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D. GLOBAL AND REGIONAL KINEMATICS FROM SLR STATIONS

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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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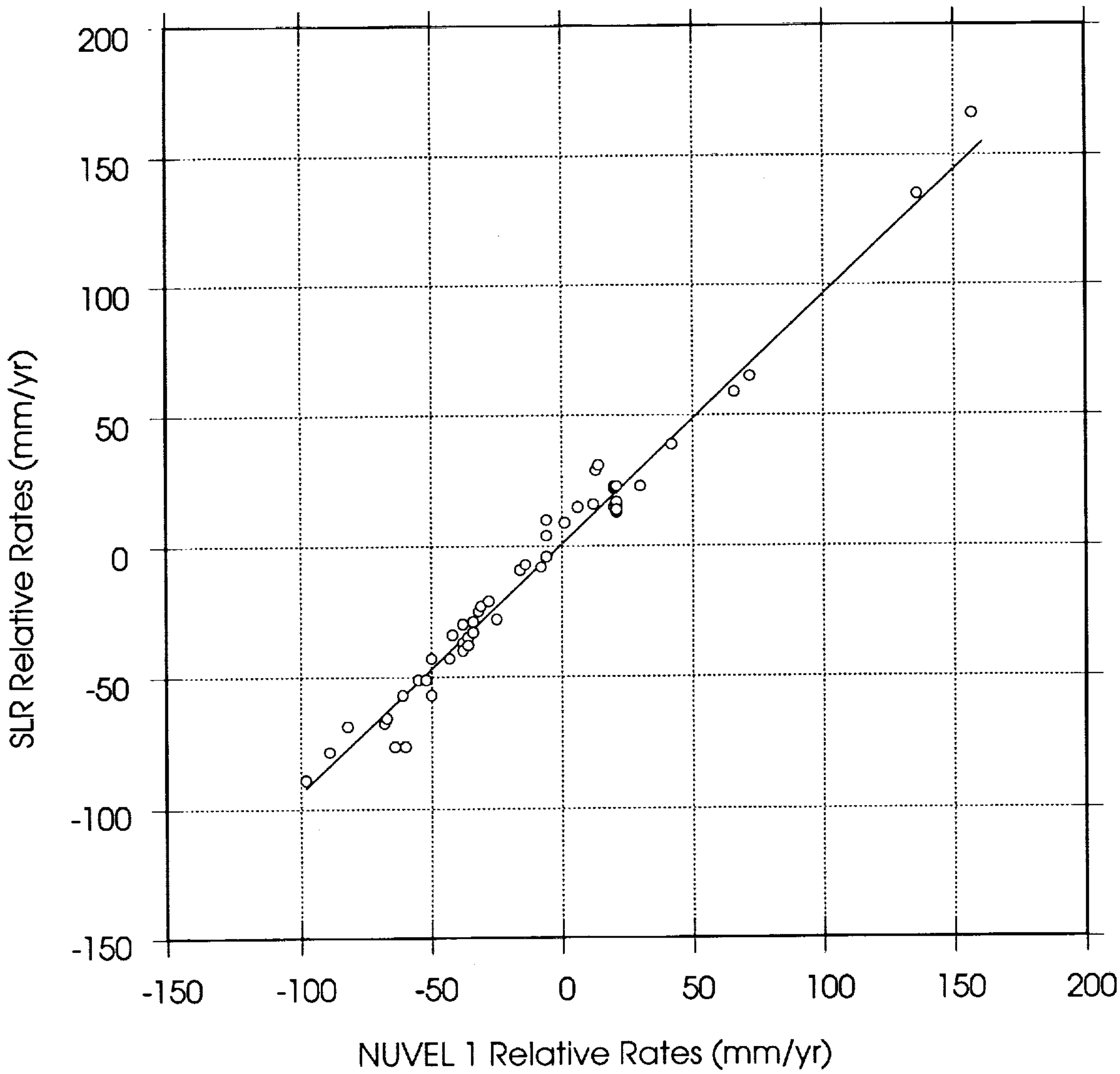

Fig. 1 Geodesic rates between SLR stations move more slowly than is predicted by NUVEL-1: the slope of the line is 0.95. The geophysical model assumed a paleomagnetic time scale which has recently been revised to reduce this discrepancy.

