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ABSTRACT

Satellite Laser Ranging (SLR) is presently making important contributions in the fields of geodesy, oceanography, geodynamics and to our knowledge of the geopotential. With the best current systems SLR has successfully defined an absolute vertical datum to 3 cm and a relative horizontal datum with comparable accuracy. In the areas of earth and space physics SLR has demonstrated its ability to provide information regarding the vertical and horizontal movements of the lithosphere, the rheology of the earth, improved understanding of the evolution of the earth-moon system, the earth's albedo and upper atmosphere, the polar wander, the frequency structure of the polar motion and in the definition of fundamental constants. Based on current assessments of the future densification of the global coverage of the laser sites, and with the anticipated improved systems accuracies and proposed 24 hour automated tracking operations, we expect an order of magnitude improvement in the accuracy of the SLR deliverables. A proportionate reduction can be expected in the SLR operation costs. A review of recent results and a discussion of future options indicates that SLR will continue to provide a unique and powerful tool for the study of space and geosciences.

THE ROLE OF SATELLITE LASER RANGING THROUGH THE 1990's

Introduction

Stringent accuracy requirements for current geodetic applications have resulted in the development of a number of space age techniques for the computation of three dimensional tracking station positions and their inter-station baseline distances. In principle, these techniques are based on the accurate timing of the propagation of radio and microwave signals, or on the timing of propagation of very high frequency, visible light signals, such as the laser. It is the intent of this paper to first briefly summarize the recent scientific contributions made through the reduction of data collected via one of these techniques, namely Satellite Laser Ranging (SLR). Furthermore, this paper is meant to present the authors' view regarding the future role of SLR in space-age geodesy.

The development of SLR systems within NASA started in the early 1960's, soon after the invention of the laser itself. Since then, laser ranging activity has grown enormously and has become one of the predominant techniques for the study of geodesy, earth dynamic processes and lunar science. The launch of Lageos in mid-1976 marked the beginning of a new era for SLR. Under support from NASA's Crustal Dynamics Project the laser systems were improved in accuracy by more than an order of magnitude within a few years with current single-shot accuracies lying between 3 and 10 cm. During the last few years SLR has produced a large quantity of good quality data collected from tracking sites distributed around the globe. Analysis of these data has demonstrated the ability of SLR to make significant contributions in a variety of scientific applications. A survey of some of the recent scientific results produced as part of the SLR activities at NASA's Goddard Space Flight Center (GSFC) will be presented. These efforts span a wide range of activities including celestial mechanics, geodesy and geophysics.

Recent Contributions of SLR to Geosciences

Dynamic reduction of SLR data provides very precise positions in three dimensions for the laser tracking network. The sensitivity of the SLR data requires that, for a well conditioned solution, the longitude of one of the tracking stations be constrained to an a priori value. The vertical components of the stations, however, through the tracking geometry provided by the global network and the accurate knowledge of orbital dynamics, are uniquely related to the center-of-mass of the earth. Current SLR solutions have demonstrated potential to define a vertical datum at the 1 cm level (1σ) from annual solutions (Christodoulidis, D.C., and Smith, D.E., NASA/GSFC TM 85078, September 1983). Horizontal positions are estimated to be better than 2 cm. Positioning on the earth's surface with such a high accuracy finds important applications in the study of regional and global geotectonics.

In the area of regional geotectonics the San Andreas Fault Experiment (SAFE) was pursued (Figure 1). New results obtained from the analysis of Lageos' data through either standard annual solutions or from "weekly" arcs employing special techniques (as those described in Christodoulidis, D.C. and Smith, D.E., NASA/GSFC TM 82133, April 1981) resulted in rates of separation between the two tracking sites, agreeing within one sigma with the results obtained earlier through the analysis of the BE-C satellite data (Smith, D.E., NASA/GSFC TM 80642, January 1980). These measures monitor the motions along the San Andreas Fault. If the three independent rate measurements are assumed to be estimates of the same constant rate, the weighted average rate for the last eleven years becomes -6.5 ± 0.7 cm/yr.

On a global scale, under support from NASA's Crustal Dynamics Project it has been demonstrated that SLR is capable of observing inter-plate tectonic rates. These inter-plate motions were computed between four tectonic plates where SLR sites with good tracking records existed (Figure 2). The Lageos data analyzed was collected from 1979 through 1981. Since a long history of baseline changes was not available, the sample size was increased by averaging the baselines per tectonic plate to give the computed inter-plate rates shown in Figure 3. The heavy lines connect the geographic barycenter of the sites wherever more than one site was available on a plate. Horizontal changes, free of vertical displacements (and free of errors resulting from uncertainties in the vertical direction) were obtained from ellipsoidal chord changes rather than baseline changes. These ellipsoidal chords interconnect the projections of the tracking station positions onto the reference ellipsoid. Changes in the SLR chord lengths, free from height variations give the horizontal component of the velocity vectors between the tectonic plates. As such, they may be compared directly with the components of the strictly horizontal station motions suggested by the model of Minster and Jordan (<u>JGR</u>, 83, (B11), 5331-5354, 1978). The Minster and Jordan rates however reflect average movements over millions of years whereas the SLR rates are two-year averages. The computed inter-plate rates are shown in Figure 3. For the purpose of comparisons the same per plate averaging was applied to the rates implied by the Minster and Jordan model between the SLR sites. The agreement between the two independent estimates is within one sigma of the SLR values (on the average ± 2.5 cm/yr) the exception being the Australia to South American rate. This particular chord however crosses two plates (the Nazca plate and the Pacific plate) and therefore what one sees is the result of the combination of movements from four plates. If this observation is not a figment of the data, it may be of particular importance because of the tectonic uncertainties in relation with the Australian plate along the New Zealand boundary.

Although these global SLR plate motions seem to be encouraging indeed, much attention will be given to future higher quality laser results. These investigations will increase the length of the movement records for the laser sites and will thus enable a further verification of these preliminary observed inter-plate tectonic rates.

