LONG TERM MONITORING OF GEOPHYSICAL PARAMETERS USING SLR

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Abstract

The SLR observation dataset, similarly to the other space geodetic techniques, is a valuable source of data for measuring fundamental geophysical parameters and their temporal variations with respect to different time scales. As an example, the distinctive sensitivity of the SLR technique to global parameters as the origin and scale of the Terrestrial Reference Frame profits from the remarkable length of its observations dataset, allowing the stable and accurate retrieval of those parameters, turning into a reliable maintenance of the TRF.

The most recent and updated ASI/CGS analyses of Lageos-I and Lageos-II data cover two decades and provide time series of daily Earth Rotation Parameters (EOP) and Length Of Day (LOD), weekly geocenter offsets with respect to the TRF, weekly J_2 estimates, station coordinates and velocities together with orbital parameters, biases, and other technique-based nuisance parameters. The complex interrelation among all the parameters allows the cross-checking and helps in detecting real geophysical signals from the parameters time series.

Some of the results coming out from the solutions are shown, with particular emphasis to the terrestrial reference frame monitoring. Comparisons are made with the standard IERS references.

Introduction

SLR observations from Lageos-I and Lageos-II are the fundamental database of most geodetic analyses and essential for the establishment of terrestrial reference frames. The upcoming of state-of-the-art models makes necessary to re-analyze the whole dataset from time to time to retrieve homogeneous time series of geophysical parameters. The reprocessing can be accomplished thanks to the relatively small amount of computer time needed to process several years of data, almost negligible if compared, for example, to the time needed for GPS data analysis.

In the latest geodetic solutions computed at the ASI/CGS the worldwide laser tracking dataset, from January 1985 to December 2003, has been processed by means of the GeodynII/Solve software developed at the NASA Goddard Space Flight Center. Besides the long term monitoring of the consistency of the TRF, by means of 'classical' geodetic parameters(i.e. site coordinates/velocities and EOPs), the added value of these ASI/CGS solutions is the retrieval of the TRF origin offsets, i.e. the geocenter time series.

Data processing

All the normal points collected from the worldwide network in the period 1985-2003 are analysed in 15-day arcs when using Lageos-I data only and 7-day arcs when using Lageos-I and Lageos II, so that the amount of data in each arc is roughly homogeneous over the entire period (Figure 1).

Arc data reduction is performed separately for each satellite and, in this phase, the complete orbit and force model is defined together with the analysis approach (i.e. arc length, type of estimated parameters) but only the arc dependent parameters are estimated, namely those related to the orbit (i.e. state vectors and non-gravitational forces) and to the observations (i.e. measurement bias). The arc solution adopts the most recent models: ITRF2000 as *a priori* site coordinates and velocities, IERS EOPC04 for *a priori* EOP values, EGM96 geopotential (up to degree 70), GOT99.2 ocean tides model, ocean loading from Scherneck and GOT99.2 tides, taking into account the secular drift and the influence of the dynamical pole on C21 and S21 coefficients, all the major planets perturbations as well as the relativistic effects.

