

Investigating the variability of Earth gravity field's J_2 spherical harmonic coefficient using Satellite Laser Ranging data

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ABSTRACT

Spatial-temporal variations in the Earth's gravity field (expressed as a set of spherical or ellipsoidal harmonic coefficients: the geo-potential model) are caused by mass redistribution within the Earth system. Accurate determination of the Earth's gravity field is essential for a variety of geophysical applications such as oceanography, hydrology, geodesy, solid Earth science as well as being essential for precise orbit determination. As a result, improved knowledge of the variations of the Earth's gravity field could yield improved understanding of the Earth's system dynamics and associated long term climate change. The main objective of the current analysis is to investigate the variability of coefficients computed using a new Satellite Laser Ranging (SLR) program being developed at Hartebeesthoek Radio Astronomy Observatory (HartRAO). In the analysis program, Earth tide, ocean tide, pole tide and atmospheric loading models are included in SLR station position adjustment in order to improve calculated range and therefore minimise the observed minus computed (O-C) residuals. The time series for lower degree and order harmonics has been recovered utilising a *priori* J_2 coefficients based on the GRACE gravity model GGM03C. We present results of J_2 coefficients computed from about 20 SLR stations tracking LAGEOS-1 and LAGEOS-2. In addition we estimate a known secular decrease in J_2 . The ability to estimate gravity coefficients will enable further investigations into seasonal annual variations and other longer term inter-decadal and decadal variations which can be linked to global mass redistributions.

Keywords: Geodesy and Gravity, J_2 coefficient, gravity fields, satellite laser ranging, satellite orbits.

INTRODUCTION

The Earth is a complex dynamic system driven by many geophysical processes such as the coupled atmosphere-ocean system (due to tidal forcing, surface wind forcing, and atmospheric pressure forcing), varying global distribution of ice, snow, and ground water, a fluid core that is undergoing hydro-magnetic motion, a mantle and core that are thermally convecting, rebounding from the glacial loading of the last Ice Age and mobile tectonic plates (Dickey *et al.*, 2002). Consequently, these processes act to redistribute the Earth's mass thereby changing the motion in the mass of the solid Earth relative to the geocentre, as well as causing spatial and time-dependent variations of the gravitational field of Earth.

Earth's gravity field is often expressed as a set of coefficients consisting of a series expansion of spherical harmonics (global geopotential model (GGM)). The coefficients of the various terms in such a model can be determined by using a combination of different satellite orbits. A typical GGM comprises of two components, a large static component and a small but highly fluctuating component that is measured in the order of millimetres to centimetres of the geoid height (Peters *et al.*, 2002). Since the Earth's gravity field is highly dependent on the mass distribution of the Earth, any

movement of masses in, on or above the Earth introduce variations in the gravitational field of the Earth (Wahr *et al.*, 1998; Peters *et al.*, 2002; Dickey *et al.*, 2002; Cox *et al.*, 2003).

In particular, surface mass change in the atmosphere, oceans, hydrosphere and cryosphere are dominated by seasonal variations while processes such as isostatic glacial recovery and sea-level change give rise to long-term secular or quasi-secular signatures. Geodetic satellites such as Laser Geodynamics Satellite (LAGEOS) 1 and 2 have been used to detect seasonal changes (Dong *et al.* 1996; Cheng and Tapley 1999) and have contributed to studies of geopotential zonal rates (Cheng *et al.* 1997). Several of these papers present variations of the zonal and lower order and degree harmonics in good agreement with geophysical models of surface mass redistribution.

One way of measuring the Earth's gravity field is by using SLR tracking data whereby the motion of artificial satellites is observed and analysed to estimate the gravity field. As the most accurate set of space geodetic measurements, the SLR data are used for satellite orbit positioning and the recovery of gravity information. In particular, SLR has been successful in measuring temporal variations in low degree spherical harmonic components of the Earth's gravity field (Cox *et al.*,

2003). The variations of the Earth's gravity field have been observed via the perturbations in the orbits of LAGEOS 1 and 2 satellites. In addition, dedicated satellites missions such as CHAMP, GRACE and GOCE were also designed to determine Earth's gravity field with high accuracy. As a result, monitoring the variations of the Earth's gravity field with improved spatial-temporal resolution would provide an important tool for studying the Earth system changes. For a detailed survey of the recent history of the static and temporal gravity field recovery we refer to Moore *et al.*, (2006) and references therein.

An important spherical harmonic coefficient of the gravity field is the Earth's dynamic oblateness, J_2 , which is a dimensionless coefficient of degree 2 and order 0. The J_2 coefficient has a maximum at the equator and a symmetric minimum at the poles. Variations of J_2 are believed to be well determined from SLR observations. Due to the temporal variations of the density distribution of the atmosphere, ocean and the solid earth, J_2 is often viewed as the model of Earth where the time varying tides are ignored. As a result, the spatial-temporal behaviour of J_2 has been extensively studied. Some of the reported works in the literature is tabulated in Table 1. The decrease in J_2 from the individual results in the literature shown in Table 1 based on only LAGEOS data is understood to be primarily controlled by post-glacial rebound (PGR), plus secondary effects from climatic changes. Following a study by Cox and Chao (2002), it was shown that the secular decrease in J_2 reversed around 1998, roughly coincident with the 1997/1998 El Nino event. Dickey *et al.*, (2002) modelled and showed that the changes in J_2 were caused by a surge in the subpolar glacial melting and by mass shifts in the Southern, Pacific and Indian Oceans. The authors suggested that the J_2 slope reversal observed in 1997-1998 was caused by the dramatic changes in oceanic and glacial mass distribution over the 1997-1998 periods.