The observed along track acceleration of Lageos (Figure 4), which was found to be one or two orders of magnitude larger than expected (Smith, D.E., <u>Nature</u>, 304, July 1983), has been a source of puzzlement as to its cause. Early calculations suggested that charged particle drag was the principal cause for this acceleration. Since early 1983, however, the acceleration reversed sign. This reversal of sign implies that charged particle drag (which previously was thought to be almost entirely the source of this acceleration) cannot be the sole cause. The earth's albedo radiation asymmetry, either between the Northern and Southern hemispheres, or between dawn to dusk brightness has now become a candidate as a contributing source to this orbital behaviour. To further our understanding of the origin of this acceleration, continuous monitoring of the evolution of Lageos will be necessary along with a much more sophisticated earth albedo modeling.

Satellite laser ranging provides the most accurate means for tracking near-earth satellite motion. Large quantities of these data from numerous satellites including Lageos, have been incorporated in recent Goddard Earth Models (GEM's) which model the earth's gravity field. GEM-L2 (Lerch et al., GRL, Vol. 9, No. 11, 1263-1266, 1982), which is the latest "satellite only" derived field, has a long wavelength geoid (to degree and order 4) assessed to be accurate to ±8 cm. This is a major advancement in our knowledge of the low degree and order geopotential and is a direct result of the high precision tracking of Lageos. Orbital accuracies for Lageos have also experienced a fourfold improvement with the development of GEM-L2.

Important information regarding the earth's rheology was gained from the size of the effective viscosity of the lower mantle, inferred from observations of the evolution of Lageos' nodal position (Rubincam, D.P., NASA/GSFC TM 84982, February 1983). Analysis of the laser data revealed an acceleration in the node of Lageos (Figure 5) which did not seem to be due to the tidal deceleration of the earth nor did it seem to be due to the long-period 18.6 year ocean tide. Instead, the acceleration of the node appeared to be due to a change in the earth's oblateness, described as a change in the 2nd degree zonal harmonic, J_2, due to post glacial rebound of the earth. The earth is now relaxing and thus becoming more spherical. Since the size of $\dot{J}_2$ is controlled in part by the effective viscosity of the lower mantle this observation places constraints on the structure of the earth. The effective viscosity of the lower mantle computed by Rubincam (ibid.) agrees well with the L1 theoretical model of Wu & Peltier (Geophys. J.R. Astron. Soc., 70, 435-485, 1982) which has a 120 km-thick lithosphere, a 10^{21} Pa s mantle and an inviscid core.

SLR has been proven to be one of the most reliable and accurate techniques for orienting the earth within an inertial reference system. Global data, taken over 5-day intervals, provide a suitable means for directly solving for the earth's polar motion and excess length of day. SLR solutions (for data taken since May of 1976) are now routinely provided to BIH for inclusion in their annual reports for the earth's orientation. SLR earth orientation parameters are determined by rotating a rigorous station network about X, Y and Z axes in a system measured against an orbital reference over a given arc length. Current accuracies which are routinely achieved for 5 day mean values are 3 $\widehat{msec}$ for polar X and Y coordinates and 0.3 msec for change in length of day.

Comparisons of the Lageos' derived Length of Day (LOD) (Smith, D.E. et al., NASA/GSFC, TM 85078, September 1983) with the LOD derived from the exchange of the angular momentum of the atmosphere with the earth (Rosen, R.D. and Salstein, D.A., JGR, 88, C9, 5451-5470, June 1983) revealed a very high correlation between the two time series (Figure 6). This correlation holds to as high a frequency as 10 days but is presently limited by the accuracy of the atmospheric data. Atmospheric momentum contributions from each hemisphere indicate that primary exchange of momentum of the atmosphere with the solid earth is through the northern hemisphere, but not exclusively. An effort is underway to better understand the origin of the differences between the two data sets and further understand the mechanism describing the momentum interchange between the atmosphere and solid earth.

Other retro-reflector equipped satellites exist which are in close near-earth orbits. As such, they experience a much richer spectrum of geogravity and tidal effects than those experienced by the high altitude Lageos. Of special interest is the French-launched Starlette satellite, which, like Lageos, is a dense passive ball covered by retro-reflectors. It was launched exclusively as a laser target for geodetic applications. A great deal of highly accurate laser data has been acquired on Starlette and has been utilized in various phases of the Crustal Dynamic Project. These SLR activities included improved geopotential modeling and station positioning verification. Marsh and Williamson (in press, 1983) have extensively analyzed the data from Starlette and have obtained numerous results of general interest. While in the process of "tailoring" a gravity model for this orbit, they found improved tidal modeling to be a necessity. The resulting low degree tidal model which was obtained was found to be in substantial agreement with both the ocean tidal model of Schwiderski and tended to confirm the frequency dependent Love numbers for the solid earth derived by Wahr. Figure 7 shows the "lumped" Starlette solid earth tidal Love numbers for the dominant tidal frequencies before and after correction for the ocean tides (using a strictly oceanographic model). The resulting corrected values lend strong evidence to those theoretical values predicted by Wahr for his frequency dependent values of k_2.

SLR in the 1990's

Highlights of the SLR in the 1990's are shown in Table 1. The bulk of analysis will be based on data collected from permanent sites with good global distribution. Densification of the permanent network is expected to be made from sites occupied regularly, on a yearly basis employing the transportable systems. Lesser activity, but of equal importance, will be based on rapid re-occupations of numerous sites by the transportable systems for the purpose of investigating the rigidity of local networks. Improvements in the laser systems accuracies and in the models will result in a better than 5 mm normal point range accuracy (possibly single shot accuracy). The development of compact systems will be furthered. Of consequence is the effort which is under development to fully automate the laser ranging systems with the use of GPS time transfer and possibly with TDRSS data dissemination. This automation in the systems is expected to have a significant impact on the present operational costs. Our estimate is that one may expect a reduction in the operational costs as large as a factor of 10 due to automation. International commitment to continued laser ranging with the launch of new satellites looks very promising indeed. A new Lageos, Lageos II, is planned and will be launched in 1987 as a combined mission between NASA and the National Space Plan of the National Research Council of Italy. POPSAT is under development as a ESA mission and EGP, a dedicated laser satellite, will be launched by the Japanese.

