FORTNIGHTLY RESOLUTION GEOCENTER SERIES: A COMBINED ANALYSIS OF LAGEOS 1 AND 2 SLR DATA (1993-96)

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INTRODUCTION

This contribution presents the results of a combined analysis of satellite laser ranging (SLR) data from LAGEOS 1 and 2 for the determination of a high resolution (15-day) series of the so-called “center of mass motion”. The interval spanned by the data covers from 1993 until the end of 1996. We conclude that the SLR technique, being currently the most accurate one to determine absolutely the location of the tracking stations with respect to Earth’s center of mass about which the tracked satellites are orbiting, is also the best one to monitor the motion of the geocenter. The formal accuracy for the equatorial components X and Y are 1.3 mm and for Z 4 mm. The scatter of the three however is more indicative of the reliability of the series and suggests 3 mm and 11 mm respectively.

GEOCENTER MOTION

SLR, amongst a number of space techniques, provides the most accurate absolute positioning with respect to the geocenter. This is realized through the dynamics governing the motion of the satellite targets about the point which they orbit: the instantaneous center of mass of the planet. We gain access to this point through the coordinates of the tracking sites that we determine from our data. Viewing Earth as a three-part system: the atmosphere, the oceans, and the solid earth, all three undergo mass redistribution, each part with characteristically different time scales. Some of these, from the better to the less well understood, are due to: tides, oceanic and atmospheric circulation, loading, convection, etc..

The level of accuracy required by IERS in the definition of the geocenter necessitates that we recognize and account for motions that result from a constant redistribution of the terrestrial masses caused by these phenomena in the terrestrial environment. This manifests itself as a continuous motion of the geocenter with respect to the crust-fixed tracking network, albeit only by a few millimeters or so. What we are then really interested in determining is the “trajectory” of the geocenter relative to some conventional origin. The lack of a known law that governs this motion limits us to the solution of a discrete problem where we define an average geocenter over short time intervals the length of which depends on the accuracy, resolution and data availability of the utilized technique.

The ideal method would employ SLR from a well-distributed global network with enough LAGEOS-type targets to solve for one set of station coordinates on a daily basis (or even more frequently). In practice only GPS has such a global network and abundance of data to afford such frequent solutions. Unfortunately though, GPS lacks the inherently high accuracy and unambiguous nature of SLR and it will take additional modeling development until it can contribute daily at the few millimeter accuracy level. The SLR results presented here are based on 15-day solutions for the average geocenter location, though in recent years, due to the network expansion even finer resolution is possible.

APPROACH

Cartesian coordinate offsets from a conventional origin are intuitively the simplest although not the only way to visualize and describe the motion of the geocenter. As reference, we could choose a long term average from the analysis of several years of SLR tracking data.

On the other hand, since the model describing the geopotential depends on the adopted coordinate system, any changes in the definition of that system introduce changes in the parameters describing the geopotential as well. These are time-dependent changes and for the most part, they affect the lower degree and order terms, [Heiskanen and Moritz, 1967]. In that respect, every one of the seven parameters describing a similarity transformation between two Cartesian coordinate systems has a corresponding parameter in spherical harmonic space, the most common representation for the geopotential in geodetic computations.

This sensitivity provides for an alternate but equivalent way of describing the motion of the geocenter: a series of the three harmonics that correspond to the linear origin offsets ΔX, ΔY, ΔZ. These are $C_{1,1}$, $S_{1,1}$ and $C_{1,0}$ respectively. The exact relationship between the two sets of parameters is as follows (*ibid.*):

$$\begin{Bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{Bmatrix} = a_e \sqrt{3} C_{0,0} \begin{Bmatrix} \Delta C_{1,1} \\ \Delta S_{1,1} \\ \Delta C_{1,0} \end{Bmatrix}$$

where $C_{0,0}=1$. This relationship can be used to transform such estimates between systems for comparison purposes. To distinguish between the two, we call the Cartesian offsets derived from coordinate solutions the "geometric" method, while the offsets obtained from the gravitational harmonics' changes the "dynamic" method.

