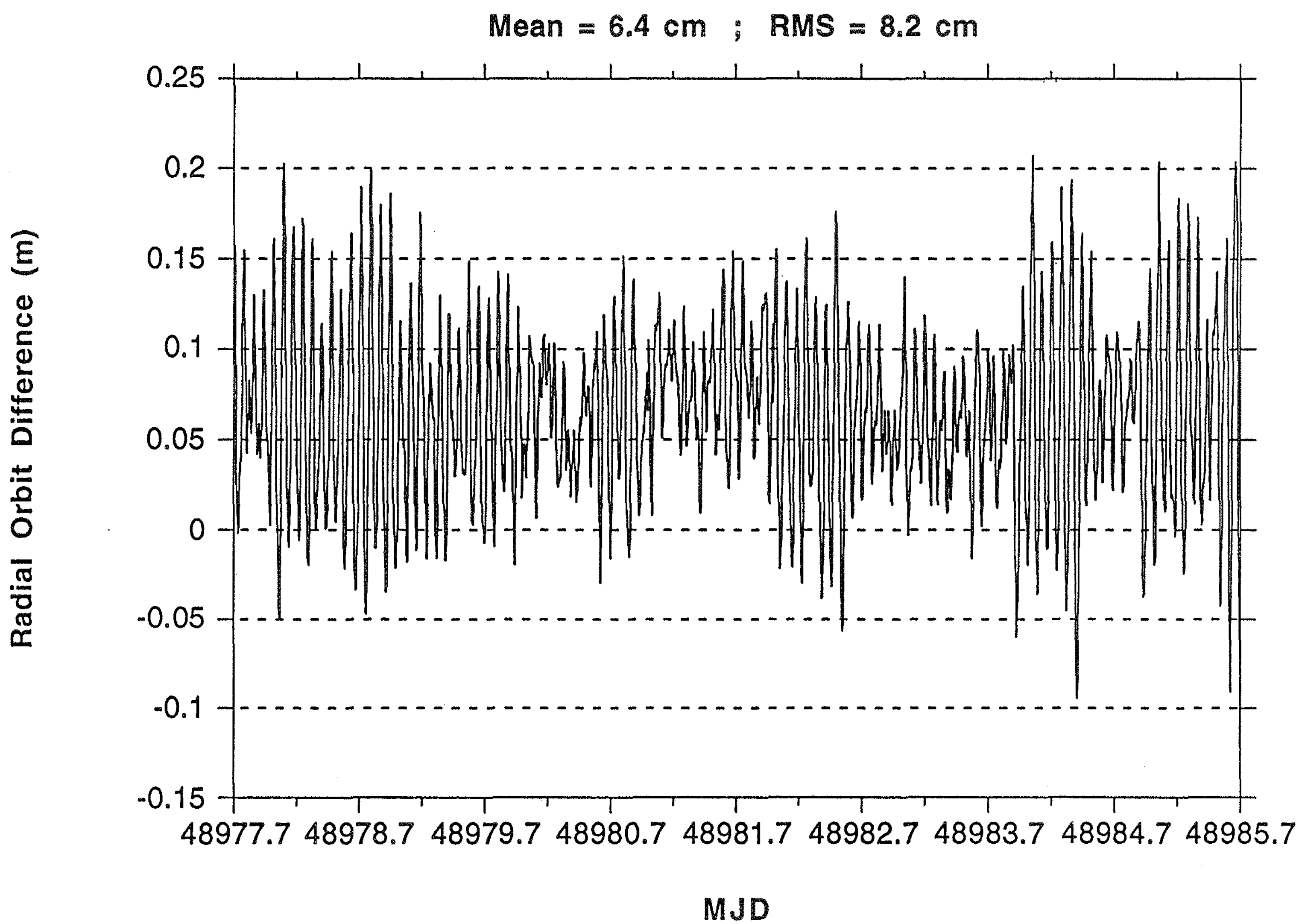


Figure 3. TOPEX Cycle 10: Radial Orbit Difference vs. Time
UT/CSR Slr vs. JPL GPS



I. RADAR ALTIMETER CALIBRATION USING SLR

S.M. Klosko

Accurate absolute calibration of radar altimeters is essential to separate possible hardware drift from long-period phenomena in the measured ocean topography. Monitoring sub-centimeter global sea level changes is one of the major goals of these missions.

OVERVIEW

Historically, all NASA altimeter missions have flown a laser retroreflector array. The most accurate space-based measurement of absolute distance is now achieved with SLR. In principle a calibration experiment is designed to enable a direct, orbit-independent comparison of the laser ranges, with their sub-centimeter accuracy, to the radar altimeter, in order to independently assess the range bias and drift within the radar system at the noise level of the closure of these measurements. The accurate calibration of radar altimeters is increasingly more critical to the overall success of these altimeter missions. Constant offsets in the radar range measurements are troublesome, but are less troubling than bias drift, which differentially affects ocean topography measurements. These differential changes, if undetected, obscure the monitoring of long period and secular changes in global sea level.

ALTIMETER CALIBRATION EXPERIMENTAL DESIGN

Given the unprecedented accuracy being achieved by the TOPEX/Poseidon mission for the altimetric mapping of the ocean surface, it is clearly feasible that these data can provide a direct and unambiguous measure of global sea level change which is directly referenced to the Earth's geocenter. An altimeter-based measurement of global sea level change avoids many of the problems associated with attempts at determining the same effect using historical tide gauge data. From tide gauges, one measures the relative height of sea level with respect to a fixed point on the Earth's crust. However, the height and secular motion of the gauges themselves are uncertain at levels comparable to the global sea level signal due to post-glacial rebound.. Post-glacial rebound predominates over regions which provide the most dense tide gauge networks (e.g. Europe and North America) and have required rebound models of uncertain accuracy to separate crustal from sea level trends.

In all likelihood, TOPEX/Poseidon is the first of a series of high class altimeter missions which will provide altimetric mapping of the Earth's ocean topography on a continuous basis from this time onward. Therefore, experimental and resource considerations for a direct calibration of these instruments need to be addressed, and will remain of concern for an extensive period of time.

It is a significant requirement to calibrate altimeter instrument performance continuously over their active lifetimes. This is facilitated by the availability of a complementary, absolute ranging system. The most accurate space-based measurement of absolute distance is now achieved with SLR. In principal, the ideal altimeter calibration experiment is designed to enable a "direct" (orbit-independent) comparison of the laser ranges, with their sub-cm accuracy, to that of the radar altimeter, in order to independently assess the range bias and drift within this radar system.

Constant offsets in the altimeter instrument are inherently less troubling than bias drift, which differentially affects ocean topography measurements and can mask sea level secular trends. Careful consideration of each element of altimeter calibration is required to limit absolute errors. Time-dependent biases must be resolved by regular repetition of rigorous calibration tests. A primary challenge in the design of a good altimeter calibration experiment is the ability to make sufficiently precise observations to permit frequent and accurate determinations of altimeter bias and drift parameters. This allows an absolute comparison of altimeter-based ocean topographies separated by large intervals of time and across altimeter missions.

TOPEX/Poseidon

The TOPEX/Poseidon (T/P) mission is ongoing and producing a synoptic mapping of the ocean's topography comparable in accuracy with that achieved using standard tide gauge instruments. This is an unprecedented improvement in satellite altimetric performance which has been achieved through:

- 0 Dramatic improvement in the precision orbit determination, with T/P now benefitting from orbit knowledge radially at the 3 cm level. This is an order of magnitude better orbit knowledge than has previously been seen; and

- 0 Improved environmental corrections for the altimeter range measurement made possible through the dual-frequency measurements acquired by the NASA altimeter system, and the excellent performance of the T/P radiometer to measure the integrated water vapor content in the sub-satellite atmospheric column.

The ongoing calibration of the TOPEX altimeter is not benefitting from a direct overflight of an SLR site and is producing results at the 2-3 cm RMS level (see Figure 1 from Christensen et al., 1994). A direct overflight experiment, on the other hand, is likely the only means to produce an orbit-independent instrument calibration which achieves the accuracy needed to support global sea level monitoring.

Extended calibration of the TOPEX altimeter is presently taking place using the Harvest Platform (oil tower) off the coast of California, near Vandenburg Air Force Base (see Figure 2). T/P overflies the tower approximately every ten days, at which time the following data is taken on the tower:

- 0 Tide height measured by an underwater pressure gauge operated by the University of Colorado;
- 0 Vertically integrated water vapor measurements using a microwave radiometer operated by JPL; and
- 0 Meteorological data (pressure, temperature and humidity) recorded and retrieved remotely by NOAA.

During the early calibration stage, JPL also operated a GPS receiver on the platform in order to monitor its position relative to the Quincy laser site and to deduce integrated electron content to compute Ku-band altimeter ionospheric corrections. However, the platform showed no periodic or long-term motion and a sufficiently precise tie between Harvest and Quincy was obtained.

A second calibration site in the Mediterranean Sea on Lampedusa Island was also supported early in the mission but has been suspended since this time. Calibration activities at this site may recommence at those times when the Lampedusa laser site is reoccupied by a TLRS or MLRS mobile laser tracking system.

The calibration procedure consists of accomplishing a "closure" measurement. The direct measurement to the sea surface is made by the altimeter, although this observation must be corrected for the effects of wet and dry tropospheric propagation, ionospheric propagation, and EM-bias. Errors due to imperfect altimeter performance from variable sea state and off-nadir pointing must also be accommodated, as well as antenna offset at the satellite center of mass. The sea state in the vicinity of the Harvest Platform has been a persistent problem causing tide guages to disagree with one another at the 2 cm level and have caused altimeter range corrections from this source which have significant uncertainties.

The indirect measurement of the distance between the satellite and the sea surface is based on the following:

- 0 A satellite orbit based on either a short arc of laser data from at least two or three co-observing sites, a SLR/DORIS "long arc orbit", or on GPS data including observations from a receiver on the tower. In the case of the laser short arc orbit, the reference point is at one of the laser sites, while the GPS technique provided a reference point on the tower. Of note, the Harvest experiment requires a 3-D orbit determination.

0 A geometric tie between the laser site and the tower, which for Harvest has been made using a GPS receiver at Quincy and one at the tower.

0 A survey tie on the tower between the GPS receiver reference point and the tide guage reference point.

0 A tide guage measurement of the water surface relative to the reference point. At Harvest, there were originally two NOAA tide guages as well as the one provided by the University of Colorado, which was subsequently decided to be more reliable.

The uncertainty in the altimeter measurement due to noise in the Ku-band measurement is typically in excess of 10 cm at a data rate of 20 pps. The altimeter telemeters down filtered data, which although it has correlated errors, has a noise level close to 2 or 3 cm when averaged over a second for very low sea states. High sea state is common at Harvest and the data noise is usually substantially higher.

The calibration task requires the estimation of orbits, followed by the collection of data for making the required corrections and computing bias estimates. Nevertheless, reconciliation of all the segments of the closure experiment is the key issue, and reduction of errors in each segment reduces the overall error in the absolute accuracy of the calibration itself. Yet, given the complexity and environmental setting of the Harvest Experiment, inadequate calibration accuracy is being achieved. While +/- 2-3 cm knowledge (from 10-day samples) of the TOPEX range bias is quite good, it is not sufficient to detect mm/year trends in instrument performance.

SUMMARY

Clearly a calibration of the TOPEX altimeter (and future TOPEX-class altimeters) which is more accurate and better meets the demands of global sea level trend monitoring is warranted. T/P is well into its second year of data acquisition; if it survives or surpasses its two to five year projected baseline, an unprecedented opportunity for monitoring global sea level trends at mm/y levels will have been lost due to insufficient accuracy in its altimeter calibration. It is therefore paramount to revisit the design of the T/P calibration experiment and implement a more direct approach which better utilizes the accuracy of SLR to perform this needed bias assessment.

References

Christensen, E.J. and 14 others, *Calibration of TOPEX/Poseidon at Platform Harvest,* J.Geophys.Res., special TOPEX/Poseidon Issue, in preparation, 1994.

