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A. SCIENTIFIC ANALYSIS OF SATELLITE RANGING DATA

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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

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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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