

Part III

Geodetic and Atmospheric Measurements

SEARCH'92 Campaign: NOAA Earth Orientation Results Using VLBI Observations	
J. R. Ray, M. D. Abell, W. E. Carter, W. H. Dillinger, M. L. Morrison, and D. S. Robertson	III-1
Earth Orientation from VLBI During SEARCH'92	
C. Ma and J. M. Gipson	III-9
Earth Rotation Parameters Derived from SLR Data on LAGEOS-1	
B. A. C. Ambrosius, D. C. Kuyper, H. Leenman, G. J. Mets, R. Noomen, and K. F. Wakker	III-17
High Resolution EOP from LAGEOS SLR Data Analysis at GSFC	
E. C. Pavlis	III-21
High Resolution Earth Rotation Parameters as Computed from SLR and GPS Data	
Ch. Reigber, H. Montag, G. Gendt, and G. Dick	III-37
GPS Data Analysis for Earth Orientation at the Jet Propulsion Laboratory	
J. Zumberge, F. Webb, U. Lindqwister, S. Lichten, D. Jefferson, R. Ibanez-Meier, M. Heflin, A. Freedman and G. Blewitt	III-45
Effective Atmospheric Angular Momentum Functions Computed from the Japan Meteorological Agency Data	
T. Ozaki, K. Kuma and I. Naito	III-55

SEARCH'92 CAMPAIGN: NOAA EARTH ORIENTATION RESULTS USING VLBI OBSERVATIONS

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ABSTRACT. Earth orientation results are reported for the SEARCH'92 campaign period (21 June - 22 September 1992) based on VLBI observational data analyzed by NOAA.

1. Analysis Procedures

The very long baseline interferometry (VLBI) data sets and the analysis procedures, methods, and models used by the U.S. National Oceanic and Atmospheric Administration (NOAA) have been described by Carter *et al.* (1993). The only significant difference in the analysis results presented here is the inclusion of more observational data, primarily collected during 1993. For the current solution, a total of 849,480 bandwidth-synthesis group delay observations from 1336 one-day observing sessions was included, 21.8% more than in our previous report. In general, the latest *IERS Standards* (McCarthy, 1992) are enforced and our reference frames are aligned with the IERS celestial (ICRF-91) and terrestrial (ITRF-91) frames.

Data from 14 new VLBI sites were used, including: six of the 25-m VLBA antennas, the newly erected 14.2-m antenna at Fortaleza (Brazil), the new 20-m Kokee antenna on Kauai (Hawaii, USA), a new 10-m dish at Mizusawa (Japan), and the 9-m antenna at the O'Higgins Base (Antarctica). Geocentric coordinates for all the VLBI reference points (at epoch 1988.0) are given in the file SSC (NOAA) 93R03. The associated three-dimensional velocities for these sites are given in SSV (NOAA) 93R03. Of the 69 sites, 31 have insufficient data spans (less than about 2 years) to permit meaningful velocity estimates. For those sites (denoted by velocity uncertainty values of zero), the NNR-NUVEL-1 global plate motion model (Argus and Gordon, 1991) has been used to project station coordinates to the 1988.0 reference epoch.

The number of radio source positions in our current solution, RSC (NOAA) 93R03, has increased by 45 to 152. However, most of the new sources are only sparsely observed.

Our Earth orientation parameter (EOP) time series are presented in two files. Results from the 24-hour observing sessions are given in EOP (NOAA) 93R07. File EOP (NOAA) 93R08 contains an independent series of quasi-daily UT1 values from the 1-hour single-baseline IRIS 'Intensive' observing sessions.

2. Tidal Variations in Earth Rotation

The NOAA analysis procedures to account for tidal variations in the rotation of the Earth have already been described by Carter *et al.* (1993). However, because of the significance of sub-daily tidal effects, their relevance to the SEARCH'92 campaign objectives, and the fact that this frequency regime is not dealt with in the *IERS Standards*, our methodology is repeated here.

In the least-squares modelling of the VLBI delay observables, five Earth orientation offset parameters are adjusted for each 24-hour observing session: x and y coordinates of the pole position, UT1, and celestial pole offsets in longitude and obliquity. (For the 1-hour Intensive sessions, only UT1 is adjusted.) Consequently, it is important that the time-variation of the *a priori* EOP values, apart from a possible offset error, reflect as closely as possible the actual variations of the Earth's rotation. Most significant in this respect are tidal variations with periods of about one day or less. The procedure we have developed to form *a priori* EOP values at any VLBI observation epoch is: 1) tabulated EOP values are taken from a previous NOAA solution for the set of all IRIS-A, NAVNET, and NEOS-A observing sessions (with spacings of 3.5, 5, or 7 days depending on epoch); 2) known tidal contributions based on models described below are removed from the tabular values; 3) a cubic spline interpolation is performed on the tidally corrected EOP values from the five nearest tabular epochs; 4) the model tidal contributions are restored. The models used to account for the tidal contributions are: 1) 'UT1S' tidal terms, which include periods between 5.64 days and 18.6 years with corrections due to oceanic tides for the largest terms (see *IERS Standards*, McCarthy, 1992); 2) diurnal and semi-diurnal variations of x , y , and UT1 derived by Herring (1992) based on analysis of 8.5 years of VLBI data. To minimize the effects of residual unmodelled Earth orientation variations, the EOP adjustments are made at the weighted mid-point epoch of each observing session. Non-periodic sub-daily EOP variations will be at least partially averaged out in our analysis. The EOP results reported here are 'total' values, in the sense of including the effects of diurnal and semi-diurnal variations, rather than being strongly smoothed over the 24-hour observing periods or otherwise modified after the least-squares adjustment.

Our *a priori* modelling of the time-variation of the nutation offsets follows analogously the procedure described above for x , y , and UT1. However, the ZMOA-1990.2 nutation model of Herring (1991) is used instead of a tidal model. The reported nutation offsets are with respect to the IAU 1980 model.

3. Discussion of Results

The NOAA EOP results for the SEARCH'92 period (21 June through 22 September 1992) are displayed in Figures 1-3 relative to the IERS combination series EOP (IERS) 90C04. Corrections for diurnal and semi-diurnal variations in x , y , and UT1 have been applied using the model of Herring (1992). Results from a few regional networks, with poor sensitivity to EOP variations, have not been included in Figures 1-3. The weighted rms differences, after removing mean offsets, are: 399.4 μ s for x , 496.2 μ s for y , 31.4 μ s for UT from the 24-hour sessions only, 32.7 μ s for UT from all sessions including the 1-hour 'Intensives', 594.0 μ s for nutation offset in longitude ψ , and 248.6 μ s for nutation offset in obliquity

ε. Included in these statistics are results from 62 24-hour VLBI sessions plus an additional 68 1-hour sessions to measure UT1.

The NOAA-IERS residuals are not entirely random but appear to be most systematic for UT1. Figure 1 shows periods of a week or longer with apparently systematic variations of up to about 100 μ s. Considering that the results are determined from a variety of independent observing networks and that the largest VLBI technique-dependent systematic errors (such as atmospheric propagation effects) are expected to be primarily site-dependent, we conclude that the systematic residuals are caused either by: 1) deficiencies in the NOAA analysis methods or 2) excessive smoothing of UT1 variations in the IERS combination series EOP (IERS) 90C04. Comparisons of our results with independent analyses of the same VLBI data sets should determine whether the first possibility is significant.

In addition, there are occasional VLBI results that appear to be true outliers. The most obvious example is the UT1 determination from the Intensive session on 22 August 1992 (see lower plot in Figure 1). In this particular case, only one of the usual two low-declination radio sources produced useful data. Apparently, the nearly 50% increase in the formal error for that session, compared to neighboring Intensive sessions, does not fully account for the systematic UT1 error introduced by this data loss.

4. References

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- Carter, W.E., Abell, M.D., Dillinger, W.H., Morrison, M.L., Ray, J.R., and Robertson, D.S. (1993) 'NOAA Earth orientation time series and reference frames from VLBI observations: 1. Description of analysis procedures', in P. Charlot (ed.), *IERS Tech. Note 14*, IERS, Observatoire de Paris, pp. R-47 - R-52.
- Herring, T.A. (1991) 'The ZMOA-1990 nutation series', in J.A. Hughes, C.A. Smith, and G.H. Kaplan (eds.), *Proc. IAU Coll. 127 -- Reference Systems*, U.S. Naval Observatory, Washington, pp. 157-166.
- Herring, T.A. (1992) 'Diurnal and semi-diurnal variations in Earth rotation', in M. Feissel (ed.), *Adv. Space Res.*, **13**, Pergamon, pp. 11281-11290.
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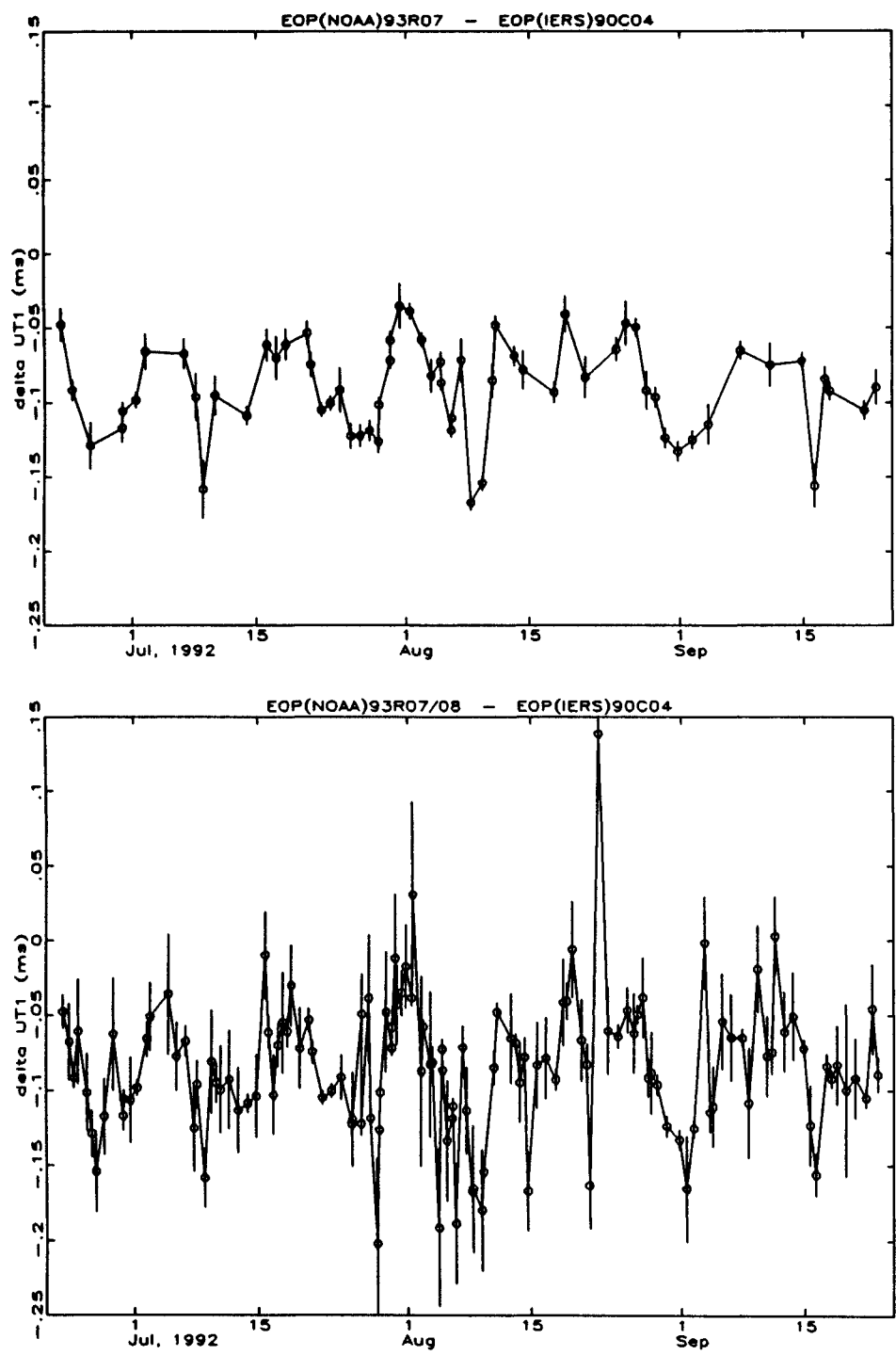


Figure 1. NOAA UT1 results for the SEARCH'92 period relative to the IERS combination series EOP (IERS) 90C04. Results for only the 24-hour sessions are shown in the top plot; 1-hour sessions are included in the bottom plot. Corrections for diurnal and semi-diurnal variations (Herring, 1992) have been applied.

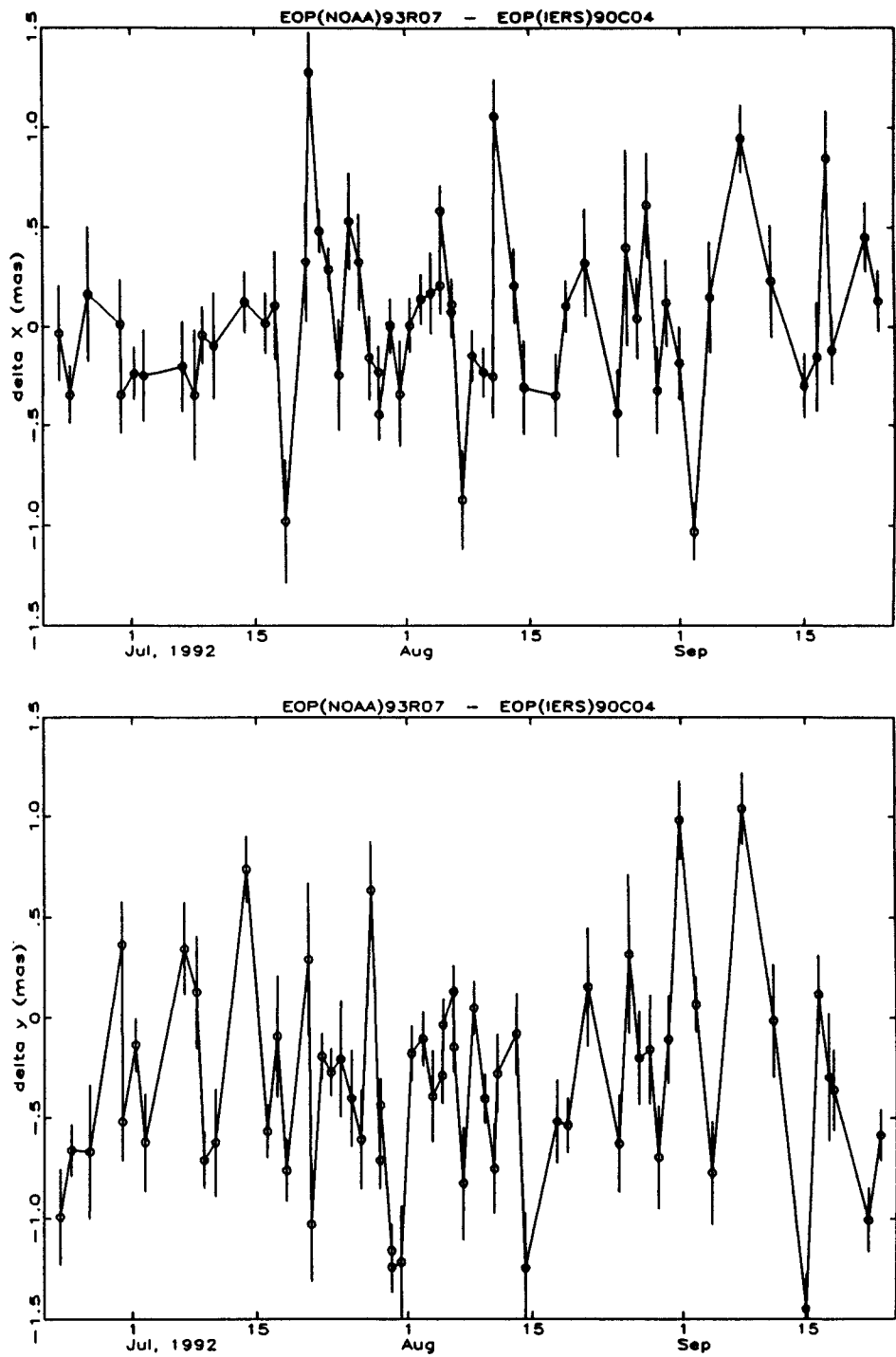


Figure 2. NOAA results for pole coordinates x (top) and y (bottom) shown relative to the IERS combination series EOP (IERS) 90C04. Corrections for diurnal and semi-diurnal variations (Herring, 1992) have been applied.