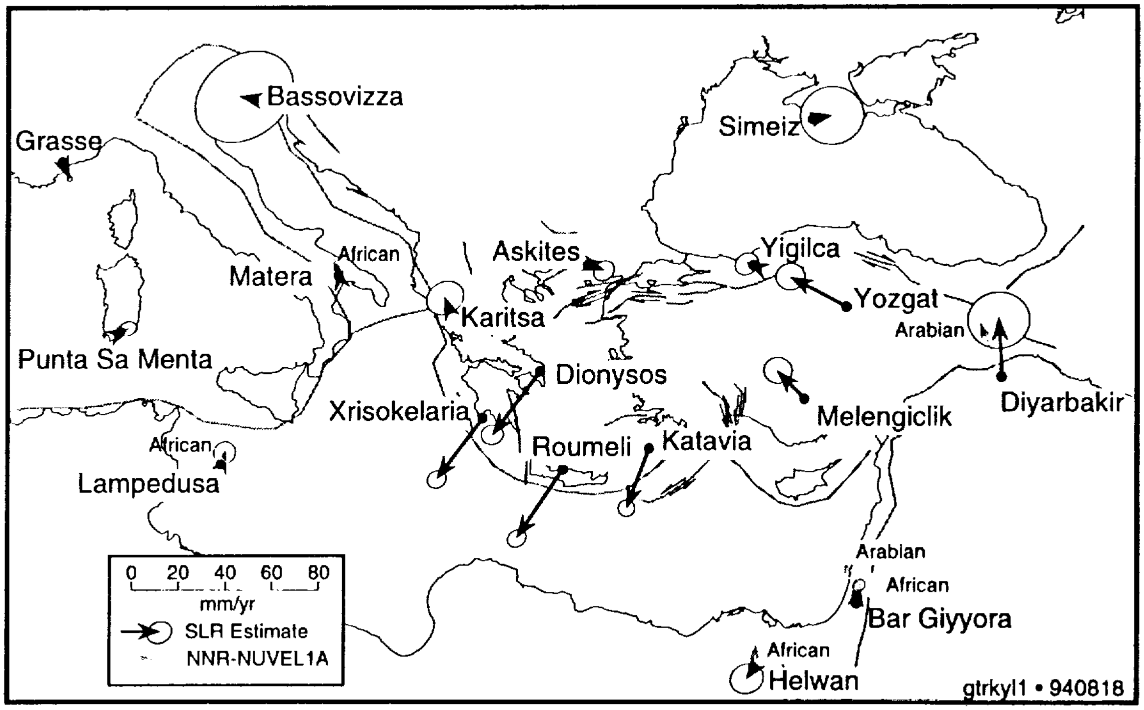

Fig. 2 Horizontal motion vectors in the Mediterranean relative to northern Europe support some of the extension in the Aegean expected from seismic data analysis. The deformation in NW Greece and SE Aegean cannot be accounted for by slip in earthquakes this century.

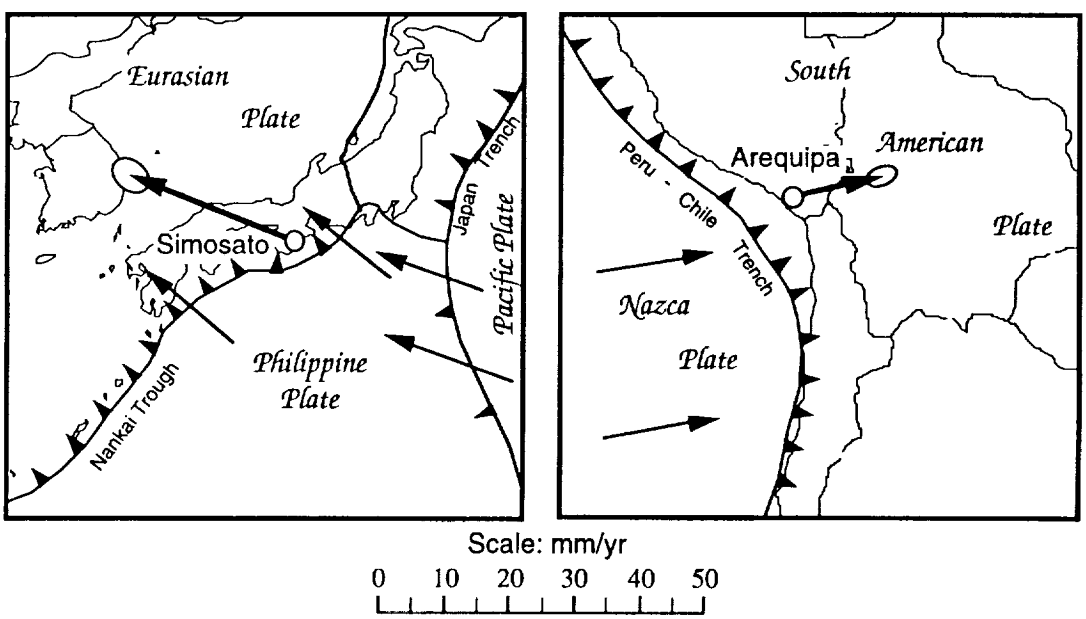

Fig. 3 Vector differences between SLR and NUVEL-1 show that Simosato and Arequipa both move at a rate carried over from the oceanic plate, and this provides a new measure of deformation occurring behind island arcs. Thinner arrows show the subduction relative to the overriding plate.

