HIGH RESOLUTION EOP FROM LAGEOS SLR DATA ANALYSIS AT GSFC

E. C. PAVLIS
Laboratory for Terrestrial Physics
NASA/Goddard SFC
Space Geodesy Branch, Code 926
Greenbelt, MD 20771-0001
U S A

ABSTRACT. A six-hour resolution Earth Orientation Parameter (EOP) series was the product of a complete re-analysis of the 1992 observational data set of Satellite Laser Ranging (SLR) to LAGEOS. This new analysis is a first step towards the complete reduction of the entire tracking data set since LAGEOS' launch (1976). Several improvements in the modeling of the observations have been incorporated. In addition to the EOP series a set of station positions was recovered along with the Fourier coefficients describing the tidally coherent motions of the center of mass implied by this network of stations.

1. Introduction

The improvement of mathematical and physical modeling of the processes involved in the analysis of precise laser ranging data to artificial satellites necessitates the revision of those analyses at a few years' intervals. GSFC revises their modeling at yearly or bi-yearly intervals. Currently we are in the process of analyzing the entire set of data with several new modeling options recently incorporated in our software package (Geodyn/Solve II). While doing so, we have used the tracking data obtained over 1992 as a test data set to verify those new models. The series obtained from this analysis has been included here as a contribution of the SLR group to the characterization of the Earth's variable orientation during the SEARCH '92 campaign.

2. Orbit and Measurement Models

The numerical values of adopted constants and the majority of orbit (force) and measurement models utilized are described in Table 1. In comparison to our previous submission to IERS (in IERS Tech. Note No 14, [Charlot,1993]), it is worth pointing out the major changes in our analysis strategy. We adopted a six-hour averaging interval for the estimation of polar motion and length-of-day variations. Weak *a priori* constraints were applied to prohibit the singularities on intervals void of data. We estimated site-network implied center-of-mass variations at tidal frequencies: semi-daily, daily, and long period. In addition to center of mass motions at tidal frequencies, we have implemented the capability of modeling and estimating Fourier coefficients describing similar effects in polar motion and Earth rotation. These however were not applied in the present solution. Though we still use the IAU 1980 nutation series, we have adopted the IERS-disseminated (VLBI-derived) $\delta\Delta\psi$, $\delta\Delta\varepsilon$ correction series to complement our model.

As far as the force model is concerned, more frequent (every five days) adjustment of a constant along-track acceleration and two once-per-revolution accelerations in the along-track and cross-track directions were deemed appropriate. These are still necessary until

we develop a definitive model of the atmosphere-driven perturbations to reduce the impact on LAGEOS' trajectory, [Klosko et al., 1993]. This is one of the major topics to be addressed in the new analysis (SL9). A departure from the IERS recommendations (IERS Standards, Tech. Note No 13, [McCarthy, 1992]), is the use of the latest gravitational model, JGM-2 and an expanded set of tides' coefficients including the 18.6 yr tide. Our evaluation of the new solution over a variety of orbital configurations indicates that JGM-2 is significantly superior to our older solution GEM-T3, [Nerem, 1993].

3. Results

We will refer to the results presented herein as our solution SL9.0. This is our internal number that indicates a preliminary solution within the frame of the final major re-analysis SL9. The solution comprises 12 monthly arcs. The overall rms of fit to the data is 29.3 mm.

3.1 CONTENT

The results obtained from this solution include a set of station positions at epoch 1988.0 with unadjusted velocities constrained to the *a priori* values, the EOP series at six hour intervals (polar motion and length-of-day variations), a set of Fourier coefficients describing the motion of the center of mass (at tidal frequencies) with respect to the origin implied by the (adjusted) tracking site positions, and a number of nuisance parameters required to fit the data to the orbit (e.g. initial state-vector and acceleration parameters per arc). There is no smoothing of any kind applied to the EOP series. In addition to these direct products, we also computed the excitation functions for the resulting EOP series so that they can be later compared to the effective atmospheric angular momentum equivalents.

3.2 EOP COMPARISONS

The resulting EOP series are compared to the *a priori* series, IERS 90 C 04, and to the Kalman filtered combination series SPACE '92 [Gross, 1993a]. The residual differences with respect to these series are displayed in figures 1, 2, 3, and 4. Tables 2 and 3 summarize the statistics of the differences between our results and the aforementioned series.

There is a total of 1460 reporting epochs, 1459 for LODR, of which only 133 had to be constrained for lack or very poor data distribution. Considering that there is at least one occasion per arc that we need to apply absolute constraints on the value of UT1, we conclude that for this particular year we were able to estimate six hour averaged EOPs with a success rate of 92%. This can be further improved when the data from additional stable targets such as LAGEOS II are combined into a single solution. This is intended to be the case for the final SL9 product. Preliminary results of such a combination were shown by M.H. Torrence at the 1993 Fall AGU, [Smith et al., 1993].

For the proper interpretation of the tabulated statistics, one must consider that the displayed kurtosis values are normalized. That is to say, the nominal value of this statistic for a normal distribution (=3) has been subtracted from the tabulated values. The SL9.0 results agree slightly better in rms with the *a priori* series, but they show a slightly smaller mean difference with respect to SPACE '92. The UT1 series were obtained by a simple integration of the LOD values. Since the only estimable quantity in the orbit determination problem is the variation of UT1, i.e. LOD, we have to apply absolute constraints on UT1 to keep it as close as possible to the values implied by the *a priori* series. It is no surprise then that in terms of UT1, our results agree better in the mean as well as in the rms with the *a priori* series. Interestingly, the skewness and

kurtosis values indicate that the shape of the residual distribution is still closer to normal for the comparison with SPACE '92. This in fact is true for all four components of the series.

3.3 EXCITATIONS

The effective atmospheric angular momentum (EAAM) functions χ_1, χ_2, and χ_3 as archived and distributed by the AAM Sub-bureau were kindly provided by David Salstein [private communication, 1992]. The series covered the SEARCH'92 period with values given at six hour intervals. Both, the NMC and the ECMWF series were provided, however, we limit our comparisons to the NMC series using their wind terms to the top of the model (50 mb). For the pressure terms we have compared to both EAAM series, those consistent with the Inverted Barometer (IB) hypothesis as well as the ones that do not invoke it (non-IB). These comparisons are limited to the period over which the EAAM data are available to us: Jun. 21 - Sept. 22, 1992, Day-of-Year (DoY): 173-266.

