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Combinations of Earth-orientation measurements: SPACE97, COMB97, and POLE97

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Abstract. Independent Earth-orientation measurements taken by the space-geodetic techniques of lunar and satellite laser ranging, very-long-baseline interferometry, and the global positioning system have been combined using a Kalman filter. The resulting combined Earth-orientation series, SPACE97, consists of values and uncertainties for universal time, polar motion, and their rates spanning the period 28 September 1976 to 3 January 1998 at daily intervals. The space-geodetic measurements used to generate SPACE97 have then been combined with optical astrometric measurements to form two additional combined Earth-orientation series: (1) COMB97, consisting of values and uncertainties for universal time, polar motion, and their rates spanning the period 20 January 1962 to 1 January 1998 at 5-day intervals, and (2) POLE97, consisting of values and uncertainties for polar motion and its rate spanning the period 20 January 1900 to 21 December 1997 at monthly intervals.

Key words: Earth rotation – Combination – Kalman filter

1 Introduction

Reference series of Earth-orientation parameters (EOPs) obtained by combining independent measurements of the Earth's orientation are generated annually at the Jet Propulsion Laboratory (JPL) in support of tracking and navigation of interplanetary spacecraft. This report describes the generation of the most recent such combined Earth-orientation series: SPACE97, COMB97, and POLE97. Since the procedures used to generate these most recent series are similar to those used to generate previous such combinations, only a brief description of their generation is given here. Further details about the approach used at JPL to annually combine independent measurements of the Earth's orientation can be found in Gross (1996) and Gross et al. (1998).

2 SPACE97

2.1 Data sets combined to form SPACE97

SPACE97 is a combination of independent space-geodetic measurements of the Earth's orientation. Table 1 lists the space-geodetic series used in generating SPACE97, giving their identifiers, the number of measurements from each series that were actually incorporated into SPACE97, and the time period spanned by those measurements. Note that the UTCSR satellite laser ranging (SLR) universal time (UT) values were not used in generating SPACE97 due to problems associated with separating this component of the Earth's orientation from the effects of unmodeled forces acting on the satellite causing the node of its orbit to drift (see Gross et al. 1998, p. 217 for further discussion of this point). Similarly, no global positioning system (GPS) length-of-day (LOD) values have been used in generating SPACE97.

Since it was desirable to combine only independent measurements of the Earth's orientation, only those series listed in Table 1 were used even though other space-geodetic series are available from other analysis centers. When more than one series determined by the same measurement technique was used, care was taken to make sure that the measurements themselves were not included more than once. In particular, measurements from the Scripps GPS series were used until the start of the JPL GPS series on 1 June 1992, measurements from the JPL GPS series were used until the start of the International GPS Service (IGS) combined series EOP(IGS) 95 P 01 on 1 January 1995, measurements from the IGS combined series EOP(IGS) 95 P 01 were used until the start of the IGS combined series EOP(IGS) 95 P 02 on 30 June 1996, and measurements from the IGS combined series EOP(IGS) 95 P 02 were used thereafter. Similarly, measurements from the NOAA IRIS Intensive UT1 series were used until it ended on 31 December

Table 1. Data sets combined to form SPACE97. *DSN* Deep Space Network; *GPS* Global Positioning System; *GSFC* Goddard Space Flight Center; *IGS* International GPS Service; *IRIS* International Radio Interferometric Surveying; *JPL* Jet Propulsion Laboratory; *LLR* lunar laser ranging; *NASA* National Aeronautics and Space Administration; *NEOS* National Earth Orientation Service; *NOAA* National Oceanic and Atmospheric Administration; *NRCan* Natural Resources Canada; *SGP* Space Geodesy Program; *SIO* Scripps Institution of Oceanography; *SLR* satellite laser ranging; *T* transverse; *USNO* United States Naval Observatory; *UTCSR* University of Texas Center for Space Research; *V* vertical; *VLBI* very long baseline interferometry; *VOL* variation of latitude