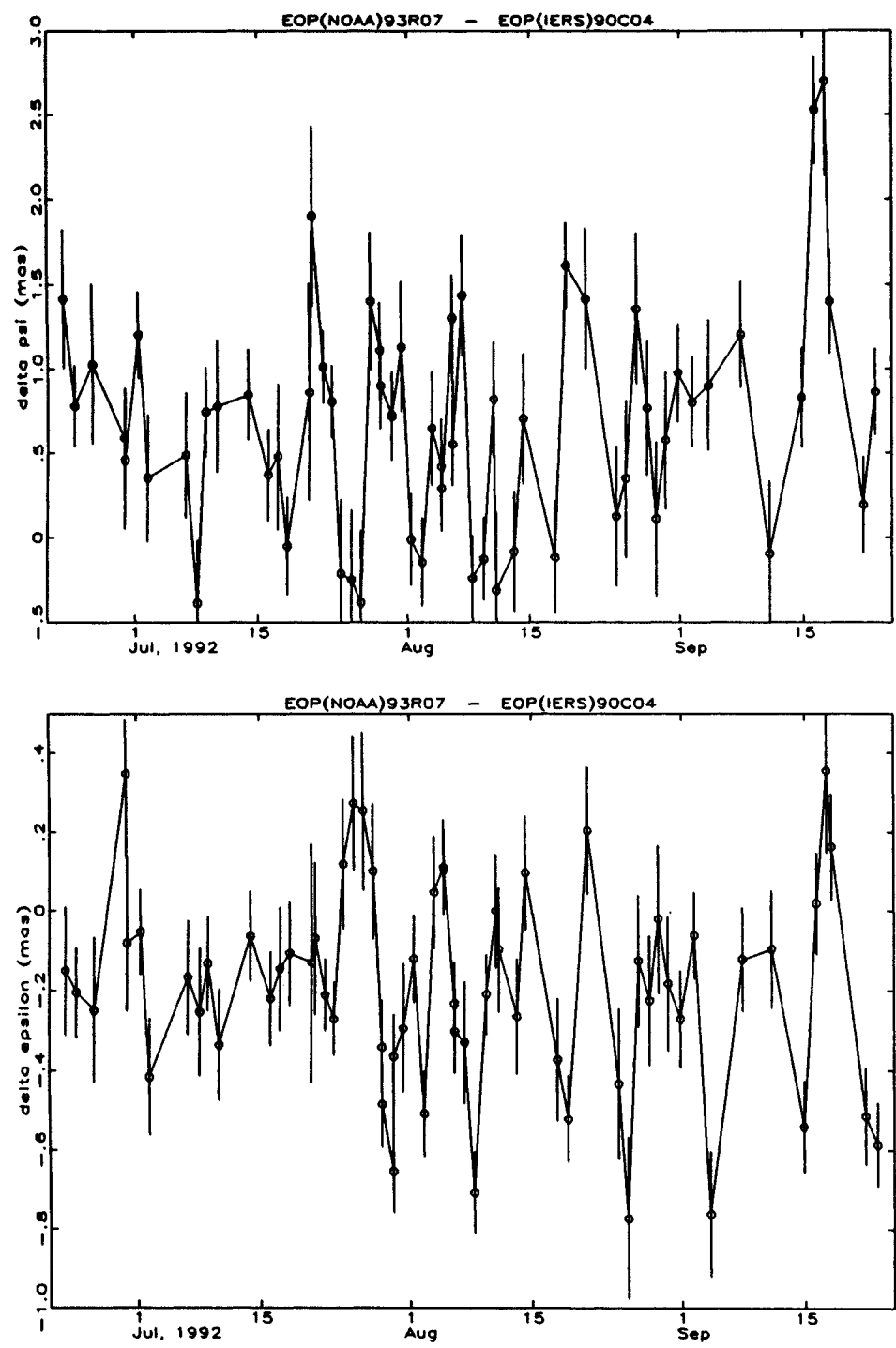


Figure 3. NOAA nutation offset results relative to the IERS combination series EOP (IERS) 90C04.

SUMMARY SHEET FOR THE DESCRIPTION OF THE TERRESTRIAL SYSTEM ATTACHED TO A SET OF STATION COORDINATES

- 1 - Technique: Bandwidth-synthesis Mark III VLBI

- 2 - Analysis Center: NOAA VLBI Analysis Center, N/OES13
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- 3 - Solution ID: solution rundate = 05 January 1994
IERS filenames: SSC (NOAA) 93R03, SSV (NOAA) 93R03,
RSC (NOAA) 93R03, EOP (NOAA) 93R07 and 93R08

- 4 - Software Used: COREL and FRNGE for the Mark III data correlation;
DE200 ephemerides, CALC-7.6, and SOLVE-3 for data analysis

- 5 - Relativity Scale: Radio source coordinates are in solar system barycentric system;
Terrestrial site coordinates are geocentric (ignoring the local
gravitational potential of the Earth)

- 6 - Permanent Tidal Correction on Station: No correction is applied to remove the zero-
frequency displacement introduced by the solid Earth tide model.

- 7 - Tectonic Plate Model: NNR-NUVEL-1 is used to specify the large-scale motion of the
entire terrestrial reference frame in both translational and rotational
senses for nine VLBI sites (see Carter *et al.*, 1993); the same model
is also used to propagate the relative positions of sites with data
spans too brief to permit reliable determinations of VLBI velocities.

- 8 - Velocity of Light: 299792458. m/s

- 9 - Geogravitational Constant: not applicable

- 10 - Reference Epochs: Station coordinates -- 1988 January 01
Source coordinates -- J2000.0
EOP fixed epoch -- 1991 August 12 19:49:50 UT

- 11 - Adjusted Parameters: XYZ geocentric station coordinates and linear station velocities
adjusted globally for all sites at their mean observation epochs;
radio source coordinates adjusted globally for all sources;
pole x and y coordinates, UT1, nutation longitude and obliquity
offsets adjusted for each 24-hour observing session;
UT1 is the only EOP adjusted for 1-hour Intensive sessions;
clock polynomial coefficients adjusted for all but one station in each
observing session;
atmosphere offset parameters for each hour interval for each station

for each 24-hour observing session (no atmosphere parameters are included in the analysis of the 1-hour Intensive sessions)

- 12 - Definition of the Origin: The coordinate origin of the terrestrial reference frame is specified by setting the vector sum of the adjusted coordinates for 16 VLBI sites equal to the corresponding vector sum for ITRF-91 (see Carter *et al.*, 1993); the right ascension origin of the celestial reference frame is specified by setting the sum of the adjusted right ascensions for 36 radio sources equal to the corresponding sum for ICRF-91
- 13 - Definition of the Orientation: The relative orientation of the terrestrial and celestial reference frames is specified by fixing the EOP values to those interpolated from the EOP (IERS) 90 C 04 series (corrected for the offsets and drift rates reported by the IERS to give consistency with the ITRF-91 and ICRF-91 frames) for the reference epoch 1991 August 12 19:49:50; the interpolation method is described in the text.
- 14 - Constraint for Time Evolution: The secular translational velocity and rotational velocity of the terrestrial reference frame are specified through constraints; see item 7 above and text.

Format Notes:

SSC & SSV files -- Instead of the DOMES information in fields 2-4, the CDP monument number is given. X, Y, and Z values and their formal errors are reported to the 0.1 mm level so that the decimal points are shifted by one column from the specified format. Instead of reporting the time span of observations for each site in field 10, the number of observations is given.

RSC file -- Fields 11 (correlation coefficient), 12 (epoch of coordinates), 14 (time span of source observations), and 15 (number of sessions for each source) are filled with 0 values.

EARTH ORIENTATION FROM VLBI DURING SEARCH'92

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ABSTRACT. 66 VLBI sessions suitable for measuring Earth orientation parameters were conducted during SEARCH'92 including normally scheduled programs and a special continuous period with simultaneous networks between July 27 and August 10, inclusive. 53491 group delay observations from 24 stations spanned 1372 hours with 240 hours of overlapping networks. Both one-day and hourly Earth orientation values have been estimated. The best 1σ formal errors of the one-day values are $90\ \mu\text{s}$ in pole and $4\ \mu\text{s}$ for UT1, and the best corresponding errors of the hourly values are $140\ \mu\text{s}$ and $8\ \mu\text{s}$.

1. INTRODUCTION

Since its inception in 1980, geodetic VLBI measurements to monitor Earth orientation parameters (EOP) have provided the stable reference series for geophysical and geodynamical research. The connection of VLBI to the essentially inertial celestial reference frame of extragalactic radio sources provides the key link for the long term measurement of UT1, while the precision of VLBI permits estimates of EOP at intervals much less a day. During SEARCH'92 a particular effort was made to collect as much useful VLBI data as feasible for the purposes of comparison and investigation of subdiurnal harmonic and nonharmonic signals. The cooperation of the coordinating organizations and participating observatories was essential to achieve this goal.

2. OBSERVING PROGRAMS

During the SEARCH'92 period the groups engaged in VLBI geodesy conducted an unusually

extensive set of observations. These included the routine twice-weekly EOP measurements using the IRIS-A and NAVNET networks coordinated by NOAA (National Oceanic and Atmospheric Administration) and USNO (U. S. Naval Observatory), respectively, and the monthly EOP sessions using the IRIS-S(outh), IRIS-P(acific), and SHS (Southern Hemisphere Survey) networks coordinated by the Institute for Applied Geodesy (Germany), National Astronomical Observatory (Japan), and NOAA, respectively. The Space Geodesy Program (SGP) of the National Aeronautics and Space Administration had its regular monthly R&D sessions to test advances in geodetic VLBI technique as well as several sessions to improve the terrestrial reference frame. In addition, mobile VLBI measurements were made in Germany, Norway and Iceland with networks including stations in North America. In support of SEARCH'92 special sessions using the SGP R&D and the USNO NAVEX (NAVY EXTENDED) networks were scheduled to fill the gaps between the normal IRIS-A and NAVNET days in the period from July 27 to August 10. The SGP network used the stations KAUAI (Hawaii), GILCREEK (Alaska), LA-VLBA (New Mexico), FD-VLBA (Texas), WESTFORD (Massachusetts), and WETTZELL (Germany), while the NAVEX networks included MATERA (Italy), HARTRAO (South Africa), KASHIMA (Japan), NRAO85 3 (West Virginia), and SANTIA12 (Chile). The 66 dates, session types, and stations are shown in Table 1. Each session was ~24 hours or more. Eleven other sessions during SEARCH'92 used networks unsuitable for measuring EOP and were not included in the work below. Most of the SGP R&D and USNO NAVEX time between July 27 and August 10 overlapped. With six other days of simultaneous networks, the total overlapping time during SEARCH'92 was 240 hours. In all 1372 hours (61%) of the total SEARCH'92 interval was covered by VLBI observations.

The observing schedules for each SGP and NAVEX session were prepared using an automatic schedule algorithm developed at the Geodetic Institute of the University of Bonn and enhanced at Goddard. The software permits both covariance optimization and rule-based selection. The schedules were optimized for measuring EOP and atmosphere parameters while having a wide distribution of observing geometry at each station. The SGP observations were distributed quite unevenly over the sources with ~5 sources having the preponderance of the observations. The NAVEX schedules used a larger set of sources with more even distribution. While the same radio source catalog was used each day, the exact sequence of sources and the distribution of observing elevations and azimuths were different.

Since one aspect of the SGP R&D program is the study of troposphere modeling as an undesirable, nongeodetic signal, very low elevation observations were scheduled at certain stations. However, because the current troposphere models are insufficiently accurate at the lowest elevations, not all the data were included in the analysis. With a 7 degree cutoff, 14975 SGP observations and 2283 NAVEX observations were analyzed during the July 27 - August 10 period along with 3187 IRIS-A and 1294 NAVNET observations.

3. DATA ANALYSIS

The EOP values included in the present work were taken from a much larger complete solution including 1098090 observations between August 1979 - August 1993. The adjusted global parameters included positions and velocities of 117 sites and positions of 224 sources. The arc parameters included pole position, UT1, UT1 rate, offsets in obliquity and longitude, and piecewise-linear, continuous clocks and atmospheres. The geophysical, astronomical, and theoretical VLBI models generally followed the IERS standards. In addition, a model for the

TABLE 1. Stations and
type for each session

		ADDFG	HHHKK	LMMN	ORSSW	WHKT
		LSSDI	AAQAA	AAEOR	NIAEE	EOAR
		GSS-L	RYBSU	-TDJA	SCNSS	TFRO
		O14VC	TSAHA	VEIAO	AHTHT	TNLM
		P55LR	RTRII	LRCV8	LMIAF	Z BS
		A BE	AATM	BAIE5	AOANO	E UO
		R AE	OC2A	A N1	6N12R	L RN
		K K	K6	A23	0D25D	L GO
1	\$92JUN22XI	IRIS-A	----	----	----	----
2	\$92JUN23XH	IRIS-South	----	----	----	----
3	\$92JUN23XO	USNO NAVEX	----	----	----	----
4	\$92JUN25XO	USNO NAVNET	----	----	----	----
5	\$92JUN29X	SGP Polar	----	----	----	----
6	\$92JUN29XI	IRIS-A	----	----	----	----
7	\$92JUN30X	SGP Research	----	----	----	----
8	\$92JUL02XO	USNO NAVNET	----	----	----	----
9	\$92JUL06XI	IRIS-A	----	----	----	----
10	\$92JUL07XQ	SGP Quake	----	----	----	----
11	\$92JUL08XH	IRIS-South	----	----	----	----
12	\$92JUL08XO	USNO NAVEX	----	----	----	----
13	\$92JUL09XO	USNO NAVNET	----	----	----	----
14	\$92JUL13XI	IRIS-A	----	----	----	----
15	\$92JUL15X	SGP Pacific	----	----	----	----
16	\$92JUL16XO	USNO NAVNET	----	----	----	----
17	\$92JUL17XP	IRIS-Pacific	----	----	----	----
18	\$92JUL20XI	IRIS-A	----	----	----	----
19	\$92JUL20XS	NGS S. Survy	----	----	----	----
20	\$92JUL21X	SGP Global	----	----	----	----
21	\$92JUL22X	SGP Global	----	----	----	----
22	\$92JUL23XO	USNO NAVNET	----	----	----	----
23	\$92JUL25X*	Europe Mobil	----	----	----	----
24	\$92JUL26X*	Europe Mobil	----	----	----	----
25	\$92JUL27XI	IRIS-A	----	----	----	----
26	\$92JUL28X	SGP Research	----	----	----	----
27	\$92JUL28XO	USNO NAVEX	----	----	----	----
28	\$92JUL29X	SGP Research	----	----	----	----
29	\$92JUL29XO	USNO NAVEX	----	----	----	----
30	\$92JUL30XO	USNO NAVNET	----	----	----	----
31	\$92JUL31X	SGP Research	----	----	----	----
32	\$92AUG02X	SGP Research	----	----	----	----
33	\$92AUG03XI	IRIS-A	----	----	----	----
34	\$92AUG04X	SGP Research	----	----	----	----
35	\$92AUG04XO	USNO NAVEX	----	----	----	----
36	\$92AUG05X	SGP Research	----	----	----	----
37	\$92AUG05XO	USNO NAVEX	----	----	----	----
38	\$92AUG06XO	USNO NAVNET	----	----	----	----
39	\$92AUG07X	SGP Research	----	----	----	----
40	\$92AUG09X	SGP Research	----	----	----	----
41	\$92AUG10XI	IRIS-A	----	----	----	----
42	\$92AUG10XO	USNO NAVEX	----	----	----	----
43	\$92AUG10XS	NGS S. Survy	----	----	----	----
44	\$92AUG11X	SGP T. Asia	----	----	----	----
45	\$92AUG12X*	Europe Mobil	----	----	----	----
46	\$92AUG13XO	USNO NAVNET	----	----	----	----
47	\$92AUG17XI	IRIS-A	----	----	----	----
48	\$92AUG18XH	IRIS-South	----	----	----	----
49	\$92AUG20XO	USNO NAVNET	----	----	----	----
50	\$92AUG24XI	IRIS-A	----	----	----	----
51	\$92AUG25X*	Europe Mobil	----	----	----	----
52	\$92AUG26X*	Europe Mobil	----	----	----	----
53	\$92AUG27XO	USNO NAVNET	----	----	----	----
54	\$92AUG28X*	Europe Mobil	----	----	----	----
55	\$92AUG29X*	Europe Mobil	----	----	----	----
56	\$92AUG31XI	IRIS-A	----	----	----	----
57	\$92SEP01X	SGP Research	----	----	----	----
58	\$92SEP03XO	USNO NAVNET	----	----	----	----
59	\$92SEP07XI	IRIS-A	----	----	----	----
60	\$92SEP10XO	USNO NAVNET	----	----	----	----
61	\$92SEP14XI	IRIS-A	----	----	----	----
62	\$92SEP15XP	IRIS-Pacific	----	----	----	----
63	\$92SEP16XS	NGS S. Survy	----	----	----	----
64	\$92SEP17XO	USNO NAVNET	----	----	----	----
65	\$92SEP21XI	IRIS-A	----	----	----	----
66	\$92SEP22XO	USNO NAVEX	----	----	----	----

diurnal and semidiurnal effects of ocean tides on UT1 and pole position was applied. The coefficients of this model (Gipson et al., 1993) were estimated directly from VLBI data in an earlier solution using the tidal frequencies and are given in Table 2. The effect of atmospheric pressure loading was calibrated using local pressures and coefficients derived from VLBI data and from global weather models (MacMillan and Gipson, 1994).