The polar motion excitation functions obtained from the raw six-hour values are displayed in figure 5. At this resolution and scale they seem random, with no underlying structure. The EAAM functions are given at the same interval but they are actually based on a single set of measurements per day, the other values being "model" values that are reported at six hour intervals during the assimilation process. One therefore would not expect the model to be able to forecast high frequency, very rapid changes. After passing the polar motion excitations and our LODR series through a moving average procedure, we start to see the same structure as that depicted by the EAAM functions. We have used various windows from 12 hours to 1, 2, 5 , 10, and 30 days. As expected, the longer windows produce results that agree with the EAAM series only at long wavelength.

The series we show here for comparison purposes are the 2 and 5-day window results. From the six cases we investigated, these seem to depict best the agreement in structure with the EAAM functions. Figures 6, 7, and 8 display these series. The top figure is the windowed EOP excitation functions and the bottom figure shows the corresponding EAAM functions (both non-IB and IB cases). In the polar motion series, the non-IB case functions seem to agree better than do the IB ones. In the LOD case the excitation function seems to wonder between the two cases, sometimes in better agreement with one and at other times with the other. A slope difference is obvious.

What seems to emerge from this comparison is the need for (even short) intensive atmospheric data gathering campaigns during different periods of the year (covering the four seasons). If we are to understand the rapid changes in the EOP series, we need to be able to compare them with data of equivalent frequency content. The EAAMs are the best candidates for the explanation of those rapid changes [Barnes et al., 1983].

3.4 CENTER OF MASS MOTION

The point about which a satellite orbits is the instantaneous center of mass of the planet. We can view our planet as a three-part system: the atmosphere, the oceans, and the solid earth. If there is no mass redistribution within each of these parts and no relative motions between them, then the center of mass remains at rest with respect to the system. We know however that this is not the case for any of the three parts. Most notably, the fluid parts, the atmosphere and the oceans, undergo continuous mass redistribution due to winds, currents, and external (tidal) forces. The solid part is affected by rather well known tidal forces, as well as other sources of mass redistribution that work on geological time-scales (e.g. convection currents, plate tectonics). We cannot expect of course to see the effects of the latter with such a short data set.

The tidally driven redistribution though, produce coherent changes in the inertia tensor that in turn induce motions of the pole, changes in the spin rate of the planet, and translations of the "ensemble" center of mass from its equilibrium position due to the asymmetric distribution of land and oceans over the surface of the planet. Such changes

impose a time dependence on the low degree and order gravitational harmonics which are associated with the inertia tensor [Heiskanen and Moritz, 1967]. The standard solutions for gravity field models do not account yet for these effects. Moreover, they impose an absolute constraint on the origin of the reference frame in which the coefficients are described, namely, to be the center of mass, (i.e. $C_{10}=C_{11}=S_{11}\equiv 0$). The origin of that frame is defined by the estimated positions of the tracking stations, all attached to the solid earth. Those positions, except for the tectonic motions and the standard tidal and loading corrections, they are mean positions over the span of the data. That implies that they also define an origin which coincides with the mean center of mass over that time span. A high resolution and precision EOP series requires that these perturbations be either modeled or estimated.

The rotational perturbations were theoretically predicted as early as 1983 [Baader et al., 1983], and the translational ones in [Brosche and Hövel, 1982]. Recently, several new elaborate theoretical studies have been published addressing both parts [Brosche and Wünsch, 1993], [Gross, 1993b], [Ray et al., 1994]. Additionally, all modern space techniques have observed one or the other (or both), [Herring and Dong, 1993], [Watkins and Eanes, 1993], [Gross and Lindqwister, 1992], [Pavlis and Rowlands, 1993]. In SL9.0 we tested the ability of our analysis procedure to estimate a wide spectrum of tidally coherent motions of the center of mass. We allowed for the annual, the semi-annual, the monthly, the fortnightly, the daily and the semi-daily frequencies to be solved for. With a single year of data, we would not place a lot of confidence on the annual and semi-annual components. The other frequencies though should be close to what we will obtain from the complete data set analysis. The results for this preliminary solution are tabulated in Table 4. The astronomical arguments and the phase convention used is consistent with the IERS Standards.

4. Summary

We produced a high resolution Earth orientation series at six hour intervals covering the entire 1992. The series was based on the analysis of LAGEOS SLR data. The analysis procedure follows closely the one proposed for the re-analysis of the entire LAGEOS data set (1976-present), within the framework of the SL9 solution. The present series indicates a very good agreement with smoothed series based on several techniques, e.g. IERS 90 C 04 and SPACE '92. Comparisons of the derived excitation functions with the EAAM functions indicate that the latter are not of sufficient resolution at the reported six hour interval. The 2 and 5-day smoothed EOP excitations though show very good agreement, indicating that with higher resolution atmospheric data we should be able to explain a significantly larger variance in the EOP excitations. Station positions were also estimated for the tracking sites and at the same time a model for the tidally coherent translations of the center of mass with respect to the origin defined by these positions was also solved for.

5. References

Baader, H.R., P. Brosche, W. Hövel (1983) 'Ocean tides and periodic variations of the Earth's rotation', *J. Geophys., 52*, 140-142.

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson (1983) 'Atmospheric angular momentum fluctuations, length-0f-day changes and polar motion', *Proc. Roy. Soc. London, Ser. A*, 387, 31-73.

Brosche, P. and W. Hövel (1982) 'Tidal friction for times around the presence' in P. Brosche and J. Sündermann (eds.), Tidal Friction and the Earth's Rotation II, Springer, Berlin-Heidelberg-New York, 175.

Brosche, P. and J. Wünsch (1993) 'Variations of the Earth's center of mass due to oceanic tides', *Astron. Nachr.*, 314, 2, 87-90.

Gross, R.S. (1993a) 'A Combination of Earth Orientation Data: SPACE92', an electronic article with the disseminated series, 1-11.

Gross, R.S. (1993b) 'The effect of ocean tides on the Earth's rotation as predicted by the results of an ocean tide model', *Geophys. Res. Letters*, 20, 293-296.

Gross, R.S. and U.J. Lindqwister (1992) 'Atmospheric Excitation of Polar Motion During the GIG'91 Measurement Campaign', *Geophys. Res. Letters*, 19, 849-852.

Heiskanen, W.A. and H. Moritz (1967) 'Physical Geodesy', W.H. Freeman and Company, San Francisco and London.

Herring, T.A. and D. Dong (1993) 'Measurement of Diurnal and Semidiurnal Rotation Variations and Tidal Parameters of the Earth', submitted to *J. Geophys. Res.*.