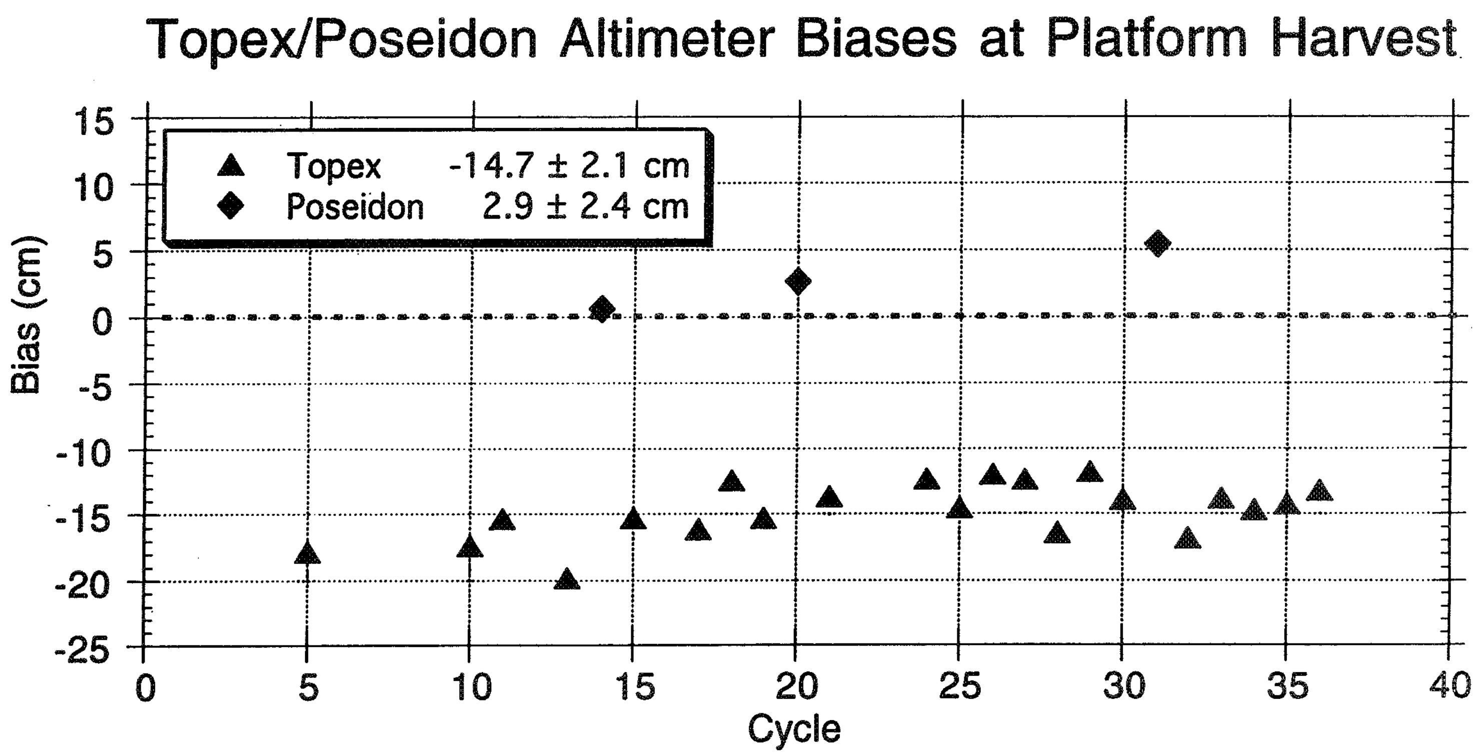

Topex/Poseidon Altimeter Biases at Platform Harvest
Topex -14.7 ± 2.1 cm
Poseidon 2.9 ± 2.4 cm
Bias (cm)
15
10
5
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Cycle

Figure 1.

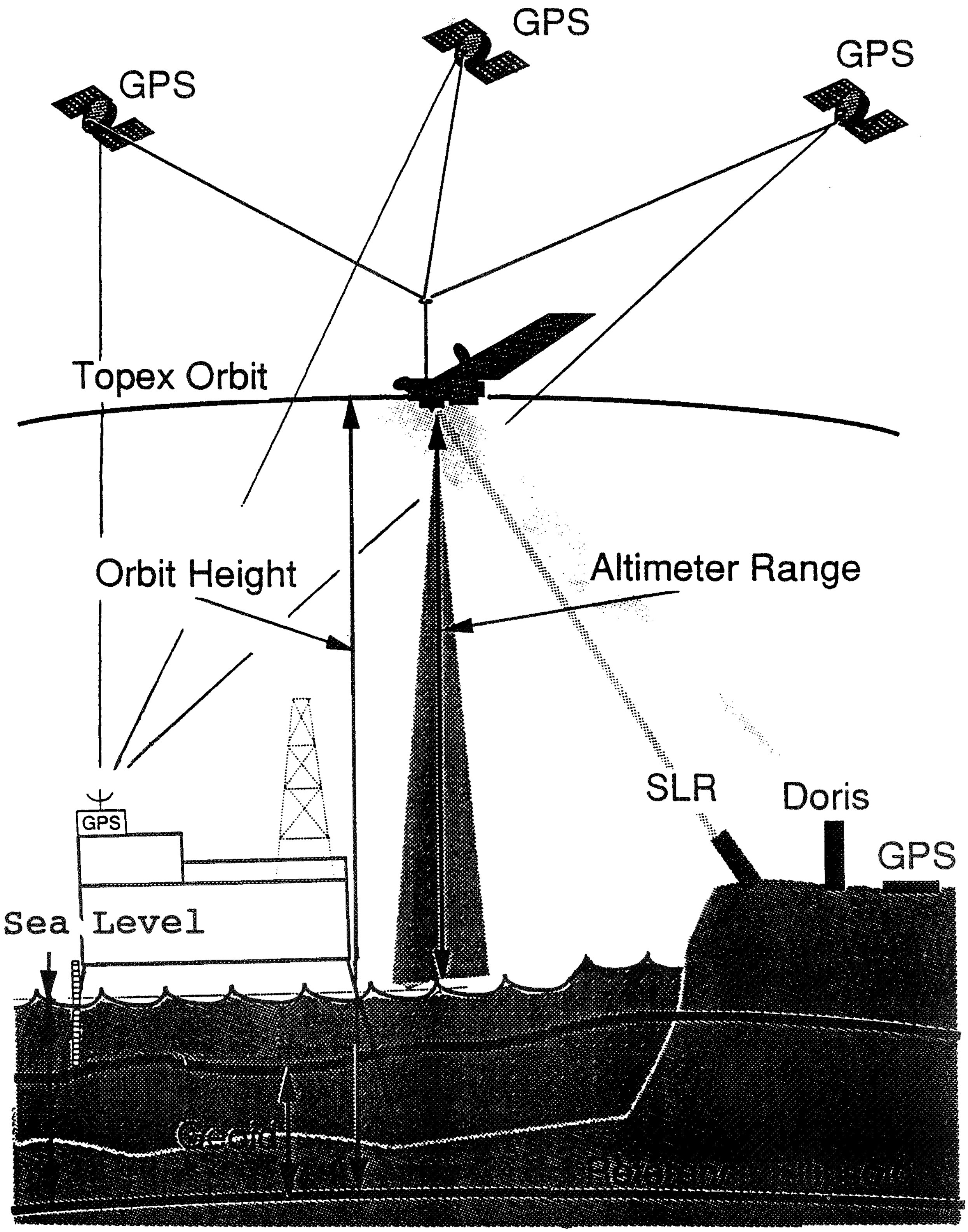

GPS
GPS
GPS
Topex Orbit
Orbit Height
Altimeter Range
GPS
SLR
Doris
GPS
Sea Level

Figure 2.

N95- 14284

J. THE ROLE OF SLR AND LLR IN RELATIVITY

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4P

J.C. Ries

While General Relativity has been adopted as the standard theory of relativity, there are alternative theories, with important implications for gravitational physics, which can only be discounted with tests of sufficient accuracy. Table 1 indicates the status of some of these tests. In addition to its contributions to lunar and solar system dynamics, Lunar Laser Ranging (LLR), in combination with other solar system data, continues to refine some important limits [Dickey et al., 1994]. SLR tracking to geodetic satellites can provide similar tests, but the accuracy is usually limited by the variety of gravitational and nongravitational perturbations [Vincent, 1986].

One important exception is the proposed Lageos-III mission, which would provide a measurement of the Lense-Thirring precession. The Lense-Thirring precession is the gravitomagnetic, or "frame-dragging", effect on a satellite orbit, in which the orbit plane is "dragged" in the direction of the Earth's rotation. The analogous effect on a gyroscope, called the Schiff precession, is expected to be measured by the Gravity Probe B mission to better than one percent. Using a pair of high-density, high-altitude satellites in orbits with supplementary inclinations, the existence of the gravito-magnetic effect could be confirmed, providing experimental support for the general relativistic formulation of the Mach Principle [Ciufolini, 1986]. The supplementary inclinations provides for a precise cancellation of the most important gravitational perturbations, while the orbital height and small area-to-mass ratio reduces the surface forces to a level which can be effectively modeled.

It is estimated that a three-year Lageos-III mission could verify the Lense-Thirring precession at the few percent level, with further improvement possible if extended over a longer period [Tapley and Ciufolini, 1989; Ries et al., 1993]. While there are a number of forces acting on the satellite which affect the orbit plane to some degree, none of them appears to affect the secular drift of the orbit plane sufficiently to interfere with the experiment. Preliminary analysis indicates that the Lageos-III satellite could be launched supplementary to Lageos-1 or Lageos-2 with about the same results. With the dual satellite configuration in place, there also may be other relativistic and geophysical experiments possible that have not yet been imagined.

SLR tracking to Lageos has also provided the most accurate determination of the Earth's gravitational coefficient (GM) and demonstrated the importance of considering the relativistic consequences of the definition of time in the various reference frames (Ries et al., 1992). The accurate determination of GM is critical in the definition of the absolute scale of the geocentric reference frame, affecting intercomparisons of SLR-determined station coordinates with VLBI and the determination of absolute ocean height from altimetric satellites. In addition, the Lageos SLR analysis has demonstrated the need for considering additional relativistic geopotential effects in the solar system barycentric model or near-Earth applications [Ries et al., 1988]. The precise determination of absolute distance is a primary reason for the sensitivity of SLR to relativistic effects, and the continued improvement in the SLR system will increase the accuracy in the determination of the scale of the geocentric frame.

References:

Ciufolini, I., Phys. Rev. Lett., 56, 278, 1986.

Dickey, J., et al., submitted to Science, 1994.

Ries, J., R. Eanes, C. Shum, and M. Watkins, Geophys.Res. Lett., 19, 529, 1992.

Ries, J., C. Huang, and M. Watkins, Phys. Res. Lett., 61, 903, 1988.

Ries, J., R. Eanes, B. Tapley, and M. Watkins, Spring AGU, 1993.

Tapley, B., and I. Cuifolini, CSR 89-3, Center for Space Research, 1989.

Vincent, M., Cel. Mech., 39, 15, 1986.

Table 1. Solar System Relativity Tests

Light deflection by the Sun (Viking Lander data)	verified $\gamma = 1 \pm .002$
Excess perihelion precession of Mercury	verified $\beta = 1 \pm .003$
Gravitational redshift (Gravity Probe-A)	verified effect of gravity on time
Weak equivalence principle	verified to few parts in 10^{11} in laboratory
Strong equivalence principle	LLR limit on Nordtvedt effect $\Rightarrow \beta = 1 \pm .0006$
PPN constants due to preferred frame effects or violation of conservation of total momentum	deviations from GR less than 10^{-3}
Geodetic (de Sitter) precession	verified to <1% via LLR and VLBI
Gravitomagnetic, or 'frame-dragging' effect not yet directly observed	'Lense-Thirring' precession of orbit 'Schiff' precession of gyroscopes
$\dot{G} / G$	limit from LLR + solar system data < 10^{11}/yr

(β and γ are Parameterized Post-Newtonian parameters which are identically 1 in General Relativity)

K. SLR TRACKING OF GPS-35

E.C. Pavlis

NASA's GSFC and the NRL co-sponsored an experiment to launch a corner cube retroreflector (CCR) array on one of the Global Positioning Satellites (GPS). After more than a year of negotiations with the USAF, the launch on Aug. 31, 1993 ushered in the era of SLR tracking of GPS spacecraft. Once the space operations group finished the check-out procedures for the new satellite, the agreed upon SLR sites were allowed to track it. The first site to acquire GPS-35 was the Russian system at Maidanak and closely after the MLRS system at McDonald Observatory, Texas.