TABLE 2. Diurnal and semidiurnal EOP coefficients

Ten components for UT1								Tidal
Tidal vector						cos	sin	Component
						(microseconds)		
0	0	0	0	0	-1	7.486602	16.707637	K1
0	0	2	-2	2	-1	-3.500205	-5.392255	P1
0	0	2	0	2	-1	-15.575852	-16.762598	O1
1	0	2	0	2	-1	-3.394904	-3.902930	Q1
0	1	0	0	0	-1	.593333	1.932245	S1
1	0	0	0	0	-1	1.003345	1.299982	M1
0	0	0	0	0	-2	.261715	3.896805	K2
0	0	2	-2	2	-2	-1.182862	8.706599	S2
0	0	2	0	2	-2	-8.517385	12.338927	M2
1	0	2	0	2	-2	-4.378455	1.168543	N2

Twelve components for X and Y pole								
Tidal vector							cos	sin
							(microarcseconds)	
0	0	0	0	0	1	125.285183	-38.476327	K1 p
0	0	-2	2	-2	1	-54.470359	26.152833	P1 p
0	0	-2	0	-2	1	-136.319298	63.668538	O1 p
-1	0	-2	0	-2	1	-33.990240	18.096315	Q1 p
0	0	0	0	0	-2	-15.899321	15.676795	K2 r
0	0	2	-2	2	-2	-76.296961	105.813157	S2 r
0	0	2	0	2	-2	15.018756	285.140733	M2 r
1	0	2	0	2	-2	-24.572257	58.610024	N2 r
0	0	0	0	0	2	22.589310	-5.801947	K2 p
0	0	-2	2	-2	2	-7.259654	-11.309321	S2 p
0	0	-2	0	-2	2	30.337902	-72.186765	M2 p
-1	0	-2	0	-2	2	-11.643736	-30.168262	N2 p

The orientation of the terrestrial reference frame (TRF) is essentially arbitrary and is derived from the EOP values adopted for the reference day, Feb. 12, 1993, and from the celestial angles of the standard precession/nutation models for the same reference day. The right ascension origin of the celestial reference frame is defined by the value assigned to the radio source 0420-012. The origin of the TRF is set by minimizing the adjustment of nine widely distributed, well observed stations with respect to their a priori values, which are within a few cm of ITRF92. The remaining degeneracies are removed by requiring no net rotation or vertical translation of eight stations (WESTFORD, GILCREEK, ONSALA60 (Sweden), WETTZELL, KAUAI, DSS45 (Australia) and HOBART26 (Tasmania)) with respect to the NUVEL-1 NNR plate model (Argus and Gordon, 1991). These stations are chosen to be minimally affected by plate boundary deformations, local movements, and as yet unexplained anomalies. It should be noted that any differences between the real relative motion of the

reference stations and that predicted by the NUVEL-1 NNR model will cause all the stations to have fictitious apparent motions in the TRF.

The entire set of one-day EOP values and UT1 rates was estimated iteratively to improve the short-term accuracy, which affects the fit of each session. For each VLBI session, an offset from the a priori model was estimated for each component of polar motion. In addition, an offset and a rate were estimated for UT1. The total EOP at the middle of each session and the UT1 rate served as input to a simple Kalman filter, which estimated the EOP values at daily intervals. This new one-day-interval series served as the new a priori model for EOP. The a priori EOP values between tabular points at each observation epoch were obtained by linear interpolation. The one-day nutation offsets from the last iteration were spline fit to obtain daily nutation estimates for use in estimating the subdiurnal EOP values.

The solution to estimate subdiurnal EOP parameters modeled X-pole, Y-pole and UT1 as piecewise-linear, continuous functions with very weak constraints (1000 mas for pole, 100 ms for UT1) to bridge data gaps. The length of each linear segment was one hour. The global parameters and non-nutation arc parameters were the same as the solution for one-day EOP. The one-day-interval nutation series described above was used to remove the nutation errors that would have aliased into diurnal polar motion. Because of the weakness of the constraints, the hourly EOP values are noisy. However, the diurnal and semidiurnal harmonic signals are not significantly attenuated. A harmonic analysis of the hourly values from the complete solution gives components that are consistent with the direct estimate of the coefficients. With a stronger constraint to reduce the (visual) noise level, the simultaneous determination of hourly EOP from different networks shows generally good agreement. See Figure 1.

4. EOP RESULTS

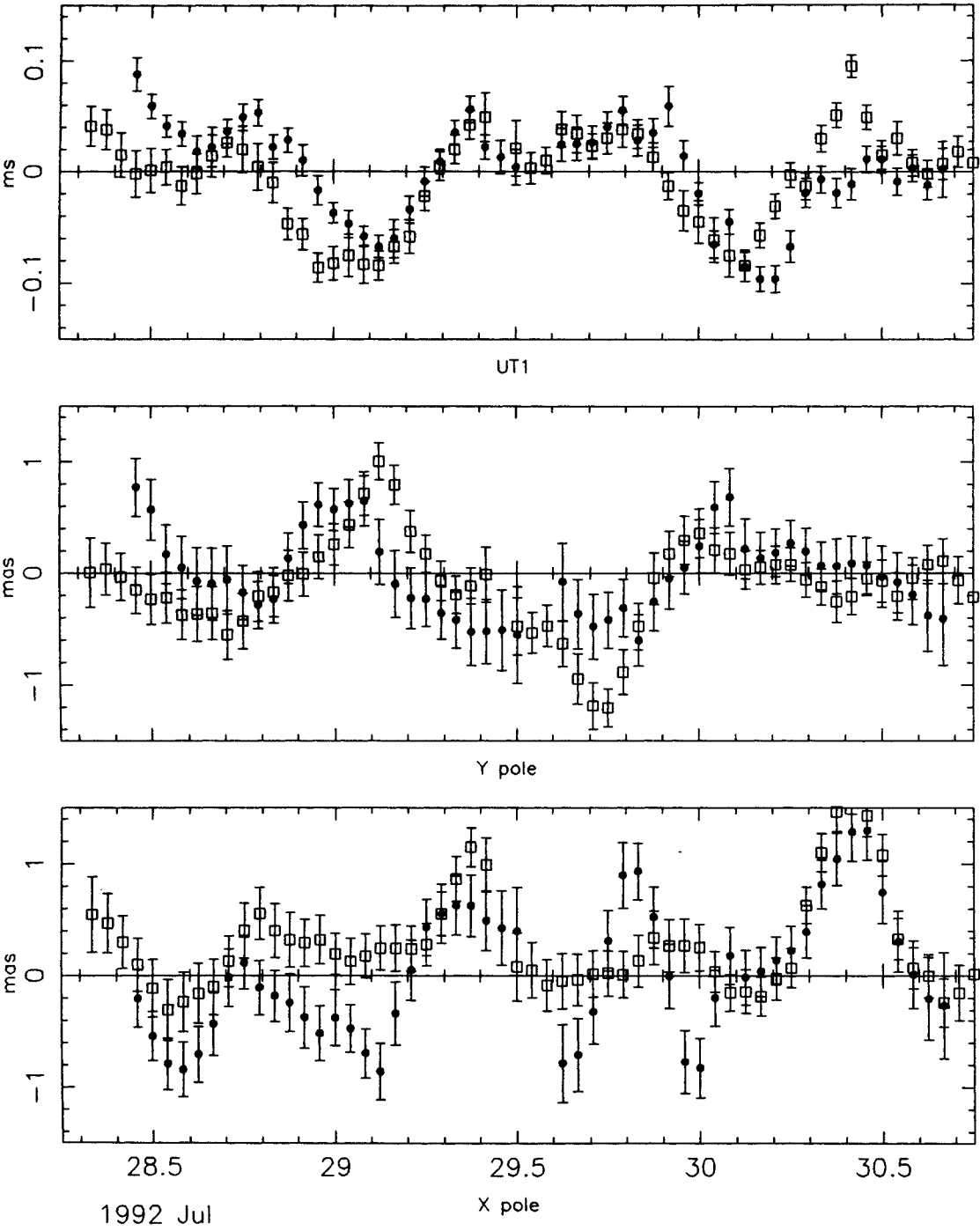
The EOP results are presented in two forms. The one-day estimates are submitted in the standard IERS format as EOP (GSFC) 93 R 06. It should be noted that the values include the diurnal and semidiurnal tidal effects evaluated at the stated epoch as well as terms with longer periods. No smoothing or model removal has been done. The hourly values are submitted in a straightforward format for each session as EOP (GSFC) 93 R 07. Some epochs appear more than once because observing sessions using different networks overlapped in time. Only the formal uncertainties are given.

The formal uncertainties of the results during SEARCH'92 are quite good. The best 1σ one-day errors are 90 μ as in pole and 4 μ sec in UT1. The best one-hour errors are 140 μ as in pole and 8 μ s in UT1. The median errors are somewhat worse for the one-day values, 190 μ as in pole and 7 μ s in UT1, but the median hourly errors are considerably worse, 650 μ as for pole and 29 μ s for UT1. The hourly EOP results are more affected by data dropouts.

5. OTHER ACTIVITIES

Because of the success of continuous VLBI EOP measurements during SEARCH'92, the Goddard VLBI group in cooperation with USNO and the VLBA (VLBI Array) undertook a similar continuous observing period called CONT94 between January 10-28, 1994. Up to three networks observed simultaneously. The SGP network included KOKEE (Hawaii), GILCREEK, LA-VLBA, FD-VLBA, WESTFORD, WETTZELL, and ONSALA60 and observed for 12 days

Figure 1. R&D (dot) and Navex-G (square) Measurements of EOP



between the routine weekly NEOS-A sessions. With 98% data yield, 42000 observations are expected. The remaining VLBA stations were used as an independent network. Because of extreme weather conditions and some station problems (particularly at Hancock and Kitt Peak), the data only covered 10 days with 40000 observations expected. The USNO NAVEX network observed on nine days with varying networks including NRAO85 3, ALGOPARK (Canada), FORTLEZA (Brazil), MATERA, HARTRAO, KASHIMA, MIZNAO10 (Japan), HOBART26, and KAUAI. The best EOP results should be a factor of two better than the results from SEARCH'92. The raw data will be correlated at the Mark IIIA correlators at the Haystack Observatory and USNO. This set of data will provide a complementary set to SEARCH'92 during the winter when the wet troposphere should be nearly negligible. The data and results should be available to investigators before the end of 1994.

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EARTH ROTATION PARAMETERS DERIVED FROM SLR DATA ON LAGEOS-1

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ABSTRACT. This paper describes the computation of ERP(DUT) 93L05A, the contribution of Delft University of Technology to the SEARCH'92 Campaign. The analysis is based on satellite laser range observations to LAGEOS-1. The resulting 5-daily solutions for x , y and UT1 agree with IERS EOP90C04 at a level of 0.4 and 0.8 marcsec and 0.045 ms, respectively.

1. Introduction

The orbital characteristics of the geodetic satellite LAGEOS-1 (altitude 5900 km, inclination 109 degrees) make it a highly visible target for Satellite Laser Ranging (SLR) observatories around the world. Combined with the fact that the trajectory of the satellite can be modeled with an unparalleled accuracy, LAGEOS-1 is an ideal instrument to study a variety of global geodetic phenomena. Delft University of Technology (DUT) has been involved in the analysis of SLR data on this satellite since 1977. The analysis effort is aimed at crustal deformations and earth rotation in particular. Here, the computation of Earth Rotation Parameters (ERPs) for the SEARCH'92 Campaign (June 21 - September 22, 1992) will be discussed. The emphasis of this paper is on the computation procedure.

2. Technique

The computation of crustal deformations is a primary goal of the analysis of LAGEOS-1 SLR measurements at DUT. Serving this objective, the observations are processed in batches of 13 weeks on average. The deformations are then computed from the differences between the resulting consecutive network solutions.

The computation of the ERPs is performed in three steps. First, solutions for all global parameters (station coordinates and 5-daily ERPs) are computed for each of the quarterly intervals independently. The model that is used for the analysis is summarized in Table 1. It closely follows the IERS Standards (McCarthy, 1992), with a few exceptions: (i) the NASA/GSFC JGM-1 solution for the representation of the gravity field and ocean tides, including constants like GM , a_e and the flattening of the Earth and time-dependent terms, is used instead of the advised GEM-T3 and Schwiderski models; (ii) the effect of atmospheric pressure loading and ocean loading on station positions is not taken into account; and (iii) no plate motion is applied during each 13-week sub-interval. The orbital analysis and parameter estimation is performed using the GEODYN-II/SOLVE-II software package (Eddy et al., 1990; Majer, 1986). To limit the effect of potential dynamic errors in the computation model, each sub-interval is divided into a number of consecutive 1-week data arcs, and the trajectory of LAGEOS-1 is fitted to the observations for each data arc independently, adjusting a state-vector at epoch and a few force-scaling parameters only. It is important to realize that, to

avoid the inversion becoming numerically singular, the longitudes of the ascending nodes of each week arc are kept fixed at values derived in a preliminary data analysis, where polar motion is not adjusted but kept fixed at the a priori (IERS 90C04) values. Consequently, it is to be expected that the UT1 solutions presented here will very closely follow the IERS values, and cannot be considered as a very meaningful analysis result.

In the second step, the series of individual, independent 13-week solutions for the global network of laser stations are converted into a model for the position of each individual station as a function of time. In this way, it is possible to eliminate potential systematic differences between the global network solutions, and bring coherency into the terrestrial reference frame. The model for the station positions includes an initial position at a reference epoch and a simple linear time-dependency for each position component. Although the SEARCH'92 Campaign is limited to 3 months in 1992 only, the analysis was actually performed on LAGEOS-1 observations acquired in the 1983-1992 time frame. The length of this time frame guarantees that very accurate solutions for the tectonic motions for each station can be derived. To eliminate numerical singularities in this step, the motion of a total of 12 globally well-distributed stations was kept fixed at the value given by the NUVEL-1 No Net Rotation model (DeMets et al., 1990). These stations (Yarragadee, Easter Island, Greenbelt, Platteville, Huahine, Mazatlan, Maui, Wettzell, Graz, RGO, Orroral Valley and Kootwijk) are located on the rigid part of 5 of the major tectonic plates, and have a good tracking history.

Finally, the model for station positions as a function of time is then back-substituted and provides the means to bring coherency into the series of ERP solutions. The latter are adjusted without any constraint, whereas the station positions (and the longitudes of the ascending nodes of the weekly satellite state-vectors) are kept fixed at the interpolated values of step 2. Since the normal equations that were already generated for step 1 are being used here, the computation model is the same as the one described in Table 1.

3. Results

The resulting ERP solutions are presented in Table 2. The solution is designated ERP(DUT) 93L05A. It represents an improved version of the ERP(DUT) 93L02 solution, which was submitted to the IERS Central Bureau for inclusion in the 1992 Annual Report. Column 4 provides UT1-UTC values. The standard deviations are 1- σ formal uncertainties. The number in the final column indicates the sub-interval, from which the solutions were taken. For the SEARCH'92 Campaign, only intervals 36 and 37 are relevant.

Statistics of the differences with respect to the a priori values (IERS EOP90C04) are shown in Table 3. After subtraction of the mean difference, the pole position solutions show an agreement of 0.39 and 0.81 marcsec, which is about 3-4 times the formal uncertainty provided along with the solutions here. As for the UT1 values, the agreement is about 0.045 ms, which exceeds the formal uncertainties by a factor of 3-4 also.

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Table 1: Models and constants applied in the analysis.

<i>Dynamic model:</i>	
Gravity field	NASA/GSFC JGM-1 model, truncated at 20x20
GM	398600.4415 km ³ /s ²
c	299792.458 km/s
a _e	6378.1363 km
1/f	298.2564
Solid earth tides	Wahr model
Ocean tides	NASA/GSFC JGM-1 model
Solar radiation	CR fixed at 1.13; occultation by Earth and Moon; umbra and penumbra
Along-track acceleration	constant value; adjusted
Radial acceleration	sine and cosine 1cpr term; adjusted
Third body attraction	Sun, Moon, Venus, Mars, Jupiter, Saturn; positions from JPL DE200/LE200 ephemeris
Pole tide (dynamic part)	applied
<i>Reference frame:</i>	
Station coordinates	adjusted (step 1); SSC(DUT) 93L05 (step 3)
Earth rotation	adjusted at 5-day intervals; IERS EOP90C04 a priori values
CIS	mean equator and equinox of J2000.0
Precession	IAU 1976 (Lieske model)
Nutation	IAU 1980 (Wahr model)
Plate motion	not applied
Tidal uplift	h ₂ = 0.609; l ₂ = 0.0852
Pole tide (geometric part)	applied
Atmospheric, ocean loading	not applied
<i>Measurement model:</i>	
Observations	release A normal points, computed at Bendix (June); quick-look normal points (July-September)
Data weighting	overall model accuracy plus system characteristics
Tropospheric refraction	Marini-Murray model

Table 2: The solution ERP(DUT) 93L05A. Only parameters for the interval June 21 - September 22, 1992, are selected here.

date (mjd)	x (marcsec)	y (marcsec)	UT1-UTC (s)	$\sigma(x)$ (marcsec)	$\sigma(y)$ (marcsec)	$\sigma(UT1-UTC)$ (s)	interval
48794	-152.90	356.19	-0.54265923	0.48	0.44	0.00003646	36
48799	-146.66	367.30	-0.55079802	0.29	0.23	0.00002428	36
48804	-141.85	380.24	-0.55816557	0.33	0.26	0.00002062	36
48809	-135.73	390.83	0.43571062	0.28	0.22	0.00001770	36
48814	-127.29	402.32	0.42957544	0.23	0.19	0.00001554	36
48819	-124.15	412.26	0.42320903	0.19	0.19	0.00001493	36
48824	-112.47	424.05	0.41646921	0.18	0.18	0.00001461	36
48829	-101.18	433.90	0.40893665	0.17	0.20	0.00001693	36
48834	-91.95	443.70	0.40174805	0.16	0.19	0.00001461	36
48839	-81.60	455.29	0.39408749	0.15	0.17	0.00001306	36
48844	-71.63	466.30	0.38579321	0.16	0.17	0.00001594	36
48849	-61.92	478.40	0.37731885	0.22	0.21	0.00001678	36
48854	-48.83	486.10	0.36840449	0.15	0.15	0.00001287	36
48859	-33.21	491.68	0.35904445	0.19	0.17	0.00001446	36
48864	-17.61	501.74	0.34899572	0.34	0.27	0.00002395	36
48869	-6.38	503.10	0.33930739	0.27	0.21	0.00001772	37
48874	5.92	506.21	0.33025067	0.16	0.14	0.00001375	37
48879	17.88	507.84	0.32037788	0.19	0.15	0.00001389	37
48884	29.54	509.15	0.31051683	0.14	0.13	0.00001094	37

Table 3: Statistics of the differences between ERP(DUT) 93L05A and IERS EOP90C04. The numbers in the column "rms difference" are obtained before and after subtraction of the mean value, respectively.

quantity	number of solutions	rms difference
x	19	0.52/0.39 marcsec
y	19	1.70/0.81 marcsec
UT1-UTC	19	0.064/0.045 ms

HIGH RESOLUTION EOP FROM LAGEOS SLR DATA ANALYSIS AT GSFC

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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) $\delta\Delta\psi$, $\delta\Delta\epsilon$ 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 wander 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. $C_{10}=C_{11}=S_{11}=0$). 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.