Klosko, S.M., R.S. Nerem, N.K. Pavlis and R.G. Williamson (1993) 'Long Wavelength Atmospheric Tides from SLR Data', (abs.), *EOS Trans. AGU, 74(43), 1993 Fall Meeting Suppl.*, 196.

McCarthy, D.D. (ed.) (1992) 'IERS Standards (1992)', *IERS Technical Note 13*, Central Bureau of IERS, Observatoire de Paris.

Nerem, R.S. (1993) 'Gravity Model Determination from Satellite Data: Current Status and Future Developments', (abs.), *EOS Trans. AGU, 74(43), 1993 Fall Meeting Suppl.*, 64.

Pavlis, E.C. and D.D. Rowlands (1993) 'Daily Resolution Earth Orientation Series During SEARCH '92', (abs.), *EOS Trans. AGU, 74(43), 1993 Fall Meeting Suppl.*, 189.

Ray, R.D., B.F. Chao, D.J. Steinberg and D.E. Cartwright (1994) 'Diurnal and semidiurnal variations in the earth's rotation rate induced by oceanic tides' in H. Hus (ed.) Proceedings of the 12th International Symposium on Earth Tides, Aug. 4-7, Beijing, China.

Smith, D.E., R. Kolenkiewicz, P.J. Dunn, S.M. Klosko, J.W. Robbins, M.H. Torrence, R.G. Williamson and E.C. Pavlis (1993) 'Earth Orientation Parameters from GSFC Solution SL8.2 GSFC 93 L 01', in P.Charlot (ed.), *IERS Technical Note 14*, Central Bureau of IERS, Observatoire de Paris.

Smith, D.E., R. Kolenkiewicz, M.H. Torrence and P.J. Dunn (1993) 'A Multi-Satellite Global SLR Solution', (abs.), *EOS Trans. AGU, 74(43), 1993 Fall Meeting Suppl.*, 185.

Watkins, M.M. and R.J. Eanes (1993) 'Tidally Coherent Diurnal and Semidiurnal Geocenter Variations Observed with Lageos Laser Ranging', (abs.), *EOS Trans. AGU, 74(16), 1993 Spring Meeting Suppl.*, 103.

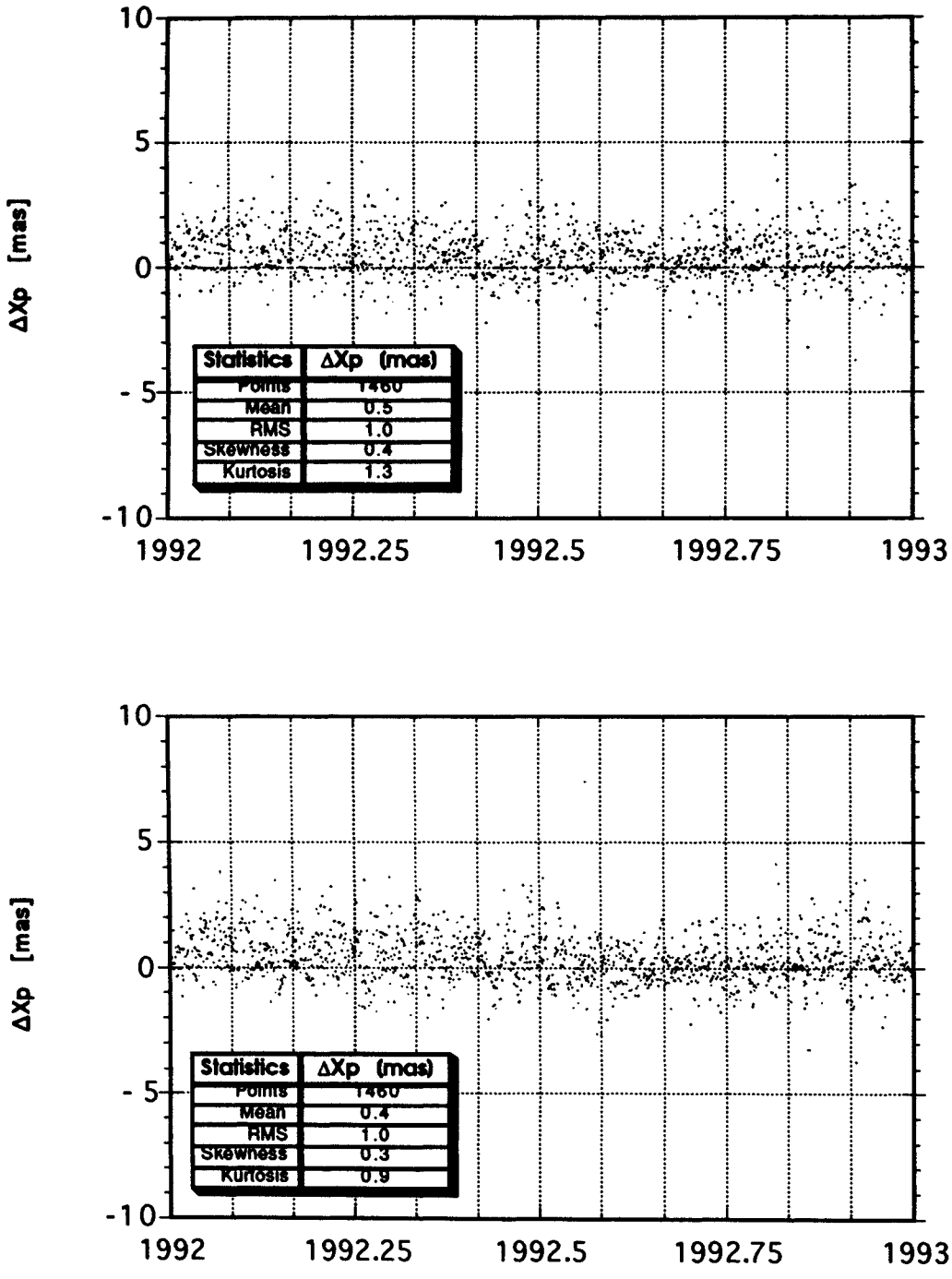

Figure 1. Comparison of the x component of polar motion from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