Data set name	Data type	Analysis centre	Reference	Data span	Number
LLR (JPL97M01; VOL, UT0)					
McDonald Cluster	LLR	JPL	Newhall et al. (1997)	5 Oct 1976 to 5 Nov 1996	533
Cerga	LLR	JPL	Newhall et al. (1997)	7 Apr 1984 to 7 Nov 1996	605
Haleakala	LLR	JPL	Newhall et al. (1997)	10 Feb 1985 to 11 Aug 1990	67
UTCSR (CSR96L01)					
Lageos Polar Motion	SLR	UTCSR	Eanes and Watkins (1996)	28 Sep 1976 to 4 Feb 1996	2194
DSN (JPL97R01; T, V)					
California–Spain Cluster	VLBI	JPL	Steppe et al. (1997)	26 Nov 1979 to 28 Sep 1997	681
California–Australia Cluster	VLBI	JPL	Steppe et al. (1997)	28 Oct 1978 to 30 Sep 1997	673
NASA/GSFC SGP (GLB1083c)					
Multibaseline	VLBI	GSFC	Ma and Ryan (1997)	4 Aug 1979 to 16 Jul 1997	2237
Westford–Fort Davis	VLBI	GSFC	Ma and Ryan (1997)	25 Jun 1981 to 1 Jan 1984	105
Westford–Mojave	VLBI	GSFC	Ma and Ryan (1997)	21 Mar 1985 to 6 Aug 1990	18
USNO (N9708)					
Multibaseline	VLBI	USNO	Eubanks et al. (1997)	23 Jul 1997 to 31 Dec 1997	43
NEOS Intensive UT1	VLBI	USNO	Eubanks et al. (1997)	4 Jan 1995 to 3 Jan 1998	757
NOAA (NOAA95R02)					
IRIS Intensive UT1	VLBI	NOAA	Ray et al. (1995)	2 Apr 1984 to 31 Dec 1994	2358
GPS (SIO93P01; Polar motion)					
Scripps	GPS	SIO	Bock et al. (1993)	25 Aug 1991 to 31 May 1992	265
GPS (JPL95P02; Polar motion)					
JPL	GPS	JPL	Heflin et al. (1995)	1 Jun 1992 to 31 Dec 1994	793
GPS (IGS95P01; Polar motion)					
IGS Combined	GPS	NRCan	Kouba and Mireault (1997)	1 Jan 1995 to 29 Jun 1996	533
GPS (IGS95P02; Polar motion)					
IGS Combined	GPS	NRCan	Kouba and Mireault (1997)	30 Jun 1996 to 3 Jan 1998	546

1994, with measurements from the USNO NEOS Intensive UT1 series used thereafter, and measurements from the NASA/GSFC SGP multibaseline very-long-baseline interferometry (VLBI) series were used until it ended on 16 July 1997, with measurements from the USNO multibaseline VLBI series used thereafter.

2.2 Data preprocessing and treatment of tide-induced rotational variations

The Earth-orientation series listed in Table 1 were first preprocessed by both removing leap seconds from the UT1 values and, when necessary, correcting the UT1 values to be consistent with the new definition of Greenwich Sidereal Time (GST) as adopted by the International Earth Rotation Service (IERS; IERS 1997, p. I–49). Since most of the series listed in Table 1 were already consistent with the new definition of GST, this correction was applied to only the JPL lunar laser ranging (LLR) series and the NOAA IRIS Intensive UT1 series.

Rotational variations caused by solid Earth and ocean tides were also removed from the UT1 values. The effect of the solid Earth tides was removed by using the model of Yoder et al. (1981), and the model of Desai (1996) was used to remove the effect upon UT1 of the ocean tides at the *Mf*, *Mf*′, and *Mm* tidal frequencies. Since the Yoder et al. (1981) model already includes a contribution from the equilibrium ocean tides, just the Desai (1996) oceanic corrections to the Yoder et al. (1981) model were actually removed. Also note that the Desai (1996) model was used to remove the effect of ocean tides on only UT1, not on polar motion. Ocean tide-induced polar motion variations were not removed from any of the polar motion observations. Finally, the only Earth-orientation series listed in Table 1 to include the effects of semidiurnal and diurnal ocean tides on the Earth's orientation is the NOAA IRIS Intensive UT1 series. This series included these effects by adding to the released UT1 values the model of Herring (1993; also see Herring and Dong 1994). Hence, the same Herring (1993) model was used to remove these effects.