The geometric method is more sensitive to the tracking network configuration variations between averaging intervals, while the dynamic one smoothes over such variations using the orbit as a filter. This peculiarity in the sensitivity of each technique introduces slight differences in the derived estimates which however are below their formal accuracy. Although we will show these differences, we will concentrate our evaluation of the results on the dynamic method. All accuracy estimates we quote are 3σ values scaled so that $\chi^2=1$.

MODELING

The analysis of SLR data requires numerous and elaborate models describing the forces acting on the satellite, the observing station, and the medium that separates the two. Most of these models are continuously revised and improved, the community however strives to follow the adopted "conventions" to facilitate comparisons of results. In our analysis we have followed with only a few exceptions (which we explain here), the "IERS Conventions (1996)", [McCarthy, 1996].

The deviation of our modeling from the conventions is restricted to the use of the EGM96 static and tidal gravity model [Lemoine et al., 1997] and the use of the older Solar and Planetary Ephemeris DE-200 instead of the more recent DE-403. With regards to the second, we should clarify that despite the use of DE-200 for third body ephemerides, the new nutation model <u>was</u> used, as it is required by the Conventions.

The use of the more recent gravity model was warranted in order that we obtain the highest quality of orbits possible. EGM96 is far superior to its predecessors and above all, its static and tidal components have been developed simultaneously, assuring full compatibility in describing the instantaneous total potential acting on a satellite.

The data were analyzed in 15 day batches, each batch forming one arc with a single set of initial conditions that were fit to the data in a least squares adjustment. In addition to the initial conditions, we adjusted a set of ad hoc accelerations: a Fourier pair at the orbital frequency for each satellite in the along-track and in the cross-track direction, and constant acceleration in the along-track direction. A new set of such accelerations were adjusted every 5 days (i.e. three sets per arc). The solar radiation pressure coefficient was constrained for both satellites at the nominal values of 1.13 and 1.14. Earth albedo and anisotropic thermal effects were modeled for both LAGEOS 1 and 2 [Rubincam, 1988, 1990], [Rubincam and Mallama, 1995], [Martin and Rubincam, 1996] and [Rubincam et al., 1997]. The orientation of the satellite spin axis, required in modeling thermal effects, was obtained from the model described in [Farinella et al., 1996]. In addition to the terrestrial and lunisolar perturbations, we have modeled those arising from the planets Mercury, Venus, Mars, Jupiter, Saturn, Uranus and Neptune. The metric used in the formulation of the equations of motion and the observer-dependent data corrections was that of Einstein's theory of general relativity (according to the Conventions).

The Terrestrial Reference Frame (TRF) origin was described by the tracking station coordinates with *a priori* values from GSFC's SSC/SSV 96L02 [IERS, 1997]. All station positions were adjusted with the exception of a set of minimal constraints to remove the usual singularities. In particular, the latitude and longitude of one site (Greenbelt, Maryland) and the latitude of an additional site (Maui, Hawaii) were kept fixed to *a priori* values. The evolution of the network due to tectonic motions at the sites was described by the adopted velocity model. Even though SLR is a primary system in determining such motions, the length of the analyzed data set (only four years) was deemed inadequate to reliably resolve these motions at all sites. The *a priori* orientation of the reference frame was described by the Earth orientation series SPACE96, [Gross, 1996]. Our analysis adjusted daily for the two components that describe the orientation of the instantaneous rotational axis with respect to the TRF (polar motion) and the excess length of day.

The sites' displacement due to ocean loading effects was modeled with the coefficients provided by H.-G. Scherneck (HGS) according to the IERS Conventions. Another effect of the ocean tides that has become an important source of variance in the definition of the TRF is their influence on Earth orientation and the geocenter itself. Estimates of these effects on the basis of SLR data were reported already in [Pavlis and Rowlands, 1993] and [Pavlis, 1994], and there have been numerous other models developed using other techniques (VLBI, GPS), or based on theory and some of the recently developed ocean tide models. In particular, we used the ocean loading set from HGS that includes implicitly the correction due to the tide-induced motions of the geocenter at the diurnal and semi-diurnal frequencies, derived on the basis of the CSR3.0 ocean tides. Similarly, for the corrections of tidal origin in polar motion and Earth rotation at the diurnal and semi-diurnal frequencies we used the IERS Conventions model of R. Ray.