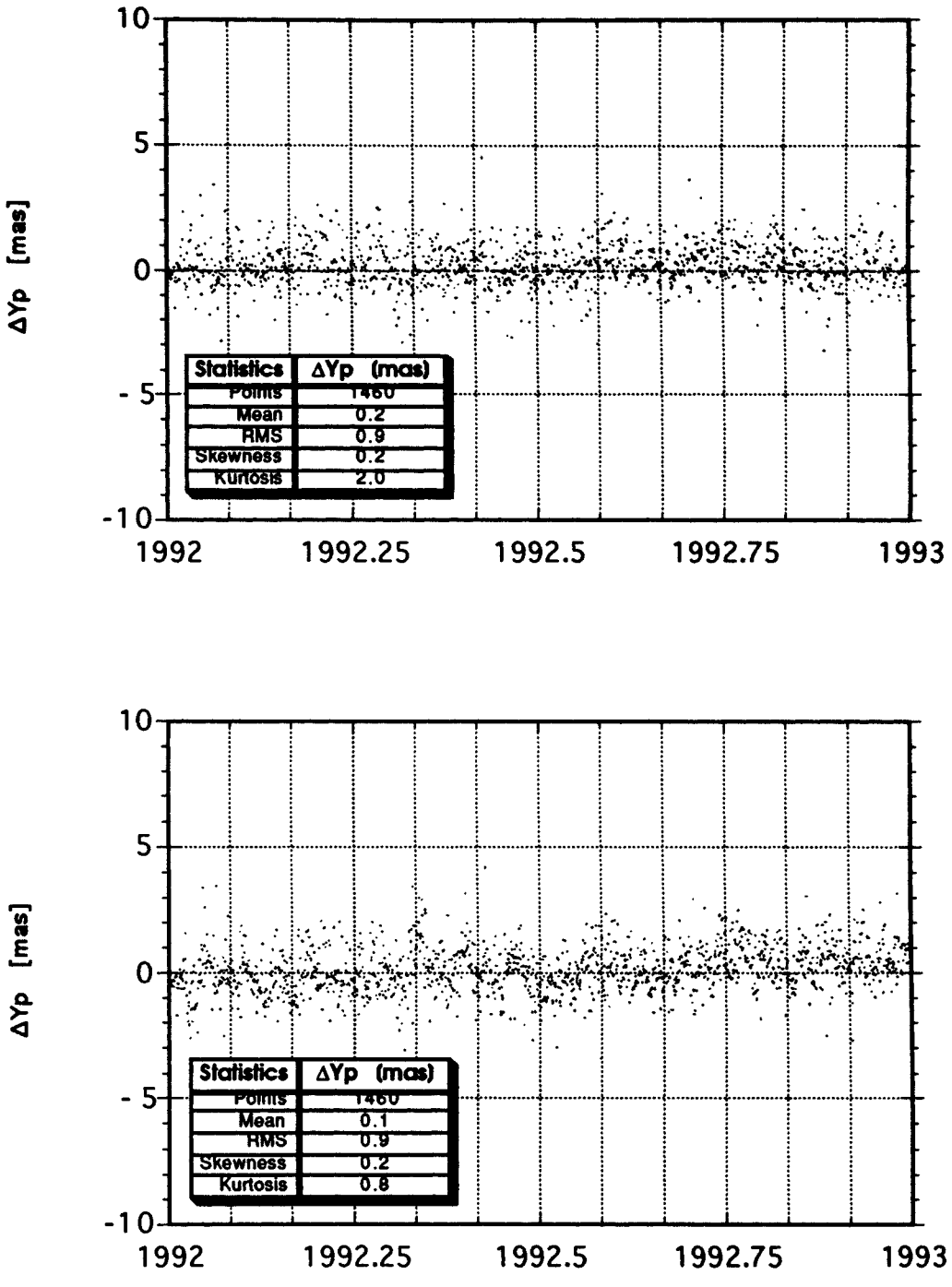

Figure 2. Comparison of the y component of polar motion from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