2.3 Adjustments made to space-geodetic series prior to combination

Prior to combining the series listed in Table 1 to form SPACE97, series-specific corrections were applied for bias and rate, the stated uncertainties of the measurements were adjusted by multiplying them by series-specific scale factors, and outlying data points were deleted. Values for the bias-rate corrections and uncertainty scale factors were determined by an iterative procedure wherein each series was compared, in turn, to a combination of all others. In order to minimize interpolation error (see Gross et al. 1998, pp. 223–225), the comparison of each series to its reference combination was done at the epochs of the measurements of that series by generating its reference combination using a Kalman filter that interpolates to and prints its EOP estimates at the exact epochs of those measurements. All the series listed in Table 1 were included in the iterative procedure, except the USNO multibaseline VLBI series which was treated separately as described below. Details of the iterative procedure, including (1) the use of a reference series, SPACE96 (Gross 1997), for initial bias-rate alignment, (2) the analysis of each data type in its own natural reference frame, (3) the clustering of the McDonald LLR stations and, separately, the DSN VLBI stations in California, Spain, and Australia, (4) initial convergence on values for the series-specific bias-rate corrections and uncertainty scale factors prior to the start of outlier detection and deletion, and (5) final convergence on these values after detecting and deleting all data outliers, are described in Gross (1996) and Gross et al. (1998) and will not be repeated here. At the end of the iterative procedure, relative bias-rate corrections have been determined that make the series agree with each other in bias and rate, uncertainty scale factors have been determined that make the residual of each series (when differenced with a combination of all others) have a reduced chi-square of one, and outlying data points (those whose residual values were greater than three times their adjusted uncertainties) have been deleted. A total of 272 data points, or about 2% of those available, were thus deleted.

The USNO multibaseline VLBI series was not included in the above iterative procedure for bias-rate correction and uncertainty scale factor determination since there is not enough overlap between its independent portion and the other series for reliable determinations of these corrections to be made (see Table 1). Instead, the bias-rate corrections and uncertainty scale factors for this series were determined by comparing it to a reference series, called its complementary smoothing, formed by combining all the other series after they had had the bias-rate corrections and uncertainty scale factors applied to them that had been determined for them as described above. In order to be able to determine a reliable rate correction for the USNO multibaseline VLBI series, all of its data points after 1 January 1993 were used for this purpose, even though only those after 23 July 1997 ultimately get incorporated into SPACE97. Thus, in order for the reference series to be completely independent of the USNO multibaseline VLBI series, only that portion of the NASA/GSFC SGP multibaseline VLBI series before 1 January 1993 was selected and included in the reference series. Besides determining the bias-rate corrections and uncertainty scale factors, outlying data points were also detected and deleted when comparing the USNO multibaseline VLBI series to its complementary smoothing. Two such outlying data points were found in that portion of the USNO multibaseline VLBI series that is ultimately incorporated into SPACE97, that is, in that portion after 23 July 1997.

Finally, each series was placed within a particular IERS reference frame by applying to it an additional bias-rate correction that is common to all the series. This additional correction was determined by first combining all the series, including the USNO multibaseline VLBI series, after applying to them the relative bias-rate corrections and uncertainty scale factors that had been determined for them as described above. This intermediate combination was then compared to the IERS combined Earth-orientation series EOP(IERS) 97 C 04 (IERS 1997, p. II–64) during the interval 1987–1997 in order to obtain the additional bias-rate correction required to make it, and therefore each individual series, agree in bias and rate with the IERS series.

The total bias-rate corrections and uncertainty scale factors determined by the procedures outlined above are given in Table 2. Except for the USNO multibaseline VLBI series (whose entries in Table 2 are simply those determined when comparing it to its complementary smoothing), the values of the bias-rate corrections given in Table 2 are the sum of all the incremental corrections applied during the iterative procedure, the corrections applied to initially align the series with each other, and the additional common correction applied in order to place each series within that particular IERS reference frame defined by the IERS combined Earth-orientation series EOP(IERS) 97 C 04. The values of the uncertainty scale factors given in Table 2 are the products of all the incremental scale factors determined during the iterative procedure. The uncertainties of the bias-rate corrections given in Table 2 are the 1σ standard errors in determining the incremental bias-rate corrections during the last iteration. There are no bias-rate entries in Table 2 for components that were either not used (e.g. the UTCSR SLR UT1 component), or not available (e.g. the NOAA IRIS intensive polar motion components). Note that the same IERS rate correction is applied to all the data sets, including those, such as the Scripps GPS polar motion series, for which no relative rate correction could be determined. Therefore, the rate corrections given in Table 2 for those series for which no relative rate corrections could be determined are simply the IERS rate corrections, but given, of course, in the natural reference frame of that series. In these cases, no uncertainties for the rate corrections are given.