The laser tracking network is currently tracking the GPS spacecraft known as GPS-35 or PRN 5 with great success. From the NASA side there are five stations that contribute data regularly and nearly as many from the international partners. Upcoming modifications to the ground receivers will allow for a further increase in the tracking capabilities of several additional sites and add some desperately needed southern hemisphere tracking within the coming month. Figure 1 indicates the amount of collected data by site and geographical region. In the meantime we are analyzing the data and we are comparing SLR-derived orbits to those determined on the basis of GPS radiometric data.

The nature of the SLR data set is such that data collected as late as the previous day can be incorporated in the daily analysis on a regular basis. A long-arc (~80 days) reduction produces a trajectory with an rms discrepancy of only 24 mm (Figure 2). The entire data transfer, preprocessing, reformatting, and computation of the orbit requires a maximum of two hours and involves one person. This implies that results can be disseminated to the users' network within the same day. To this day, the radiometric data derived orbits are not available to users sooner than 10-14 days after the data collection occurs. Furthermore, these orbits are disjoint, with possible biases between consecutive arcs. The data set is now being scrutinized along with radiometric data to evaluate the possible biases in the latter and identify their source. Analyses with more dense tracking when it becomes available, can give us some insight on the many sources of systematic errors in the radiometric data. Due to the nature of these measurements (one way, RF), complete separation of clock errors from orbital errors is not possible. Residual ionosphere errors and errors from tropospheric refraction result in additional degradation of the radiometric products. The reflection of rf signals near the antenna site (multipath) is an additional source of error which varies from site to site and is quite difficult to quantify on the basis of radiometric data alone. A proper characterization of the error spectrum of the on-board clocks is also of interest, especially to those using GPS signals for time-transfer. Another source of error in computing orbits for the GPS spacecraft is the description of attitude changes, especially during eclipsing seasons. The currently available theoretical model known as ROCK4, is being used for all spacecraft with only a scale adjustment and a discrimination between Block I and Block II types. Better handling of the non-conservative force modeling can be achieved using precise SLR tracking and the resulting orbits, to "tune" these models to each spacecraft individually. Finally, geodetic positioning can benefit from the increased accuracy orbits of CCR-carrying GPS spacecraft in two ways:

- The better orbits result directly in better positioning and they can also allow for the reliable resolution and "fixing" of the ambiguities of doubly-differenced phase measurements; and

- The latter strengthens the estimation procedure since it converts in effect the very precise but relative measure of change in range to absolute range.

The results of these preliminary studies were presented to the International GPS Geodynamics Service (IGS) governing Board at their meeting during the Fall 1993 AGU. The Board endorsed the continuation of the SLR tracking of GPS-35 and were eager to exploit the use of the more precise ephemerides and the SLR data set themselves. The upcoming launch of the last Block II GPS spacecraft (not before March 9, 1994), will place in orbit a second CCR array. Double differences that involve these two spacecraft will be the best data set to test the effectiveness of ambiguity fixing and better orbit quality on geodetic products, e.g. positions, baselines, Earth orientation, etc.

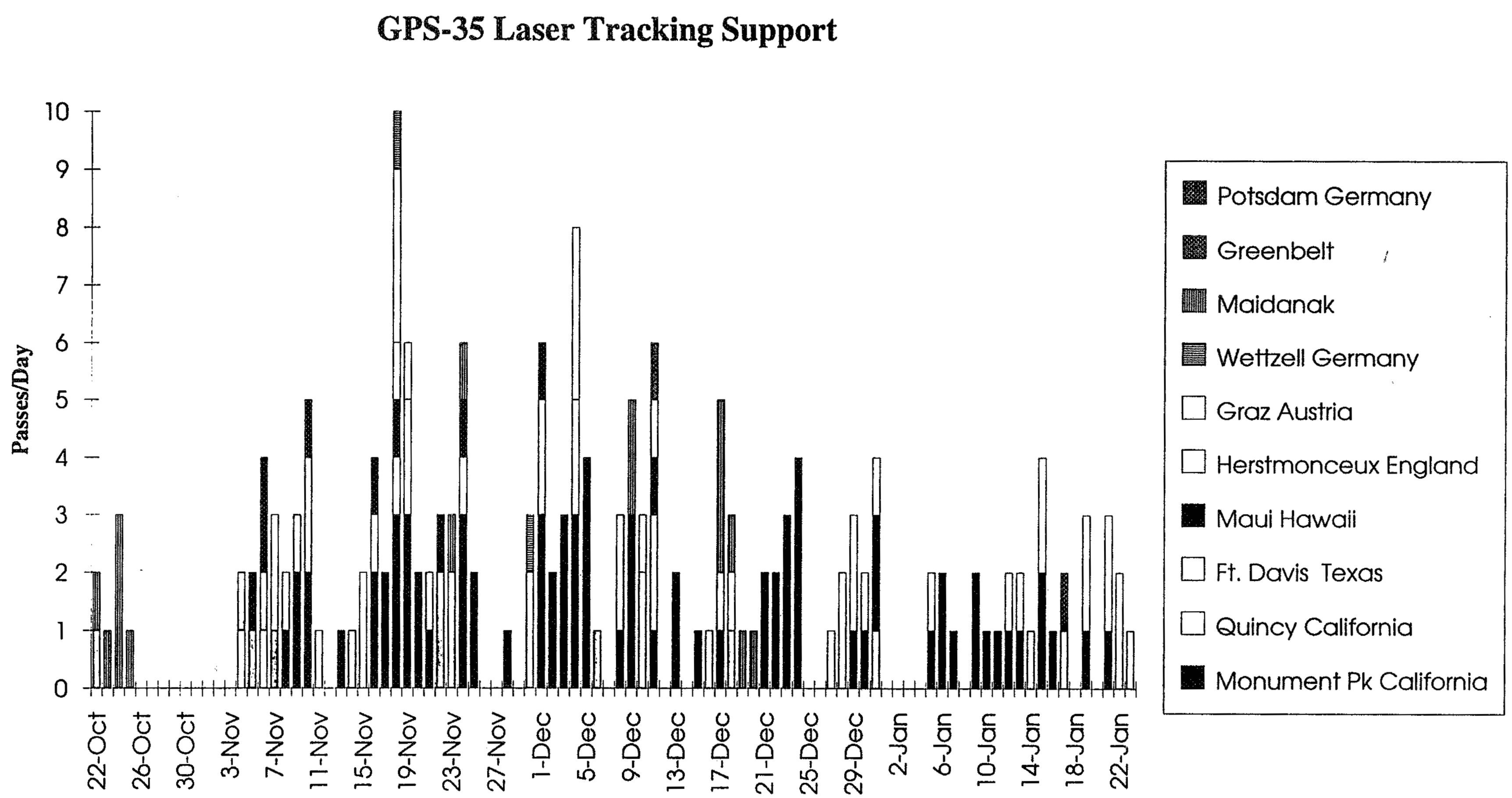
GPS-35 Laser Tracking Support
Passes/Day
0
1
2
3
4
5
6
7
8
9
10
22-Oct
26-Oct
30-Oct
3-Nov
7-Nov
11-Nov
15-Nov
19-Nov
23-Nov
27-Nov
1-Dec
5-Dec
9-Dec
13-Dec
17-Dec
21-Dec
25-Dec
29-Dec
2-Jan
6-Jan
10-Jan
14-Jan
18-Jan
22-Jan
Potsdam Germany
Greenbelt
Maidanak
Wettzell Germany
Graz Austria
Herstmonceux England
Maui Hawaii
Ft. Davis Texas
Quincy California
Monument Pk California

Figure 1.

GPS-35 (PRN 5) Orbit Determination From SLR Tracking

80-day Arc: Nov. 5, 1993 - Jan. 26, 1994

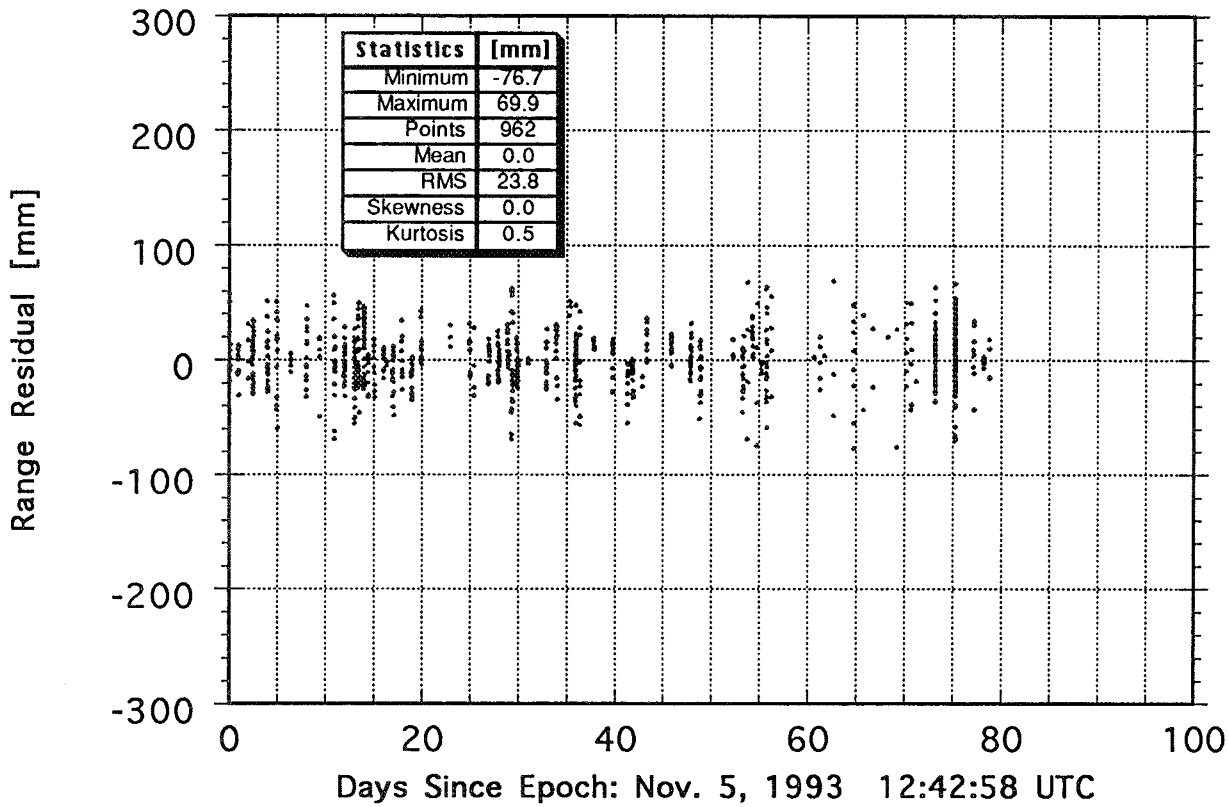

Figure 2.

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L. SYNERGISM OF SLR AND GPS

B.E. Schutz

The launch of GPS-35 (PRN 5) with a laser retroreflector has provided an opportunity to compare SLR-determined orbits of a GPS satellite with those determined by GPS receivers operated with the transmitted radio signals on the L_1 and L_2 frequencies. Operational considerations of the SLR and hardware design have influenced the amount and quality of SLR data collected on this satellite. As of February 1, 1994, all of the collected SLR data have been collected from northern hemisphere stations. Adequate southern hemisphere coverage is required to fully compare the results obtained from GPS L_1/L_2 and from SLR.

Preliminary comparisons have been made to provide an early assessment of the orbits determined by SLR and GPS L_1/L_2. Using all available SLR data on GPS-35 covering 56-days after launch, the RMS of the SLR residuals was about 9 cm. Within this arc, day 322 of 1993 was one of the best tracked by SLR (except for the lack of southern hemisphere coverage). This day was extracted from the multiweek arc for comparisons with GPS L_1/L_2. Several one day arcs were used for the comparison with the SLR-determined orbit. The orbit was determined by UT/CSR using 25 globally distributed Rogue-class receivers. The data from these receivers was used in a double difference mode. In addition, ephemerides were generated by the University of Berne, EMR of Canada, European Space Agency (Darmstadt), National Geodetic Survey, and University of California/Scripps. The comparison of each ephemeris with the SLR result for a one day arc is shown in Table 1.