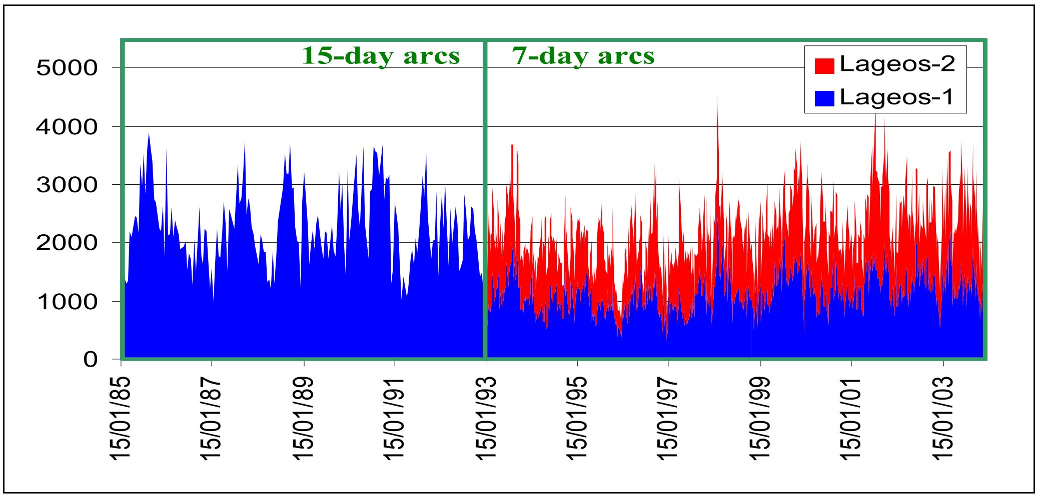


Figure 1. Dataset

A measure of the differences, on average, between the calculated ranges and the observed ones is shown in Figure 2 (series labelled Lageos-1 and Lageos-2) through the weighted root mean square of the residuals (wrms) . The time series of the arc wrms reflect both the precision of our orbital fit and the improvement of the laser tracking systems: values around 4 cm at the beginning of the analysed period, lower down to less than 2 cm.

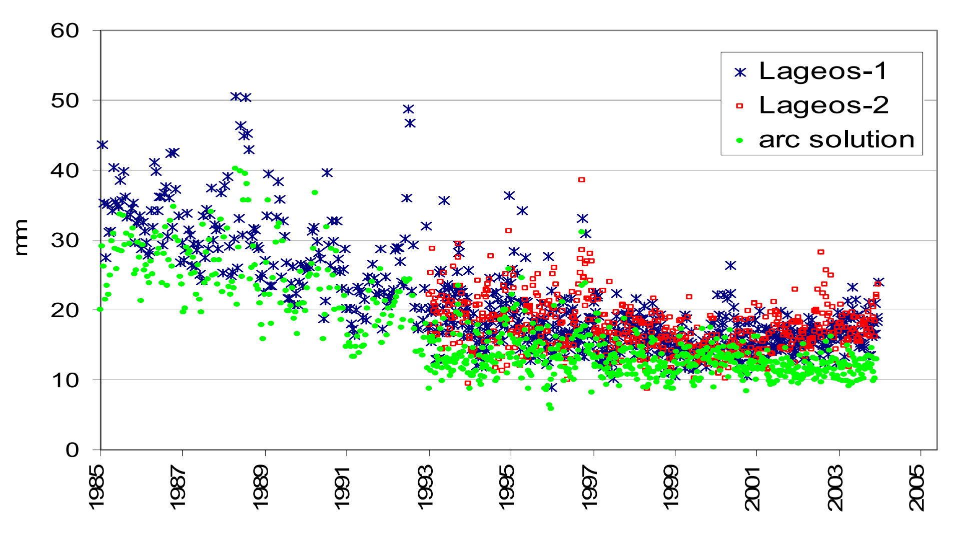


Figure 2. Weighted root mean square of the satellite residuals

The normal equations built in the arc data reduction are then combined and inverted to estimate the so-called ‘global’ parameters (site coordinates, EOPs, geocenter offsets etc.) and update the arc dependent parameters. Two strategies can be adopted to combine the equations over the two decades: a *long arc solution* or a *short arc solution* strategy *(*fortnightly/weekly solutions).

Long arc solution

This analysis approach provides a unique final solution from the inversion of the combination of all the arc normal matrices, in which all the global parameters are solved in a least squares sense and provided with their full covariance matrix: fortnightly or weekly C_{10}, C_{11}, S_{11} (immediately related to the geocenter offsets), 3-D site coordinates and velocities, 3-day (until 1992) and daily (from 1993 on) EOP (X,Y,UT1R-UTC) and LOD. The realization of the reference frame is constrained to ITRF2000 by fixing to those values the position and velocities of two sites, Greenbelt (7105) and Herstmonceux (7840). The tight realization of a unique terrestrial reference frame, constrained throughout the solution, permits the estimation of the center of mass offsets. The global wrms of the coordinate residuals, measuring the robustness of the chosen TRF realization, is 18 mm.

Short arc solutions

This approach provides a time series of solutions, one for each arc from the combination of Lageos-I and II, in which only the parameters (and their covariance matrix) relevant to that arc are present. For each arc, the site coordinates and EOP/LOD are estimated and the arc dependent parameters updated. The reference frame is loosely constrained to ITRF2000 site by setting a value of 1 meter as *a priori* constraint to the site coordinates and EOPs. The geocenter offsets are not retrieved as directly estimated parameters but they are obtained in a geometric way by a 7-parameter Helmert transformation, projecting each solution into ITRF2000. The time series of the residual wrms is shown in Figure 2, labelled as 'arc solution'.