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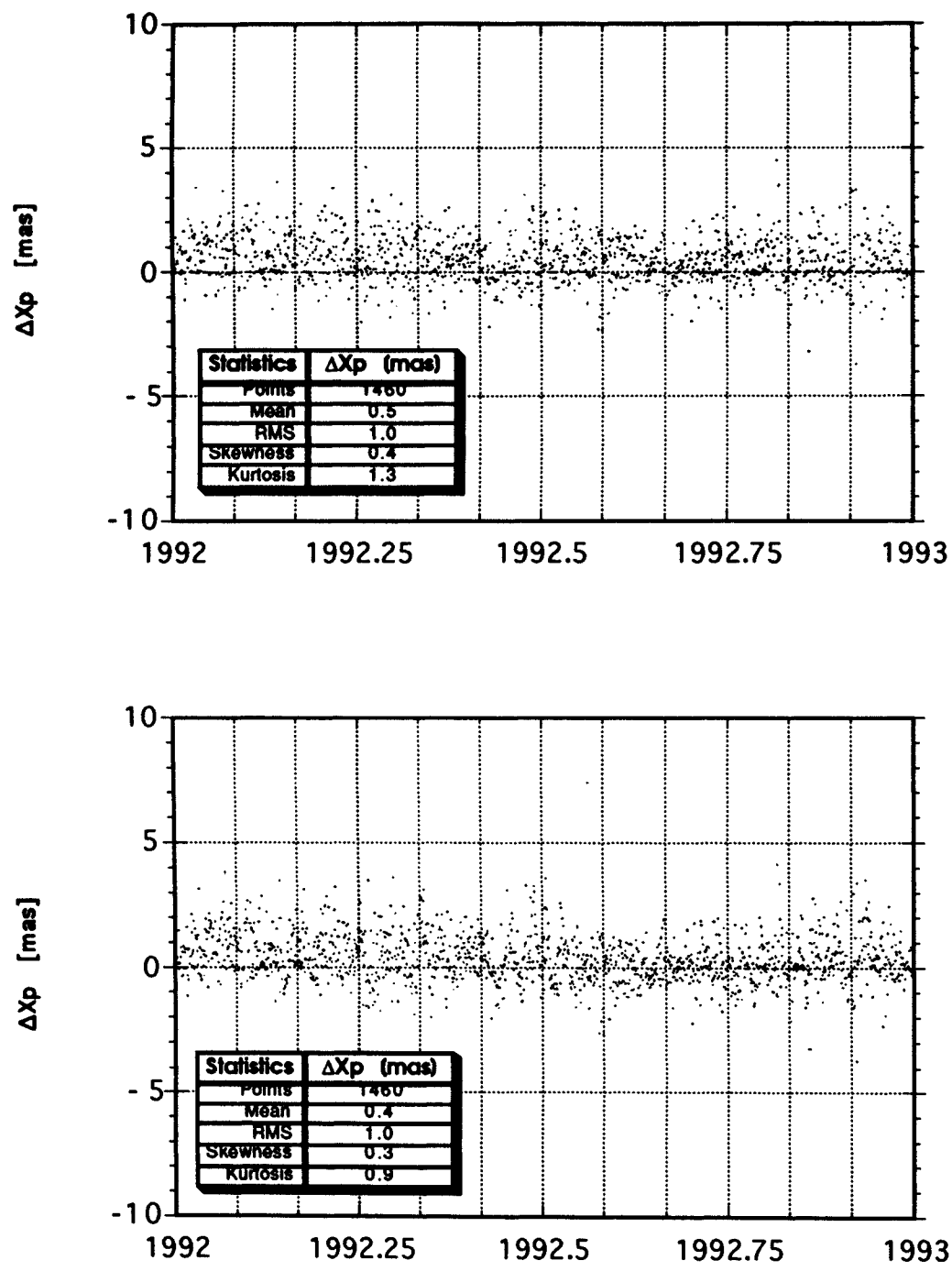


Figure 1. Comparison of the x component of polar motion from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

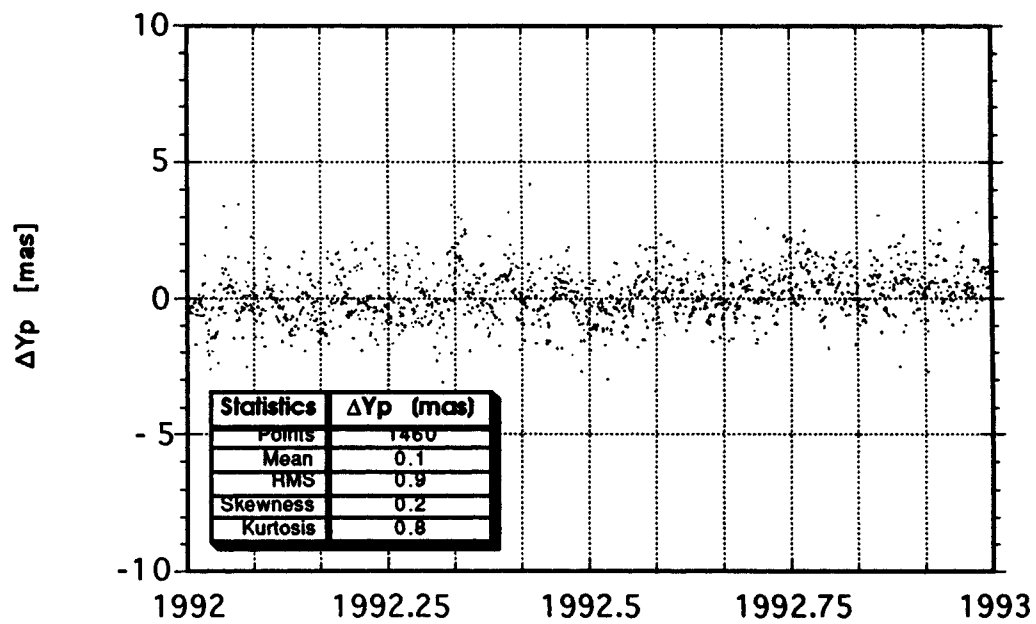
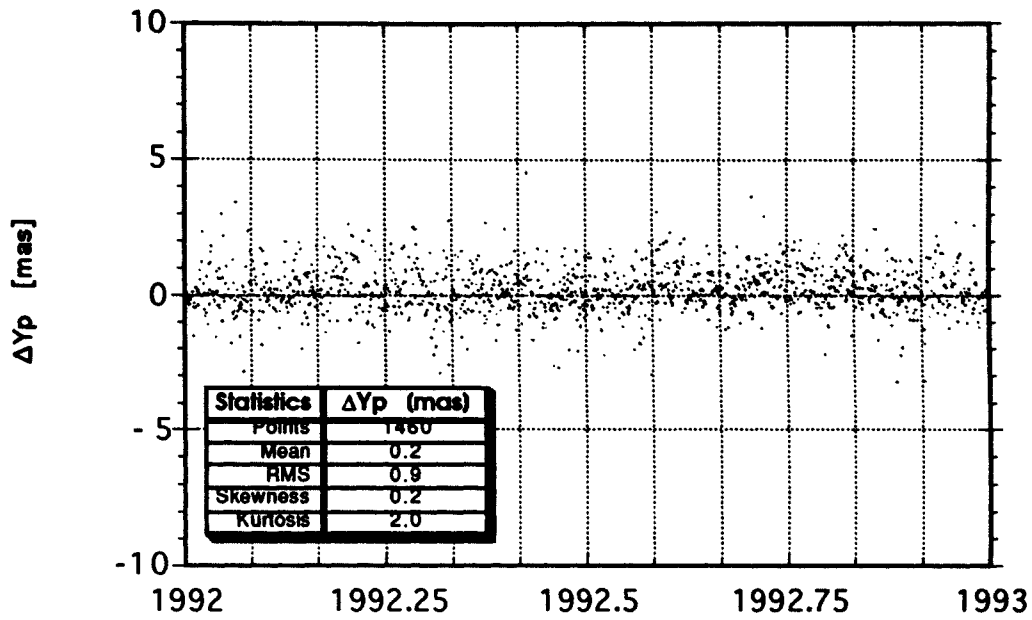


Figure 2. Comparison of the y component of polar motion from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

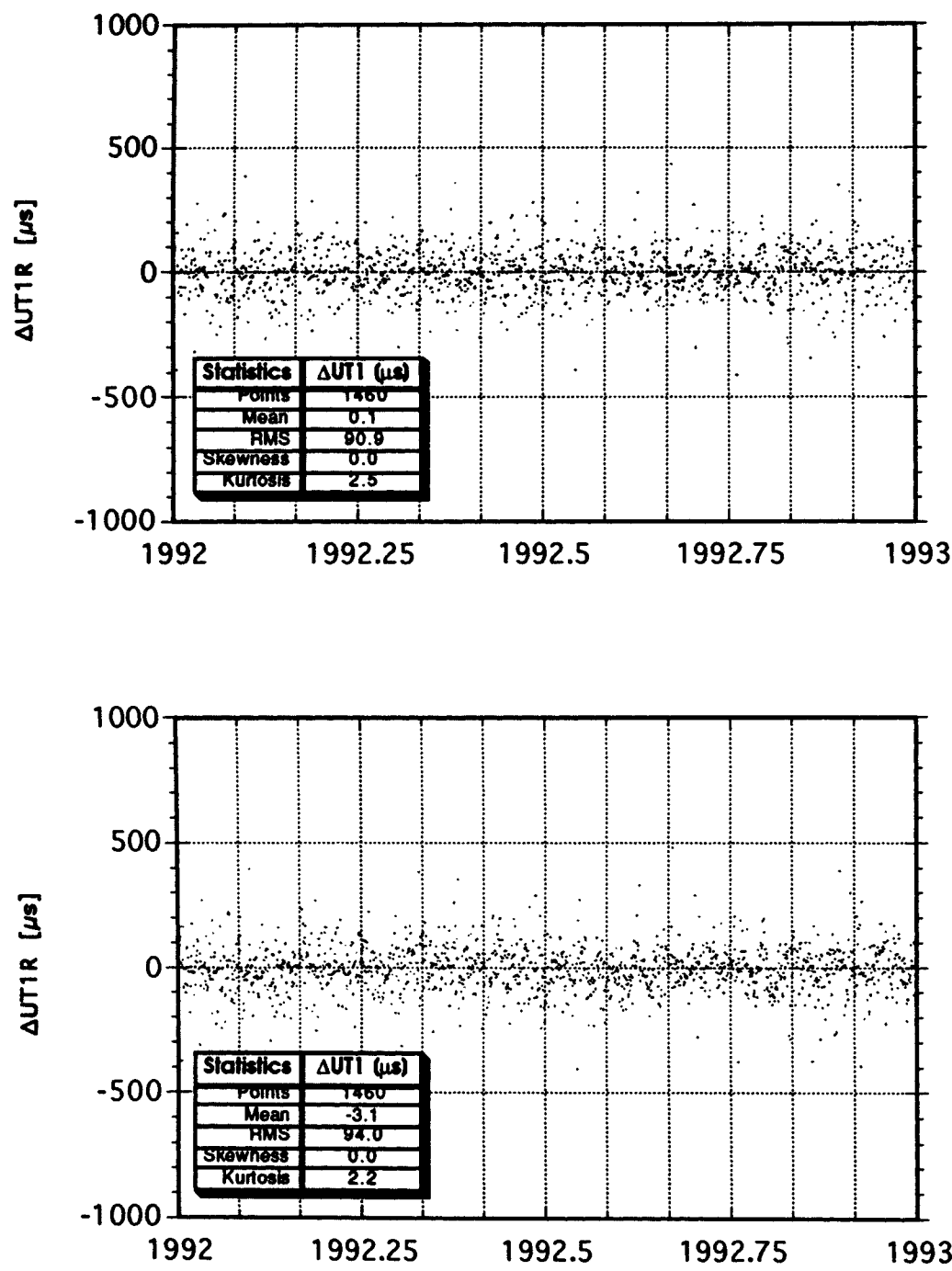


Figure 3. Comparison of inferred UT1R from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

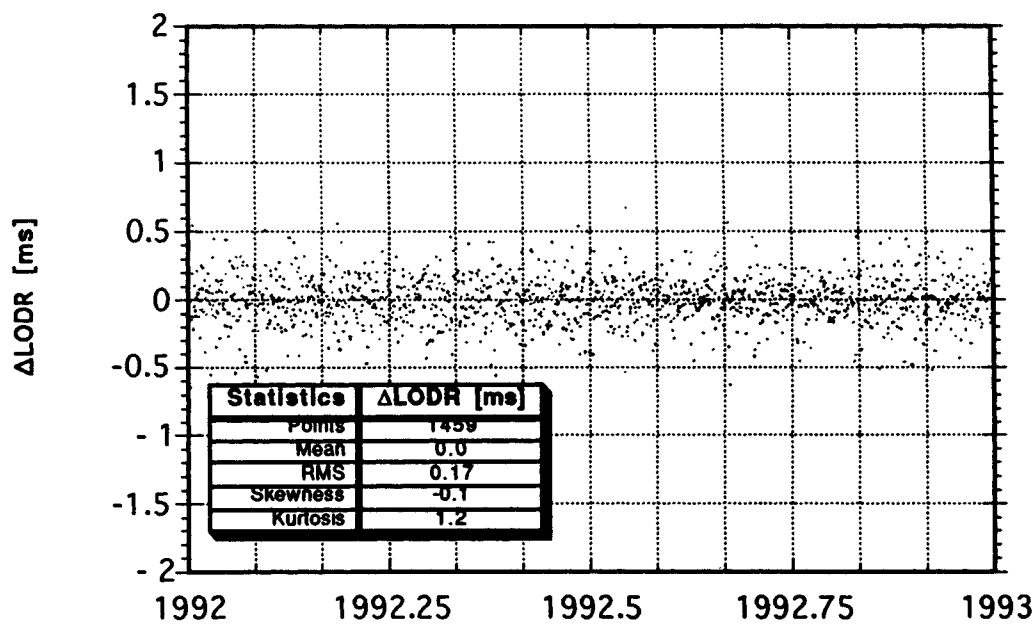
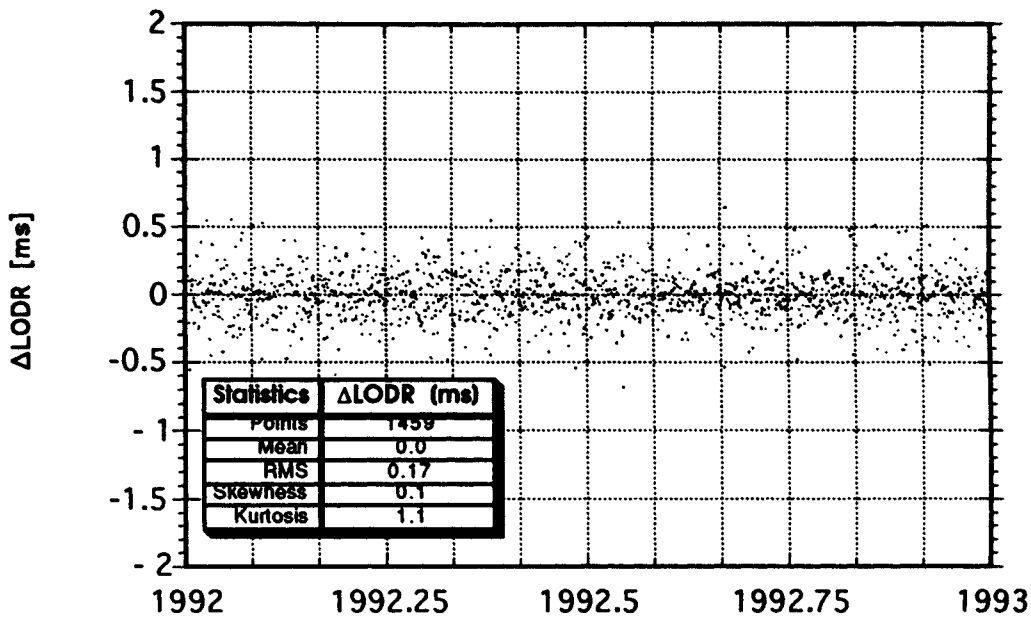


Figure 4. Comparison of Length-of-Day variations from SL9.0 to IERS 90 C 04 (top) and SPACE '92 (bottom).