SLR Products in the 1990's

Highlights of the SLR products and scientific involvement in the 1990's are shown in Table 2. With better than 1 cm total positioning accuracy in three dimensions, the permanent laser network will serve as a fiducial set of points distributed throughout the globe. This network of points will be capable of maintaining in time a global datum, at the 1 cm level of accuracy. Continuous monitoring of the rigidity of this network will play a very important role in modeling tectonic motions, plate deformations and vertical station movements on a global scale. Furthermore, the SLR Network can be used to define the vertical component of an altimeter spacecraft to a high level of accuracy, thereby permitting enhanced oceanographic modeling for missions like TOPEX and ERS.

The study of intra-plate deformation and stability will also be greatly enhanced through the three dimensional determinations of SLR fiducial points. Stresses between geologically distinct regions within a given plate, and the possible causes of earthquakes which occur far from plate boundaries can in this way be investigated over continental scales. Along with the SLR global datum, better than 0.6 msec polar motion and 0.03 msec LOD may be anticipated. Earth orientation parameters of such high accuracy can have a significant impact on a large number of scientific applications. Among them the study of the polar motion frequency structure at Chandler, annual, semi-annual, diurnal, etc., periods, as well as the nature of the Chandler excitation. The relationship between polar motion, earthquakes and mass displacements in the earth may also be investigated together with the yielding of the earth with movements of the rotation axis. Finally, the impact of atmospheric movements and mass transport on the orientation of the earth, and the core/mantle coupling can be studied.

Continued laser ranging to a number of satellites in combination with altimetry taken by missions such as TOPEX may result in further improvement in geopotential modeling of perhaps a factor of four or more. Continuous monitoring of the evolution of the orbits of satellites will permit the observation of changes in the geopotential. Such an accurate geopotential, monitored in four dimensions, may find very important applications for modeling the earth's rheology through observations of post-glacial response and mantle convection. Further it can monitor seasonal ground water variations and also the ice loading and unloading and its effect on the sea level. Through the changes in the C_{21} and S_{21} coefficients of the geopotential one can observe the rate of drift of the earth's mean figure axis. In addition, accurate observations of the gravitational constant may put a bound on the $\dot{G}$ theories. Finally, very accurate knowledge of the geopotential will play a very important role in navigation, in supporting altimetric missions, and in resource exploitation.

Reduction of SLR data requires the development of very accurate models describing the forces acting on satellites. Orbital residuals therefore provide a highly accurate means of monitoring unknown forces acting on satellites. Long records of orbital evolutions, however, are necessary for understanding the structure of the signals and for de-coupling the unknown signal from other candidate effects. Two areas we believe will benefit from future orbital residuals analysis are (a) the origin and nature of drag at very high altitudes (~6000 km), and (b) the accurate modeling of the earth's albedo.

Better knowledge of the earth and ocean tidal responses, especially those of low degree, will also be forthcoming. These results, in and of themselves, may have wide ranging earth science applications. Such applications include the measurement of tidal dissipation, the measurement of the rate of the earth-moon separation and the modeling of the largely unknown zonal tides and their departure, if any, from equilibrium. Computation of frequency dependent Love numbers and load deformation coefficients through SLR could play an important role in many areas including the study of the core-mantle resonances and the computation of the earth's Q at intermediate frequencies through observations of, for example, the 18.6 year tide. The computation of ocean tide coefficients on the other hand from orbital residuals has been, and will continue to be, an important check on the quality of purely oceanographic solutions of the Laplace Tidal Equations.

Summary

In the areas of earth and space physics, SLR has demonstrated its ability to provide information regarding the vertical and horizontal movements of the lithosphere, the rheology of the earth and improved understanding of the evolution of the earth-moon system, the earth's albedo and the upper atmosphere. The polar wander, the frequency structure of the polar motion and certain fundamental constants can also be defined with SLR data analysis. With the best current systems, SLR has successfully defined an absolute vertical datum to 3 cm and a relative horizontal datum with comparable accuracy.

As early as 1984, during the MERIT campaign, there are expected to be 28 active, globally distributed, SLR sites representing over 20 countries (Figure 8). International interest and involvement in SLR seems to be growing constantly. The densification of the global coverage of the laser sites, the large number of scientific products, the anticipated improved systems accuracy, and reduction in cost indicate that SLR will continue to provide a unique and powerful tool for the study of space and geosciences.