Authors	J_2 estimated values
Yoder <i>et al.</i> 1983: Lageos 1 (1976 – 1981)	-3.0×10^{-11}
Rubincam 1989: Lageos 1	$-2.6 \pm 0.6 \times 10^{-11}$
Nerem and Klosko 1996: Lageos 1&2, Ajisai, Starlette (1986 – 1994)	$-2.8 \pm 0.3 \times 10^{-11}$
Cazenave <i>et al.</i> 1996: Lageos 1 and 2 (1984 – 1994)	$-3.0 \pm 0.5 \times 10^{-11}$
Cheng <i>et al.</i> 1997: Lageos 1&2, Starlette, Ajisai, Etalon 1&2, BEC (1975 – 1996)	$-2.7 \pm 0.4 \times 10^{-11}$
Devoti <i>et al.</i> 1998: Lageos 1 and 2, Starlette, Stela (197 – 1997)	$-3.3 \pm 0.3 \times 10^{-11}$
Cheng and Tapley 2000: Multiple satellites for 26 years	$-2.67 \pm 0.15 \times 10^{-11}$

Chapanov and Georgiev 2002: Lageos 1 and 2 (1984 – 2000)	$-2.7 \pm 0.2 \times 10^{-11}$
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Table 1. Selected literature covering J_2 spherical harmonic coefficient

In this contribution, a time series of J_2 derived from SLR tracking data of LAGEOS 1 and 2 since December 2005 sampled equally three times in month (i.e., at a sampling interval of ten days) is used to investigate the variability of J_2 coefficient and corroborate with those recovered from SLR tracking to other satellites.

METHOD AND RESULTS

SLR observations of LAGEOS 1 and 2 collected from 20 SLR tracking stations were processed using an SLR program developed at HartRAO (Combrinck *et al.*, 2007). The observations were based on satellite orbital paths formed by combining one day arcs of each satellite orbit. Solid Earth tide, ocean tide, pole tide and additional non-gravitational forces consisting of atmospheric loading, solar and Earth radiation pressure were included in the program to improve the accuracy of the calculated range and therefore minimise the observed minus computed (O-C) residuals.

In the present contribution, the data was analysed for the period of December 2005 to December 2007 at a constant time interval of ten days. The SLR program was set to simultaneously compute separate solutions of LAGEOS 1 and 2 observations. Each solution consists of estimates for the satellite positions, velocities of the laser sites, J_2 zonal harmonic coefficient, and unnormalized geo-potential coefficients C_{21} and S_{21} . In addition, normal point range bias and time bias were also estimated.

The time series extracted from LAGEOS 1 and 2 satellites are plotted in Figure 1 and Figure 2 respectively. Both series show short-term fluctuations that can be associated to the seasonal variations in the Earth's dynamic oblateness. On examining the plotted J_2 values computed between LAGEOS 1 and 2 visually, a generally poor correlation could be inferred, however a negative correlation of ~ -0.57 was obtained from the linear correlation function in Matlab. According to the time series there are outliers observed in some days possibly due to weak station geometry and lack of data.

We combined the J_2 solutions from LAGEOS 1 and 2 data to obtain a combined J_2 coefficient. The combined solution is plotted in Figure 3. The time series shows significant changes with large signals corresponding to the possible outliers (e.g. MJD 53745 and 53865) observed in the individual time series.

The three time series were fit with a linear trend and second order polynomial in order to recover the first-order derivative of the J_2 coefficient and the trend of the

fluctuations. Linear trend drifts of the order of $\sim 10^{-15}$, 10^{-14} and 10^{-16} respectively are observed in each time series due to fluctuations of the J_2 coefficient. A polynomial fit suggest that the J_2 coefficient could be experiencing seasonal changes as reported by Dickey *et al.*, (2002). The fluctuations could also be related to PGR as suggested by Cox and Chao (2002) and references therein. The first-order derivative of J_2 calculated in the present analysis are compared with the published J_2 coefficients (see table 1), and the results show poor agreement. The inconsistency in the rate of change of J_2 coefficients could be explained in three ways. Firstly, it could be due to our sampling interval which provides a big gap within the data. Secondly, the *a priori* J_2 is constrained hence it suffers from coefficient insensitivities, and lastly, the differences observed in the J_2 could be attributed to the different schemes used to compute J_2 in the SLR analysis software.

