

TEMPORAL VARIATIONS IN J_2 FROM ANALYSIS OF SLR DATA

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Abstract

Mass redistribution within the Earth system causes variations in the Earth's gravity field over a wide range of spatial and temporal scales. Improved knowledge of the variations in the Earth's gravity field can yield improved understanding of the Earth's system dynamics and associated long-term climate change. In particular, satellite-derived secular variations in the Earth's gravity field provide a critical global constraint on postglacial rebound since the last ice age, on mass balance of the polar ice sheets and on contribution to sea level rise. Satellite laser ranging (SLR) data represents the most accurate and unambiguous set of space geodetic measurements. As such, they are especially important for satellite orbit positioning and the recovery of gravity information. We present the results for the temporal variations in the J_2 from analysis of SLR data of multiple satellites with the longest time span covering 26 years.

SLR data analysis

Mass variations within Earth system have a temporal spectrum ranging from hours to 18.6 years and secular and are related to both long-term and short-term climate changes. The long-term SLR tracking data have recorded the global nature of these variations. SLR data sets from Lageos-1, Lageos-2, Ajisai, Etalon-1, Etalon-2, Starlette, Stella, BE-C and TOPEX/POSEIDON (T/P) span over 26 years. BEC is one of the few targets in a low inclination (41 degrees) and is particularly sensitive to the lower-degree zonal rates. For this reason, after 13 years without tracking, the ILRS (International Laser Ranging Service) has approved a request for retracking the BEC satellite by the global SLR network as of July 15, 1999 to support gravity studies. It is not an ideal target because its non-spherical shape leads a difficulty in minimizing the drag effects, and its geomagnetically stabilized attitude renders the BEC laser array not visible from Southern Hemisphere stations with latitudes below approximately -20 degrees. The complicated shape of T/P makes it particularly difficult for modeling the nongravitational forces. However, the intensive tracking of T/P satellite makes it possible to reduce the orbit error through adjusting a sufficient number of empirical acceleration parameters. T/P can thus contribute to measuring the variations in the geocenter and non-zonal geopotential coefficients, but the interesting signals for the zonal variations are absorbed in the empirical parameterization [Cheng, 1998]. Thus, SLR data from TOPEX is not able to contribute to the study of the zonal variations.

Among these SLR targets, Lageos-1 satellite has been a critical resource for the study of geodesy and geodynamics. However, the spin rotation of Lageos is slowing and the spin orientation in space is uncertain, which has a dramatic effect on the surface forces (Métris, et al., 2001). The errors in the modeling of the spin orientation lead to a significant anomalous eccentricity excitation on the orbit, which makes the SLR data tracked after 1996 for Lageos-1 to be useless for the determination of the odd-degree zonal variations. Because of its significant sensitivity to the gravity signal, its spherical shape with a small area-to-mass ratio and its long tracking history, the Starlette data set becomes a primary resource for studying the long-term changes in the Earth's gravity field.

Figure 1 shows the number of SLR stations tracking Lageos-1 and Starlette over the time period from March 1975 to October 2001. Figure 2 shows the number of observations collected for the same two satellites. In the past, SLR stations could only track the satellites at night, and for some, this is still true. The temporal distribution of the data will vary with the period of the satellite node respect to the sun, which describes the resonance between the satellite motion and the diurnal apparent motion of the sun (73 and 560 days for Starlette and Lageos-1, respectively). Such variation in the distribution of the tracking data can cause aliasing with the $S1$ tide perturbation of the satellite orbit [Cheng and Tapley, 1999].