Results

A geodetic solution covering so many years gives a tremendous amount of information and sets the basis for further and deeper investigations. The results shown in this paper are the immediate output of the analysis and are mainly given in terms of time series of geophysical parameters.

A discussion of the main analysis results relevant to the long term monitoring of the TRF, including the geocenter motion, is reported in the following. In addition, the global results relevant to the time variations of the low-degree geopotential coefficients are reported, with a few hints on the satellite accelerations, estimated in the ASI/CGS solutions as empirical parameters, to make evident some still unmodeled effects acting on the satellites and influencing the accuracy of the estimated geophysical parameters.

- *Monitoring of TRF classic parameters: Site Coordinates/velocities and Earth Orientation Parameters*

The 1985-2003 ASI/CGS solution realizes the terrestrial reference frame in different ways, according to the different analysis strategy.

The *long arc solution* provides a unique estimate of coordinates at a certain date and an associate linear velocity field, adopting as constraints the ITRF2000 *a priori* values for two sites (Greenbelt, Herstmonceux). This is a logical but arbitrary realization of the TRF as ITRF2000. The robustness of this realization can be measured by a complete 14-parameter Helmert transformation, whose estimated values are reported in Table 1.

HELMERT PARAMETERS [mm, mas, mm/yr, mas/yr)]							
	Tx	Ty	Tz	Scale	Rx	Ry	Rz
Val:	6.1	-6.6	-3.8	2.8E-011	-0.28	-0.17	-0.021
Sig:	0.5	0.61	0.65	8.9E-011	0.029	0.023	0.017
	Txdot	Tydot	Tzdot	Scldot	Rxdot	Rydot	Rzdot
Val:	0.24	-0.04	0.27	-1.4E-010	0.008	0.009	-0.013
Sig:	0.09	0.10	0.13	1.6E-011	0.007	0.004	0.003

Table 1. Transformation parameters to ITRF2000

Short arc solutions provide a time series of coordinates for the global SLR sites polyhedron, loosely constrained in reference frames different from arc to arc. This approach prevents network deformation, allowing the retrieval of homogeneous time series of geophysical parameters after 7-parameter Helmert transformations to ITRF2000, one for each solution. A drawback of the method is that the network considered in the weekly (or fortnightly) solutions can be very small, thus adding a non-negligible uncertainty in a transformed parameter.

The SLR Earth Orientation Parameters endorsed by the ILRS are the X-pole, Y-pole and LOD and they are estimated both in the *long arc* and *short arc solutions*. UT1R-UTC is also estimated but, due to the high correlation with the node of the satellites, it is not a reliable parameter measured with satellite techniques. The estimation of the X and Y component of the pole rate degrades the quality of the SLR solutions and removable constraints have been applied. The plot on the left of Figure 3 shows the residuals of time series obtained from the long arc solutions: the differences with the combined IERS series EOPC04 are computed in the ITRF2000 reference frame. The mean errors for the X and Y pole components are ~0.1 mas, slightly higher in the case of the *short arc solutions*, and 0.03 ms for LOD.
The comparison with EOPC04 makes evident the existence of biases and drifts: 0.023 mas/yr and 0.036 mas/yr in X and Y respectively (see right plot in Figure 3). Since the estimated EOP are, by construction, in the ITRF2000 frame, the linear trends are most probably due to an inconsistency between ITRF2000 and the EOPC04 series. The values of the bias in 2004 are confirmed by the SLR weekly combined solutions delivered to the ILRS.