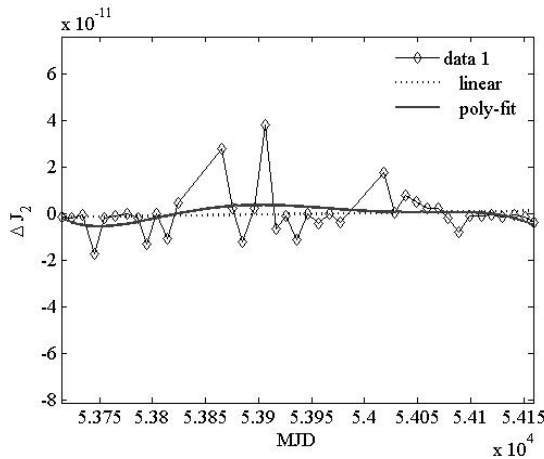


Figure 1. Time series for J_2 constrained solution extracted from LAGEOS 1 data

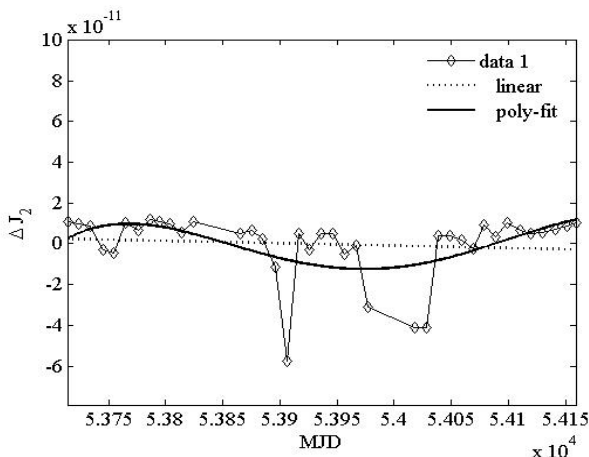


Figure 2. Time series for J_2 constrained solution extracted from LAGEOS 2 data

To investigate the sensitivity to J_2 we analysed daily estimates of J_2 using SLR data from LAGEOS 1. Here we used the J_2 *a priori* value from GRACE model, GGM03C and processed the LAGEOS 1 data from

December 2005 to May 2006. The time series for these results is plotted in Figure 4. The results show an improvement in the J_2 estimates. A comparison between our J_2 coefficients and the published coefficients show a reasonable agreement. We propose that the J_2 solution can be improved if more data is included. The average standard deviation obtained is significantly smaller compared to that from the constrained solution suggesting that the J_2 solution from the less constrained analysis can provide more accurate information about the temporal variations in the J_2 coefficient.

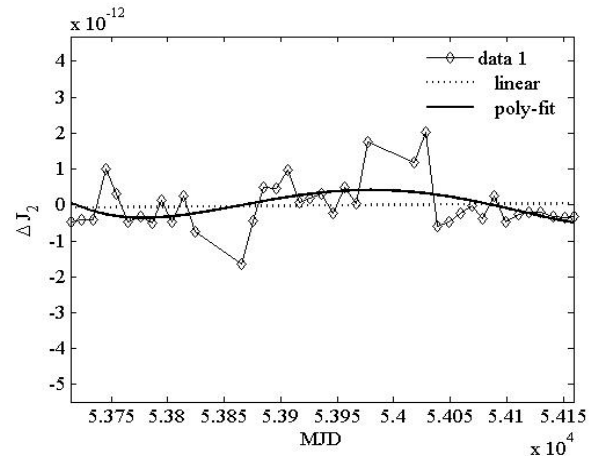


Figure 3. Time series for the combine J_2 constrained solution extracted from LAGEOS 1 and 2 data

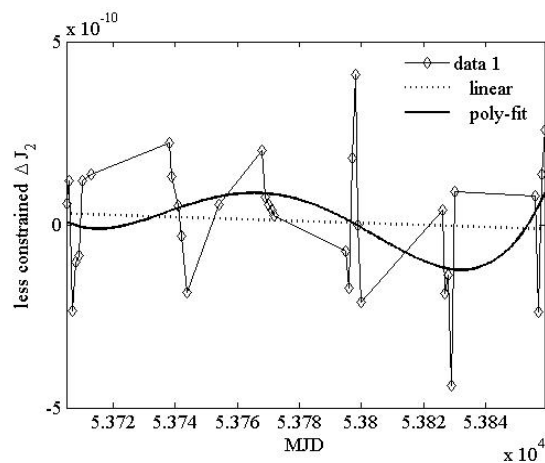


Figure 4. Time series for J_2 less constrained solution extracted from LAGEOS 1.

CONCLUSIONS

The variations in the J_2 spherical harmonic coefficient were investigated using SLR data from LAGEOS 1 and 2 for a period of 21 months. We compared our estimated J_2 coefficients from a constrained J_2 *a priori* value analysis with the previously published coefficients from different analysis and found that they show poor agreement. Further analysis of LAGEOS 1 data using less constrained J_2 *a priori* value shows an improvement in the J_2 estimated solution. Our estimated values of the J_2 rate show a reasonable agreement with the other

published coefficients. We propose that improved solutions can be achieved by using less constrained J_2 *a priori* values over a long period data. Analysis of laser ranging data from other satellites such as Etalon, Ajisai, Starlette, GRACE and CHAMP can also provide a major contribution to the study of the variations in the J_2 coefficient and will be included in future work.

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