FIGURE 1

SAN ANDREAS FAULT EXPERIMENT

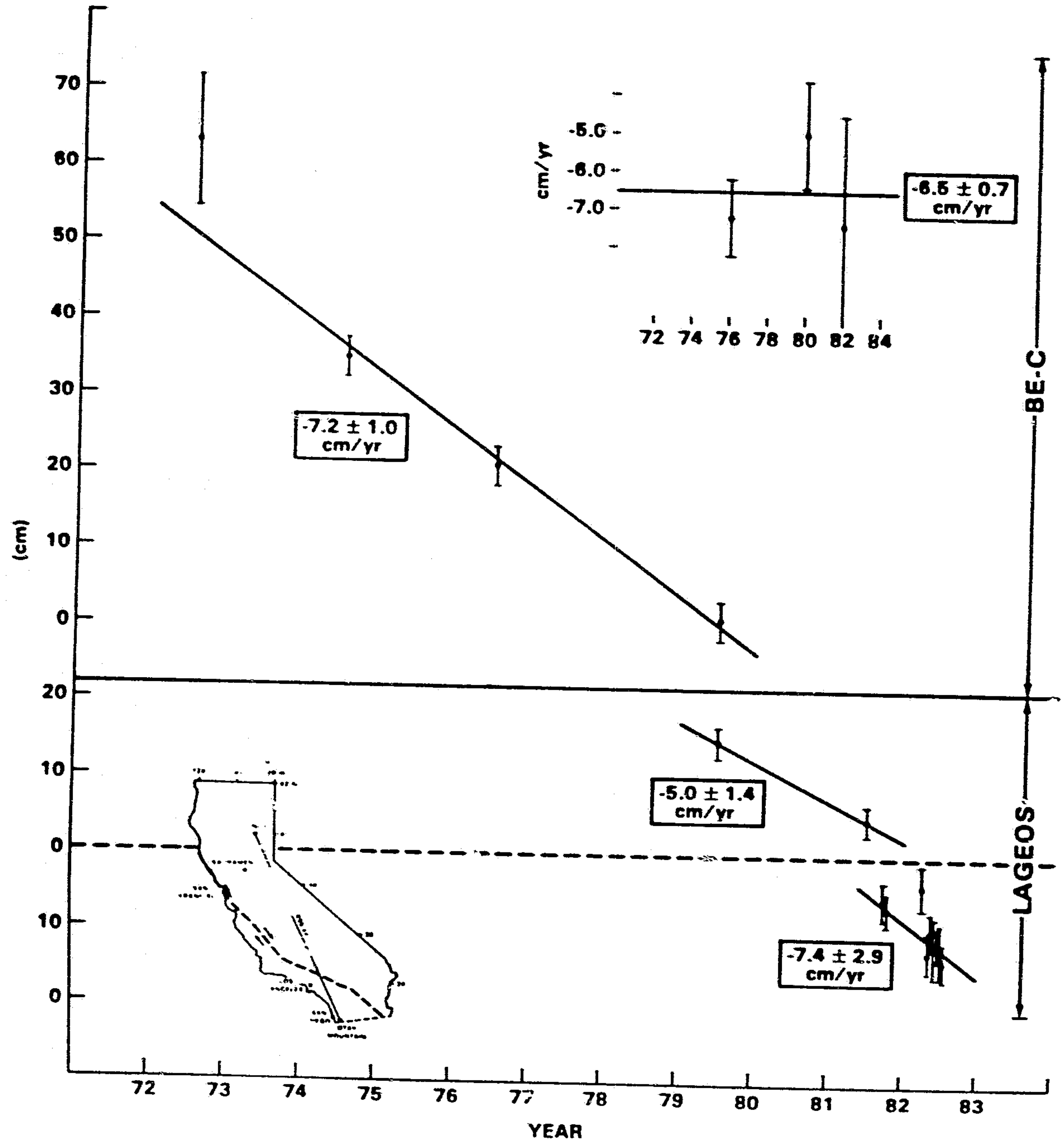

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FIGURE 2

LAGEOS TRACKING SITES

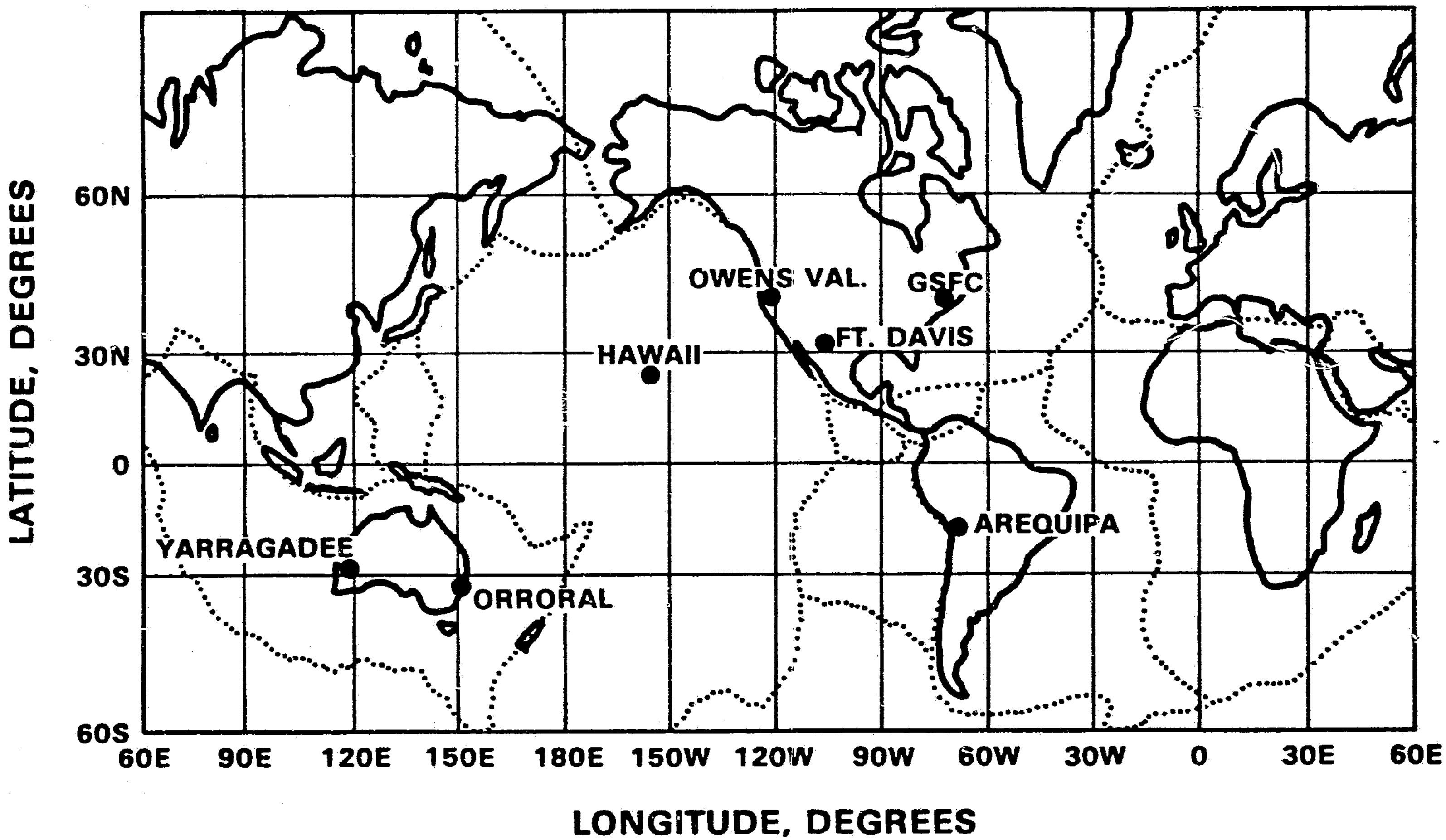

FIGURE 3

INTER-PLATE DEFORMATIONS OBSERVED BY SLR

AVERAGED ELLIPSOIDAL CHORD RATES VS. RATES GIVEN BY MINSTER & JORDAN (cm/yr.)