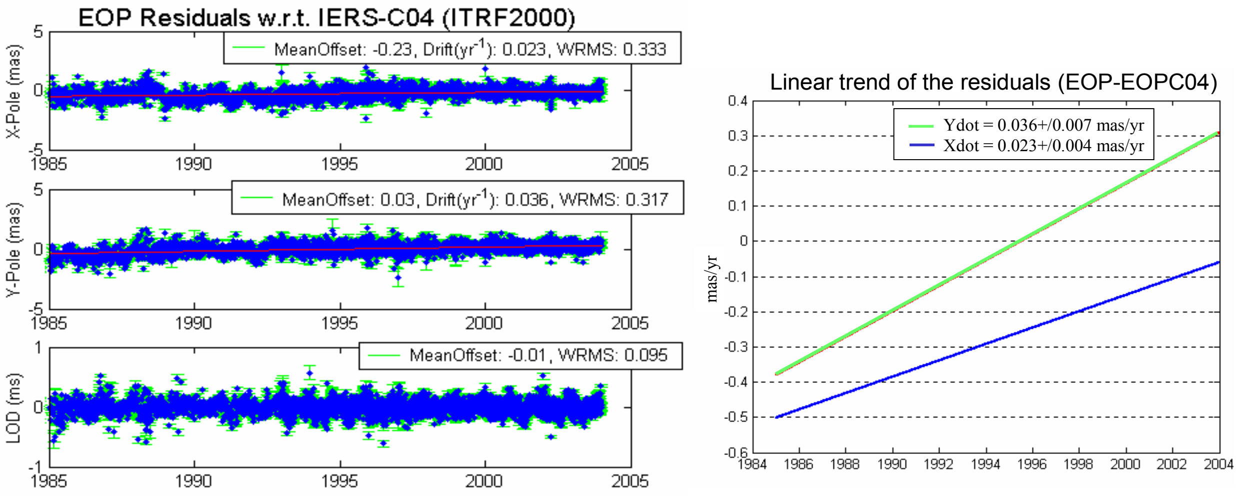


Figure 3. EOP residuals and drifts with respect to EOPC04

A preliminary spectral analysis was performed on the LOD residuals with respect to EOPC04 and significant signals were found with periods of 14 days, 148 days and 1 year.

- Monitoring the TRF origin offsets: Geocenter motion

The ITRF models, ITRF2000 and previous ones, assume that the origin of the global geodetic network is placed in the Earth center of mass. In parallel, the geopotential models, framed in the current ITRF at epoch, assume the earth center of mass, on average, in the center of the geodetic network (i.e. zero values for degree 1 geopotential coefficients).

Despite these assumptions, satellite tracking data, SLR being the most accurate in this respect, have provided evidence that the Earth center of mass is continuously changing its position relative to a crust fixed reference frame. This translation motion is generally known as "geocenter motion". Two different methods, already experienced during the IERS Analysis Campaign to Investigate Motions of the Geocenter [Devoti et al, 1999], have been applied in the ASI/CGS solution to retrieve the geocenter time series: a direct estimation of the degree one geopotential harmonics in the *long arc solution* and a computation of Cartesian coordinate offsets from ITRF using the time series of *short arc solutions*. In both cases we will obtain time series of estimated Cartesian translations, one estimate every 15 days until 1992 (Lageos-I only) and every week from 1993 on (Lageos-I and II). The first approach, from now on the "dynamic method", provides estimates of the C_{10}, C_{11}, S_{11} geopotential coefficients related to a global translation of the terrestrial reference frame as follows:

$$Tx = \alpha \cdot \overline{C}_{11} \cdot \sqrt{3}$$

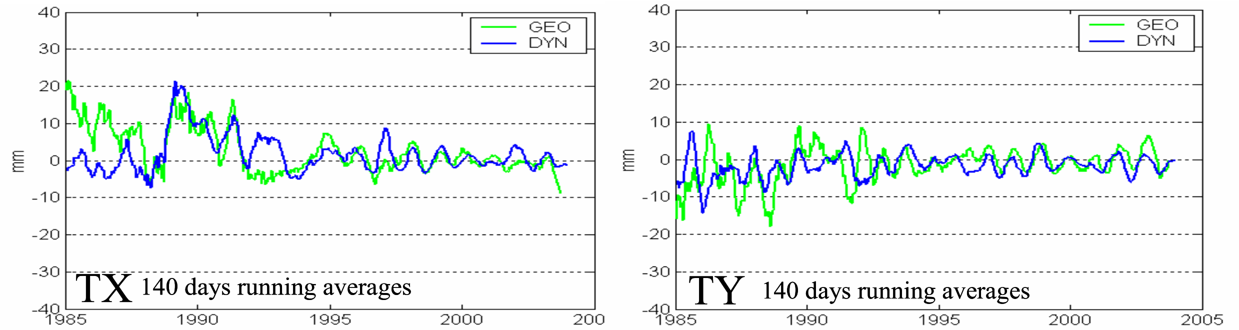
$$Ty = \alpha \cdot \overline{S}_{11} \cdot \sqrt{3}$$

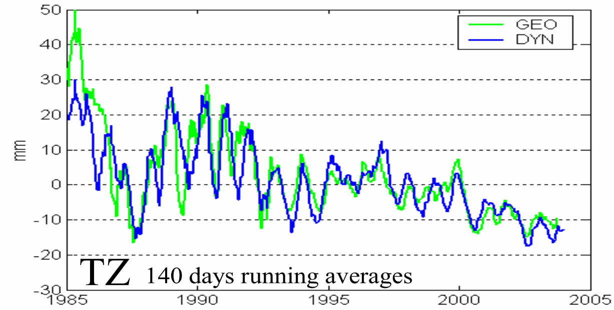
$$Tz = \alpha \cdot \overline{C}_{10} \cdot \sqrt{3}$$

where α is the mean equatorial terrestrial radius, the geopotential coefficients are normalized, the geocenter vector (Tx,Ty,Tz) defined from the ITRF origin to the Earth center of mass.