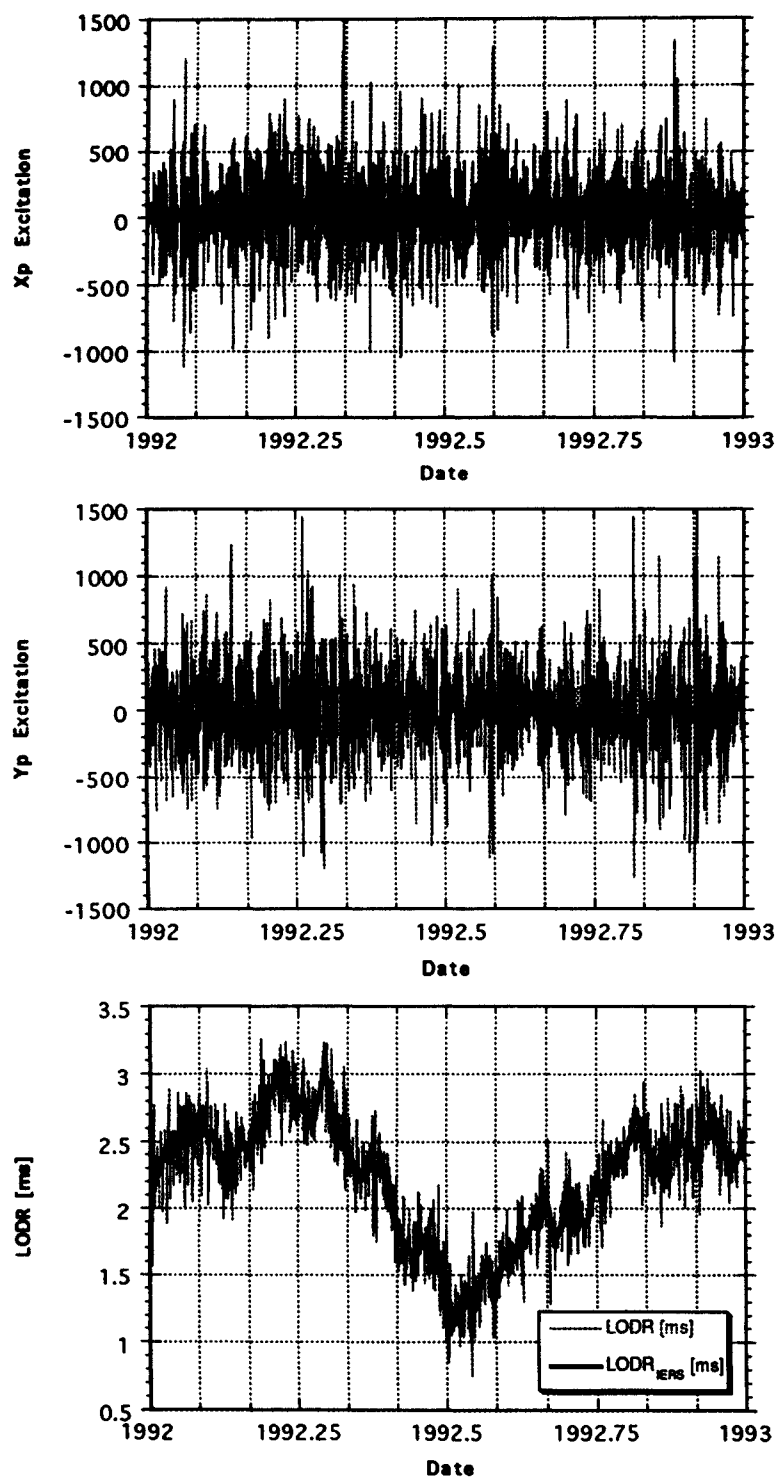


Figure 5. Polar motion and Earth rotation Excitation functions from the raw 6 hr resolution SL9.0 series.

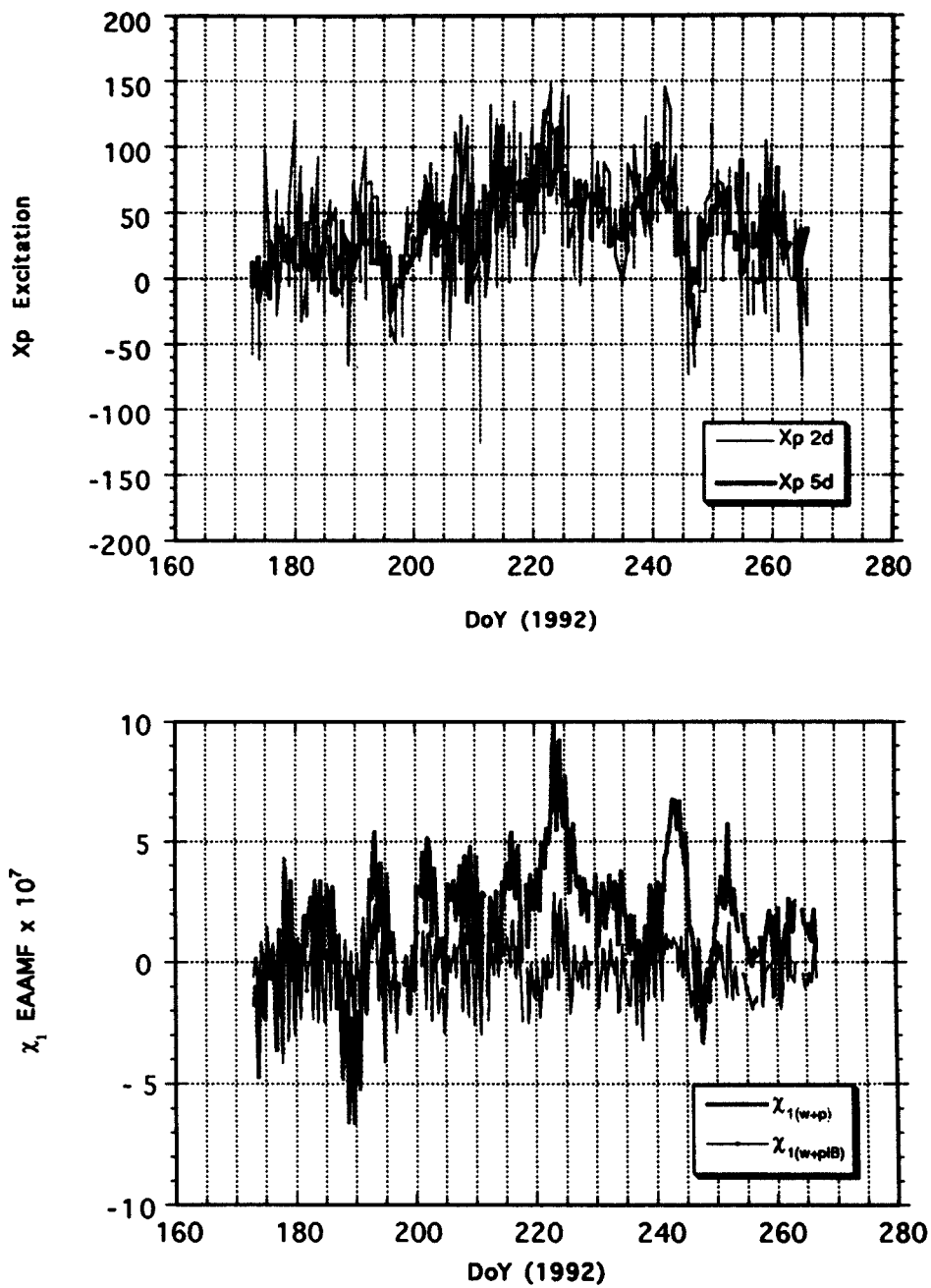


Figure 6. X component of polar motion excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_1 from NMC series (bottom) with and without the inverted barometer hypothesis.

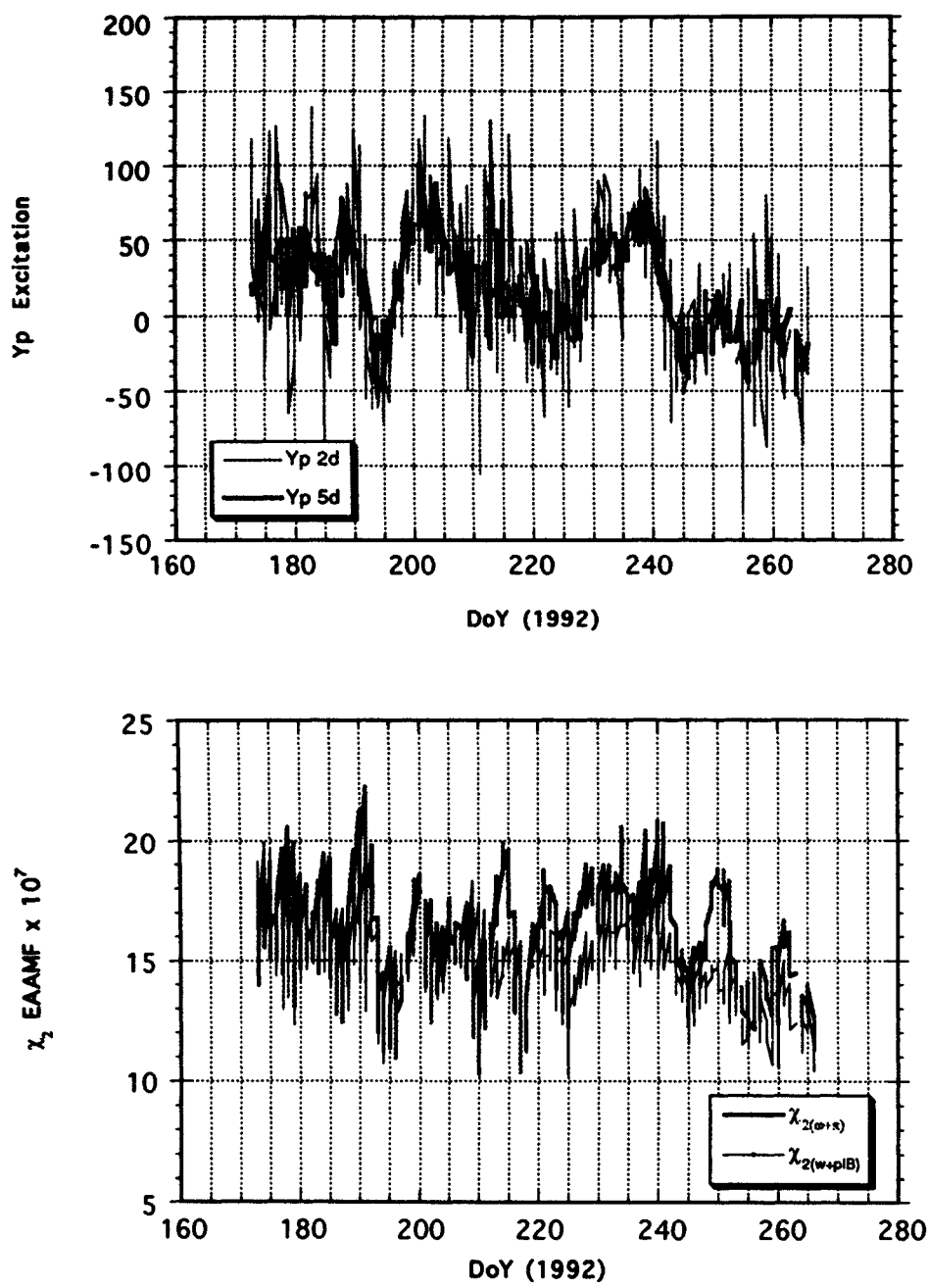


Figure 7. Y component of polar motion excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_2 from NMC series (bottom) with and without the inverted barometer hypothesis.

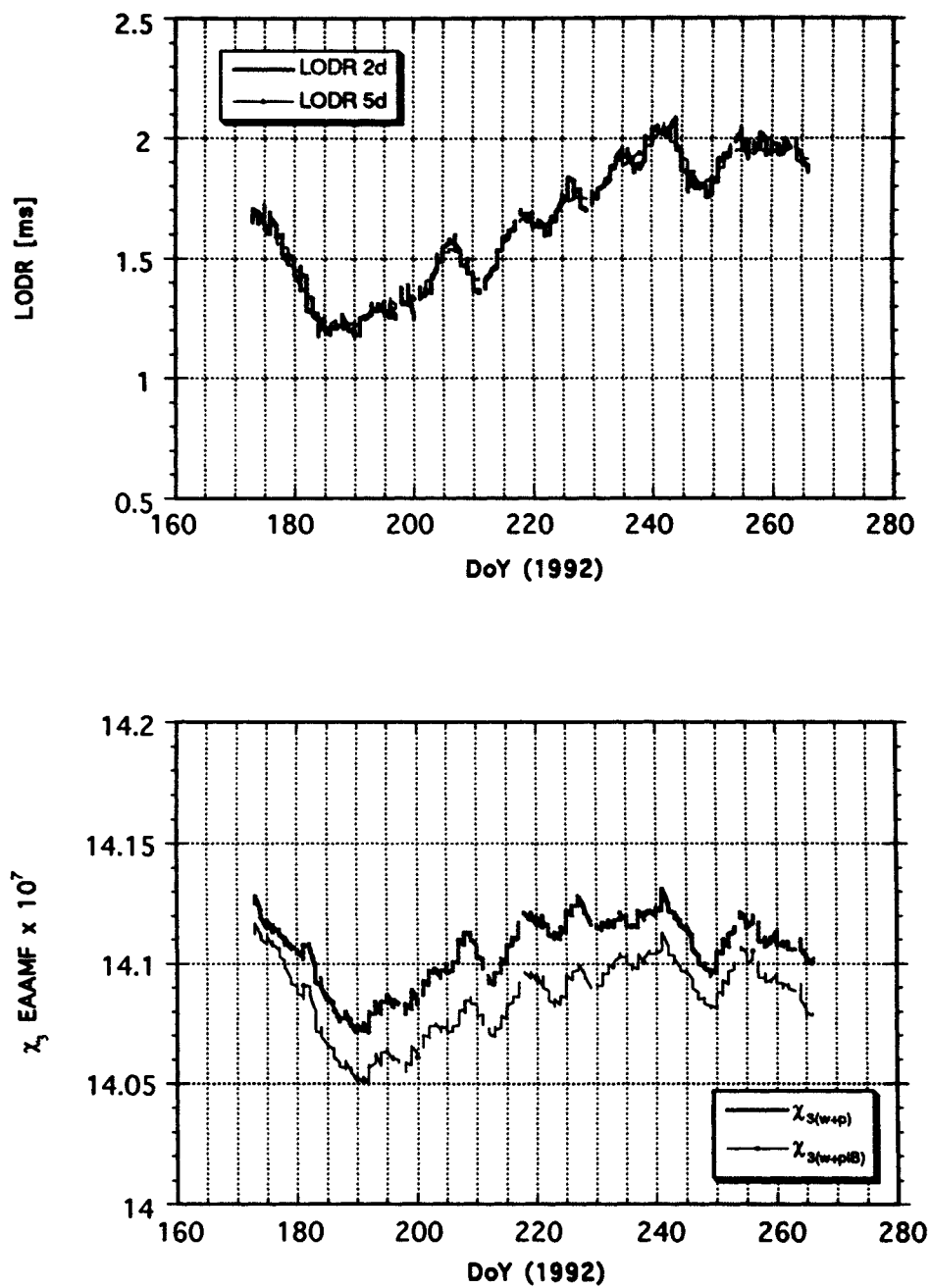


Figure 8. Earth rotation excitation functions with 2-day and 5-day sliding window smoothing (top) and EAAM function χ_3 from NMC series (bottom) with and without the inverted barometer hypothesis.