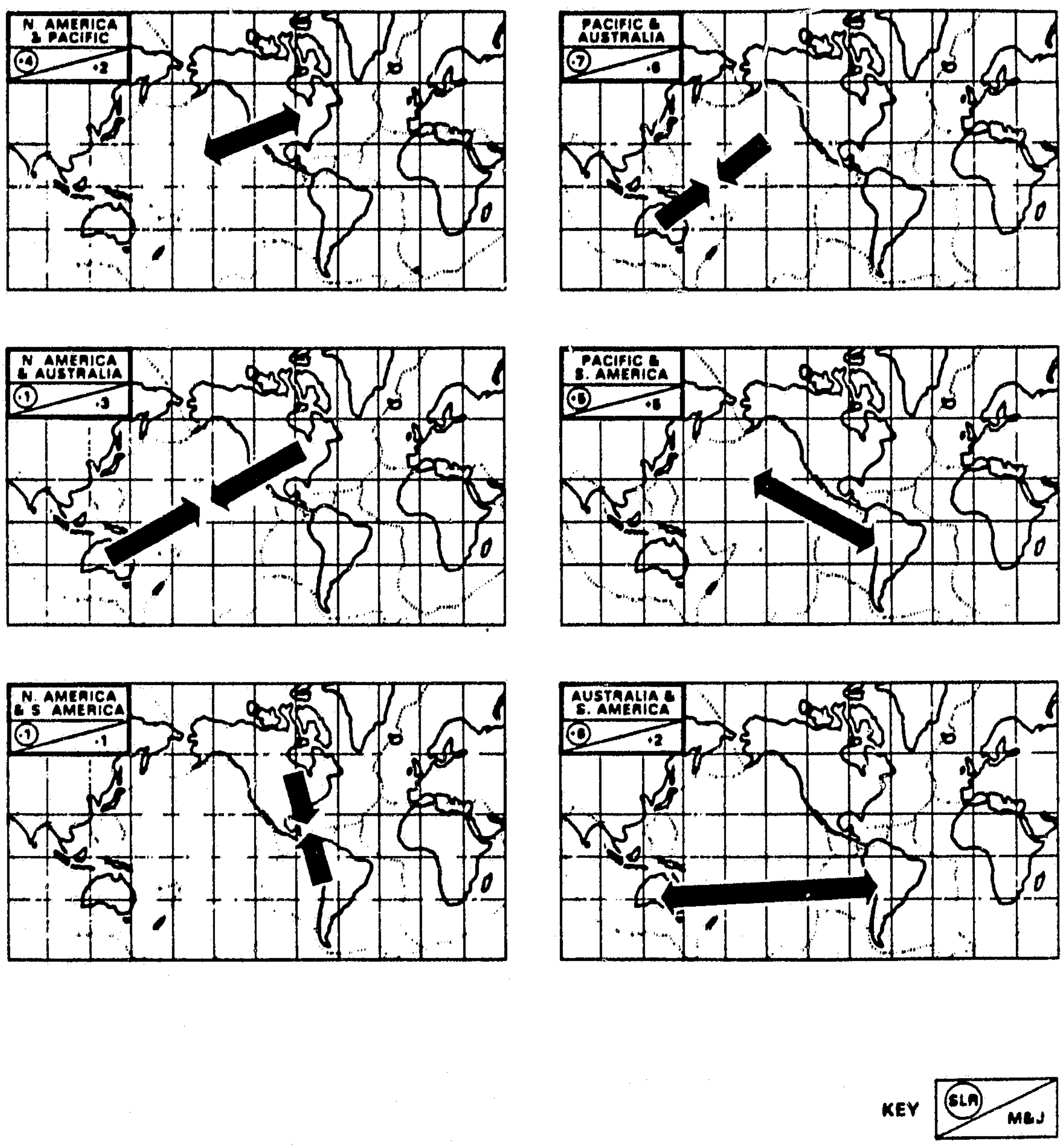

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FIGURE 4
MONTHLY ACCELERATION VALUES OF LAGEOS

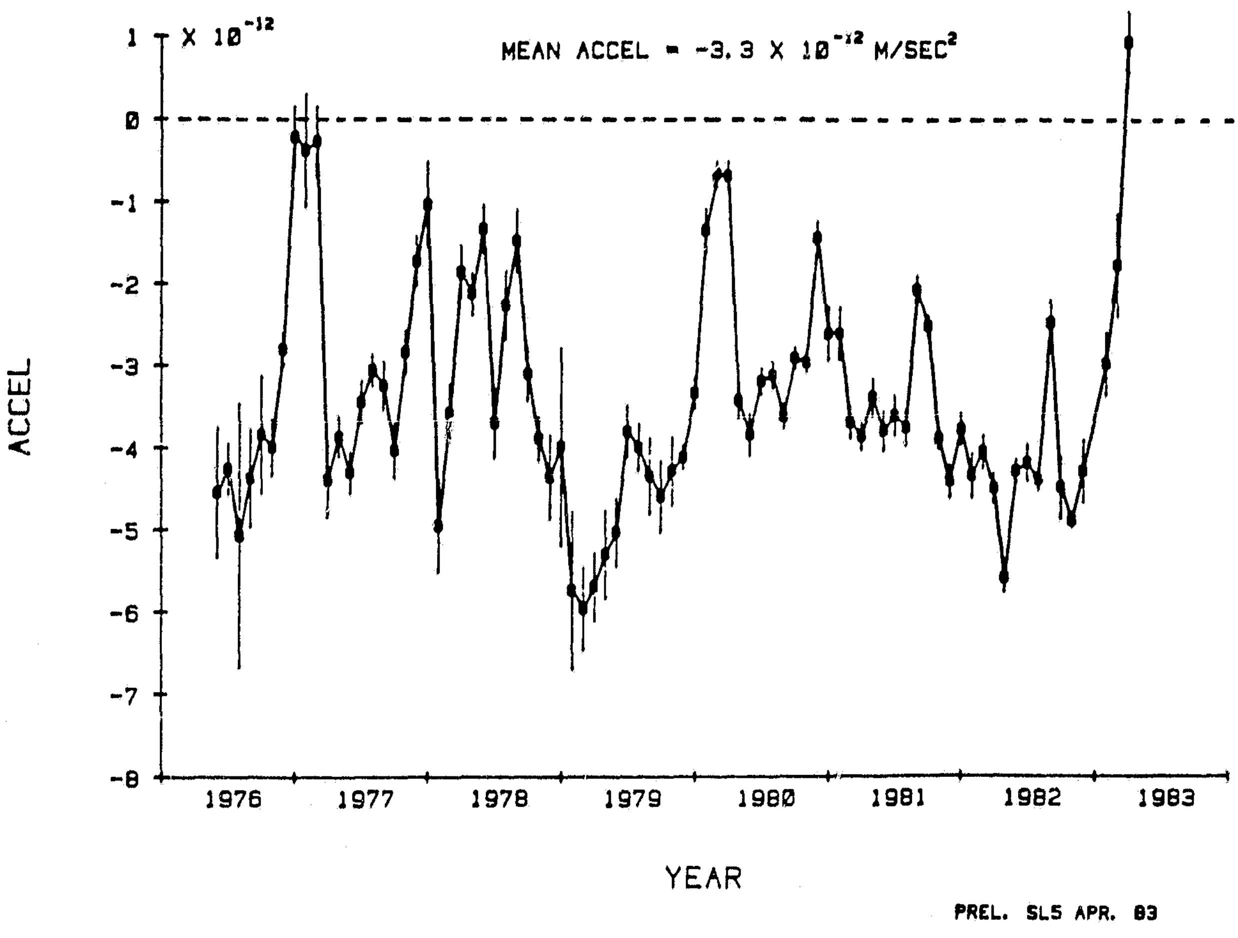

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FIGURE 5