The second way of estimating the geocenter motion is through the time series of *short arc solutions*, from now on "geometric method". Each TRF realized by the SLR stations in a loose solution places naturally its origin in the center of mass of the Earth: its Cartesian coordinate offsets from a conventional origin describe the geocenter location. The adopted conventional frame is the ITRF2000 and the translations in the 3 directions have been computed by Zuheir Altamimi (Institut Geographique National, ENSG/LAREG).

Figure 4. The geocenter motion





Both methods provide offsets with mean sigmas at the millimeter level, higher in the Tz component, more scattered in the geometric case. The three plots, above and aside, show the 140 days running average built on the dynamic and geometric translation series. The agreement is quite satisfactory with a few exceptions above all

in the period preceding the inclusion of Lageos-II data (1993). The position change in the XY plane is roughly confined in ±10 mm, with no significant drift; it is worthwhile to put in evidence the bump larger than 1 cm in the years from 1989 to 1992. It is recovered using both methods but no explanation is found at the moment: further investigation is needed.
The variation in the Z component is larger, almost double, and a linear drift of -1.3 mm/yr is present. Also in this case further investigation should be directed to understand if this is a real center of mass drift or an indirect effect (i.e. due to the network).n annual signal is clearly visible in all the translations.

- Long term monitoring of low degree geopotential coefficients: the fundamental contribution by the SLR technique

Ongoing mass redistribution over the Earth induces changes in the low degrees coefficients of the gravity field, changes that can be monitored by SLR back to decades. The uniqueness of the technique lies in its capability to provide the low degree zonal rates of the geopotential useful to constrain the rheology of the mantle and the lithospheric thickness.
Multi-satellite solutions are generally used and the satellite constellation is chosen to exploit the sensitivity of the various satellite to the different zonal degrees.

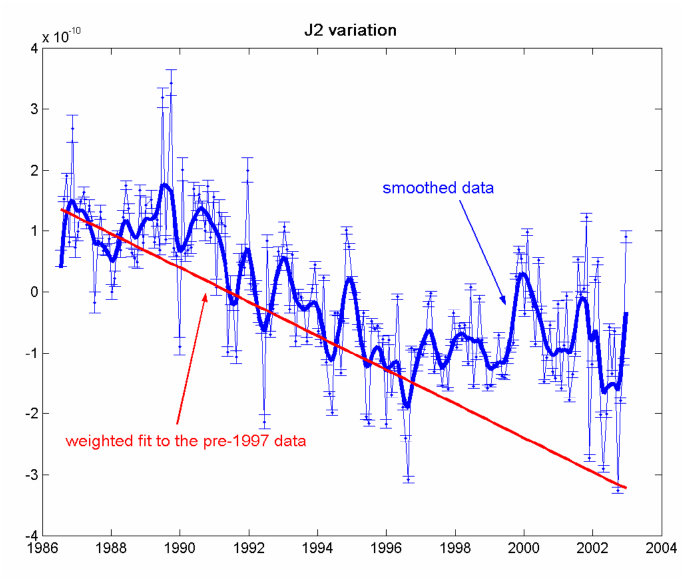


Figure 5. The J_2 time series

The latest gravity solution at the ASI/CGS is computed analysing the data from 4 satellites: Lageos-I, Lageos-II, Starlette and Stella. The overall strategy is similar to the long arc solution outlined in this paper and it is detailed in Devoti et al. [2000]. The most relevant result, the J_2 time series, is shown in Figure 5. The zonal secular drift has been estimated together with a seasonal signal (amplitude and phase) using a non-linear least squares method. In the rate estimation process the J_2 frequency dependent tidal correction has been applied following the IERS96 conventions. The J_2 linear drift, mainly driven by the post-glacial rebound, has been estimated using the data before 1997 because a clear and sudden change appears in the series with the J_2 starting to increase. Possible explanations have been found in the mass flow within the fluid outer core and along the core-mantle boundary [Cox and Chao, 2002] or in the dynamics of the oceans [Cox and Chao, 2002, Dickey et al., 2002]. A return to a decreasing trend of J_2 is expected.
Another deviation from the negative linearity is present from 1989 to 1991, even if less evident than the one discussed.
A new gravity solution is now under construction, with more satellites and covering a longer time span.