Table 1. Comparison of GPS L_1/L_2 with SLR Ephemerides

L_1/L_2 minus SLR, RMS (m)

	Radial	Along-Track	Cross-Track
UT/CSR	0.31	0.94	0.49
Berne/COD	0.25	0.99	0.55
EMR	0.24	1.05	0.50
ESA	0.25	1.07	0.51
NGS	0.26	1.15	0.71
SIO	0.26	1.25	0.67

Although each ephemeris has been corrected to the spacecraft center of mass for the comparison, the differences are meter-level, which warrant further study. The level of differences may be, in part, caused by lack of southern hemisphere data. A thorough comparison requires more complete coverage by the SLR network than the data available to date.

In addition to the use of SLR on GPS-35, the TOPEX/Poseidon (T/P) satellite carried instrumentation to support tracking by SLR, GPS and the French doppler tracking system, DORIS. Although the design of the GPS receiver limited use to periods when GPS Anti-Spoofing was deactivated, a significant amount of data was collected during the first 18 months since launch.

Direct comparisons of the T/P ephemerides determined by each of the three tracking systems has demonstrated for the first time in an on-orbit environment that GPS can produce precise ephemerides that agree with SLR/DORIS-determined emphemerides at the 2-3 cm level in the radial component and at the 10 cm level in the along-track and cross-track directions. The ephemerides used in the comparisons were obtained using similar orbit determination strategies and models, thereby demonstrating the compatability between the somewhat different technical characteristics of each technique. As noted previously, the GPS receiver on T/P was a demonstration experiment which required agreements with the Department of Defense for operation of the GPS constellation without Anti-Spoofing for some period of time. Since February 1994, Anti-Spoofing has been activated and the ability of the GPS receiver to achieve comparable ephemeris accuracy with SLR has been adversely affected. Nevertheless, the operation of SLR, GPS, and DORIS on a single spacecraft enabled the calibration of the experimental GPS system. The GPS radial bias, attributed to the location of the GPS phase center on the T/P antenna, and apparent z-axis biases were identified. Even though the sources of these biases are not completely understood, the identification of their existence was hastened by the availability of independent tracking from SLR.

IV. THE SLR PROGRAM

N95-14287

A. SATELLITE LASER RANGING OPERATIONS

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350022

M.R. Pearlman

Satellite Laser Ranging (SLR) is currently providing precision orbit determination for measurements of:

- Ocean surface topography from satellite borne radar altimetry,
- Spatial and temporal variations of the gravity field,
- Earth and ocean tides,
- Plate tectonic and regional deformation,
- Post-glacial uplift and subsidence,
- Variations in the Earth's center-of-mass, and
- Variations in Earth rotation.

SLR also supports specialized programs in time transfer and classical geodetic positioning, and will soon provide precision ranging to support experiments in relativity.

The current trend in SLR is away from localized network measurements that characterized WEGENER/MEDLAS and the California Baja programs, and more toward fixed fiducial sites as part of a fundamental network for programs in global geodynamics and for orbital coverage for specialized projects. The localized mobile networks should be transitioning to GPS in a systematic manner, with SLR then providing some portion of the global geodetic control. The fixed fiducial stations have been viewed as evolving into the geophysical observatories in line with the concepts discussed at Erice and Coolfont.

The NASA stations are introducing automation and new technologies to enhance productivity and data quality, while at the same time reducing station operating personnel. The global network continues to grow, both in terms of stations and geographic coverage, attributable almost entirely to increased foreign participation.

SLR data and data processing are also in a state of change. Field Generated Normal Points (FGNP), available within 24-36 hours of acquisition, are rapidly becoming the standard data product, superseding full-rate data that was taking up to six months or more for full availability. Data processing and assessment are rapidly being automated to speed up feedback to the field stations, both NASA and foreign.

GLOBAL SLR NETWORK AND OCCUPATION PLAN

The global SLR network includes about 40 laser stations (see Figure 1) with capability varying from centimeter to decimeter precision. The centimeter systems are those operated by NASA and a few agencies and observatories in Europe and Australia.

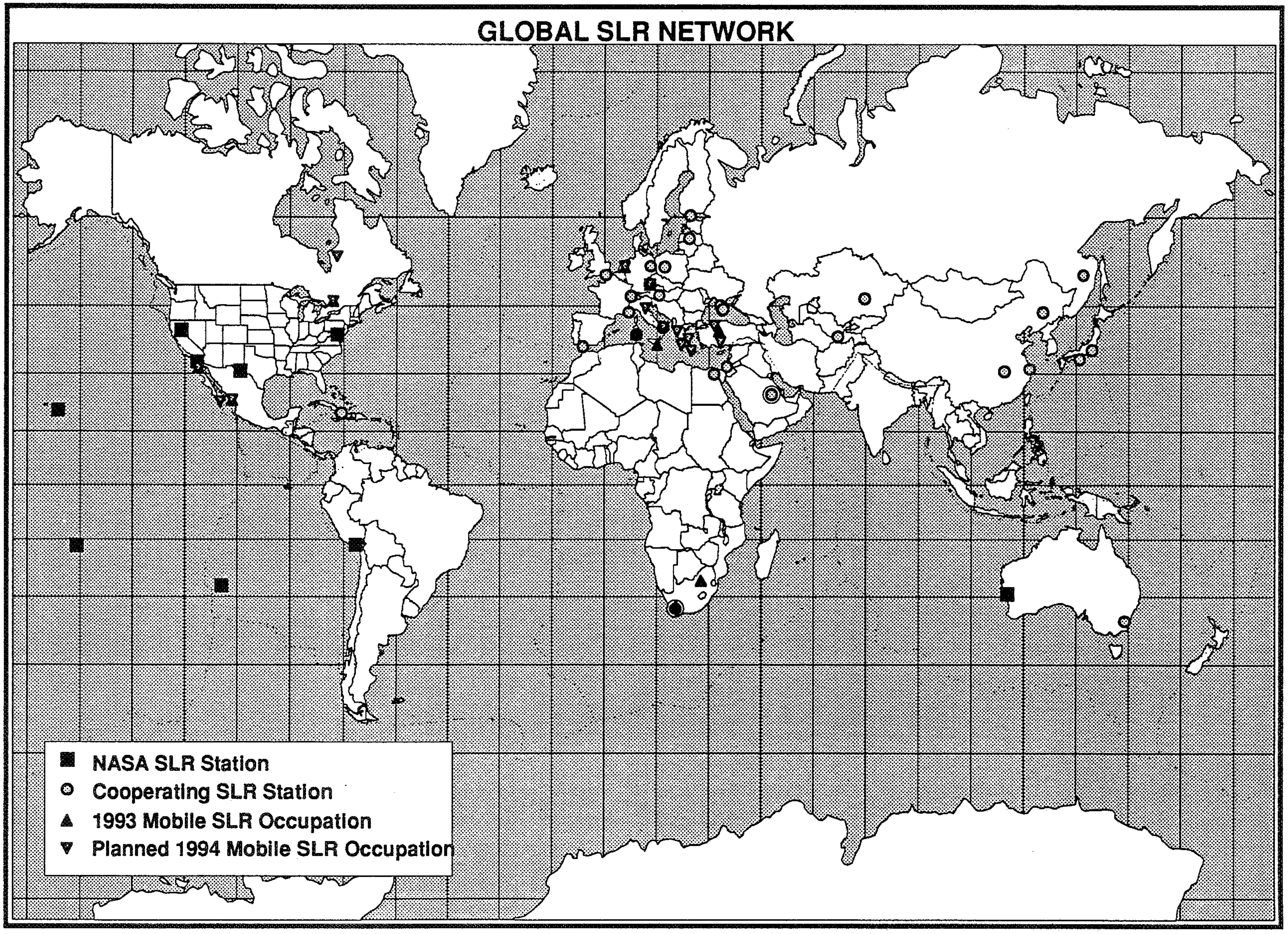
GLOBAL SLR NETWORK
NASA SLR Station
Cooperating SLR Station
1993 Mobile SLR Occupation
Planned 1994 Mobile SLR Occupation

Figure 1.

The least precise systems are primarily those operated by small observatories or groups that have recently entered the field and are working their way up the experience curve. With the recent growth in participation from China and the former Soviet Union, occupations by mobile systems, and new stations planned for deployment over the next year, global coverage is expanding. The TLRS-3 is now permanently located in Arequipa. The TLRS-2 is being moved back and forth between Easter Island and Tahiti to take advantage of the seasonal weather patterns. TLRS-1 is in the process of being transferred to ASI on long term loan for mobile occupation. Plans are also underway to provide an upgraded Moblas-6 to the South Africans for deployment at Sutherland, and for the Saudi Arabian Laser to be setup at Riyadh during the next year.

In addition to those stations shown on the map, the Russian Time and Frequency Institute is presently deploying a network of SLR stations across Russia and Asia that will be participating in global tracking activities. Groups in Europe are also planning to relocate existing systems to sites in Tunisia and South America. Gaps in global coverage that continue to exist at least for the lower satellites are over the Indian Ocean and the South Atlantic, and we continue to work options for relocation with groups presently working in the more heavily covered regions.

In 1993, mobile lasers (TLRS-1, TLRS-2, TLRS-4, MTLRS-1, and MTLRS-2) occupied sites in:

1. The Mediterranean region for WEGENER/MEDLAS;

2. South Africa to support Topex/Poseidon and general global coverage;

3. Mexico to support the California Baja Project;

4. Canada to begin measurements of post-glacial uplift (DOSE experiment); and

5. Easter Island and Tahiti to provide coverage across the South Pacific.

The plans for 1994 and 1995 are included in Table 1. In 1994, TLRS-1, MTLRS-1, and MTLRS-2 will complete the WEGENER/MEDLAS localized network measurements in Greece and Turkey, with the program then transitioning to GPS. The first GPS measurements were made at these sites in 1993; the second occupation will take place in 1994 with the SLR occupations. Measurements are planned to continue with TLRS-4 in Canada.

After the 1994 WEGENER/MEDLAS Campaign, IfAG is planning occupations at Firusa and Zelenchukskaya in Russia (to support crustal motion and subsidence measurements) prior to moving on to Asia and the South Pacific to participate in the ASEAN Program. Kootwijk is considering keeping MTLRS-2 in Greece, mainly at

Dionysos, under partial support from the National Technical University. The Italian Space Agency (ASI) is considering 1995 occupations of TLRS-1 in Africa, one of the sites being at Malindi.

The French continue to work on the FTLRS. As a result of problems with their prime contractor, the control system software will have to be rewritten, keeping it out of action probably until 1995. At that time it will be available to support the altimeter missions from sites in the Mediterranean and Africa.

TABLE 1

MOBILE STATION OCCUPATIONS
(Planned for 1994 and Beyond)

	TLRS-1	TLRS-4
1994	Matera Medicina Basovizza Xrisokellaria Matera (Upgrade)	Enceneda Cabo San Lucas La Grande Algonquin Mazatlan
1995*	Upgrade Mediterranean/ Africa	Canada
	MTLRS-1	**MTLRS-2**
1994	Kootwijk (Upgrade) Wettzell Yigilca Melengiclik	Kootwijk (Upgrade) Roumelli Karitsa Dionysis
1995*	Russia, Asia	Greece
	FTLRS	**HTLRS**
	Mediterranean/ Africa	Japan/Islands

* Final Full-Site Occupations for WEGENER/MEDLAS (Second GPS Occupation)

SATELLITES

In the late-1980s, the SLR network was tracking Lageos-1 for Crustal Dynamics plus Starlette and Ajisai for gravity field modelling. Since that time, the role of the network has expanded dramatically (see Figure 2). Ten additional satellites have been added to the list including the altimeter satellites ERS-1 and TOPEX/Poseidon, the gravity mission Stella, and the large complex of high altitude satellites associated with the GPS and Glonass programs. The slate of new retroreflector satellites scheduled over the next three years is equally as impressive, including many specialized satellites requiring SLR for both routine tracking and as part of the on-board experiment/measurement system.

