

## C. MEASURING TEMPORAL GRAVITATIONAL VARIATIONS USING SLR DATA

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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

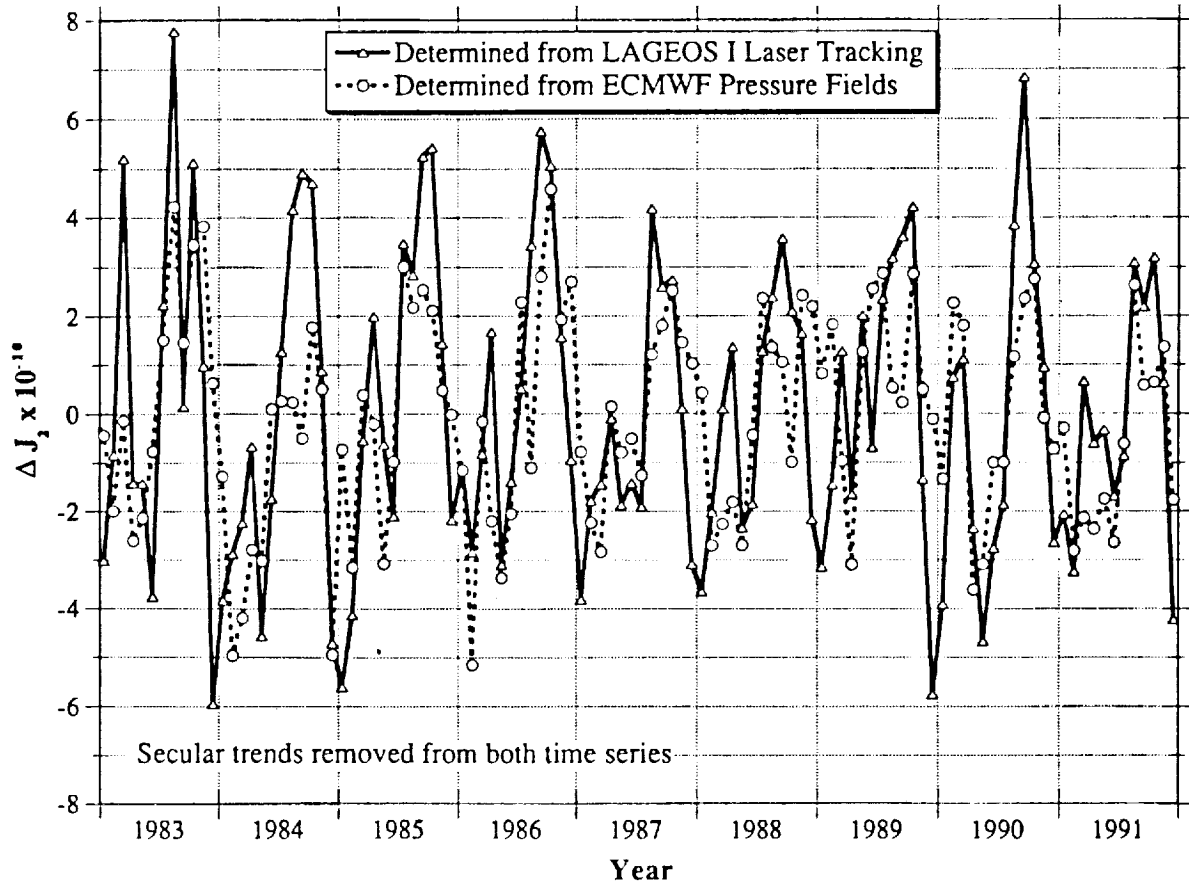


Figure 1. Time variations of the  $J_2$  Earth gravitational coefficient, which describes the oblateness of the Earth, from 1983 to 1991. Two estimates of the variations in  $J_2$  are shown; measured values using Lageos satellite laser ranging (SLR) data and predicted values from the European Center 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.

## LAGEOS Accelerations Measured Using SLR Data

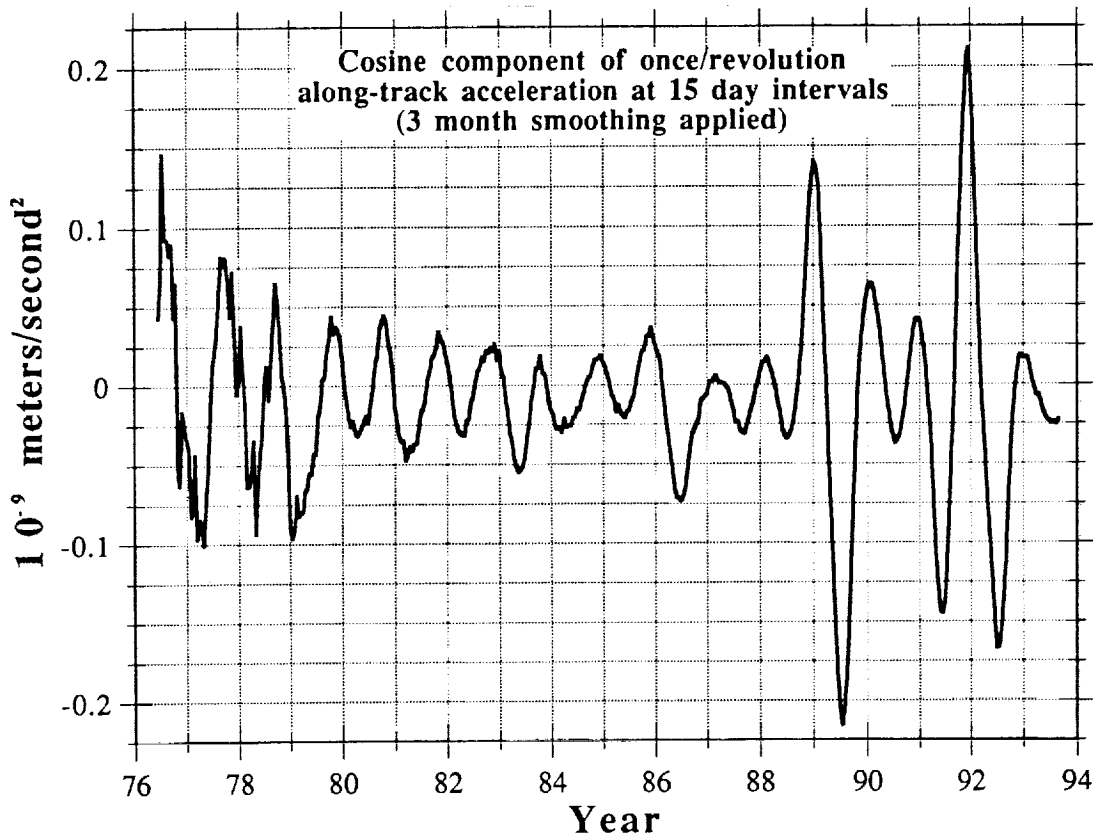


Figure 2. Cosine component of the estimated once/revolution along-track acceleration on Lageos determined using SLR tracking data from 1976 to 1993. The time series is dominated by annual and 560 day variations. The annual variation is probably caused by a real variation in  $J_3$ , possibly due to redistribution 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.