- A critical issue: unmodeled satellite accelerations

The residual unmodeled perturbations on the satellite orbits due to the non-gravitational forces are absorbed by the estimation of empirical accelerations in the along-track (constant and once-per-revolution) and cross-track directions (once-per revolution). The accurate modelling of non-gravitational forces is important in trying to separate the gravity response of the geodetic satellites. Although the theories were widely discussed during the 90's, the observed residual forces were never fully explained by the proposed models for the involved forces (i.e. charged and neutral particles, thermal drag).

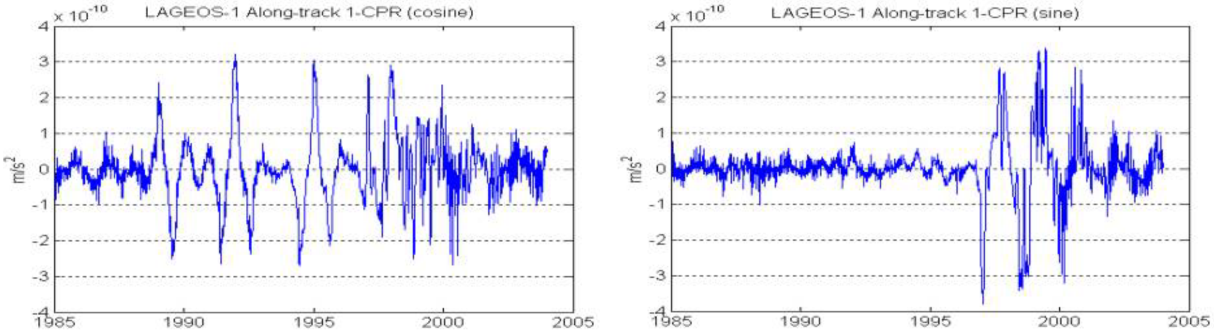


Figure 6. Lageos-I along-track once-per-rev accelerations

The along-track accelerations shown in Figure 6 are obtained from the *long arc solution*. It's interesting to note the different patterns in subsequent time spans which can indicate a change in the satellite state occurred in two specific years and precisely: 1989 and 1997. A similar situation doesn't occur when looking at the Lageos-II accelerations. Also in this case, the estimates provide material for further investigations.

Summary

The contribution of SLR data analysis to the long term monitoring of geophysical parameters is of key importance for its capability to profit of a two decadal acquisition dataset. Besides, the sensitivity of the SLR technique to the Earth center of mass makes this technique a unique tool to detect the geocenter motion at various time scales.
The ASI/CGS SLR global solutions exploit these capabilities; the choice to simultaneously follow two different strategies permits to check the implemented methods by comparing the equivalent parameters and gives a feeling of the weakness and strength of the two approaches. As an example, in one case the reference frame is well established but you can only estimate linear velocities, in the other, a time series of coordinates is obtained but the problem of managing different reference frames must be faced. The latest trend in the worldwide analysis community goes toward the short arc solution approach to monitor some geophysical parameters in quasi-real-time but this tendency has to be complemented with the global view given by a long arc solution.

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References

Cox CM and Chao, BF. Detection of a Large-Scale Mass Redistribution in the Terrestrial System Since 1998, Science, 297, 5582, 831-833, 2002.

Devoti R, Fermi M, Sciarretta C, Luceri V, Pacione R, Rutigliano P, Vespe F, CGS geocenter time series from SLR and GPS data, in Ray, J.R. (ed.)*, IERS Technical Note 25,* Paris Observatory, pp. 39–46, 1999.

Devoti R, Luceri V, Sciarretta C, et al., The SLR secular gravity variations and their impact on the inference of mantle rheology and lithospheric thickness, Geophys. Res. Lett., (5): 855-858 MAR 1 2001

Dickey JO, Marcus SL, de Viron O, and I. Fukumori, 2002. Recent Earth oblateness variations: Unraveling climate and postglacial rebound effects, Science, 298, 1975-1977