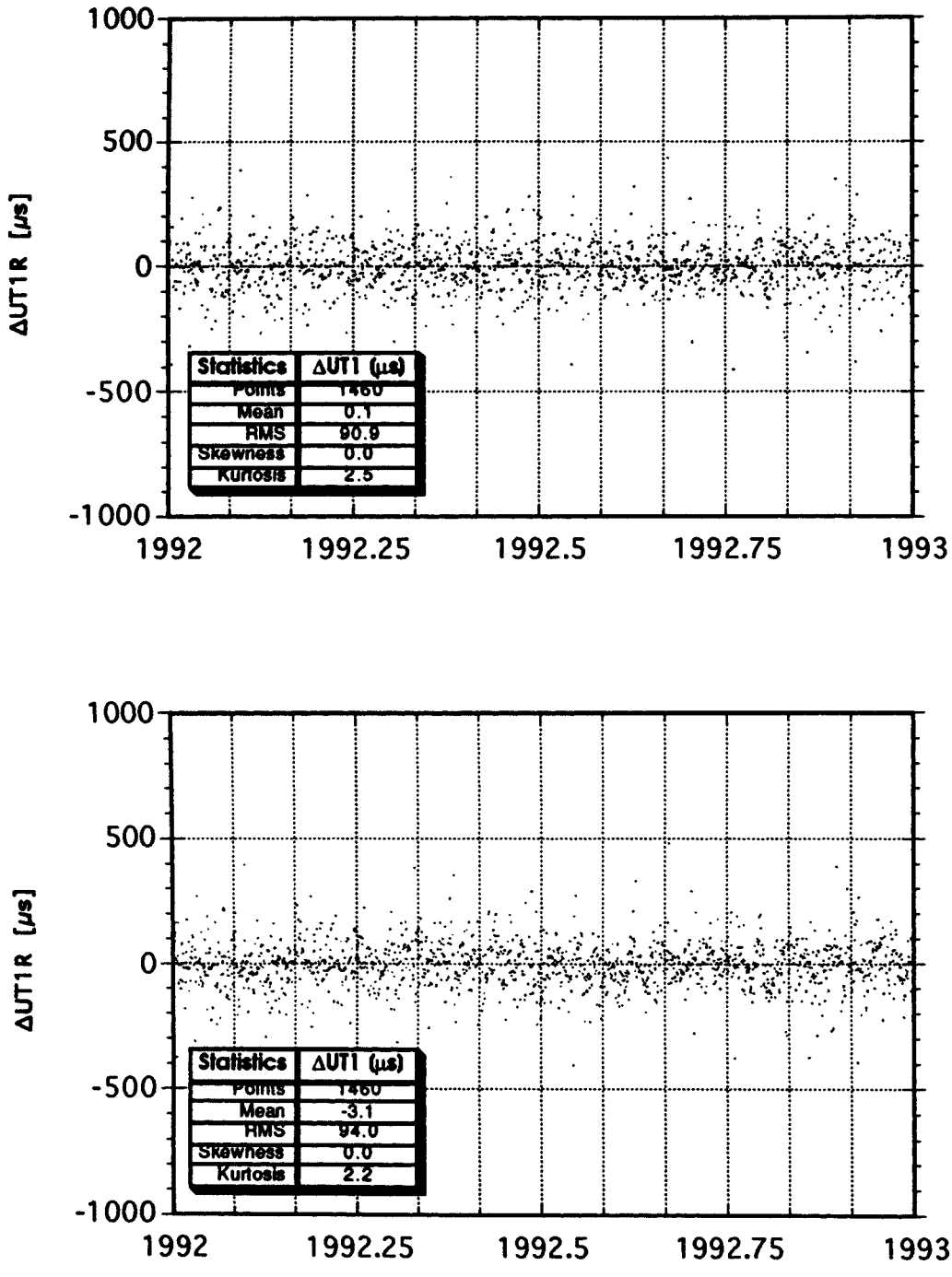

Figure 3. Comparison of inferred UT1R from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

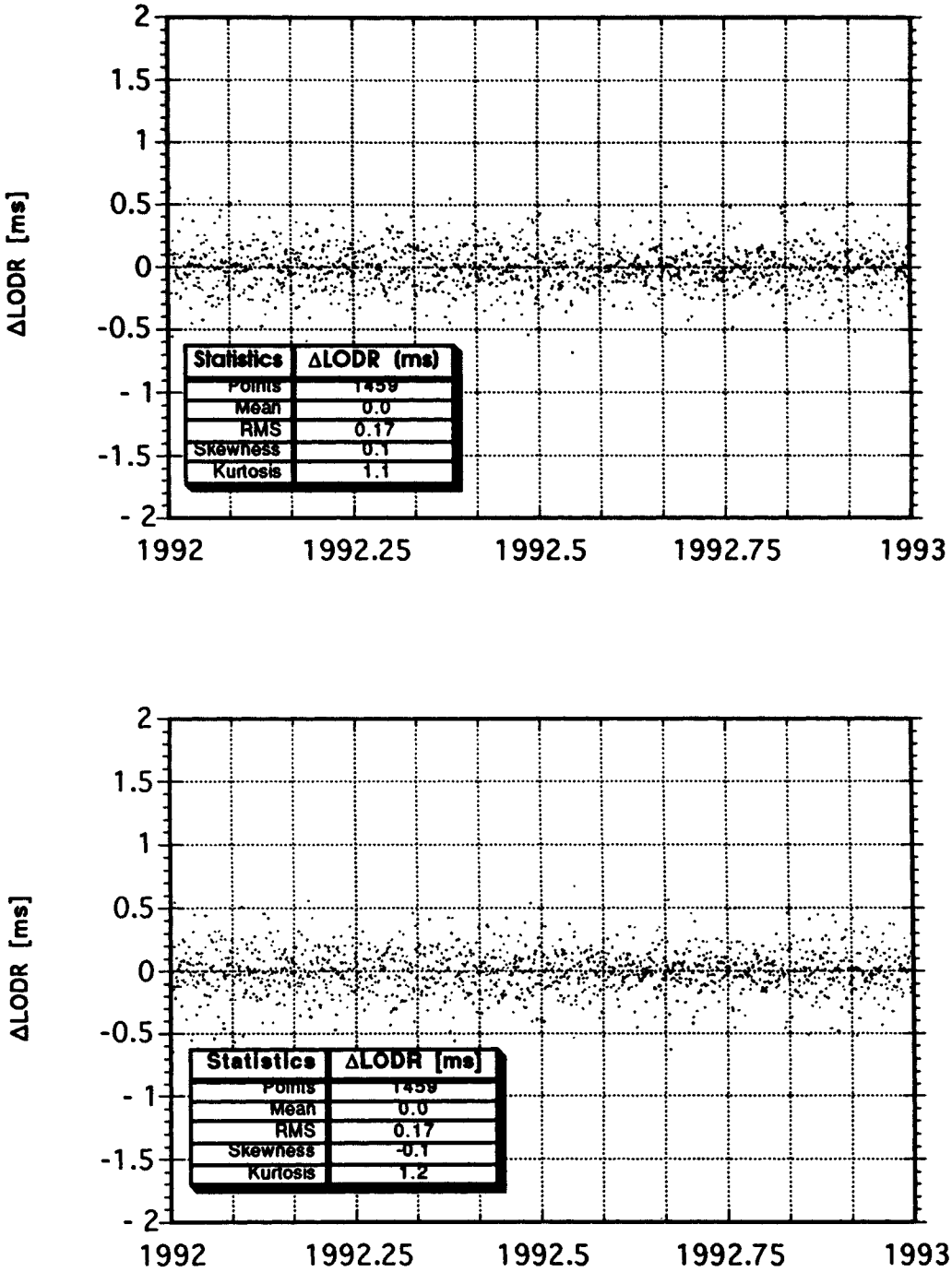

Figure 4. Comparison of Length-of-Day variations from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