In addition to applying known data biases, we allowed for measurement bases for all stations, solving for them in the final stage on a per site mode, based on the tracking of both satellite targets. This characterizes them as a "site" rather than a "target" parameter, which is more appropriate for the case of identical satellites. The estimation of these biases becomes also more robust due to the increased amount of data and tracking geometry.

Finally, the last set of parameters allowed to adjust are the low degree and order harmonic coefficients that describe the time dependence induced in the gravitational model due to mass redistribution of other than tidal origin. Rotational deformation induced changes in the second degree - order one harmonics were modeled according to our extended model accounting for secular wandering of the mean pole [Marsh et al., 1988]. Post-glacial relaxation effects on the second zonal harmonic J_2 were modeled as a secular rate at the value used in the development of EGM96.

RESULTS

The results of primary interest to the IERS geocenter campaign are the series of biweekly average position of the geocenter with respect to the conventional origin defined through the adopted network site positions and velocities. As we already discussed this in a previous section, we derived these series in two different but equivalent ways. The series that are illustrated in Figure 1 are the result of the "dynamic" approach. It is quite evident that the magnitude of the variation for the equatorial components ΔX and ΔY, and that of the axial component ΔZ is markedly different. The reason behind this of course is the fact that Earth rotation efficiently averages signals sectorially, never allowing for the build-up of large signals, while the much slower seasonal changes produce much more significant variations between northern and southern hemispheres. This disparity between components was detected by all of the participating techniques in this campaign.

The statistics for each of the two approaches as well as their differences are given in Tables 1 through 3. The expected high degree of agreement between the two series is obvious. It is however stressed that their differences are not insignificant and quite important. The statistics show that while the two approaches do not differ in the mean, the root mean square discrepancy between the two can reach over 50% of the scatter either of them exhibits. The repercussions of this we will discuss further below.

DISCUSSION

The geocenter series that were made available through the IERS campaign covered nearly every space technique that is capable of defining the geocenter. Due to various reasons, nearly every one of these series has a different resolution and that makes it difficult for point by point comparisons. Nevertheless though their statistical summaries indicate that most of them agree quite well. In particular, we examine the similarities of our series with those submitted by the Uni. of Texas/CSR group, which are also based on the SLR data from LAGEOS 1 and 2, but reported as 12-day averages. Figure 2 shows a 1-year portion of the two series covering the period 1995-96. At this large scale one can see that despite the different averaging interval, the two series are exhibiting similar trends during the same periods of time.

The level of difference between the two could be used as another measure of how reliably we can determine geocenter variations with the SLR technique today. In order to be able to compare the two series in a more rigorous way, we formed the 60-day running average for each one, as a four point average of the GSFC results and a five point average of the CSR results (60 days being the least common factor of 15 and 12 days). Figure 3 displays for each of the three components the smoothed series. The coherence between them is quite remarkable, even for the z-component which overall does show the largest discrepancy. Summary statistics for the smooth series (Table 4) indicate that indeed, the equatorial components agree extremely well, while in the z-component there is an 80% increase in the observed variation of the GSFC vs. the CSR series. Further inspection of Figure 3 suggests that this increase is caused primarily by a couple of isolated points in the middle of 1994 and 1995, and the estimates spanning the summer of 1996. This implies that the problem is probably due to the different weighting/treatment of some sites which are not participating throughout the period. We should also point out that depending on which approach we use to estimate the motion of the geocenter, we can easily see differences at the level of a few millimeters. This is something to keep in mind when contributions from different techniques/approaches are compared. A more careful and close inspection of the individual periods with above average discrepancies will be required to resolve this issue completely. At this point the differences, as seen visually from the figures displaying the original series as well as from the figures and statistics summarizing the two smoothed series, indicate that the reliability of these series is not better than 3-4 mm in each of the equatorial components and about 10 mm for the axial component.