Temporal variation in J_2

A monthly time series for the variations in the zonal harmonic coefficients with degree up to 4 are determined using the SLR data from 8 satellites to study the seasonal variations in the Earth's gravity field. This study used the entire SLR data history for 7 satellites: Starlette, Ajisai, Stella, Lageos-1 and 2, Etalon-1 and 2, and the new tracking data for BEC from July 15, 1999 to October 2001. The solution was derived in such a way that the solutions for J_2 , J_3 and J_4 were first based on the Starlette and Lageos-1 SLR data before August 1986, then SLR data from the satellites, Ajisai, Etalon-1 and 2, Lageos 2, Stella and BEC were included one after another when it was available. Figure 3 shows the estimated variations in the second-degree zonal harmonic coefficient J_2 . The standard deviation of solution is reduced as the data accuracy is improved and data from more satellites is included. A significant linear trend, annual and long period with 18.6 year variation in the J_2 estimates are the evidence of the long-term mass variations within the Earth system. Rate of J_2 is $-2.67 \pm 0.15 \times 10^{-11}$ /year, the amplitudes of annual, semi-annual and 18.6 year are 3.11 ± 0.08 , 0.77 ± 0.07 and 1.24 ± 0.18 (in unit, 10^{-10}), respectively, from a least square fit to this 26-year time series of J_2 variation. Models for the atmosphere, ocean and continental water storage over same 26-year time period are not available yet for interpreting those observed seasonal variations. However, a detailed comparison indicates that the observed annual variation in J_2 is in good agreement with that predicted from current models of mass redistribution in the atmosphere, ocean and continental water over the time period from 1993 to 1996 [Cheng and Tapley, 1999]. The observed 18.6-year variation in J_2 is largely due to the anelasticity effects on the Earth tide at the 18.6-year period, which was not modeled in the satellite orbit computation [Zhu et al., 1996; Cheng et al., 1997]. The secular variation in J_2 has been intensively studied during the past two decades, since it provides information regarding the lower mantle viscosity [Peltier, 1983; Ivins et al., 1993; Mitrovica & Peltier, 1993; Cheng et al., 1997, 2000]. SLR data derived J_2 has been a critical global constraint on postglacial rebound studies.

Monthly estimates of J_2 have also been determined using SLR data from Lageos-1 and Starlette alone, respectively. The estimated annual variations are in good agreement from both satellites [Cheng & Tapley, 1999]. The standard deviation for the solution of J_2 variation from Starlette is significantly smaller than that from Lageos-1. A small uncertainty suggests that the signals of the J_2 variation in the Starlette data is stronger than in the Lageos-1 orbit. Thus, Starlette can provide a major contribution to the study of the Earth's time variable gravity field, in particular in the combination of data from other satellites, including CHAMP.

Analysis of the residual of the monthly solution of the J_2 variations from combination solution after removing a linear trend as well as annual, semi-annual and 18.6 year periods shows a significant signal with a period of ~ 12 years. Amplitude of this signal is larger than that for 9.3 years. Same frequency was also found from the J_2 variation time series derived from both Starlette and Lageos-1 along although the amplitudes are different. This variation

seems to be correlated with solar cycle, which causes the radiation related perturbations in the satellites orbits. However, it is possible that this variation is due to the aliasing effect with the variations in the temporal distribution in the SLR data as discussed above. Further efforts are required to understand the cause of these variations.

The sensitivity of a satellite to the gravitational perturbations depends on the inclination and altitude of its orbit. The observations from a single satellite contain only the lumped effects the Earth's gravity field and its temporal changes. Thus the long-term temporal and spatial distribution of tracking data (i.e., satellites at various altitudes and inclinations) is particularly stringent for separating and constraining the individual spherical harmonics of the Earth's gravity field. The correlation coefficient between two estimated parameters is the indication of their separation in a simultaneous solution. Figure 4 shows the time series of the correlation coefficient between J_2 and J_4 monthly solution from 8 satellites. Figure 4 clearly indicates that Lageos-2 increased the correlation from the combination of Starlette, Lageos-1, Ajisai, Etalon 1 and 2 data. However, BEC and Stella compensated the Lageos-2 effect and significantly decorrelated the solution of J_2 and J_4 in the multisatellite combination.

Summary

Significant secular and seasonal variations in the lower-degree zonal harmonic coefficients, such as J_2 , were observed from analysis of the multisatellite SLR data. The annual variation of J_2 is well determined and compares well with results from modeling the atmospheric and oceanic mass redistribution and changes in the surface water. The long-term SLR data are a valuable geophysical resource for determining and monitoring the long-term changes in the Earth's gravitational field and an invaluable augmentation for the geophysical studies contemplated for the GRACE and ICESAT missions.