2.4 *SPACE97*

A Kalman filter was used to combine the series listed in Table 1 after the bias-rate corrections and uncertainty scale factors listed in Table 2 had been applied to them. The resulting combined Earth-orientation series,

Table 2. Adjustments to space-geodetic series. Reference date for bias-rate adjustment is 1993.0. See Table 1 for definitions of acronyms

Data set name	Bias (mas)			Rate (mas/year)			Uncertainty scale factor		
LLR (JPL97M01)		VOL	UT0		VOL	UT0		VOL	UT0
McDonald Cluster		0.195 ± 0.119	−0.343 ± 0.099		−0.038 ± 0.040	−0.128 ± 0.033		1.437	1.131
Cerga		0.235 ± 0.056	−0.019 ± 0.037		0.134 ± 0.021	−0.023 ± 0.013		1.823	1.370
Haleakala		1.177 ± 1.069	−1.771 ± 0.711		−0.101 ± 0.215	−0.172 ± 0.150		1.867	1.656
DSN (JPL97R01)		T	V		T	V		T	V
California–Spain Cluster		−0.622 ± 0.023	−0.176 ± 0.055		0.102 ± 0.009	0.120 ± 0.024		1.431	1.115
California–Australia Cluster		0.780 ± 0.019	0.524 ± 0.052		0.028 ± 0.007	0.023 ± 0.021		1.392	1.053
NASA SGP (GLB1083c)		T	V		T	V		T	V
Westford–Fort Davis		14.318 ± 3.765	9.725 ± 6.657		1.333 ± 0.378	1.037 ± 0.666		1.276	0.966
Westford–Mojave		0.572 ± 0.205	0.082 ± 0.331		−0.023	−0.037		2.587	0.731
NASA SGP (1083c)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multibaseline	−0.095 ± 0.008	0.077 ± 0.007	0.186 ± 0.013	−0.068 ± 0.003	0.020 ± 0.003	−0.066 ± 0.004	1.636	1.571	1.650
USNO (N9708)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multibaseline	0.021 ± 0.024	−0.162 ± 0.019	−0.280 ± 0.035	−0.023 ± 0.008	0.028 ± 0.006	0.051 ± 0.012	1.943	1.767	1.652
USNO (N9708)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
NEOS Intensive	–	–	−0.209 ± 0.091	–	–	0.038 ± 0.028	–	–	1.243
NOAA (95R02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IRIS Intensive	–	–	0.309 ± 0.021	–	–	−0.026 ± 0.006	–	–	0.943
UTCSR (96L01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Lageos	−0.077 ± 0.012	0.775 ± 0.010	–	0.054 ± 0.004	0.102 ± 0.003	–	0.907	0.799	–
GPS (SIO93P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Scripps	−1.123 ± 0.033	−0.952 ± 0.039	–	−0.030	−0.160	–	1.874	1.913	–
GPS (JPL95P02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
JPL	−0.114 ± 0.022	0.497 ± 0.021	–	0.121 ± 0.019	−0.077 ± 0.017	–	2.843	2.516	–
GPS (IGS95P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IGS Combined	0.152 ± 0.082	0.350 ± 0.063	–	0.159 ± 0.029	0.255 ± 0.023	–	2.420	1.244	–
GPS (IGS95P02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IGS Combined	−0.748 ± 0.020	−0.543 ± 0.011	–	0.104	0.103	–	8.833	1.041	–