We next examined the spectral content of the GSFC series to identify any significant concentration of variance at the most likely periods (biennial, annual, semi-annual and seasonal). The results are summarized in Table 5 and indicate that as far as the equatorial components are concerned, the majority of the variance is concentrated in the annual terms with an amplitude of about 1 mm. For the axial component however the spectrum is a lot richer throughout the band covered by the data. The biennial term shows an amplitude of 4 mm, the annual ~ 3 mm, the semi-annual ~2 mm and the seasonal ~1.3 mm. Amplitudes at or below the 1 mm level would hardly be considered significant for this sample.

SUMMARY

We analyzed SLR data from LAGEOS 1 and 2 collected over the period 1993 up to the end of 1996 with the goal of defining a high resolution (15-day average) geocenter motion series. Our results indicate that the geocenter exhibits a markedly different behaviour in its motion on the equatorial plane vs. that along the axial direction. On the average the equatorial components vary by ±10 mm peak-to-peak, while the axial component is more energetic and displays a ±35 mm variation. The formal accuracy estimates of our results and comparisons with independent solutions indicate that the accuracy we can determine these motions at 15-day intervals is ~3 mm for the equatorial components and ~11 mm for the axial component. Our comparison of two different approaches in determining these motions indicates that at present we cannot reliably detect motions that are below the 2 mm and 8 mm level respectively.

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Table 1. Statistics for the results from the geometric approach.

Geometric Offsets	$-\Delta X$ [mm]	$-\Delta Y$ [mm]	$-\Delta Z$ [mm]
Minimum	-12.1	-10.1	-31.4
Maximum	9.9	9.2	33.4
Points	102	102	102
Mean	-1.6	-1.5	2.1
Std Deviation	3.7	3.9	12.6

Table 2. Statistics for the results from the dynamic approach.

Dynamic Offsets	$\sqrt{3}a_eC_{1,1}$ [mm]	$\sqrt{3}a_eS_{1,1}$ [mm]	$\sqrt{3}a_eC_{1,0}$ [mm]
Minimum	-7.7	-11.3	-25.8
Maximum	5.9	10.3	35.4
Points	102	102	102
Mean	-1.3	-1.2	3.5
Std Deviation	2.8	3.3	11.0

Table 3. Statistics for the difference between the results from the two approaches.

Residual Offsets	$\sqrt{3}a_eC_{1,1}-\Delta X$ [mm]	$\sqrt{3}a_eS_{1,1}-\Delta Y$ [mm]	$\sqrt{3}a_eC_{1,0}-\Delta Z$ [mm]
Minimum	-5.2	-5.4	-26.6
Maximum	6.2	6.1	28.4
Points	102	102	102
Mean	0.3	0.3	1.4
Std Deviation	2.0	1.9	7.8

Table 4. Smoothed SLR series summary statistics.

Series	Minimum	Maximum	Mean	RMS	Std Deviation
$\{GSFC-\Delta X\}_4$	-5.9	7.6	1.5	2.8	2.4
$\{GSFC-\Delta Y\}_4$	-7.8	11.3	1.2	3.1	2.9
$\{GSFC-\Delta Z\}_4$	-35.4	25.8	-3.4	10.4	9.9
$\{CSR-\Delta X\}_5$	-7.6	6.8	-0.3	2.8	2.8
$\{CSR-\Delta Y\}_5$	-8.8	14.0	0.3	3.5	3.5
$\{CSR-\Delta Z\}_5$	-20.5	14.0	0.0	5.5	5.5

Table 5. Spectral contents of the GSFC SLR analysis geocenter series.