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 km ³ /s ²
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 <i>a priori</i> .
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	ΔX_p (mas)	ΔY_p (mas)	$\Delta UT1$ (μs)	$\Delta LODR$ (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	ΔX_p (mas)	ΔY_p (mas)	$\Delta UT1$ (μs)	$\Delta LODR$ (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	S _a
	-9.5 1.	-5.0 1.	Y	
	-12.0 3.	14.0 3.	Z	
57555	3.1 ± 1.	-3.5 ± 1.	X	S _{sa}
	0.3 1.	-2.6 1.	Y	
	-10.8 2.	5.2 2.	Z	
65455	2.3 ± 1.	-0.4 ± 1.	X	M _m
	-0.6 1.	0.0 1.	Y	
	-3.2 2.	-5.9 2.	Z	
75555	-1.6 ± 1.	-0.7 ± 1.	X	M _f
	-3.5 1.	1.6 1.	Y	
	-12.3 1.	- 2.4 1.	Z	
135655	-0.4 ± 1.	-3.5 ± 1.	X	Q ₁
	-6.1 1.	-0.8 1.	Y	
	-1.5 1.	-0.9 1.	Z	
145555	-6.0 ± 1.	-1.0 ± 1.	X	O ₁
	-2.2 1.	1.0 1.	Y	
	-2.5 1.	-1.1 1.	Z	
163555	3.8 ± 2.	3.6 ± 2.	X	P ₁
	-6.7 2.	-6.4 2.	Y	
	-5.2 1.	1.8 1.	Z	
164555	-2.9 ± 2.	13.6 ± 2.	X	S ₁
	14.3 2.	4.7 2.	Y	
	-2.4 1.	8.1 1.	Z	
165555	6.0 ± 2.	1.8 ± 2.	X	K ₁
	3.7 2.	-2.3 2.	Y	
	-2.5 1.	-5.1 1.	Z	
245655	-1.9 ± 1.	3.5 ± 1.	X	N ₂
	0.8 1.	-1.3 1.	Y	
	1.0 1.	0.1 1.	Z	
255555	0.0 ± 1.	5.3 ± 1.	X	M ₂
	1.8 1.	4.1 1.	Y	
	-0.3 1.	-3.6 1.	Z	
273555	0.9 ± 1.	0.9 ± 1.	X	S ₂
	-6.5 1.	-5.8 1.	Y	
	-1.2 1.	-0.7 1.	Z	
275555	8.3 ± 1.	-4.9 ± 1.	X	K ₂
	-4.1 1.	-9.1 1.	Y	
	-1.0 1.	0.0 1.	Z	

HIGH RESOLUTION EARTH ROTATION PARAMETERS AS COMPUTED FROM SLR AND GPS DATA

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ABSTRACT. Earth rotation parameters with a daily and sub-daily resolution were determined using SLR and GPS data. Although both techniques can deliver highly accurate results the GPS data have clear advantages because of the better data distribution.

1. Introduction

The daily and sub-daily resolution of the Earth Rotation Parameters (ERP's) with an aimed accuracy of 0.1 mas and 0.01 ms, respectively, is currently an area of intensive investigations, particularly also of the SEARCH'92 Campaign. Both the higher time resolution and accuracy will essentially contribute to a further improvement of the understanding of the interaction of outer and inner forces with the Earth's rotational behaviour.

One of the problems of all methods of determining high-frequency ERP's is the decomposition of EOP's and nutation terms. In the case of satellite methods the correlation with orbital elements has an additional influence (Montag et al. (1993)). Therefore, the high resolution of ERP's requires high-accurate measurements and modelling. Furtheron the data should be fairly even distributed around the whole day. This latter condition can be better fulfilled by GPS measurements than by Satellite Laser Ranging (SLR). On the other side using dense distributed SLR data for certain time intervals high-accurate ERP's results can be obtained as an independent reference for comparisons.

2. Model Parameters, Data and Reference Frame

The analyses were performed by means of the GFZ orbital program packages EPOS.P.V1 for SLR and EPOS.P.V2 for GPS data. The model parameters used are according to IERS standards, generally. The exceptions are:

GM	398600.440 km ³ s ⁻² (initial, adjusted)
Lageos:	
Cross-section to mass relation	0.000694 m ² /kg
Nominal reflectance coefficient	c _R = 1.12 (adjusted)
Empirical acceleration	c _e (adjusted)
GPS	
Tropospheric correction	Saastamoinen, 1973
Solar radiation pressure	ROCK 4 and 42 including thermal reradiation
Vehicle masses	Fliegel (1992), Feltens (1991)

Lageos data were analysed since 1980. The typical orbital fit for a 5-day arc is ± 4 cm. In the case of GPS undifferenced ionospheric-free phases were analysed since the IGS '92 campaign. The sampling rate is 6 minutes and the arc length 32 hours. Different parameters were adjusted for different time intervals (Gendt et al (1993 a, b)), namely:

SLR:

- c_o, c_R - global, every 30 days
- Orbital parameters - 5- or 6-day intervals
- ERP's - 5, 3, 2 days; for selected intervals further 1d, 12h, 6h
- Station coordinates - quarterly, semiannual or for longer time intervals

GPS:

- Orbital parameters - 32-hour arcs
- c_R and y-bias - 32-hour arcs
- ERP's - 1d, 12h
- Tropospheric zenith path delay - e. g. 4h
- Ambiguities
- Epoch time parameters

As a result of the analyses two sets of station coordinates were obtained. The laser station coordinate set SSC (GFZ) 93L01 consists of 101 monument positions. The average accuracy is better than ± 2 cm. The comparison after a 7-parameter similarity (Helmert) transformation with the combined ITRF solution is shown in Table 1. Besides the position for 69 monuments also the motion velocities were adjusted (the other sites were fixed to the NUVEL-1 model motions).

The fiducial-free GPS station coordinate set SSC (GFZ) 93G01 shows a similar accuracy (Tab. 1).

TABLE 1. Comparison with combined ITRF-SSC

	rms (cm)	Scale (10 ⁻⁸)	Translation of geocenter (x, y, z; in cm)		
SSC (GFZ)93G01 - SSC (ITRF)93C01	1.6	.38	8.3	2.6	- 2.2
SSC(GFZ)93L01 - SSC (ITRF) 91	1.9	.01	- .4	-0.3	2.8

3. Results for the ERP's

3.1. ERP's BASED ON SLR DATA

It was shown that generally a high accuracy for highly resolved ERP's can be obtained too if at least SLR data from 4 relevant passes for each of the pole coordinates are available (Montag (1989)). But it can happen that even one well measured relevant satellite pass delivers high accurate results too. By means of numerical investigations a better criterion was found in the use of correlation between the solved-for ERP's. These correlations depend mainly from the data distribution and the sampling time interval for the solve-for-ERP's. If the correlation is higher than 0.9, certain parameters are deleted in the following way:

correlation > 0.9 between	deleted parameters
x_P, y_P	x_P and y_P
$x_P, UT (LOD)$	x_P
$y_P, UT (LOD)$	y_P
$x_P, UT (LOD)$ and $y_P, UT (LOD)$	$x_P, y_P, UT (LOD)$

TABLE 2. Percentage of deleted pole coordinates and average correlation between ERP's after deletion

Time resolution		2d	1d	12h	6h
Percentage deleted	x_P y_P	1... 2 5...10	5...10 20	25 40	45-50 55-60
Mean correlation between ERP's		0.25	0.3	0.4...0.5	0.6

TABLE 3. R.m.s. difference between high resolution solution and 3-day solution (constant offset neglected)

Time resolution	R.m.s. differences in pole coordinates in mas		
	Example 1 Example 2		
	average data distrib.		dense data distrib.
1 d	0.9	1.4	0.3
12 h	1.4	2.2	0.9
6 h	2.5	3.3	1.6

TABLE 4. R.m.s. difference between 3- resp. 5-day solution and 1-day solution of ERP's (constant offset neglected)

Time resolution of reference	R.m.s. differences in pole coordinates in mas.		
	over 2 years (from 6.90 to 9.92)	over 90 days	
		Example 1	Example 2
3 day	1.2	0.9	1.4
5 day	1.4	1.0	1.8

Using this criterion ERP's were computed with different time resolutions. For sub-daily resolution (12h, 6h) two examples were analysed:

- Example 1: 90 days from Dec. 1990 to March 1991 (incl. GIG'91 Campaign)
- Example 2: 90 days from June 1992 to Sept. 1992 (SEARCH'92 Campaign).

The percentage of pole coordinate results eliminated in this way is shown in Table 2 as a function of the time resolution. This Table further indicates that for the remaining results the average correlation ranges between 0.25 for the 2d solution and 0.6 for a resolution of 6h.

Several results having different time resolutions are displayed in Figure 1 to 3 (as corrections to IERS combined solution) together with the number of station and passes observed per day.

Figure 1 shows a part of the results of the Example 1 as correction to IERS, namely the 1d solutions for x and y, and the 12h solutions for the y component of the pole coordinates. The 3d solution is included as reference. The dependence of the scattering and the number of deleted points on the number of the stations and the observed passes is evident, especially for the 12h results. The effect of Christmas - New Year time (45249 - 257) is also clear visible.

More detailed results are shown for Example 2 (SEARCH'92 Campaign) in Figures 2 and 3. Here one can see the results for both the x- (Fig. 2) and y-component (Fig. 3) with a time resolution of 1d, 12h and 6h together with the 5d and 3d results as references. Comparing with Example 1 the scattering of the Example 2 is apparently higher. This is confirmed numerically in Table 3. It shows the r.m.s. differences (constant offset neglected) between the 3d solution on the one side and the 1d, 12h and 6h solution on the other. For an average data distribution the r.m.s. differences are in all cases significantly higher for the SEARCH'92 campaign. For the 1d resolution pole coordinates this is confirmed also using the 5d solution as a reference (Table 4). Table 4 also displays the r.m.s. differences between the 1d solution and the 3d and 5d solution for a time span of two years. Because the quality and quantity of the observations are nearly the only cause for the amount of these differences one can conclude, that apparently the SLR observing activity was during the GIG'91 campaign better, but during the SEARCH'92 campaign even worse than in average.

Selecting only time intervals with a dense data distribution the results can be much better (Table 3). The r.m.s. differences are about 0.3 mas for the 1 d resolution and still better than 1 mas (0.9) for the 12h resolution.

TABLE 5. R.m.s. difference to the smoothed mean 1-day curve (time period 1993, Jan. - June)

Time resolution	Center	Pole coordinates in mas	
		x-pole	y-pole
1d	JPL	0.71	0.73
1d	SIO	0.36	0.49
1d	EMR	0.53	0.43
1d	GFZ	0.34	0.29
12h	GFZ	0.35	0.36

3.2. ERP's BASED ON GPS

Using the GPS data of the SEARCH Campaign ERP's were determined with a time resolution of 1d (Zhu et al. (1993)). Besides the 1d resolution for 1993 also ERP's with a time resolution of 12h were analysed. A section of these results is presented in Figure 4 together with the corresponding solution of SIO. Apparently the scattering of the GPS results is generally smaller than that of SLR results. Numerically this is confirmed in Table 5. Here the r.m.s. differences to the smoothed 1d curve are shown (not to the 3d or 5d solution as in the case of SLR; this makes the GPS results somewhat more optimistic). It is clearly visible from this table that most of the IGS Analysis Centers have reached a 0.5

Figure 1. Diurnal and semidiurnal SLR polar motion results (Example 1)
3d solution (—) as reference

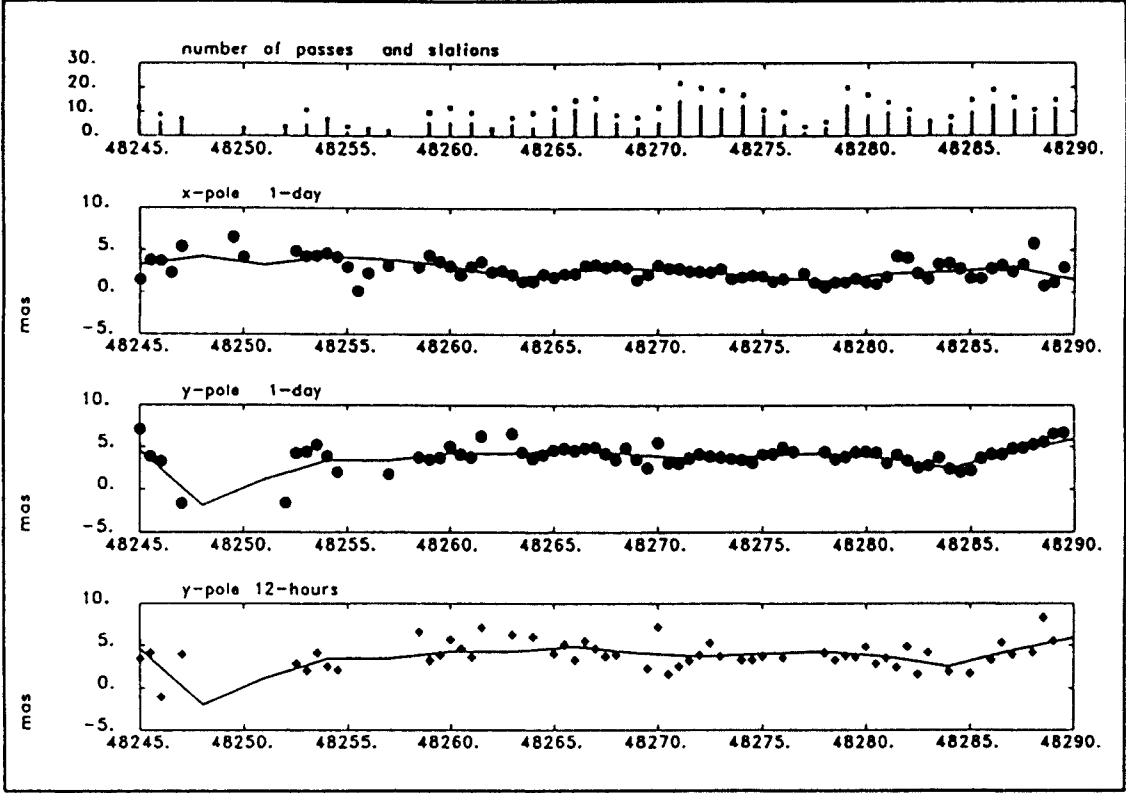


Figure 2. Highly resolved SLR x-pole (Example 2)
5d (—) and 3d (---) solution as reference

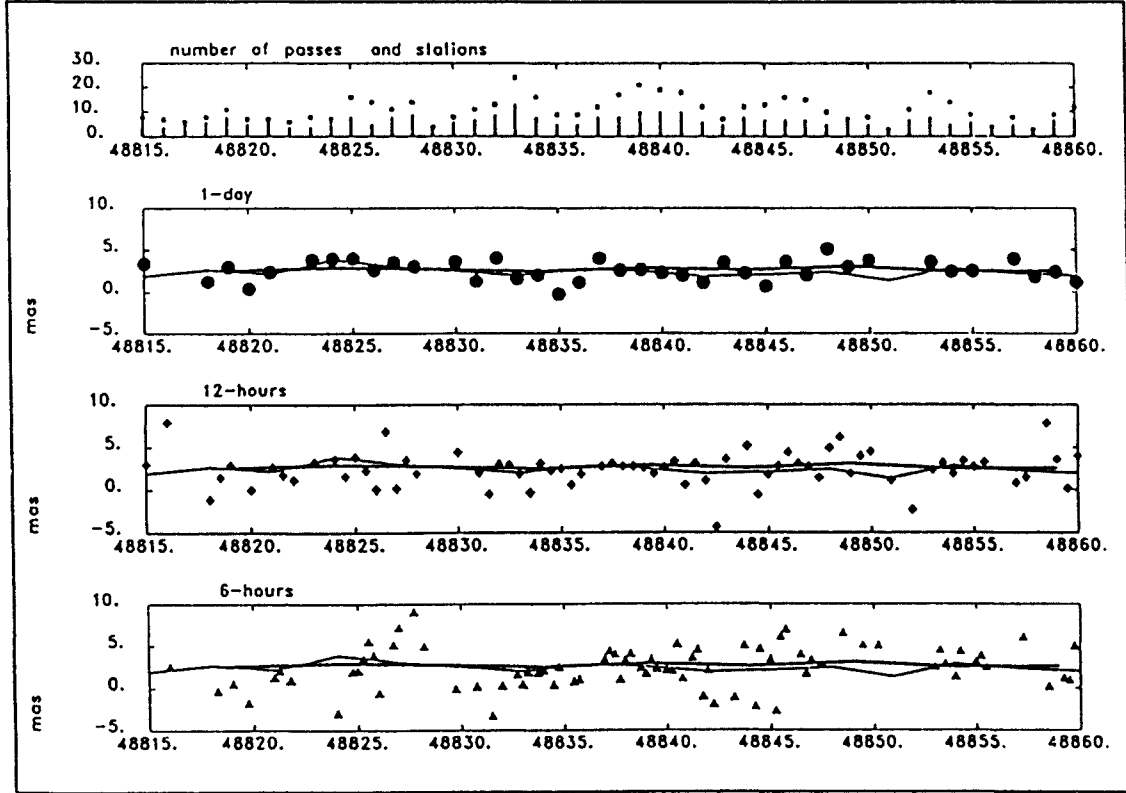


Figure 3. Highly resolved SLR y-pole (Example 2)
5d (→) and 3d (←) solution as reference