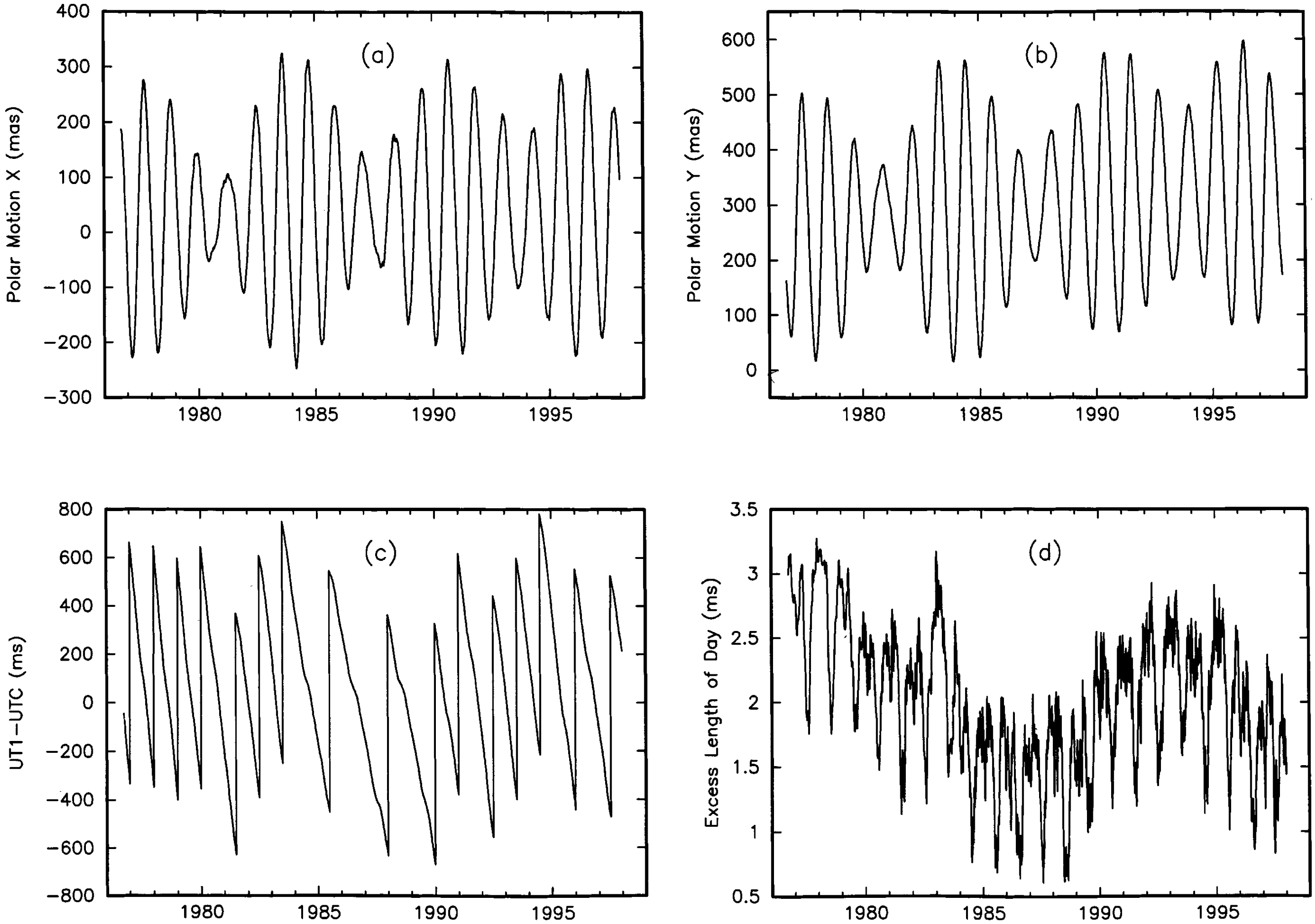

Fig. 1. Plots of **a** x component of polar motion, **b** y component of polar motion, **c** UT1–UTC, and **d** excess length of day (LOD) as given by the combined Earth-orientation series SPACE97. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Note that the UT1–UTC values displayed in **c** include the tidal variations, whereas the LOD values shown in **d** do not

SPACE97, consists of values (Fig. 1) and 1σ standard errors (Fig. 2) for universal time, polar motion, and their rates spanning the period 28 September 1976 to 3 January 1998 at daily intervals. Leap seconds have been restored to UT1, and the effects of the solid Earth and ocean tides have been added back to the UT1 values using the same models for these effects that were originally used to remove them from the raw series, namely the Yoder et al. (1981) model for the solid Earth tides and the Desai (1996) model for the ocean tides. However, semidiurnal and diurnal ocean tidal terms have not been added to, and are therefore not included in, the SPACE97 UT1 values.

3 COMB97

COMB97 extends SPACE97 by additionally incorporating the optical astrometric polar motion and UT1 series that was determined at the Bureau International de l'Heure (BIH) from an analysis of time and latitude observations by Li (1985; also see Li and Feissel 1986). This BIH optical astrometric series consists of values and uncertainties for polar motion and UT1 spanning the period 5 January 1962 to 31 December 1981 at 5-day intervals.