Amplitude:	ΔX [mm]		ΔY [mm]		ΔZ [mm]	
Period [y]	cos	sin	cos	sin	cos	sin
2	-0.05	-0.24	-0.27	-0.19	-1.79	3.45
1	-0.30	-0.77	-0.61	1.02	1.67	2.24
1/2	-0.01	0.48	0.13	-0.01	-0.93	1.57
1/4	0.04	-0.56	-0.36	0.28	-0.66	1.14

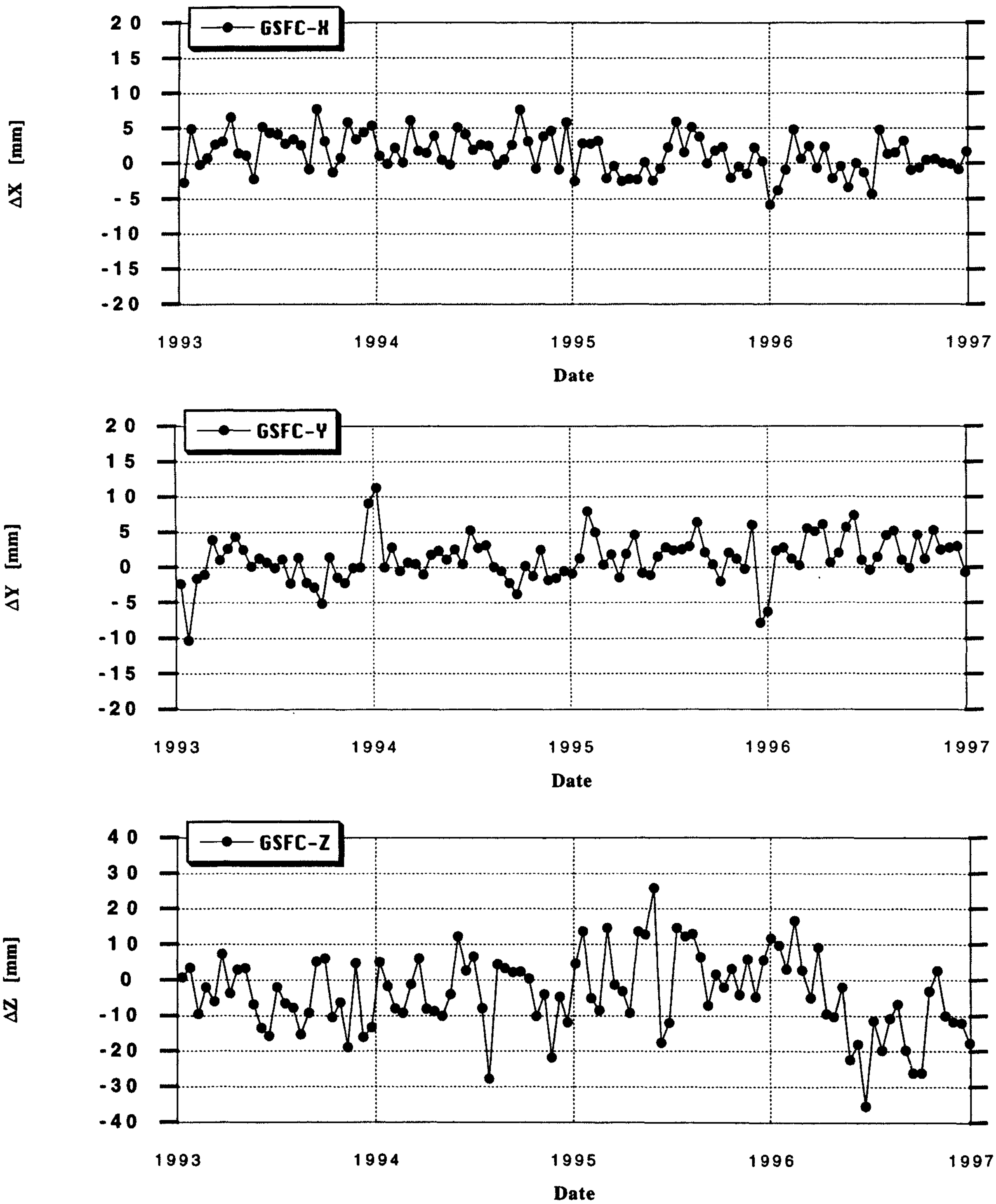

Figure 1. The GSFC SLR-based geocenter series with 15-day resolution for 1993-96.