LAGEOS NODAL RESIDUALS

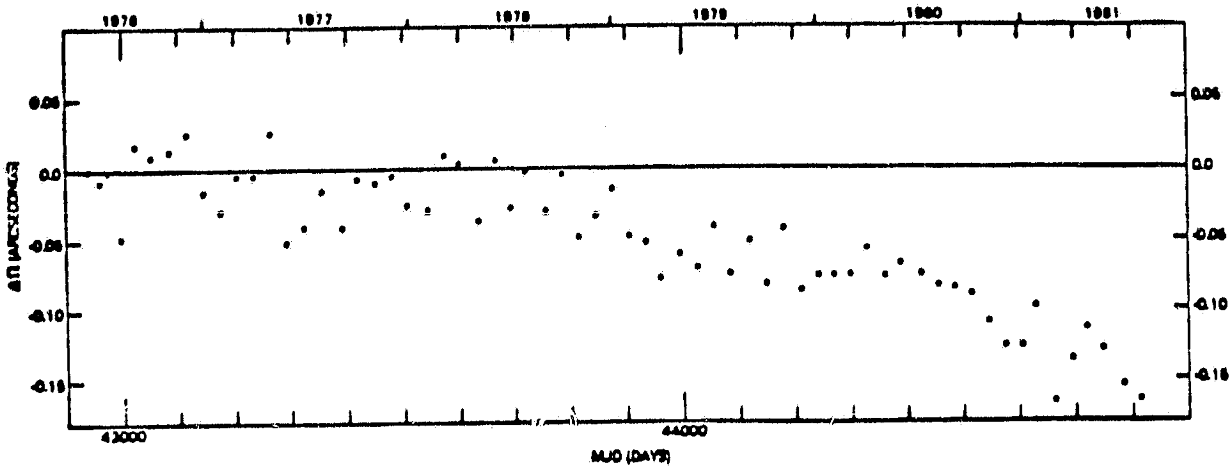

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FIGURE 6
COMPARISON OF ATMOSPHERIC ANGULAR MOMENTUM
WITH LAGEOS VARIATIONS IN LOD