3.1 Data preprocessing and treatment of tide-induced rotational variations

The BIH optical astrometric series was first preprocessed by both removing leap seconds from the UT1 values and correcting the UT1 values to be consistent with the new definition of GST as adopted by the IERS (IERS 1997, p. I–49). Rotational variations caused by solid Earth and ocean tides were also removed from the UT1 values. The same models for the tidal effects that were used to remove them from the series used to generate SPACE97 were also used to remove them from the BIH series, namely, the Yoder et al. (1981) model for the solid Earth tides and the Desai (1996) model for the *Mf*, *Mf′*, and *Mm* ocean tides. However, since the BIH UT1 measurements represent an average value over a 5-day-long observation window, and since 5 days is a substantial fraction of the monthly and shorter-period tides, the amplitudes of these solid Earth and ocean tidal terms were attenuated prior to their removal from the BIH UT1

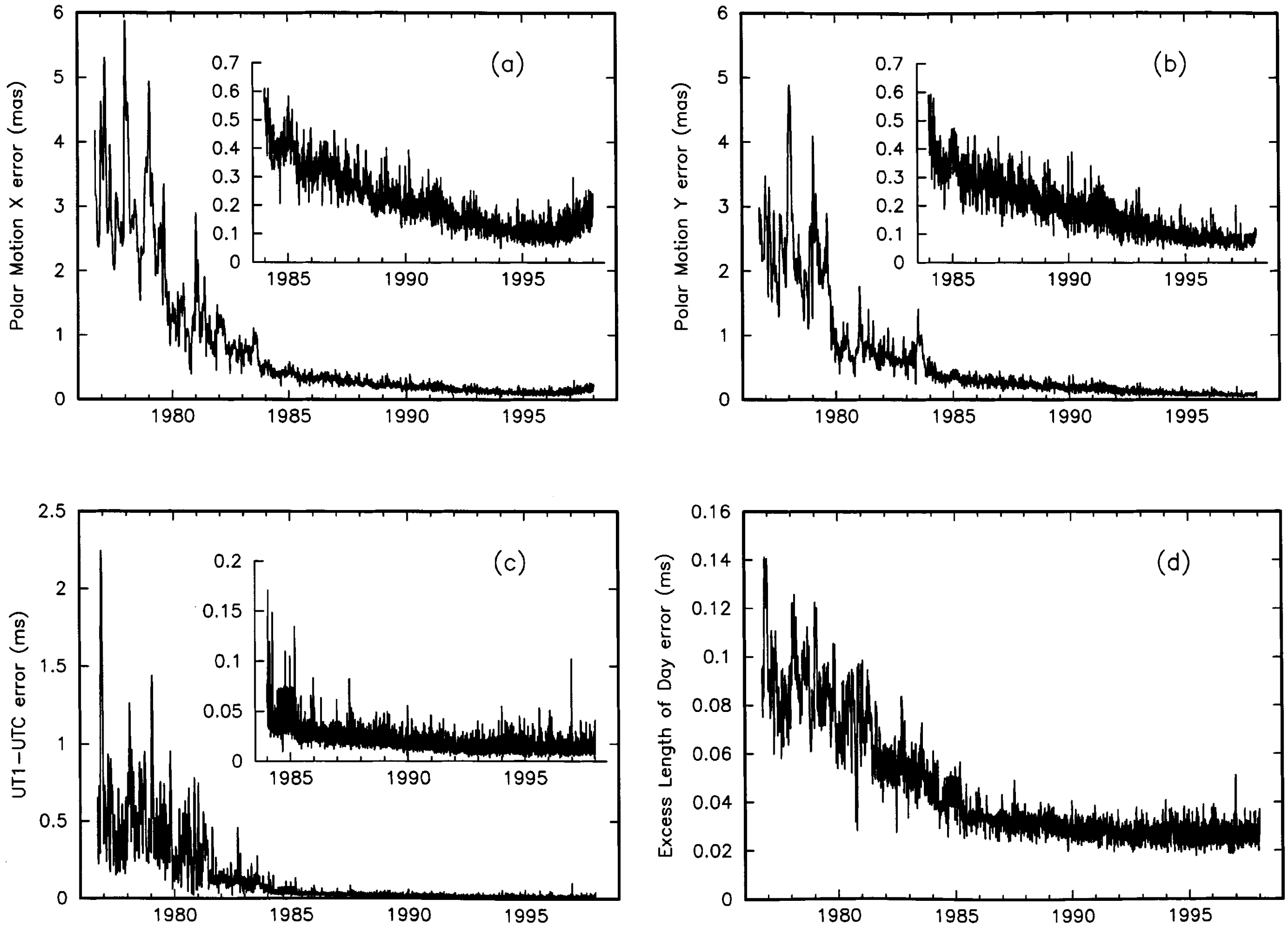

Fig. 2. Plots of the 1σ formal errors in the determination of **a** x component of polar motion, **b** y component of polar motion, **c** UT1–UTC, and **d** excess LOD as given by the combined Earth-orientation series SPACE97. The *insert* within panels **a**, **b**, and **c** shows that component's post-1984 uncertainties on an expanded scale with the same units [milliarcseconds (mas) for polar motion, milliseconds (ms) for UT1–UTC]