DATA YIELD

Data yield from the global network has grown by a factor of 3-4 over the last five years with both the NASA and foreign stations contributing to this increase (see Figure 3). The reasons for the increase in the NASA network data yield are:

- A change in operational philosophy to prioritize satellites by altitude, lowest first, and to give the station operators more flexibility in operational trade-offs;

- Additional operating shifts scheduled for Topex, but having a major impact on all satellites;

- Additional satellites; and

- System upgrades including:

    - Real-time data processing to allow increased satellite tracking coverage;

    - Satellite pass interleaving to avoid loss of passes due to conflict;

    - Improved signal link for higher satellites; and

    - Refurbishment of mounts and telescopes to improve reliability.

The increase in the data yield from the foreign network occurred for similar reasons, plus some stations are now much further up experience curve and are becoming more productive, and some new stations have become operational.

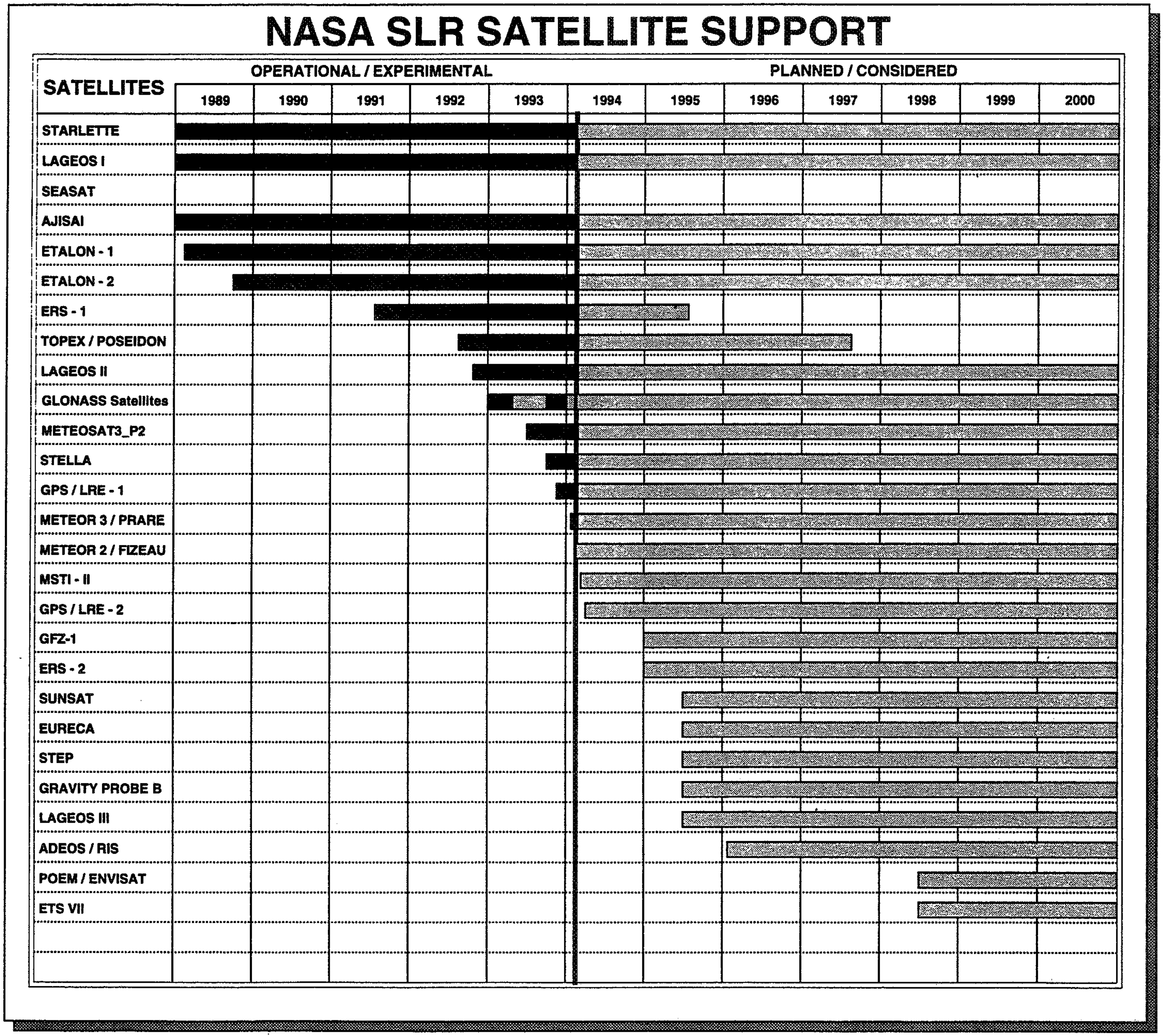
NASA SLR SATELLITE SUPPORT
SATELLITES
OPERATIONAL / EXPERIMENTAL
PLANNED / CONSIDERED
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
STARLETTE
LAGEOS I
SEASAT
AJISAI
ETALON - 1
ETALON - 2
ERS - 1
TOPEX / POSEIDON
LAGEOS II
GLONASS Satellites
METEOSAT3_P2
STELLA
GPS / LRE - 1
METEOR 3 / PRARE
METEOR 2 / FIZEAU
MSTI - II
GPS / LRE - 2
GFZ-1
ERS - 2
SUNSAT
EURECA
STEP
GRAVITY PROBE B
LAGEOS III
ADEOS / RIS
POEM / ENVISAT
ETS VII

Figure 2.

SLR Data 1988 - 1993

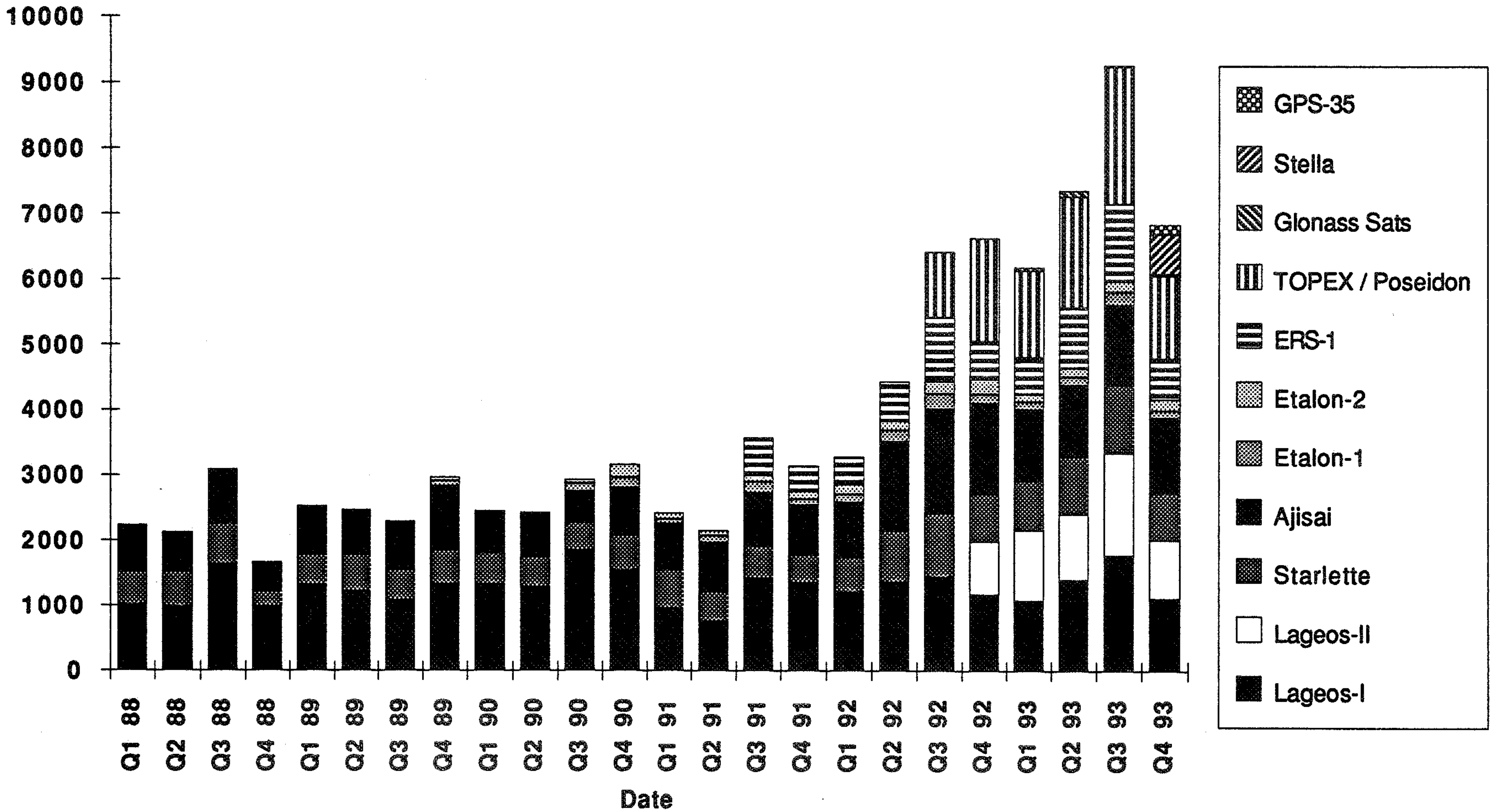

Figure 3.

PROGRAMS UNDERWAY FOR COST REDUCTION

Field Stations

The configuration of the current NASA SLR field stations is the result of their historical evolution since their design 20 years ago. They have been updated, but their upgrades have been constrained by configuration and by requirements to remain operational to support on-going programs. Original designs assumed a full crew for operations, maintenance, and safety, which included aircraft spotting, perimeter security, and the fulfillment of general OSHA requirements. In addition, alternative design and development programs, both in the US and abroad, have introduced non-uniformities in both hardware and software. Through the years, consolidations and upgrades have reduced the required station manpower and the system-to-system differences, and we continue to identify opportunities and implement provisions to reduce station operating costs and to increase standardization.

Aside from the operating cost, the relocation of mobile systems, including shipment, logistics, and personnel dislocation allowance has been very expensive. This cost will be reduced significantly as this type of activity is reduced.

In this regard, the NASA network has been focussing on the following:

- o Automation and consolidation at the field stations to reduce personnel;
- o Improvement in the utility of the network to improve performance and reliability; and
- o Best utility from the foreign network.

In terms of automation and consolidation, the following are underway or have been included in the network plan:

1. The installation of the data processing computers at TLRS-1, TLRS-2, and Moblas-2 to give all sites the capability of producing FGNP and standardizing system I/O; all of the other NASA systems and most of the foreign systems have been given this capability over the last three years.

2. The installation of aircraft radar and motion sensors to automate most of the safety functions. The prototype radar and motion sensor now working on Moblas-7 have already proved to be more effective in spotting aircraft and shutting down the system than visual spotters.

3. The computerization of logistics and administrative functions to eliminate forms and paper handling; much of

the software to handle these functions is in process and will be ready for testing on Moblas-7 later this year.

4. The installation of the new system controller to provide improved and standardized operator interface; this is under development on Moblas-6 and will be ready for full system testing mid-year.

5. The completion of Internet connections to all sites to provide standardized high-quality, reliable, low cost data communications; ARC is in the process of implementing the network requirements.

6. The installation of the GPS Steered Timing Standard at all of the NASA SLR stations to provide fully time corrected FGNP directly from the field to the users; the prototype is ready for installation and testing on Moblas-7 and the design is ready for production.

7. The improvement in the reliability of the lasers by upgrading components to current standards or by replacing subsystems with newer commercial items to eliminate the need for laser monitoring and adjustment during operations.

Moblas stations currently require three people per shift; TLRS systems require two. With the steps above, personnel could, in principle, be reduced to one person per shift, if the OSHA requirements can be met without having two people on-site. Alternatively, the second person could have much lower technical requirements than current operators or could have responsibility for other measurement systems located at the same site (to take advantage of the already existing infrastructure).