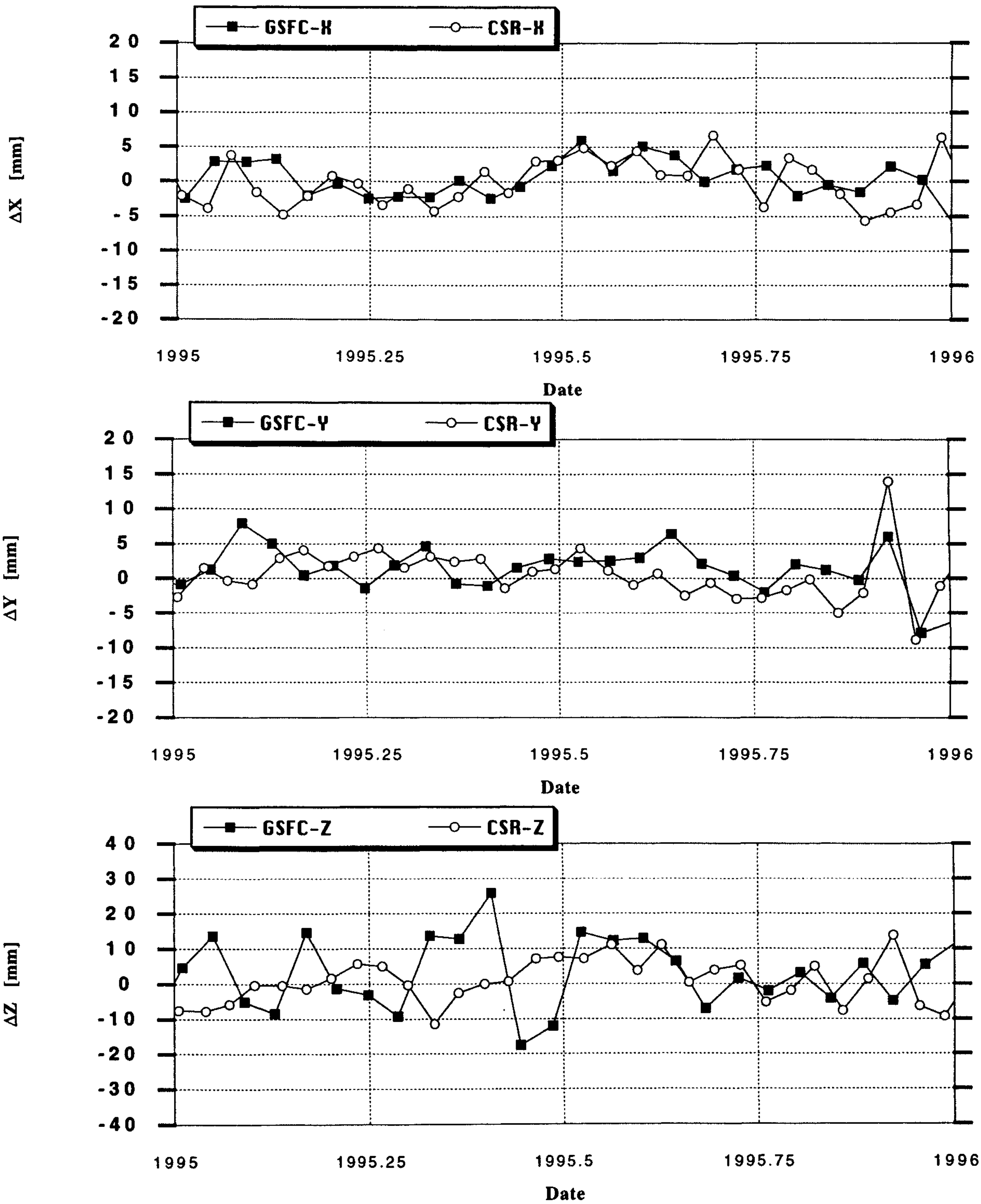

Figure 2. The motion of the geocenter in 1995 from two SLR analyses: GSFC and CSR series.