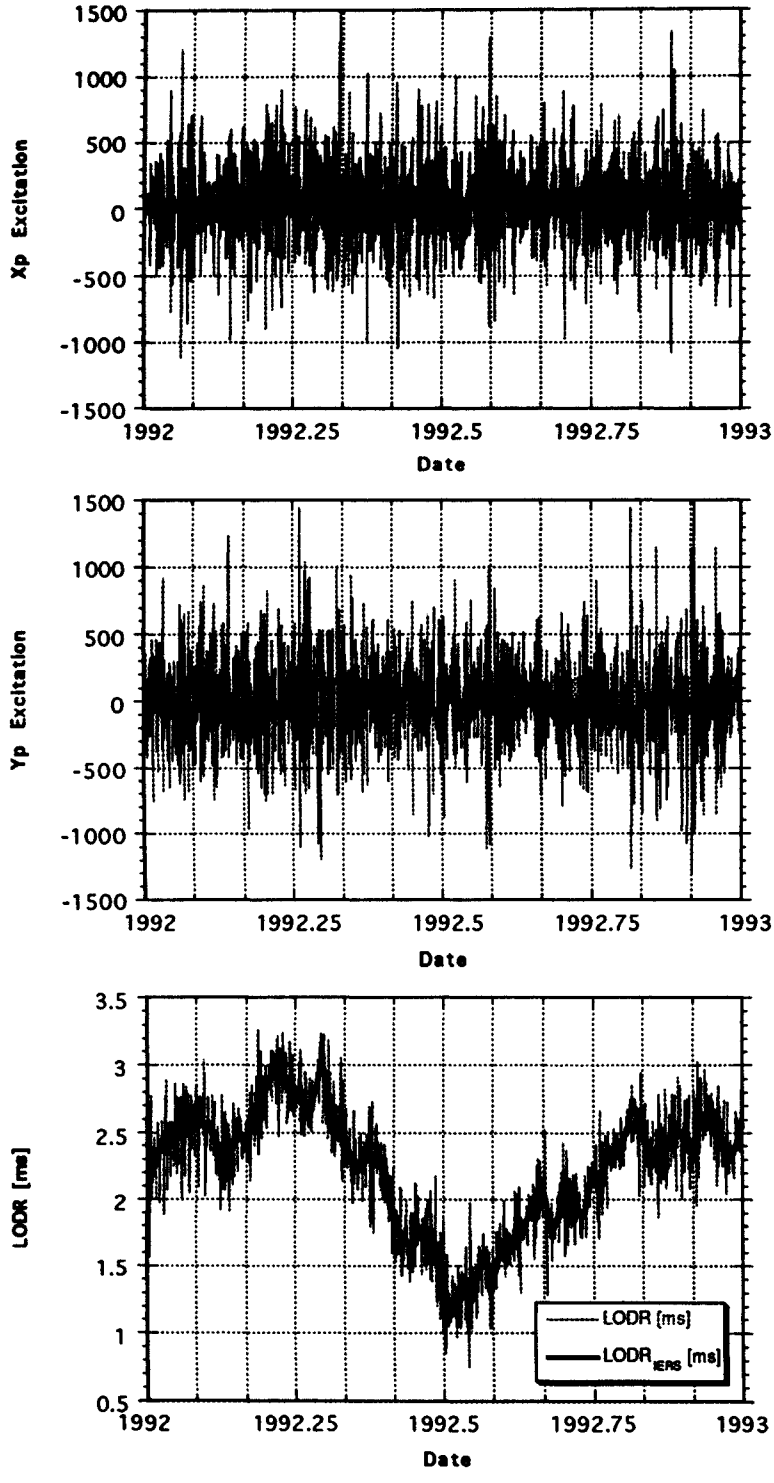

Figure 5. Polar motion and Earth rotation Excitation functions from the raw 6 hr resolution SL9.0 series.

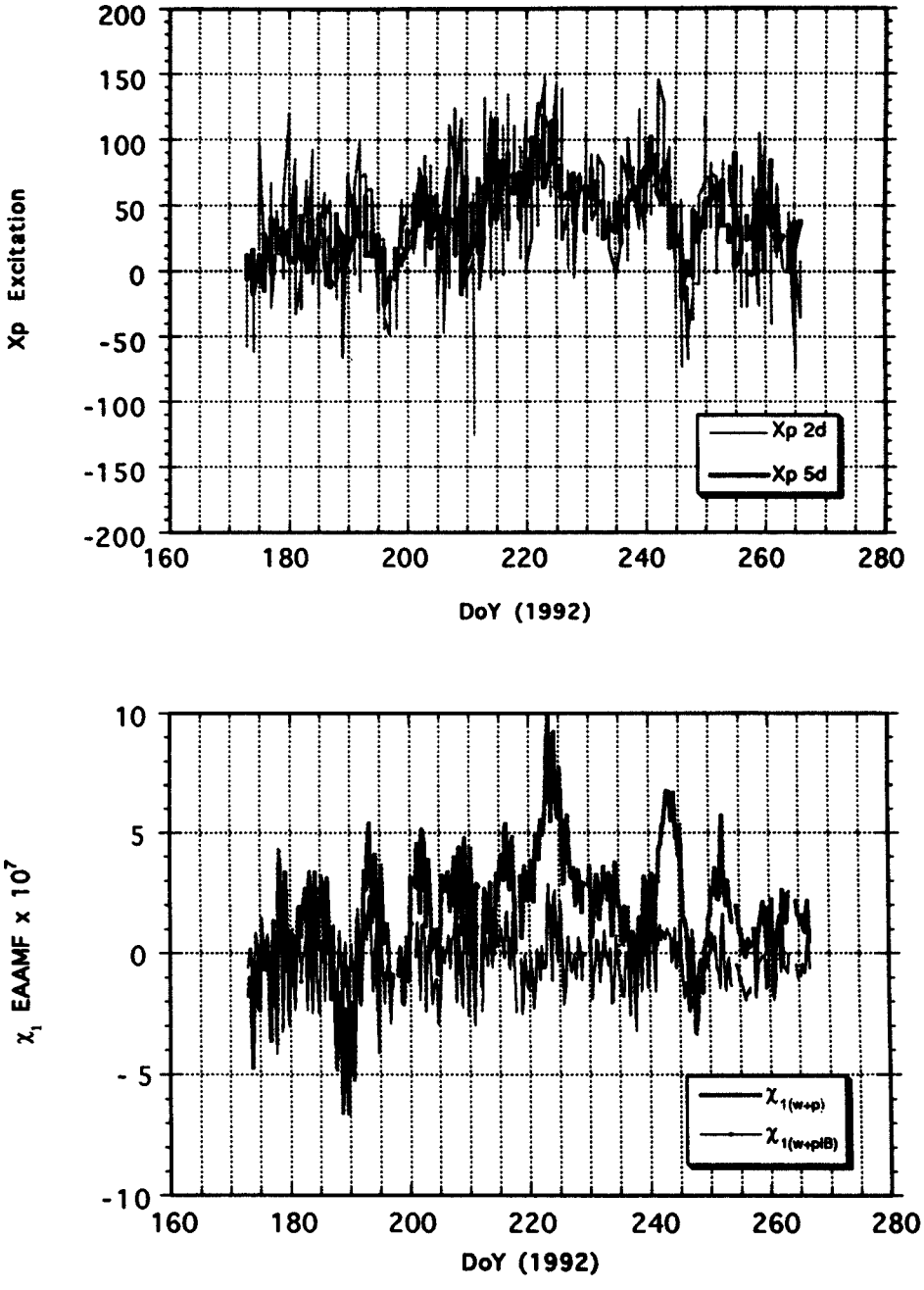

Figure 6. X component of polar motion excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_1 from NMC series (bottom) with and without the inverted barometer hypothesis.