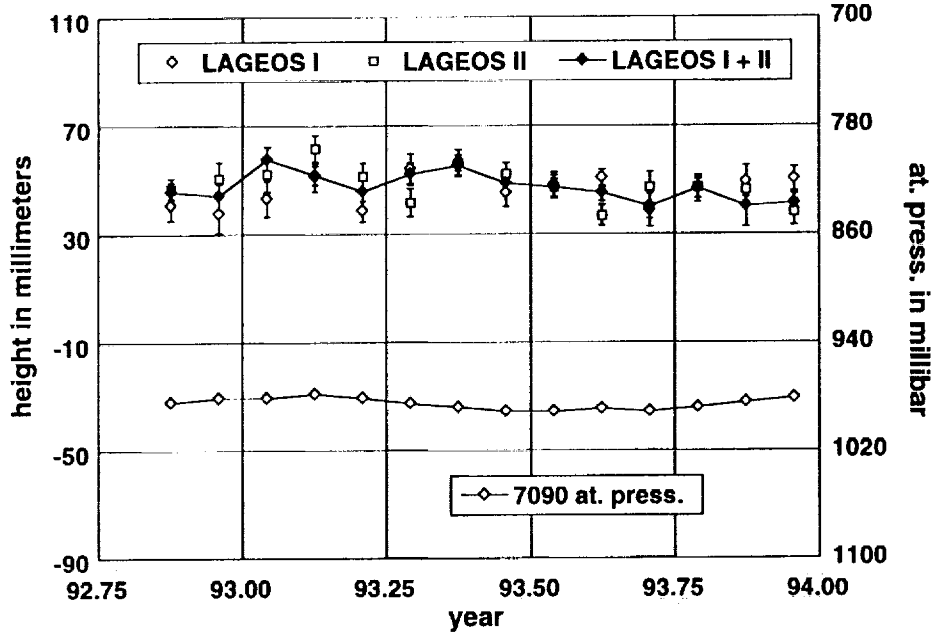

Fig. 4 LAGEOS II provides independence from force model error and helps to improve the accuracy of Yarragadee's height estimated from LAGEOS I data alone. The vertical signal from the two-satellite solution is smooth to a few millimeters and includes the effect of atmospheric pressure loading averaged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

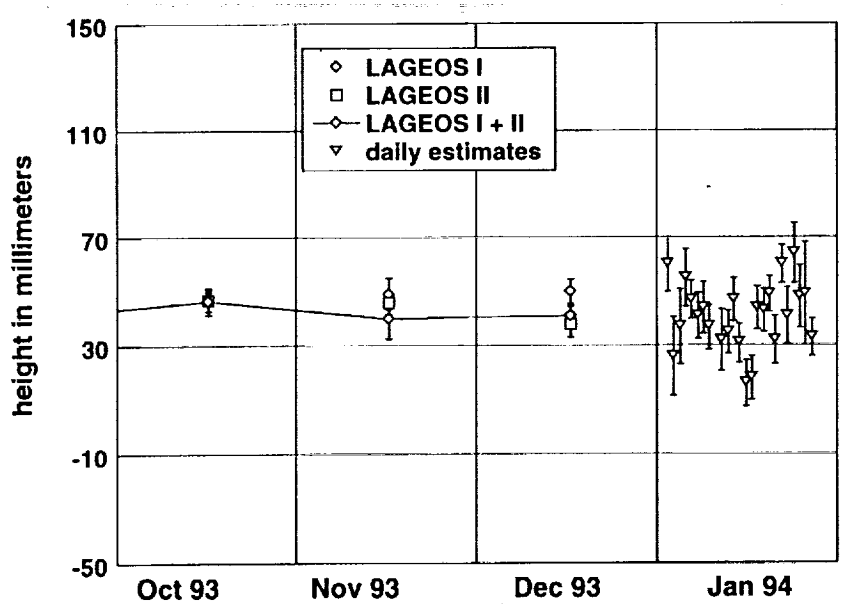

Fig. 5. The value of Yarragadee's height can be resolved within minutes of the end of the data span; daily estimates are currently good to about 15 mm., but a monthly average gives a formal error of just a few millimeters.