measurements (see Gross 1996, p. 8735 and Gross et al. 1998, pp. 226–227 for further discussion about this point).

3.2 Adjustments made to BIH series prior to combination

The preprocessed BIH optical astrometric series was combined with the space-geodetic series comprising SPACE97 after first: (1) correcting the BIH series to have the same bias, rate, and annual term as SPACE97; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the BIH series so that its residual, when differenced with SPACE97, had a reduced chi-square of one; and (3) deleting those data points whose residual values were greater than three times their adjusted uncertainties. The procedure used to determine these bias-rate and annual term corrections, uncertainty scale factors, and outlying data points has been described before (Gross 1996, pp. 8735–8738) and will not be repeated here. The annual term of the BIH series was adjusted in order to correct for systematic, seasonally varying effects that are known to be present in optical astrometric measurements. Since the values of both the BIH and SPACE97 series are given at midnight, interpolation error (see Gross et al. 1998, pp. 223–225) is automatically minimized when differencing these two series for the purpose of determining the adjustments to be made to the BIH series. Tables 3 and 4 give the resulting uncertainty scale factors and values and 1σ

Table 3. Adjustments to bias, rate, and stated uncertainty of optical astrometric series. Reference date for bias-rate adjustment of BIH series is 1980.0; reference date for bias-rate adjustment of ILS series is 1970.0

Data set	PMX	PMY	UT1
Bias (mas)			
BIH	−0.484 ± 0.837	−2.196 ± 0.658	−8.061 ± 0.724
ILS	−50.643 ± 2.206	−1.113 ± 1.719	–
Rate (mas/year)			
BIH	1.096 ± 0.476	0.891 ± 0.181	5.244 ± 0.310
ILS	0.048 ± 0.453	−0.269 ± 0.352	–
Uncertainty scale factor			
BIH	1.822	1.628	1.897
ILS	2.012	1.559	–

Table 4. Adjustment to annual term of optical astrometric series. Reference date for adjustment to annual term of BIH series is 1980.0; reference date for adjustment to annual term of ILS series is 1970.0

Data set	PMX	PMY	UT1
Coefficient of sine term (mas)			
BIH	−5.780 ± 1.005	−6.439 ± 0.630	5.268 ± 0.768
ILS	−0.481 ± 3.086	7.914 ± 2.401	–
Coefficient of cosine term (mas)			
BIH	−3.376 ± 1.060	9.233 ± 0.693	−1.001 ± 0.820
ILS	9.137 ± 3.119	−10.290 ± 2.429	–

standard errors of the bias, rate, and annual term corrections thus determined for the BIH series. When determining these uncertainty scale factors and bias, rate, and annual term corrections, four outlying data points were detected and deleted from the BIH series.

3.3 COMB97

A Kalman filter was used to combine the BIH series with the adjusted space-geodetic series comprising SPACE97 after applying to the BIH series the corrections for bias, rate, annual term, and measurement uncertainty given in Tables 3 and 4. The resulting combined Earth-orientation series, COMB97, consists of values (Fig. 3) and 1σ standard errors (Fig. 4) for universal time, polar motion, and their rates spanning the period 20 January 1962 to 1 January 1998 at 5-day intervals. Leap seconds have been restored to UT1, and the effects of the solid Earth and ocean tides have been added back to the UT1 values using the same models for these effects that were originally used to remove them, namely, the Yoder et al. (1981) model for the solid Earth tides and the Desai (1996) model for the ocean tides. The full amplitude, with no tidal terms being attenuated, of the effects of the solid Earth and ocean tides at the epoch of the time tag were added back to the UT1 values. Semidiurnal and diurnal ocean tidal terms have not been added to, and are therefore not included in, the COMB97 UT1 values.