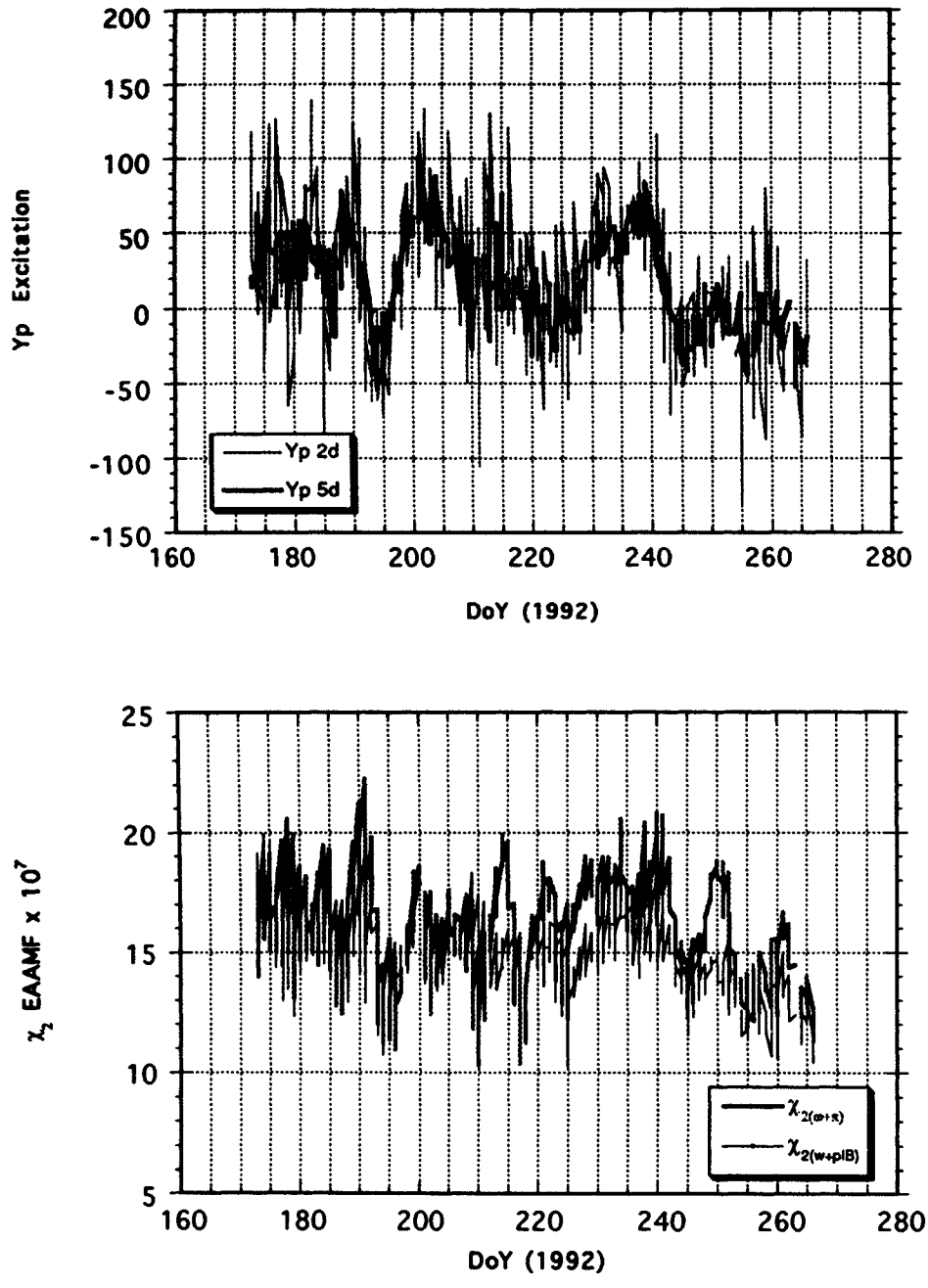

Figure 7. Y component of polar motion excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_2 from NMC series (bottom) with and without the inverted barometer hypothesis.