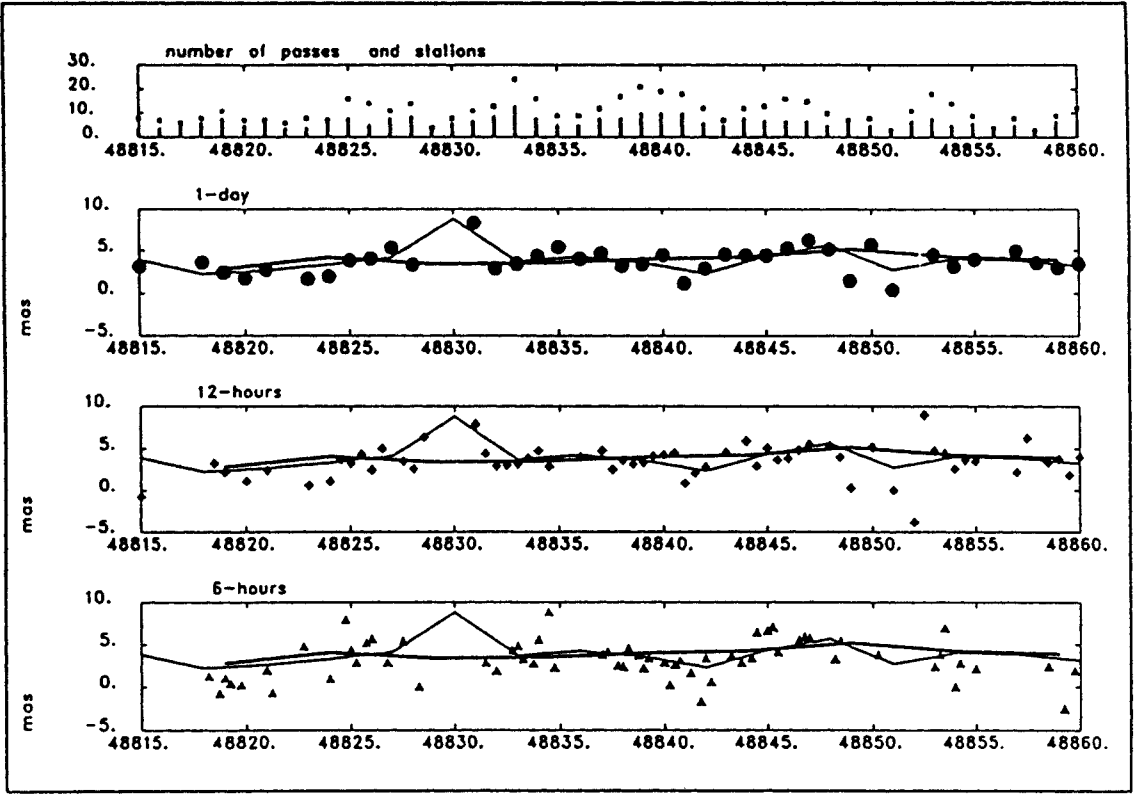
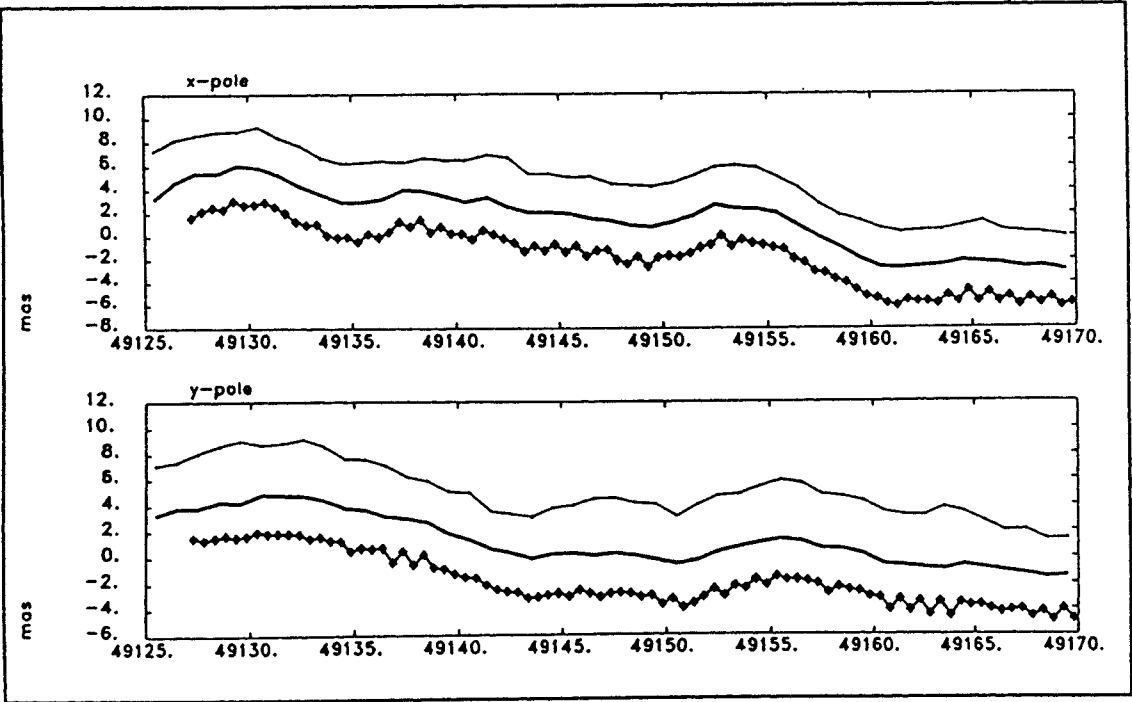


Figure 4. Highly resolved polar motion from GPS
1d GFZ (→), 1d SIO (←), 12h GFZ (♦)



mas precision for their daily products. An increase in the time resolution only slightly increases the uncertainty of the GPS derived ERP's.

4. Conclusions

For highly resolved ERP's, generally, the GPS data have advantages because of the dense data distribution (all weather capability, good coverage and geometry). This holds especially for the sub-daily products where a precision of better than 0.5 mas can be obtained for a 12h resolution.

In certain time intervals with well distributed and accurate SLR data the ERP's results also reach a precision of better than 0.5 mas, but up to a resolution of 1d only. In the sub-daily region the precision is several times worse, generally. Therefore both SLR and GPS can complement each other for the determination of ERP's with a lower time resolution (e. g. from 5d to 1d). Here the SLR results can serve as independent reference series for the investigation of systematic errors (bias, drift). On this basis ERP's with a sub-daily resolution should be derived from GPS data in the future.

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GPS DATA ANALYSIS FOR EARTH ORIENTATION AT THE JET PROPULSION LABORATORY

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ABSTRACT. Beginning in June 1992 and continuing indefinitely as part of our contribution to FLINN (Fiducial Laboratories for an International Natural Science Network), DOSE (NASA's Dynamics of the Solid Earth Program), and the IGS (International GPS Geodynamics Service), analysts at the Jet Propulsion Laboratory (JPL) have routinely been reducing data from a globally-distributed network of Rogue Global Positioning System (GPS) receivers. Three products are produced and distributed weekly: (i) precise GPS satellite ephemerides, (ii) estimates of daily polar motion and length-of-day, and (iii) a descriptive narrative of the analysis for the week. These are typically made available to the public approximately two weeks following the data recording. In addition, more sophisticated data reduction techniques have been developed for non-routine, research-oriented GPS data analysis. These have been successfully utilized to measure sub-daily Earth orientation fluctuations. Based on comparisons of our earth orientation parameters with independent techniques, we estimate daily pole position accuracies (1σ) of ± 0.6 milliarcseconds and length-of-day accuracies of ± 0.13 msec. Ongoing work at JPL is aimed at continuing the trend of producing more and higher-quality results at lower cost.

1. Introduction

The first GPS geodynamics experiment for the IERS (GIG '91), a two-week campaign in early 1991, saw the first globally-distributed deployment of precise Global Positioning System receivers, and demonstrated few-parts-per-billion precision [1] in estimates of terrestrial site locations. Largely as a result of the success of GIG '91, the International GPS Geodynamics Service (IGS) began informal operation in June 1992 and formal operation in January 1994. JPL has contributed to the IGS since it began and, in conjunction with its ongoing support of NASA's Dynamics of the Solid Earth (DOSE) program, will continue to contribute. JPL has also contributed in a research capacity to the analysis of the GPS data and resulting scientific products.

Shown in Figure 1 is the distribution of terrestrial GPS P-code receivers as of February 1993. Global coverage is very good, with only a few noticeable "holes". Within the next two years, it is anticipated that these holes will be plugged with new receivers at strategic locations. Figure 2 summarizes the steadily increasing number of stations and satellites beginning in early 1992 and continuing to the present. One can speculate on whether the trend will continue, but currently the data volume, as measured by ($\#$ stations $\times$ $\#$ satellites), doubles in just over a year!

IERS(1994) Technical Note No 16.

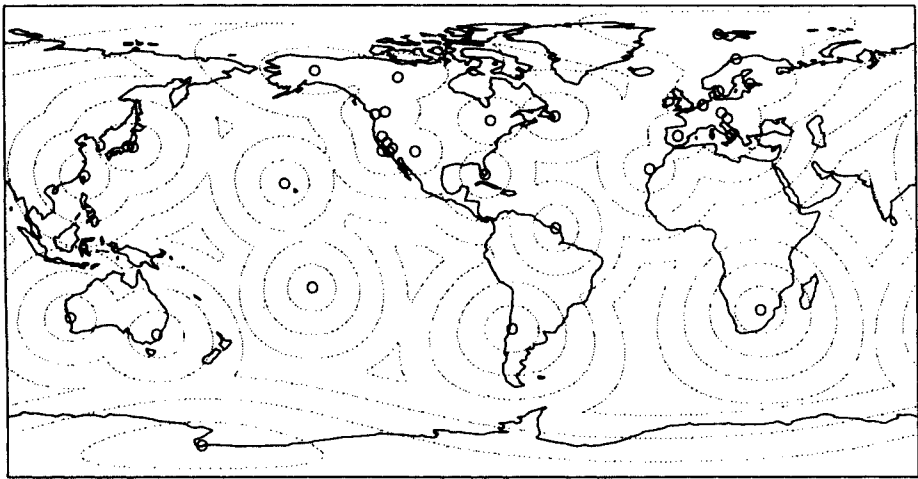


Figure 1. Distribution of terrestrial GPS receivers used in the daily analyses. The dotted lines represent contours of the distance-to-nearest-site function. The contour interval is 1000 km.

Described in this paper are the routine analysis procedures used at JPL, the resulting Earth orientation data products, and their estimated accuracies. Also described are more sophisticated and CPU-intensive analysis procedures being used for the non-routine, research-oriented tasks. We conclude with a brief look at JPL’s plans for improving the efficiency and quality of its analyses.

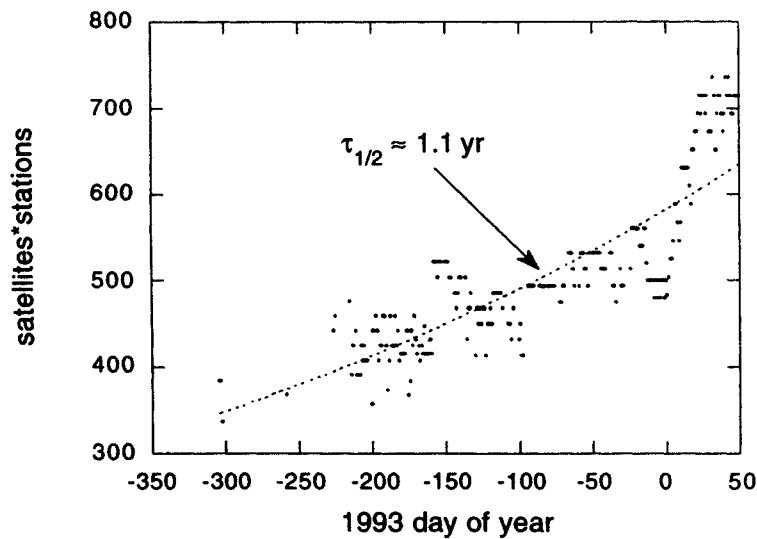


Figure 2. The number of satellites times the number of stations used in daily analyses beginning early 1992. At the current rate, the data volume doubles in a little over 1 year.

2. Procedure and Products

Figure 3 gives a simplified overview of the routine procedure. JPL's GPS Networks Operations (GNO) Group retrieves data from the global network, organizes them by time and site, converts them to the Rinex format, and makes them available for analysts. Once it is determined that sufficient data are available for a given day, a file is created which specifies what data are to be used in that day's analysis, as well as specific sites or GPS satellites from which data should be deleted or deweighted due to known problems.

Based on input from this file, a daily script that runs several programs is launched, requiring a total of approximately 19 hours of cpu time on a 17-Mflop Unix workstation when data from 30 stations and 20 satellites are included. When completed, the daily analysis results in estimates for Earth orientation, GPS satellite ephemerides, and locations of terrestrial sites.

The operational cycle is one week, during which seven daily analyses are completed. Together with the result from Saturday of the previous week and Sunday of the following week, these are used in quality control. Four files are produced and distributed weekly, with naming convention `jpl0www7`, where `www` is the GPS week and 7 indicates the results are for the entire week. The files are distinguished by their extensions: `.sum` for a narrative summary, `.sp1` or `.sp3` for GPS ephemerides [2,3], and `.erp` for Earth orientation. The orbit product and orbit accuracy comparisons are discussed further in [4].

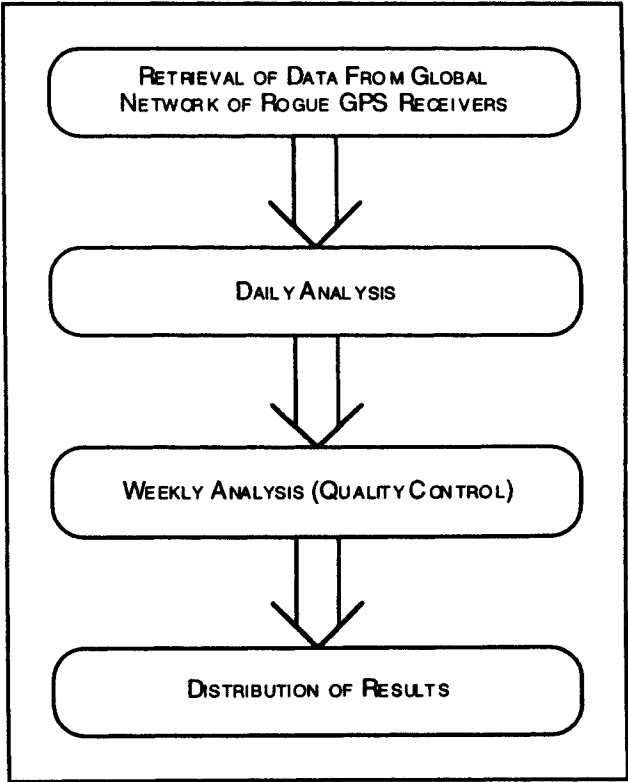


Figure 3. Simplified Flow Chart of FLINN Analysis

The analysis software used is the JPL-developed GIPSY-OASIS II. This software, which incorporates Kalman filtering, and various standard JPL GPS estimation strategies are described in detail in [5,6,7].

In normal operation, each day is processed separately using the 24 hours of the UTC day plus the last 3 hours of the previous day and first 3 hours of the following day. Normal points are formed every 10 minutes. The data types we use are the undifferenced ionosphere-free phase and pseudorange, with assumed noise of 5 mm and 50 cm, respectively.

The GPS satellite motion is modeled as a 9-parameter epoch state vector which includes three-dimensional position, velocity, and solar radiation pressure. Additional parameters allow the solar radiation pressure to vary in a stochastic way about its average value. The noise model for this variation is first-order Gauss-Markov with a 4-hour time constant and 10% standard deviation. Especially during periods when a satellite is in the Earth's shadow, the extra variation allows significantly better modeling of its motion.

The nominal value for the Earth's pole position (x and y) is obtained from the IERS Bulletin B predicts, and its deviation from that nominal is modeled as a linear function of time. The deviation of UT1R – UTC from the nominal (again, IERS Bulletin B predicts) is also assumed to be linear with time, but in this case only the rate is estimated. This rate is the negative of length of day (LODR).

The terrestrial sites include eight which are assumed to be at known locations. These are Algonquin Park, Ontario, Canada; Fairbanks, Alaska, U.S.; Hartebeesthoek, South Africa; Kokee Park, Hawaii, U.S.; Madrid, Spain; Santiago, Chile; Tromsø, Norway, and Yarragadee, Australia. The fixed values are updated at the beginning of each month to account for site velocities from ITRF91 (IGS mail message 90) [8]. Location of all other terrestrial sites are solved for every day starting from ITRF91 nominal positions.

GPS carrier phase biases are estimated as real-valued parameters. Clock biases for transmitters and receivers are estimated as white noise processes, except for one reference station clock. The zenith troposphere delay at each receiver site is modeled as a random walk process. The 1980 International Astronomical Union (IAU) nutation model, the Yoder et al. [9] Earth and ocean tide model, and the GEMT3 (more recently, JGM2) gravity field model are assumed.

3. Results

3.1. DAILY EARTH ORIENTATION

Shown in Figure 4 are the Earth orientation results. A discontinuity at days 200-201 (July 18-19, 1992) is a consequence of the change in fiducial strategy which went from three (Fairbanks, Algonquin, and Madrid) fixed sites to the eight described earlier. From July 19 through the end of 1992, excluding some days during which anti-spoofing was in effect, the average difference between JPL's pole position measurements and those from the IERS Bulletin B Final values is about 0.8 mas for x and 1.2 mas for y , with standard deviations of about 0.6 mas for both x and y .