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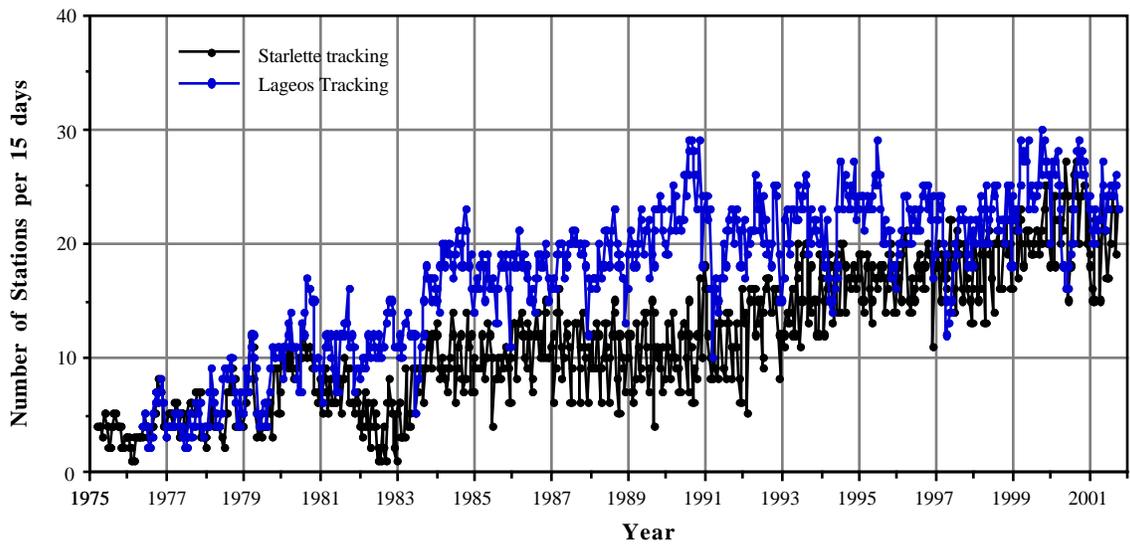


Fig. 1 Temporal distribution of the SLR stations tracking Starlette and Lageos-1 over the period from March 1975 to October 2001.

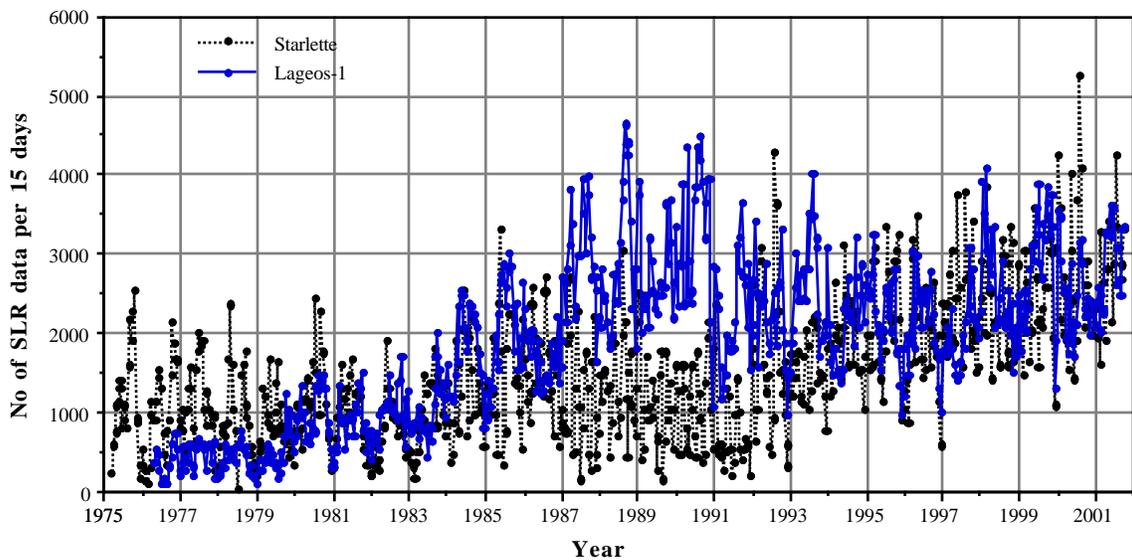


Fig. 2 Temporal distribution of the SLR data from Starlette and Lageos-1 over the period from March 1975 to October 2001