Headquarters

Reductions will continue in headquarters data staff as FGNP completes their emergence and full-rate data is discontinued. This process is made possible by the computer capability in the field, the new field software, communications, and the GPS steered timing systems. It will be expedited by providing as much standardization as possible, most notably data processing software to assure standardized algorithms, data screening procedures, and diagnostics. Data handling and review at headquarters for network feedback and quality control is now almost fully automated, with 95-98% of the data requiring no intervention. Most passes requiring personnel scrutiny are either from systems with engineering changes underway or from foreign stations with configuration issues. The processing and data handling algorithms continue to be improved to further automate the process.

The headquarters engineering staff represents a wide spectrum of technical expertise required to handle the complexities of the

SLR systems introduced by history and lack of standardization. In reality, less and less of this resource is being spent on maintenance and sustaining engineering and increasingly more of it is being dedicated to the upgrades discussed above and to the development of future, automated systems.

IMPROVEMENTS IN THE UTILITY OF THE NASA NETWORK

Eventually SLR systems must be fully automated and designed to include the already existing technology that will bring total ranging capability to the mm level. In the meantime, improved ranging performance of the current SLR system depends upon: 1) quality control to ensure that data is not corrupted by equipment or operational shortcomings; 2) improved precision of the ranging machine; and 3) better understanding of the external environment influencing the range measurement.

The most critical issue in performance is the reliability of the data quality and achievement of a more uniform data set. This situation is improving with the additional efforts that have been placed in quality control and station feedback, in great part accelerated by the needs of the TOPEX Project. However, some systematic problems are still taking too much time to diagnose and a better review process and inquiry process needs to be implemented.

The inherent instrument accuracy of the SLR technique is demonstrated by the history of collocation, or side-by-side ranging experiments by two or more systems. The NASA systems typically demonstrate comparisons at the level of a few millimeters.

The largest uncertainties in the NASA laser systems at the moment are believed to be from the external environment: the refraction correction and the spacecraft center-of-mass correction. The current refraction models should be verified over a wide range of meteorological conditions using some of the multiple wavelength technology already available. This would have a fundamental impact on the design of new generation SLR systems and on the understanding of the influence of refraction on all of the space geodetic techniques. The adequacy of the models for the satellite center-of-mass vary greatly depending up the spacecraft geometry and the amount of effort applied to each satellite. Great care should be given to the design of new arrays and to the refinement of models for current satellites.

Hardware upgrades to improve instrument precision by about a factor of four are either commercially available or have been demonstrated. These upgrades include: shorter laser output pulse, improved MCP detectors, improvements to the time interval unit, and the addition of precision optical calibration techniques. All can be retrofit into the current hardware and all would be a basic step in development for the next generation SLR.

BEST UTILITY FROM THE FOREIGN NETWORK

NASA is reducing its support for SLR while the number of retroreflector satellites continue to increase. This places increased priority on improved data quality, quantity, and flow from the foreign network. NASA is intimately involved in the coordination of the foreign network, including: scheduling, priorities, predictions, communications, and quality review. We have strong partners in these activities including the European Data Center in Munich who now shoulder a substantial part of the load. NASA has been the focal point for standardization and baselining of the global network systems including: procedures, data products, reporting, and analysis models, and to a lesser degree hardware and software. With the requirements of the TOPEX project we are now active in configuration monitoring and system modelling for data interpretation. All of these activities should be continued, and in terms of standardization and quality assurance, stress should be increased.

NASA has also been active in providing technical assistance, pieces and parts, and even full systems to other groups to operate as part of the global network. The systems at Matera, Bar Giyyora, and TLRS-1 are all very active systems on long term loan from NASA. Arrangements are now in process for similar arrangements with Moblas-6 to South Africa.

Two items that would have a very major impact on our return from the foreign network are to:

1. Provide a PC with standardized software including predictions, data processing, FGNP, reporting, communications, etc. to those foreign stations that do not yet have these capabilities in place or with whom standardization and compatibility issues have been very difficult to resolve; this would provide more uniformity, reducing the need for special engineering and data handling at headquarters. It would also provide a more uniform means of software and model updates when required.

2. Develop a portable standard that could be shipped to overseas stations to perform engineering tests to check the key subsystems. Collocations are the best means of engineering checkout. On the other hand, they are expensive and require personnel travel. The portable standard has been configured for compact shipment and operation by the local station staff.

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B. SLR 2000

J.J. Degnan

SLR 2000 is a concept for a totally automated subcentimeter SLR system presently being studied at GSFC. If funding permits, a prototype would be installed and tested at the Goddard Geophysical and Astronomical Observatory (GGAO) in FY98 and a small number of automated stations would be fielded by the year 2000.

Unlike present systems, the "SLR 2000" system is being designed to: 1) operate autonomously without the need for onsite operators; 2) present no hazards (i.e. optical, electrical, and/or chemical) to personnel in the vicinity or to overflying aircraft; and 3) have a mean time between failures (MTBF) of at least three months. It is assumed that the systems are located at "friendly" sites where some level of security is provided and where certain low level service functions (e.g. commercial power, communications, heat pump service, cleaning, etc.) are available or can be contracted for locally on an as-needed basis.

The main system, which is illustrated in Figures 1a and 1b, consists of two parts - an optical head and electronics rack. The optical head contains the laser transmitter and power supply, transmit/receive switch, optical telescope, tracking angle sensor (intensified CCD camera), detector and power supply, two angular encoders, azimuth and elevation motors, and a protective dome. The optical head mounts directly to the top of a concrete pier which contains the geodetic monument and forms part of the environmental housing for the hardware and servicing personnel. It is equipped with electronic levels for leveling the mount and monitoring its stability.

The electronics rack, depicted in Figure 2, is located inside the pier and contains the computer and hard disk with UPS (Uninterruptible Power Supply), a GPS-disciplined rubidium oscillator, gating and timing electronics, encoder electronics, azimuth and elevation servo electronics, auxiliary power supplies, security/environmental sensor interfaces, and power and communications interfaces. Temperature and humidity inside the pier is controlled by an external heat pump and an internal emergency backup heater. Two-way data communications is established via NASA Science Internet (NSI). A phone for use by maintenance personnel is provided in the central pier.

An external meteorological station continuously monitors ambient pressure, temperature, humidity, and wind speed and transmits the data to the system computer. A collocated GPS geodetic receiver also transmits its data over the NSI dataway.

SLR 2000 STATION FRONT VIEW

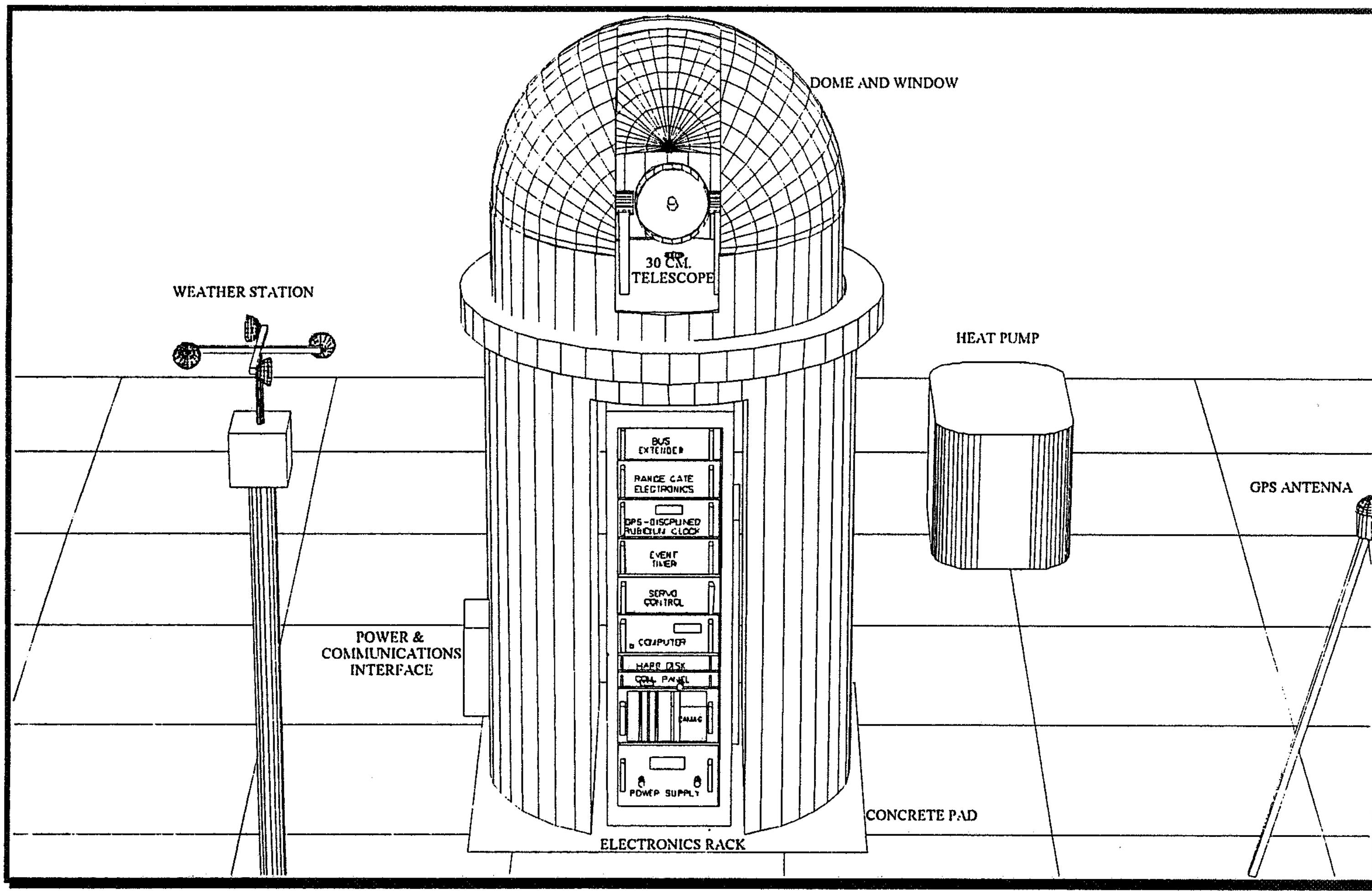

Figure 1a.

SLR 2000 CUT VIEW

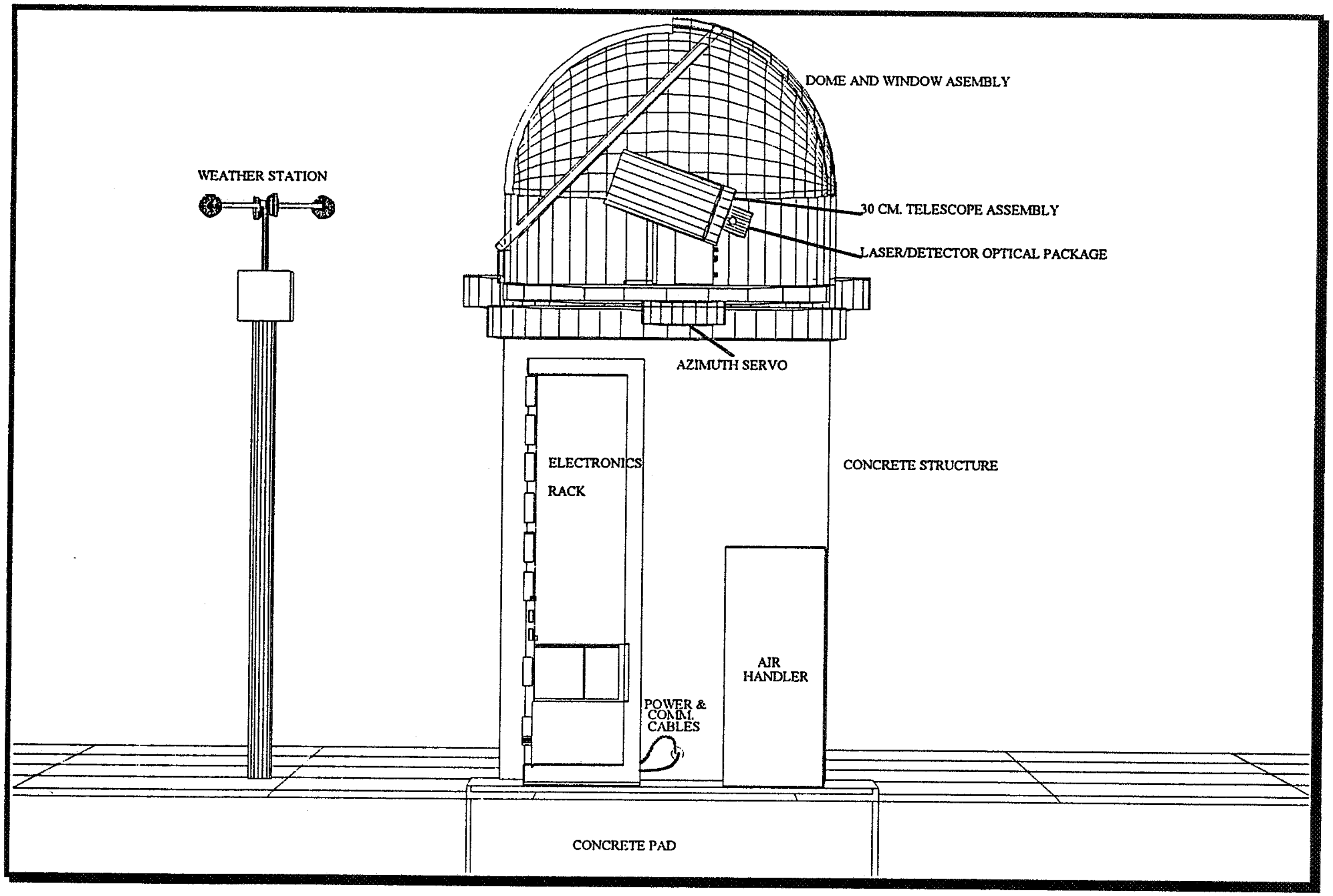

Figure 1b.