Although GPS measurements are almost completely insensitive to UT1R – UTC, they are sensitive to its time derivative, essentially the Earth's spin rate. With $T \equiv 1$ day, the quantity

$$\text{LODR} \equiv -T \frac{d}{dt} (\text{UT1R} - \text{UTC}) \quad [1]$$

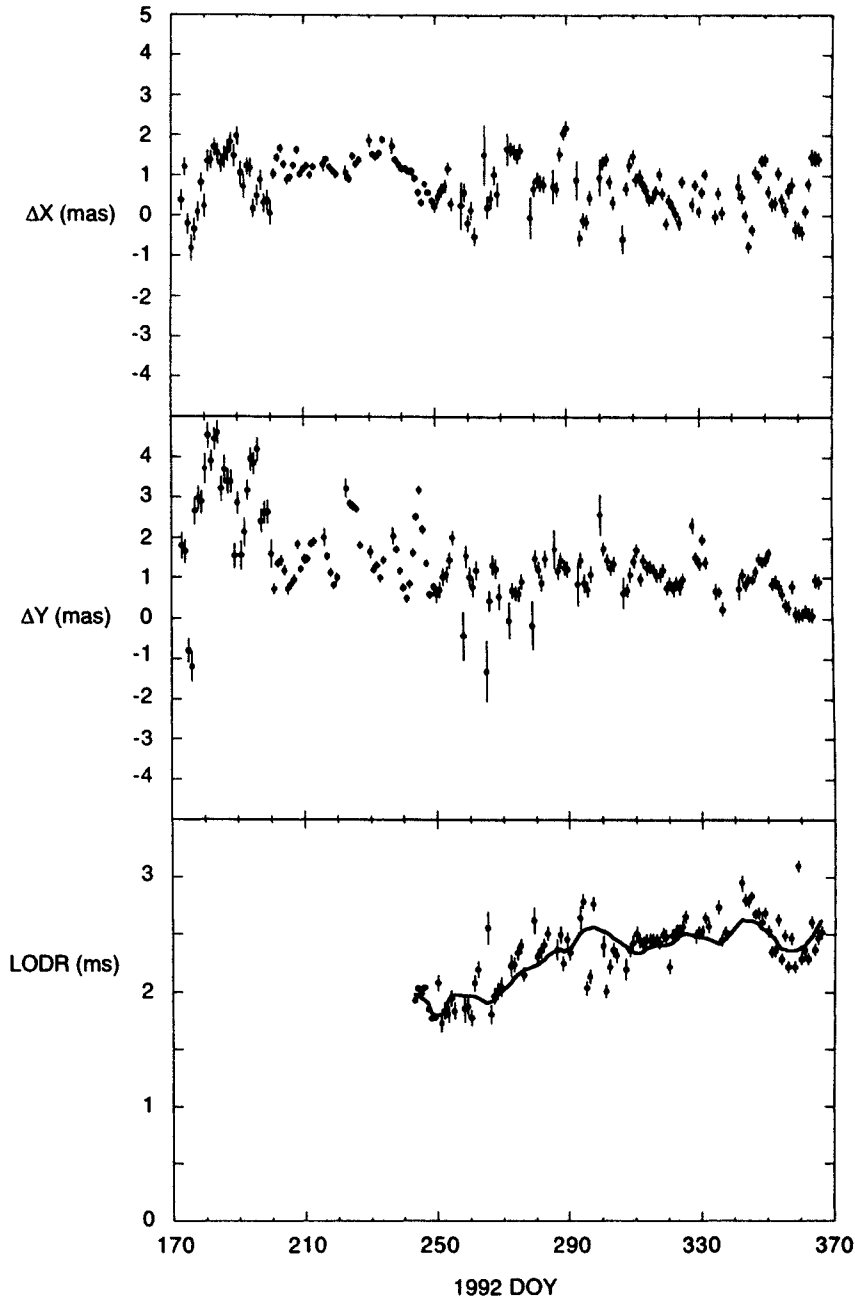


Figure 4. GPS estimates of Earth orientation parameters compared with IERS Bulletin B Final Values. For pole position, the values shown (ΔX and ΔY) are the GPS measurements minus the IERS values, and the error bars reflect the formal uncertainty in the GPS measurements. For LODR, the solid line indicates the negative time derivative of the IERS value of UT1R-UTC, and the points indicate the GPS measurements and formal uncertainties.

is the conventional measure of this spin rate. We began including daily estimates of LODR beginning with GPS week 660 (August 30, 1992). Shown at the bottom of Figure 4 are our daily estimates of LODR and a smooth curve which represents the negative derivative of the IERS Bulletin B Final values of UT1R – UTC. Excluding a few 3σ outliers, the agreement is approximately 0.13 msec (1σ) with a negligible bias.

Because the daily estimates of LODR are for the most part independent, an integration of them to recover UT1R – UTC (given some initial starting value) would exhibit random walk behavior. Thus, some method is required to prevent the walk from wandering too far away. We are currently investigating the forward-running filter

$$\text{UT1R} - \text{UTC}(t + T) = \alpha \Lambda + (1 - \alpha) [\text{UT1R} - \text{UTC}(t) + \text{LODR}(t + T/2)], \quad [2]$$

where Λ is a separate estimate of UT1R – UTC($t + T$) and α is a free parameter. (We continue to use $T \equiv 1$ day.) The parameter α should be small enough so that the resulting UT1R – UTC series will exhibit a time variation consistent with the daily GPS-measured LODR values, and only just large enough to suppress large random-walk excursions. A reasonable choice for Λ is the most-recent IERS Bulletin B *Final* value of UT1R – UTC (typically 30- to 60-days old), incremented to the present by the daily GPS measurements of LODR. In the near future we intend to include the results of such a procedure in our .erp files.

The Epoch '92 campaign, running from July 26 - August 8 1992, was a particularly intensive period of observation for other geodetic techniques. It occurred when our estimation strategy had not matured to its current state. Therefore, these days were reprocessed in early 1993 with the current estimation strategy. The results are on JPL's *bodhi* distribution computer, and are also available on the Crystal Dynamics Data Information System (CDDIS) at Goddard Space Flight Center. The reprocessed data show marked improvement over the original analyses in both orbit quality and Earth orientation accuracy.

3.2. SUB-DAILY EARTH ORIENTATION

The analysis strategy for obtaining estimates of sub-daily Earth orientation fluctuations has much in common with the operational procedure described above. Differences in strategy are discussed here; the Earth orientation results, however, are discussed in detail in Freedman et al. [this volume] and Ibanez-Meier et al. [this volume].

The principle changes made to the daily FLINN strategy deal with the use of multiple day data arcs in place of the 30-hour data arcs of FLINN. To utilize multi-day arcs, the dynamic orbit models for the GPS satellites must be modified. This may involve modifying the solar radiation pressure models or giving up the goal of a single epoch state for each satellite over the entire data arc. In addition, the estimation strategies for both UT1 and polar motion x and y are different from those of the daily analyses. Finally, two minor changes include the use of 6-minute normal point spacing and assumed data noise levels twice as large as those assumed by FLINN.

Variations in UT1 – UTC starting from an initial fixed value were estimated every 30 minutes by using a first-order Gauss-Markov process update with a correlation time of 4 hours and a steady-state process noise $1-\sigma$ constraint of 0.06 ms. Polar motion variations were modeled as a white noise process with weak (120 mas) constraints. For both UT1 and polar motion, a variety of estimation intervals were tried, ranging from the normal point interval of 6 minutes up to 3 hours. Figure 5 illustrates the UT1 values that result from various estimation intervals. All curves have been differenced with a reference series [Freedman et al., this volume] and are offset for clarity.

Curves A and B represent two sets of 30-minute estimates (whose differences are explained below), curve C shows UT1 estimated every 6 minutes, and curves D and E show two sets of 3-hour estimates. D and E differ in that an apriori diurnal and semidiurnal tide model was explicitly used in the estimation of time series E, whereas no such model was used in D. The optimal estimation interval, in the sense of yielding the best signal to noise ratio without undue attenuation of the expected diurnal signal, was 30 minutes.

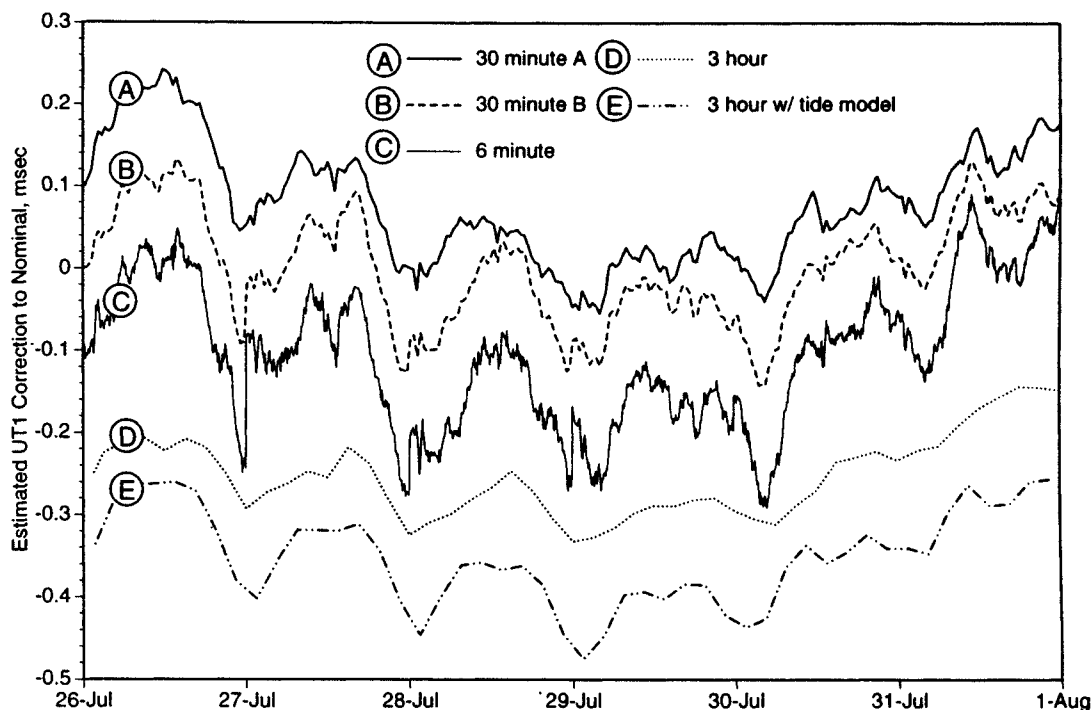


Figure 5. Comparison of sub-daily UT1 time series estimated with various strategies. Time series are offset vertically for ease of comparison. See text for explanation of curves and labels.

Two different estimation strategies for the satellite orbits were employed. In the earlier strategy [5,10], one set of satellite states (positions and velocities) was estimated for each satellite over the course of the multi-day arc. The solar radiation pressure coefficients G_x , G_y , and G_z were estimated as constants with 10 percent colored noise added and updated every hour. The biases for the G_x and G_z parameters were constrained to be 100% correlated. The stochastic portion of the solar radiation model consisted of a first-order Gauss-Markov process with a correlation time of 4 hours. We found that this strategy, although adequate for estimating UT1 – UTC variations, tended to attenuate much of the polar motion signal, presumably absorbing it within the satellite orbit and solar pressure force models. Curve A in Fig. 5 shows the 30-minute UT1 series resulting with this strategy.

A second strategy [11] consisted of re-estimating each satellite state (position, velocity and solar radiation pressure coefficients) every 24 hours. In this case, the solar radiation parameters were modeled as constants over 24 hours. The white noise restarts for each GPS satellite were staggered over a 5-hour interval around noon to maintain continuity in the UT1 series. Figure 5 curve B shows the 30-minute UT1 series obtained with this strategy, and all other curves in Fig. 5

use this latter strategy. Typical postfit rms residuals were close to 6 mm for carrier phase and 35 cm for pseudo-range data.

4. Conclusions and Future Prospects

Since the first half of 1992, JPL has made regular contributions to the IGS, consisting of precise GPS orbits and daily Earth orientation results. We expect to continue these contributions. Accuracies are currently estimated to be a few tens of centimeters for GPS orbits, about half a milliarcsec for pole position, and a bit over 0.1 msec for LODR.

Additional strategies for multi-day arcs, for routine as well as research use, are being tested. These may be utilized routinely as cpu speeds increase, and are sure to be used in future sub-daily Earth orientation research.

Accuracies of all quantities may improve significantly once we start resolving carrier phase bias ambiguities [12], which should begin sometime this calendar year (the current limitation comes from our computing resources). Quality control will be enhanced by daily monitoring of several regional baselines.

A number of weekends during 1992 saw implementation of anti-spoofing (AS). Only recently has the Rogue receiver software been upgraded to handle AS data. Since the upgrade, AS has been processed successfully, although with somewhat degraded accuracies. Analysts at JPL will be investigating modifications of the nominal strategy to better accommodate AS data.

As was shown in Figure 2, the quantity of data has steadily increased, and will probably continue to increase in the near future owing to both more satellites and more receivers. So that the computational burden remains tractable, we may need to process a select number of stations to fix orbits, and then use fixed orbits for the remaining stations.

In addition to the current offerings, new products that may be distributed soon are satellite and station clock solutions. If a demand exists, troposphere estimates and stochastic solar radiation pressure estimates could also be made available.

Finally, additional automation in routine processing may reduce the manpower required to keep up to date with the analyses. The current turnaround time of approximately two weeks could conceivably be reduced to a few days, or even less.

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EFFECTIVE ATMOSPHERIC ANGULAR MOMENTUM FUNCTIONS COMPUTED FROM THE JAPAN METEOROLOGICAL AGENCY DATA

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ABSTRACT. The Atmospheric Angular Momentum (AAM) functions based on the 6-hourly Japan Meteorological Agency (JMA) data are briefly introduced.

The effective atmospheric angular momentum (EAAM) functions proposed by Barnes, Hide, White and Wilson (1983) have been computed from the Japan Meteorological Agency (JMA) global analysis data since September 28, 1983. In general, the operational numerical weather prediction produces the three data sets called the analysis data, the initialized analysis data and the predicted values. The JMA global analysis data are the analysis data.

For the use of this file, it should be noticed that the results during 1983/12/1 - 1986/6/30 are 24-hourly (daily mean) values computed from the JMA global analysis averaged data at each grid and each level, during 1986/7/1 - 1992/6/20 are 12-hourly (00UTC and 12UTC) values computed without averaging, and from 1992/6/21 are 6-hourly (00UTC, 06UTC, 12UTC, 18UTC) values. The most important fact is that the 6-hourly values from 1992/6/21 are based on a new computational method different in part from an old computational method for the other values. It should be thus noticed that the 12-hourly values during 1992/6/21 - 1992/9/30 based on the old method are also added in the file prior to the 6-hourly values for comparison.

The JMA global analysis data have been made on 1.875-degree (2.5-degree before 1988/3/1) latitude-longitude grid system at sixteen levels (fifteen levels before 1988/3/1) from surface to 10hPa. The data are made from the forecast-analysis cycle by the following analysis and forecast models. The analysis model is based on a multi-variate optimum interpolation method with the initial guess of 6 hour forecast in troposphere, and on a sinusoidal fitting method in stratosphere. It should be noted that the predicted values are not used for the analysis above 100hPa. The forecast

model is a global spectral model with a horizontal resolution of triangular truncation at wavenumber 106 (63 before 1989/11/14, and 42 before 1988/3/1), and vertically it has 21 levels (16 levels before 1989/11/14, and 12 levels before 1988/3/1). Full physical processes are incorporated in the model through 1.125-degree Gaussian grid, and a non-linear normal mode initialization is applied. The details for the analysis and forecast models from 1989/11/14 can be found in Numerical Weather Prediction Division, Japan Meteorological Agency (1990), during 1988/3/1-1989/11/13 in Kitade (1988), and before 1988/3/1 in Kashiwagi (1987) and Kanamitsu, Tada, Kudo, Sato and Isa (1983).

For computing the EAAM functions, the sea level pressure, the height of the each level, and the wind velocity at each level of the global analysis data are used. In addition, mountain height of the same grid system made from the 10-minute (1-degree for the 12-hourly values) latitude-longitude grid data are used for estimating surface pressures on land that are computed from the geopotential height by using a cubic spline interpolation technique applied for the thickness temperatures. Also land-sea index data of the same grid system made from the 1-degree latitude-longitude grid data are used for computing sea level pressures on ocean with the Inverted Barometer (IB) hypothesis. Vertical integration of the wind terms of the EAAM functions is carried out from surface pressure on land (or the sea level pressure on ocean) to 10hPa. However, surface wind data are not used for the 6-hourly values from 1992/6/21.

The integral formula to evaluate the EAAM functions are basically due to the equations (5.1), (5.2), and (5.3) of Barnes et al (1983), but the axial component of the EAAM functions is multiplied by -1 for convenience. No smoothing have been done after evaluation. Details of the evaluation can be found in Naito, Kikuchi and Yokoyama (1987).

The file is given as

Year, Month, Day, MJD,
 Chi-1-wind, Chi-1-press without IB, Chi-1-press with IB,
 Chi-2-wind, Chi-2-press without IB, Chi-2-press with IB,
 Chi-3-wind, Chi-3-press without IB, Chi-3-press with IB

with format (I4, I3, F6.2, F9.2, 9F10.6), where the EAAM functions have been multiplied by 1.0E7.

The variations during SEARCH'92 (6/21-9/22, 1992) are shown in Figure 1.

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Figure 1. The variations of the AAM functions based on the 6-hourly JMA data during SEARCH'92 (6/21-9/22, 1992), where units are $10E-7$.

- $X_1(n-IB)$: Chi-1-Wind plus Chi-1-Press without IB.
 $X_1(IB)$: Chi-1-Wind plus Chi-1-Press with IB.
 $X_2(n-IB)$: Chi-2-Wind plus Chi-2-Press without IB.
 $X_2(IB)$: Chi-2-Wind plus Chi-2-Press with IB.
 $X_3(n-IB)$: Chi-3-Wind plus Chi-3-Press without IB.
 $X_3(IB)$: Chi-3-Wind plus Chi-3-Press with IB.