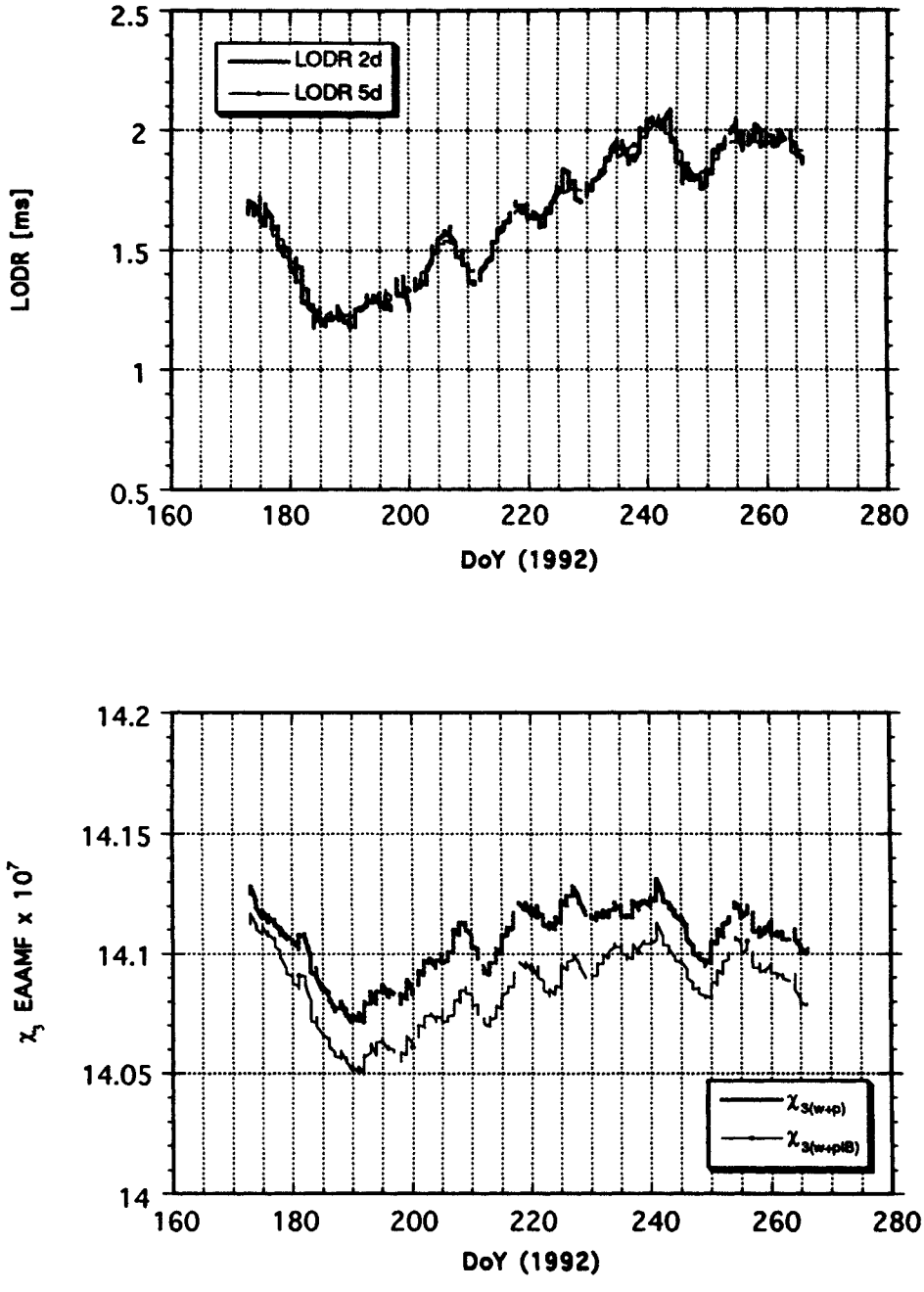

Figure 8. Earth rotation excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_3 from NMC series (bottom) with and without the inverted barometer hypothesis.

TABLE 1. Description of the Terrestrial Frame underlying the EOP(GSFC) 93 L 02 series.

1 - Technique		:	SLR to LAGEOS
2 - Analysis Center		:	NASA/GSFC
3 - Solution identifier		:	SL9.0
4 - Software used		:	GEODYN II / SOLVE II
5 - Relativity Scale		:	Local Earth
6 - Station tidal correction		:	Earth tides & ocean loading (Scherneck)
7 - Tectonic plate model		:	GSFC SL8.2
8 - Velocity of light (C)		:	299 792 458 m/s
9 - Geogravitational const. (GM_0)		:	398600.4415 km3/s2
10 - Reference epoch		:	88 01 01
11 - Adjusted parameters	Orbit	:	6 elements/30(35) days along track accel./5 days once per rev. accel./5 days
	Stations	:	Epoch positions adjusted for all sites except lat/lon of 7105 and lat of 7210.
	EOP	:	x,y and UT1 every 6hr (centered at 0300, 0900, 1500, 2100 UTC), one UT1 interval fixed per arc. Intervals without data fixed to *a priori*.
12 - Definition of the origin		:	Geocentric
13 - Definition of the orientation		:	EOP(IERS) 90 C 04
14 - Constraint for time evolution		:	SL8.2 velocity field

TABLE 2. Statistics of the comparison of SL9.0 to the *a priori* series IERS 90 C 04.

Statistics	ΔXp (mas)	ΔYp (mas)	ΔUT1 (μs)	ΔLODR (ms)
Points	1460	1460	1460	1459
Mean	0.47	0.22	0.10	0.00
RMS	1.01	0.86	90.86	0.17
Skewness	0.38	0.20	0.04	0.10
Kurtosis	1.35	1.98	2.49	1.10

TABLE 3. Statistics of the comparison of SL9.0 to the Kalman smoothed SPACE'92 series.

Statistics	ΔXp (mas)	ΔYp (mas)	ΔUT1 (μs)	ΔLODR (ms)
Points	1460	1460	1460	1459
Mean	0.39	0.13	-3.07	0.00
RMS	1.03	0.94	93.99	0.17
Skewness	0.34	0.20	0.028	-0.11
Kurtosis	0.95	0.75	2.24	1.19

TABLE 4. Estimated coefficients of tidally coherent motions of the center of mass.

Doodson's Number	Cos Coeff. [mm]	Sin Coeff. [mm]	Coordinate Component	Tidal Wave Designator
56554	4.5 ± 1.	2.0 ± 1.	X	
	-9.5 1.	-5.0 1.	Y	S_a
	-12.0 3.	14.0 3.	Z	
57555	3.1 ± 1.	-3.5 ± 1.	X	
	0.3 1.	-2.6 1.	Y	S_{sa}
	-10.8 2.	5.2 2.	Z	
65455	2.3 ± 1.	-0.4 ± 1.	X	
	-0.6 1.	0.0 1.	Y	M_m
	-3.2 2.	-5.9 2.	Z	
75555	-1.6 ± 1.	-0.7 ± 1.	X	
	-3.5 1.	1.6 1.	Y	M_f
	-12.3 1.	- 2.4 1.	Z	
135655	-0.4 ± 1.	-3.5 ± 1.	X	
	-6.1 1.	-0.8 1.	Y	Q_1
	-1.5 1.	-0.9 1.	Z	
145555	-6.0 ± 1.	-1.0 ± 1.	X	
	-2.2 1.	1.0 1.	Y	O_1
	-2.5 1.	-1.1 1.	Z	
163555	3.8 ± 2.	3.6 ± 2.	X	
	-6.7 2.	-6.4 2.	Y	P_1
	-5.2 1.	1.8 1.	Z	
164555	-2.9 ± 2.	13.6 ± 2.	X	
	14.3 2.	4.7 2.	Y	S_1
	-2.4 1.	8.1 1.	Z	
165555	6.0 ± 2.	1.8 ± 2.	X	
	3.7 2.	-2.3 2.	Y	K_1
	-2.5 1.	-5.1 1.	Z	
245655	-1.9 ± 1.	3.5 ± 1.	X	
	0.8 1.	-1.3 1.	Y	N_2
	1.0 1.	0.1 1.	Z	
255555	0.0 ± 1.	5.3 ± 1.	X	
	1.8 1.	4.1 1.	Y	M_2
	-0.3 1.	-3.6 1.	Z	
273555	0.9 ± 1.	0.9 ± 1.	X	
	-6.5 1.	-5.8 1.	Y	S_2
	-1.2 1.	-0.7 1.	Z	
275555	8.3 ± 1.	-4.9 ± 1.	X	
	-4.1 1.	-9.1 1.	Y	K_2
	-1.0 1.	0.0 1.	Z	