SLR 2000 ELECTRONIC RACK LAYOUT

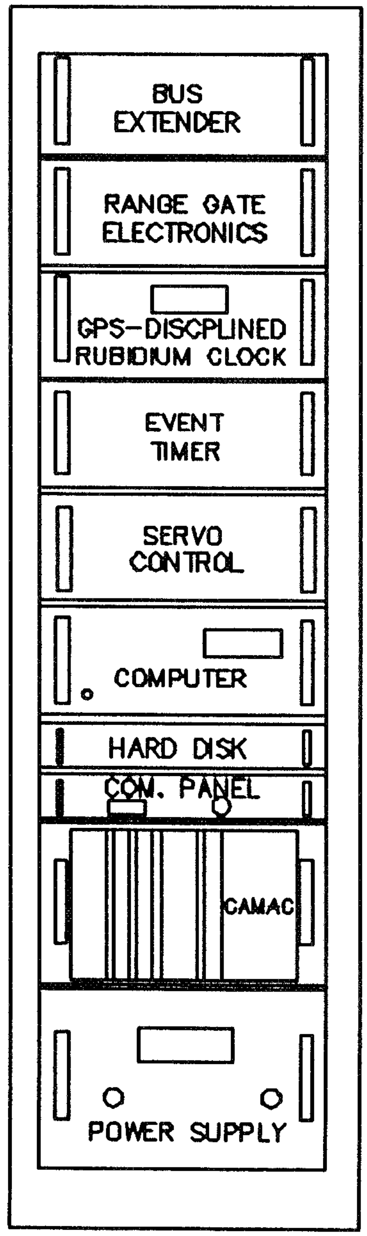

Figure 2.

To keep capital costs low, the telescope is assumed to be comparable in size to present TLRS systems, i.e. on the order of 30 cm diameter. It is further assumed that, to meet eye safety requirements at close range, the transmitter and receiver share the full aperture of the telescope. Since the single pulse eyesafe limit is 0.5 [mu]J/cm2 at a doubled Nd:YAG wavelength of 532 nm, the maximum allowable transmitted single pulse energy from a 30 cm aperture is 353 [mu]J or almost three orders of magnitude smaller than the present TLRS-3,4 energy of 100 mJ. To overcome this sizable loss in pulse energy and still maintain a comparable number of single shot ranges and precision per normal point, one must substantially increase the pulse repetition rate over the current 5 Hz and/or reduce the transmitter divergence angle from its present nominal value of 30 arcseconds full width. However, because of the integrating effects of the eye, a green laser operating at 1 KHz must be reduced to about 88 [mu]J per pulse to meet ANSI eye safety standards.

Recently developed Q-switched "microlaser" technology has demonstrated the capability to deliver over 30 [mu]J per pulse at 4 to 5 KHz rates. These diode-pumped devices are extremely small, rugged, and simple and can be mounted directly to the telescope. The demonstrated pulsewidths of 270 picoseconds are already adequate to support subcentimeter ranging and can most likely be driven below 100 picoseconds. Energy can be easily scaled upward through the use of small, passive, diode-pumped amplifiers.

Figure 3 shows the number of single shot ranges expected in one two minute normal point interval from Lageos as a function of the mean signal strength in photoelectrons (pe) and the detection threshold (1, 2, and 3 pe). If the single shot range precision is 1 cm, then 100 range returns per two minute interval would result in a 1 mm precision Lageos normal point. From Figure 3, this can be achieved with a mean signal strength of only 0.001 pe for a 1 pe threshold, 0.045 pe for a 2 pe threshold, and 0.18 pe for a 3 pe threshold.

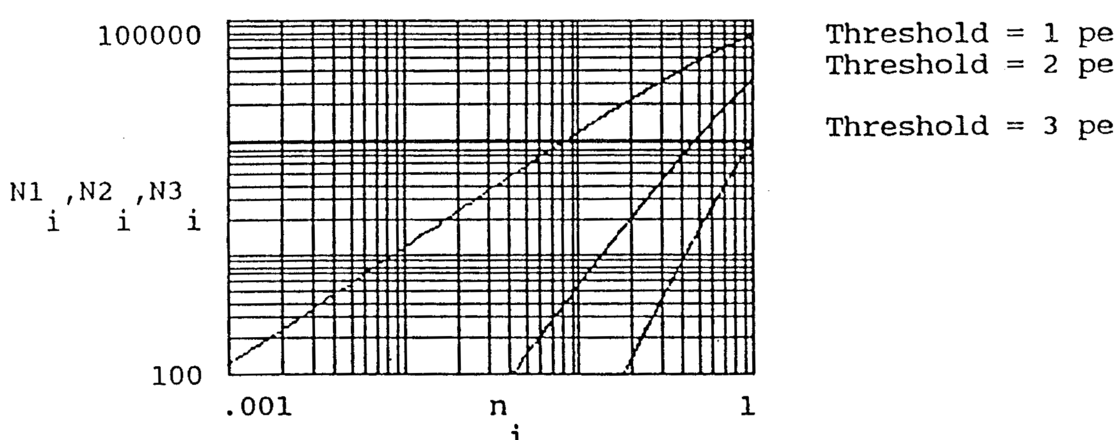

Figure 3.

Calculations show that it will be necessary to set a 2 pe threshold for daylight operation of the system although it can be lowered to 1 pe at night to increase data yield. For a "clear" atmosphere (defined as 15 Km visibility) at a minimum elevation angle of 20°, the transmitter beam divergence (and corresponding receiver field of view) must be about 8 arcseconds full width to achieve the desired data rate of 100 Lageos ranges per normal point with a 2 pe threshold, fully eyesafe beam, and 30 cm receive aperture. At night, however, this would increase to 5000 ranges per normal point by resetting the threshold to 1 pe. For higher elevation angles and better atmospheres, these numbers would increase whereas, for worse atmospheres (e.g., in the presence of light haze or cirrus clouds), they would decrease. Satellites lower than Lageos would, of course, experience much higher rates of return.

Although the eight arcsecond beamwidth has implications for acquisition and tracking, the required level of tracking precision is within the state of the art - especially with angular feedback from the intensified CCD camera. Some relaxation of detection threshold (and hence beamwidth and spatial field of view requirement) may be permitted by more effective spectral and temporal filtering. Recently developed commercial filters (Accuwave Inc.) claim spectral bandpasses as small as 0.0125 nm (with optical throughputs of 15%) compared to the conservative value of 0.3 nm used in the present calculations. Adaptive range gate widths would further reduce the false alarm rate in daylight operations. Another possibility to be considered seriously is the use of longer wavelengths, specifically the fundamental infrared Nd:YAG wavelength, which would permit the transmission of ten times more energy per pulse (~1 mJ) and provide much better atmospheric transmission. Laser transmitters at eyesafe wavelengths of 1.5 microns or higher also exist and would permit still greater energies per pulse and low repetition rates, but feasibility rests heavily on the successful development of new high speed infrared detectors (e.g. GaAs) with projected quantum efficiencies in the 5 to 10% range and efficient, compact short pulse transmitters.

In summary, the present SLR 2000 concept seems feasible but further tradeoff studies need to be completed in order to identify the optimum wavelength of operation. Additional research and development is required in areas such as the laser, event timer, spectral and temporal filtering, and detector.

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C. A STRAWMAN SLR PROGRAM PLAN FOR THE 1990s

J.J. Degnan

In developing this strawman SLR Program Plan for the 1990s, certain assumptions were made. They are:

- 0 GPS will completely take over regional deformation work from SLR and VLBI mobile systems;

- 0 One roving NASA transportable is needed in North America for station backup, system collocations, and special science studies such as post-glacial rebound in Canada, TOPEX/Poseidon calibration, etc;

- 0 A global network of well-distributed SLR stations will be needed to support terrestrial reference frame, gravity field and geoid studies, precise orbit determination, technique intercomparisons, and special science missions; and

- 0 The operational cost must be substantially reduced through increased system standardization and automation.

In keeping with these objectives, NASA should dedicate itself, in the 1990s, to achieving a series of programmatic and technical goals as outlined below.

1. Standardize The Performance Of The Global SLR Network.

There is presently a wide disparity in performance among the approximately 43 stations in the international SLR network. The single shot precision varies from about one centimeter at NASA sites (and a few foreign sites) to about 20 centimeters at second generation foreign sites. The poorest quality stations are typically located in the republics of the former Soviet Union. NASA has successfully negotiated wide-latitude space geodetic agreements with the countries which were part of or allied with the former Soviet Union. These agreements permit the exchange of data, technical and scientific information, equipment and personnel. Three Russian government entities (Russian Academy of Science, Russian Space Agency, and Russian Time and Frequency Institute) have deployed, or are deploying, as many as 15 SLR stations across the former Soviet Union. NASA should utilize the new international agreements to ensure that at least some of the Russian SLR sites, especially those within central Asia where there is little or no SLR coverage, achieve subcentimeter performance. Where warranted, NASA should also send in survey teams to ensure that local survey ties between collocated SLR, VLBI, and/or GPS monuments are performed with adequate precision. A precedent exists since, through a University of Texas grant, NASA is presently providing SLR components to Chinese stations in return for TOPEX/POSEIDON tracking support. NASA should also distribute standardized normal point software (and host PCs if necessary) to stations with chronic data format and normal point problems.

2. Improve The Geographic Distribution Of Stations.

The current SLR network consists of approximately 43 stations worldwide, but only four of these are located in the Southern Hemisphere - two in Australia, one in Peru, and one in Chile/Easter Island. There is also a shortage of good stations in Central Asia. Because of the cost of building and operating traditional SLR systems, the burden of improving SLR coverage in the Southern Hemisphere and the Asian continent in the near term will fall on NASA and its European and possibly Australian partners. NASA should:

- Continue to upgrade the decommissioned MOBLAS-6 and provide it on long term loan to South Africa for permanent deployment to either the Sutherland Astronomical Observatory (north of Capetown) or the VLBI facility in Hartebeesthoek (west of Pretoria). Both sites were already visited by the German MTLRS-1 system during the summer of 1993 and found to be good sites.

- Upgrade the TLRS-2 station performance and establish rotating occupations at Santiago and Easter Island to avoid weather outages at Easter Island. (The Huahine site has recently been terminated due to budget cuts and high per diem costs.)

- Consider the relocation of one California Moblas site (preferably Quincy because of its poorer weather) if it is no longer required to support the San Andreas Fault Experiment or TOPEX calibration at the Harvest Platform near Point Concepcion. Important alternate sites would be Ascension Island (British), India, or New Zealand.