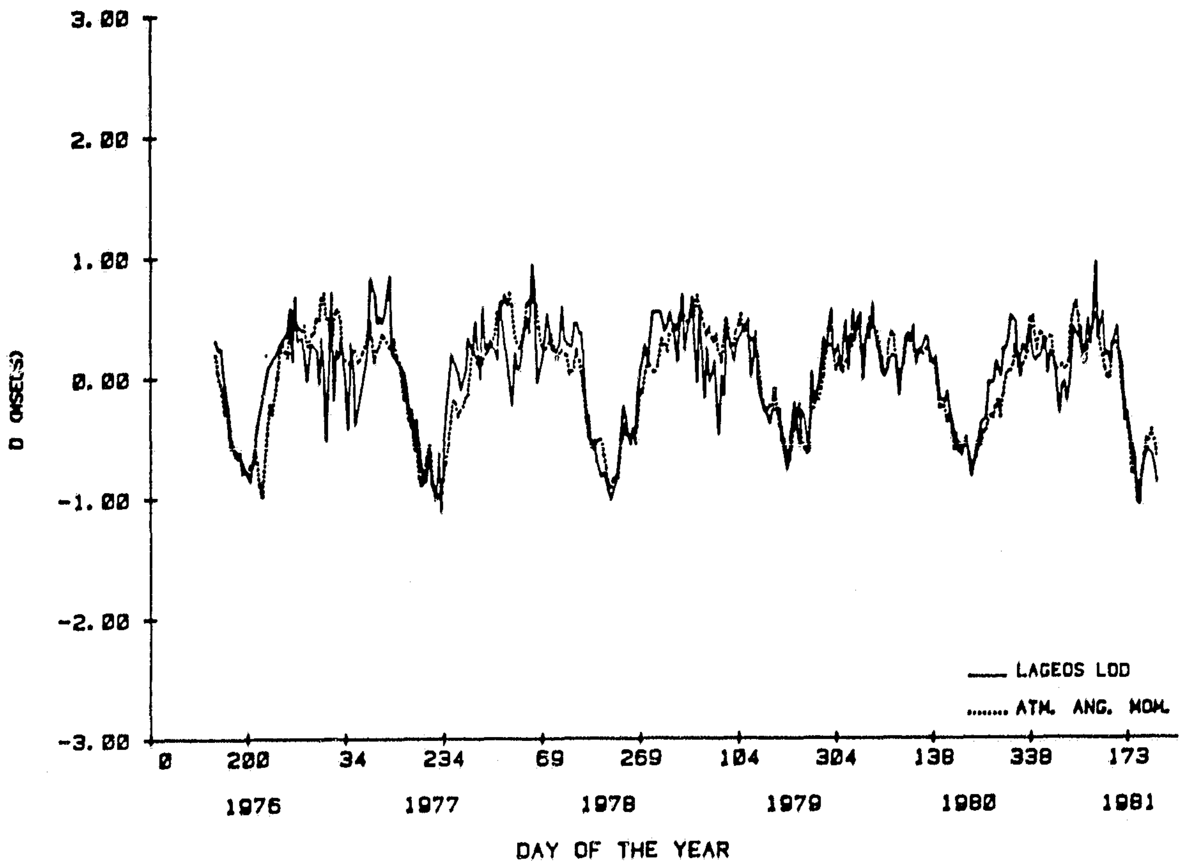
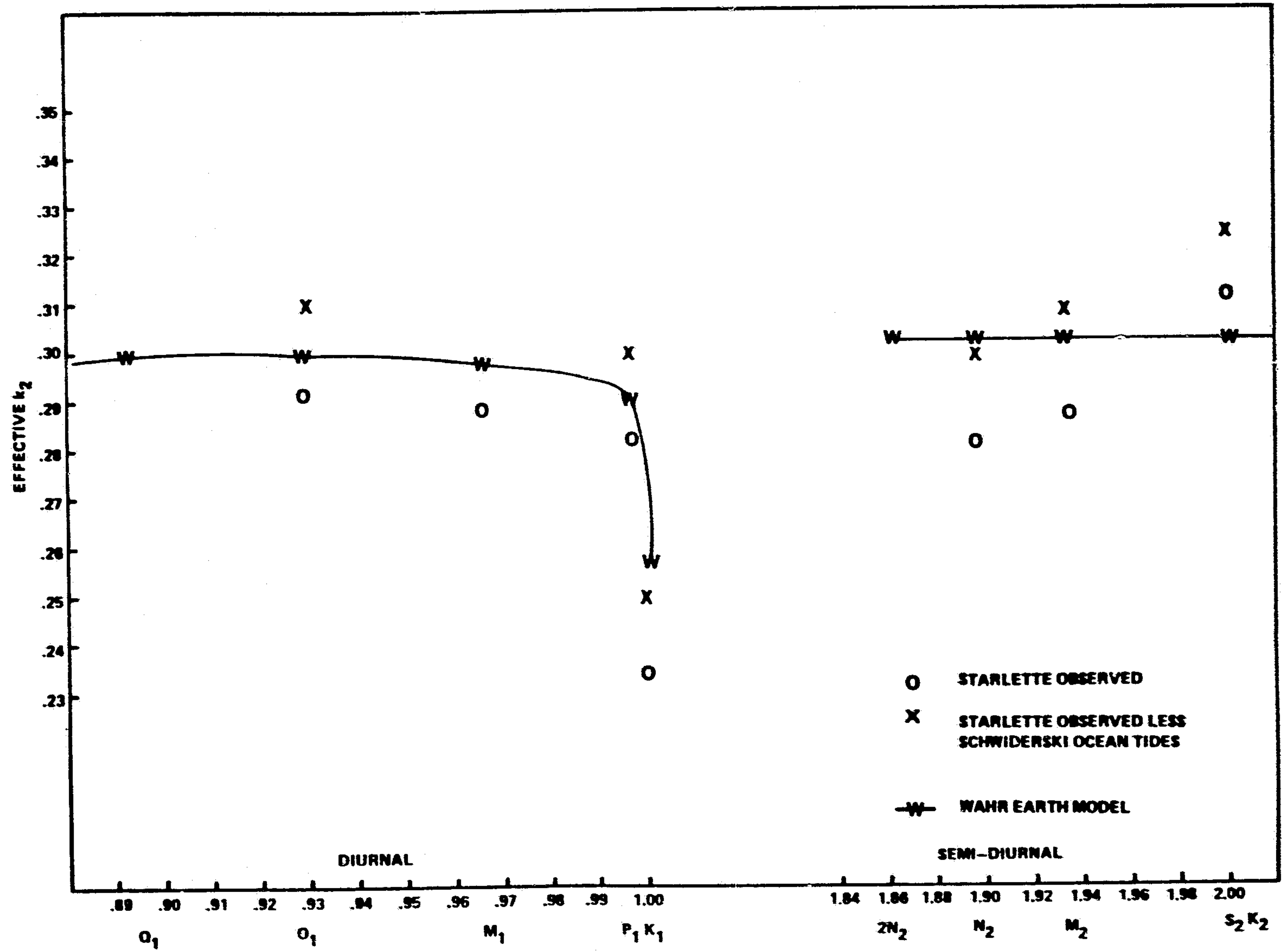