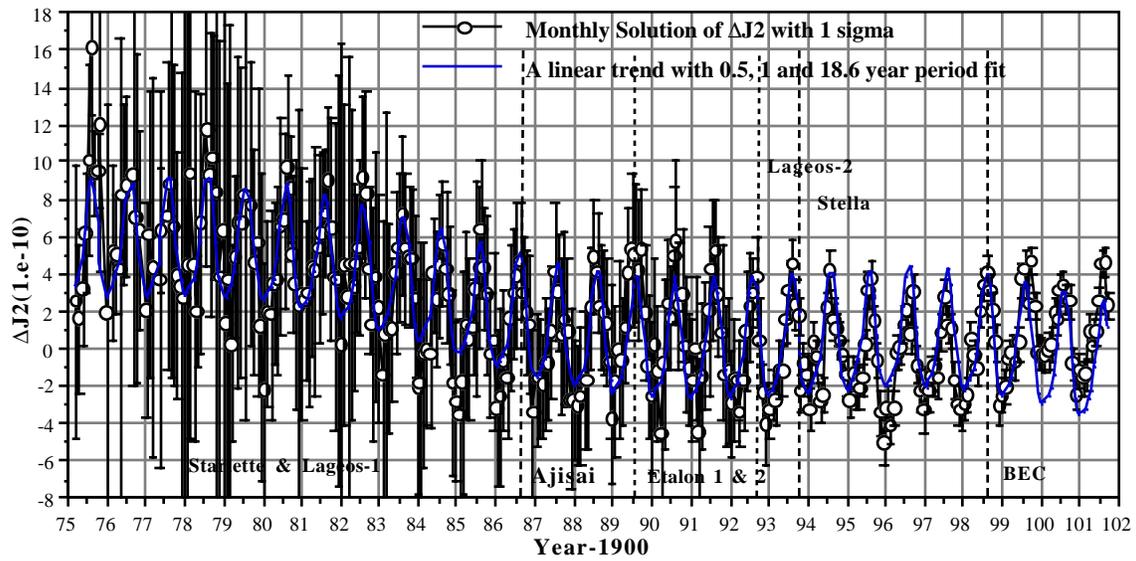


Fig 3 Monthly estimates of J_2 from analysis of SLR data over 1975-2001. As more satellites are included in the solution, the random variations are decreased.

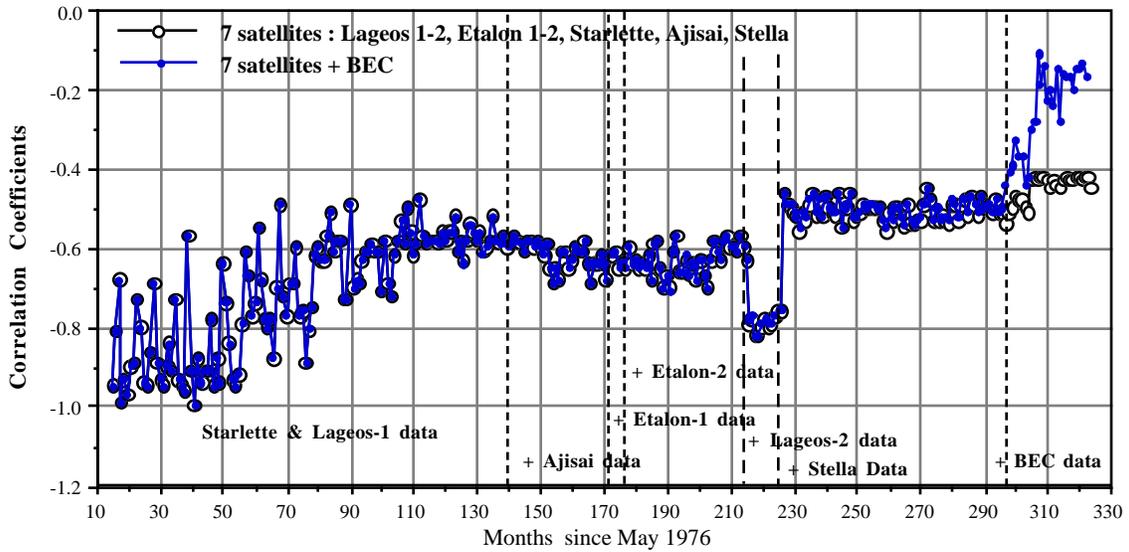


Fig. 4 Correlation coefficient between J_2 and J_4 monthly solutions from SLR data over the period of May 1976 to October 2001. As more satellites are added to the solution, the correlation is reduced.