- Encourage France to establish a permanent site with SLR, DORIS, and GPS site at Pamate in French Polynesia through deployment of the new transportable SLUM system.

- Encourage Poland to follow through on their plans to establish a new SLR station in Tunisia.

- Encourage and support Latvia in their attempts to establish a new SLR station in the Southern Hemisphere.

- Encourage the temporary or permanent deployment of the European transportables (MTLRS-1, MTLRS-2, or TLRS-1) to Southern Hemisphere sites. Toward the end of the decade, the new German TIGO (Totally Integrated Geophysical Observatories) systems could provide additional coverage.

- Encourage AUSLIG in Australia to take over the operations of Moblas-5 in Yarragadee and to work with New Zealand to establish a site there.

- O Provide enthusiastic and comprehensive laser tracking and infrastructure support to foreign entities developing new satellites which will improve our knowledge of the solid Earth, gravity field and oceans or which will test new applications of SLR such as in the fields of time transfer and relativity.

3. Reduce The Costs Of Field Operations And Data Processing.

Field and data operations within the SLR community are too manpower intensive. Factors contributing to the high cost include lack of automation, lack of standardization, system age, subsystem complexity and reliability, hardware obsolescence, and the presence of optical, electrical, and/or chemical hazards. In addition, communications costs at remote sites can be expensive if satellite links, such as INMARSAT, are used. To reduce these costs, NASA should:

- O Make maximum use of NASA Science Internet for data transfer and routine communications. This activity is coordinated within NASA by the Ames Research Center in California.

- O Install safety radars and modern controllers (with cable wrap hardware and software safeguards) to eliminate the need for a mount observer. This will reduce the required shift manpower from three to two people.

- O Provide remote key modelocked laser monitors and controls (e.g. RF frequency control and Pockels Cell pulse switch-out adjustment) to the control console. This would permit eventual single person operation of the station. Alternatively, one can consider replacing the complex modelocked oscillator with a much simpler Q-switched microlaser-amplifier system, but the latter are not commercially available at present.

- O Investigate the feasibility of highly standardized and totally automated eyesafe systems, such as SLR 2000. Build and test a prototype at GGAO.

- O Provide additional automation of the communication and data processing activities.

- O Phase out the generation and distribution of special or obsolete data products in favor of more timely distribution of standardized data products. For example, provide only tuned IRV elements (and not Keplerian elements) for satellite acquisition and online field generated normal points (instead of full rate data tapes which are redundant).

0 Distribute standardized normal point software through the CDDIS (and PCs if necessary) to stations with data format or normal point computation anomalies.

0 Encourage the phased takeover of Moblas-5 by AUSLIG.

0 Proceed with the transfer of the TLRS-1 system on long term loan to Italy.

4. Expand The 24 Hour Temporal Coverage To Better Serve The Growing Constellation Of Satellites.

At the October 1993 meeting in Potsdam, the CSTG SLR Subcommission established the following priority criteria for laser tracking. The two oceanography satellites, ERS-1 and TOPEX/Poseidon were given top priority. All remaining satellites were prioritized first with respect to altitude (lowest altitude gets highest priority), secondly with inclination angle (closest to 90° inclination gets highest priority), and finally degree of international interest.

In FY94, the international SLR network is routinely tracking 13 satellites with the following prioritization:

ERS-1 (ESA)
TOPEX/Poseidon (U.S./France)
MSTI-2 (U.S.)
Starlette (France)
Stella (France)
Meteor 3/PRARE (Russia/ Germany)
Ajisai (Japan)
Lageos-1 (U.S.)
Lageos-2 (U.S./Italy)
GPS-35 & 36 (U.S.)
Etalon 1 and 2 (Russia)

In January 1995, we expect two satellites to be added to the list:
GFZ-1 (Germany)
ERS-2 (ESA)

Other near term potential missions include a Chilean satellite (FY95) and a South African satellite (SUNSAT in FY96).

Most of the international stations provide single or double shift operations. As a result, there is a period of 8 to 16 hours per day where satellites are not tracked from a particular site. In particular, weekend or holiday coverage is often poor. Single shift operations at many key tracking sites, combined with the vagaries of weather, can result in long intervals where a given satellite is not tracked over an important geographical area.

In the near term, savings on field manpower produced by increased automation can be used to create new shifts at little or no extra cost. For example, with the implementation of the new aircraft radar at Moblas sites, two three person shifts at a Moblas can become three two person shifts, providing 24 hour coverage. This approach, of course, implies that cost savings realized through automation are allowed to remain within the program.

In the long term (1998 and beyond), totally automated stations such as SLR 2000 can be deployed. A complete transition to automated systems would require a daylight ranging capability over the full constellation of retroreflector equipped satellites ranging in altitude from 300 Km (GFZ-1) to 20,000 Km (Etalon, GLONASS, and GPS). In the event that this technologically challenging goal could not be achieved for the highest altitude satellites (i.e beyond Lageos), approximately 10 to 15 well-distributed manned sites might be required worldwide to satisfy the requirements of the lunar and GPS/GLONASS communities.

5. Improve The Absolute Range Accuracy to 2 mm at Key Stations.

Compared to radio or microwave techniques, SLR is 70 times less sensitive to the atmospheric water vapor content and is virtually unaffected by ionospheric variations. State-of-the-art SLR systems produce normal points with precisions at the 1 to 3 mm level. In terms of absolute accuracy, the limiting error source in modern SLR systems is the dry atmosphere. Estimates of the potential systematic error, due to transverse pressure gradients and/or deviation of the vertical profiles from hydrostatic equilibrium models, range from 5 to 12 mm and are largest at low elevation angles. To reduce this potential error source, NASA should:

- Continue to develop two color systems for directly measuring the atmospheric delay and to validate or improve atmospheric models.

- In the interim, consider utilizing locally available pressure data or estimation techniques to compute gradient corrections to the range data.

- Cooperate with our international partners in the design, fabrication, and/or launch of the next generation satellite laser arrays which minimize target signature effects and can make two color millimeter absolute accuracy ranging a reality.

6. Improve Satellite Force, Radiative Propagation, And Station Motion Models And Investigate Alternative Geodetic Analysis Techniques.

Improved range accuracy alone will not translate into higher geodetic accuracies without continued improvement of dynamic satellite force (gravitational and nonconservative), radiative propagation, and/or station motion models. NASA should therefore:

- Continue to search for satellite forces, propagation effects, and station motions not presently accounted for and incorporate them into GEODYN.

- Investigate the relative merits of strictly *a priori* models versus models which include a limited number of solved for parameters.

- Investigate geometric and reduced dynamic techniques using first Lageos, then Etalon, data.

- Develop improved quality control procedures and global collocation methods to provide continuous near real-time monitoring of global SLR station systematics.

7. Support Technique Intercomparisons and the Terrestrial Reference Frame Through Global Collocations.

The 1989 Coolfont Meeting set as a goal the achievement of millimeter positioning accuracies by the end of the decade. In order to fully understand the performance and accuracy limits of the various space geodetic techniques, it will be necessary to perform routine and painstaking intercomparisons at a set of global sites. For various reasons, which are both scientific and economic in nature, GPS is gradually being collocated at existing VLBI and SLR sites. However, the number of collocated SLR/VLBI sites is extremely limited - especially in the Southern Hemisphere. To correct this shortcoming, NASA should:

- Collocate TLRS-4 at selected VLBA/VLBI sites in North America

- Collocate TLRS-2 with the Peldehue VLBI station near Santiago during bad weather periods at Easter Island. A side benefit of this action is that no per diem costs are incurred when the system is at its home base in Santiago.

- Consider Moblas-6 installation at the Hartebeesthoek VLBI site in South Africa instead of Sutherland.

- Encourage European transportables to periodically visit local VLBI sites in Europe

- Monitor VLBI Mark IV development progress as a means of providing low cost VLBI capability at additional SLR sites in the Southern Hemisphere (e.g. Yarragadee, Easter Island, etc.).

- Encourage the Japanese transportable, HTLRS, to visit VLBI sites in Japan.

- Provide GPS and conventional survey support to quasi-collocated SLR/VLBI sites where anomalies exist (e.g. Shanghai, Simeiz, Orroral, etc.).

8. Investigate Potential Synergisms Between GPS And SLR.

The recent launch of two retroreflector equipped GPS satellites, GPS-35 in August 1993 and GPS-36 in March 1994, provides new opportunities for the synergistic use of SLR and GPS in a manner which takes advantage of the inherent strengths of each technique.

For its part, SLR offers an extremely stable and long term reference system which results from; 1) the subcentimeter precision and totally unambiguous nature of the laser range measurement; 2) compact, passive, and easily modelled "cannonball" target satellites; 3) insensitivity to dynamic atmospheric properties such as water vapor content; and (4) insensitivity to the ionosphere. For example, although SLR and GPS are both sensitive to the Earth center-of-mass, the SLR origin, as determined by Lageos observations, is stable at the one centimeter level over a period of years whereas independent GPS determinations show scatters of 10 to 15 centimeters. The one sigma single shot RMS laser range scatter about short GPS arcs (40 minutes or less) is about one centimeter while the corresponding five minute normal points exhibit a scatter of less than 2 millimeters. Furthermore, SLR has recently demonstrated a capability to position the GPS-35 satellite over long arcs (104 days) to better than three centimeters. Based on independent preliminary analyses carried out by NASA/GSFC and the University of Texas Center for Space Research, SLR agreement with IERS GPS-derived orbit solutions is at the decimeter level in the radial coordinate and at the 0.5 to 1.0 meter level overall.

GPS, on the other hand, offers: 1) low cost operation of stations; 2) a truly global distribution of sites; 3) site densification; and (4) continuous visibility to low Earth orbiting satellites and aircraft. Combining the two techniques should permit:

- 0 The rapid and precise positioning of retroreflector-equipped GPS satellites in the highly stable SLR reference frame and, by inference via the GPS ground network, non-equipped GPS satellites as well.

- 0 The unambiguous separation of onboard clock errors from satellite ephemeris errors.

- 0 Direct, real-time, comparisons of GPS pseudorange with laser range at collocated sites. AS potential benefits include:

    a. Monitoring and possible correction of SA and AS-induced errors;

    b. Rapid resolution of cycle ambiguities in scientific analysis; and

c. Identification of multipath or antenna phase errors.

- 0 Verification and monitoring of the accuracy of stochastic atmospheric models used in GPS data analysis.

- 0 Improved absolute accuracy of GPS-determined baselines and LEO orbit trajectories.

In order to achieve these goals, NASA should strive to:

- 0 Encourage the international community to install GPS receivers at all SLR sites and use them for the establishment of epoch time.

- 0 Deploy its own network in a manner which makes continuous tracking of Lageos and GPS feasible and encourage its international partners to do the same.

- 0 Upgrade its stations for the purpose of demonstrating reliable daylight tracking of GPS and share the technology with its international partners.

- 0 Perform "simultaneous" laser tracking of GPS and satellites which carry onboard GPS receivers and retroreflectors to produce datasets which can shed light on systematic errors. Such a dataset was first collected on the TOPEX/Poseidon calibration overflight of California in December 1993.

APPENDIX

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13. ABSTRACT *(Maximum 200 words)*

Satellite laser ranging (SLR) was first demonstrated by NASA three decades ago. Today, an international network of 43 stations in 30 countries routinely collects data from 13 satellites in Earth orbit, which has been used to study the solid Earth and its interactions with the oceans, atmosphere, and Moon. Data products include centimeter accuracy site positions on a global scale, tectonic plate motions, regional crustal deformation, long wavelength gravity field and geoid, polar motion, and variations in the Earth's spin rate. By calibrating and providing precise orbits for spaceborne microwave altimeters, SLR also enables global measurements of sea and ice surface topography, mean sea level, global ocean circulation, and short wavelength gravity fields and marine geoids. It provides tests of general relativity and a means for subnanosecond time transfer. In the 1990s, SLR faces competition in a number of applications from relatively inexpensive radio techniques, notably the Global Positioning System (GPS). In February 1994, NASA convened a two-day workshop at the Belmont Conference Center in Elkridge, Maryland, to define future roles and directions for SLR. Key technologists and analysts from the domestic space geodetic community presented short summaries reproduced in Sections III and IV of this report.

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