FIGURE 7*

DIURNAL AND SEMI–DIURNAL TIDAL RESPONSE OF THE EARTH OBSERVED BY STARLETTE



*From Marsh and Williamson, 1983

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FIGURE 8

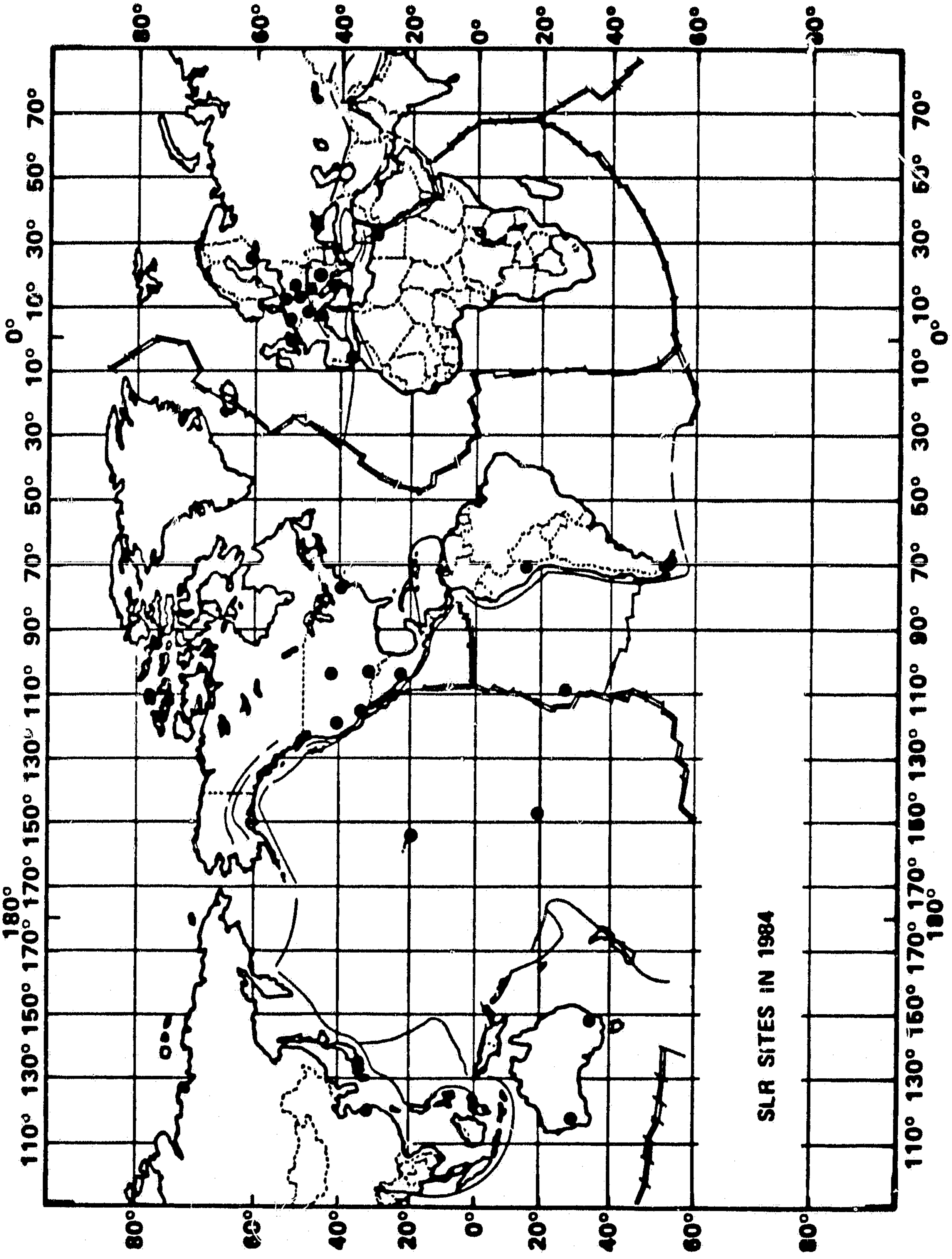

TABLE 1

SLR IN THE 1990's

GLOBAL DISTRIBUTION

- Permanent Occupations
- Regular Re–occupations
- Local Networks

SYSTEM IMPROVEMENTS

- Improved Systems Accuracy } 5 mm.
- Improved Models }
- Compact Systems
- Full Automation
- Cost Reduction

LASER SATELLITES

- LAGEOS II
- POPSAT
- EGP (JAPAN)

TABLE 2

SLR PRODUCTS IN THE 1990's

<u>Positioning</u>	o	Altimetric Missions
	o	Global Datums
	o	Tectonic Motion
	o	Plate Deformation
<u>Earth Orientation</u>	o	Polar Motion Frequency Structure
P. Motion <0.6 msec	o	Polar Wander
LOD <0.03 msec	o	Earthquake Excitation
	o	Atmospheric Excitation
<u>Geopotential</u>	o	Rheology – Post Glacial Response
	o	Mantle Convection
	o	Polar Wander
	o	Ice Loading
	o	Mission Support (Altimetry, Navigation)
	o	Gravitational Constant
<u>Surface Forces</u>	o	Albedo
	o	Drag
<u>Earth and Ocean Tides</u>	o	Tidal Dissipation
	o	Earth Moon Separation
	o	Zonal Tides and Departure from Equilibrium
	o	Improved Length of Day
	o	18.6 yr. Tide for Q at Intermediate Frequencies
	o	Core–Mantle Resonances (K_1 Tide)
	o	Love Numbers of Load Tides