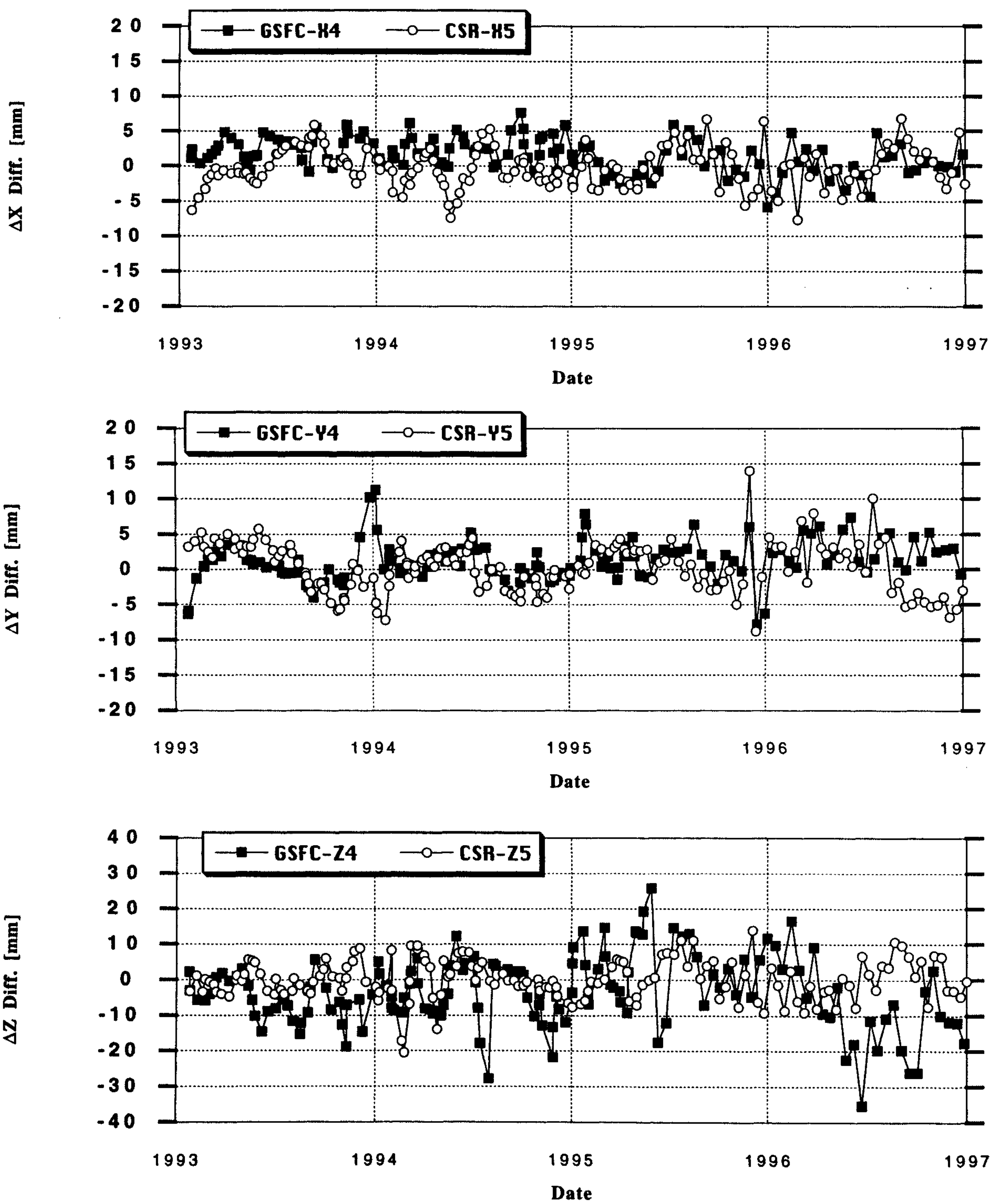

Figure 3. Smoothed series (60-day average), based on the original GSFC and CSR solutions.