4 POLE97

No optical astrometric observations taken at the stations of the International Latitude Service (ILS) were

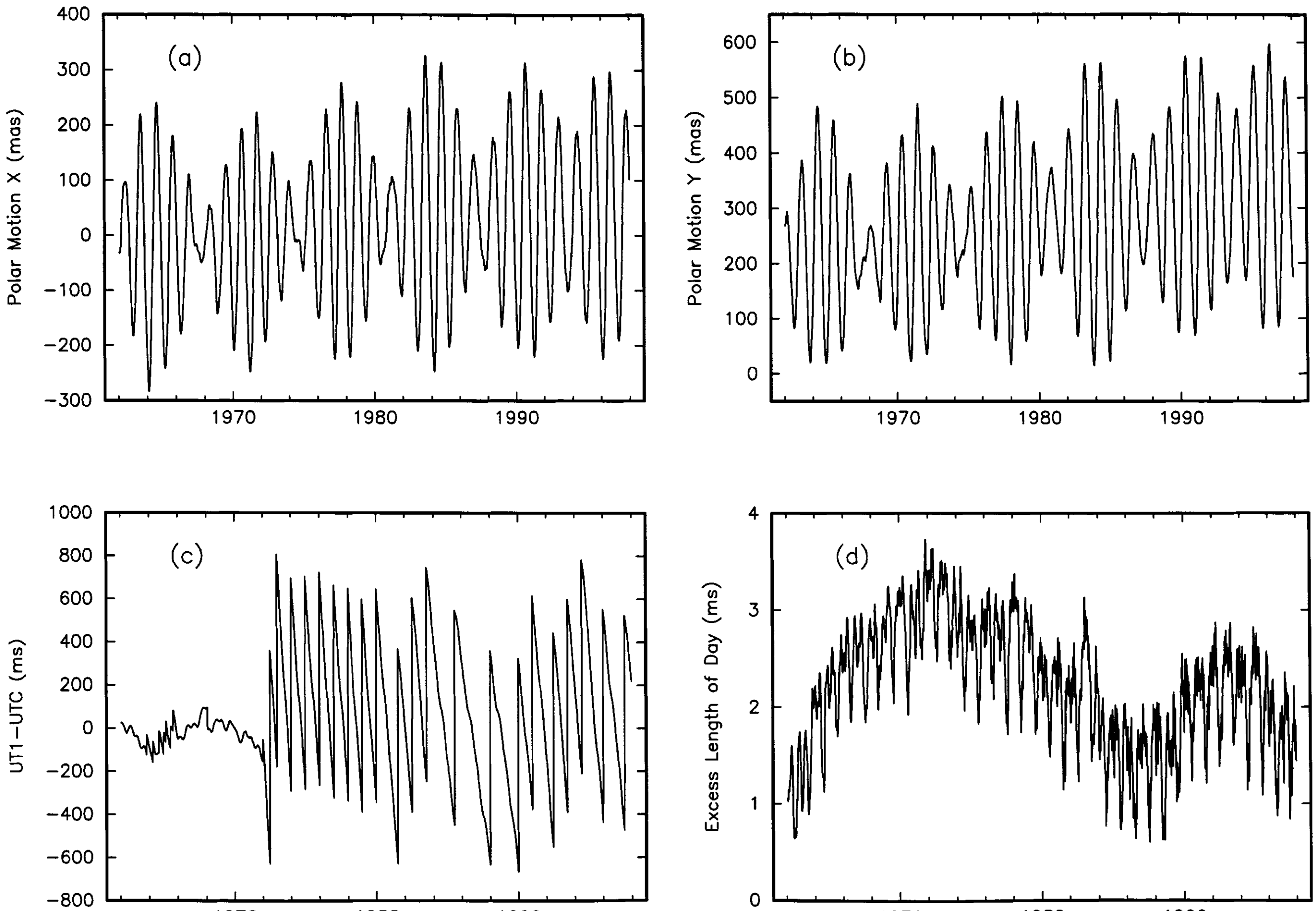

Fig. 3. Plots of **a** x component of polar motion, **b** y component of polar motion, **c** UT1–UTC, and **d** excess LOD as given by the combined Earth-orientation series COMB97. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Prior to the introduction of leap seconds in 1972, Coordinated Universal Time (UTC) was adjusted by introducing step and rate changes designed to keep it close to UT1 (e.g. IERS 1997, Table II-3), the effect of which is also readily apparent in **c**. Note that the UT1–UTC values displayed in **c** include the tidal variations, whereas the LOD values shown in **d** do not

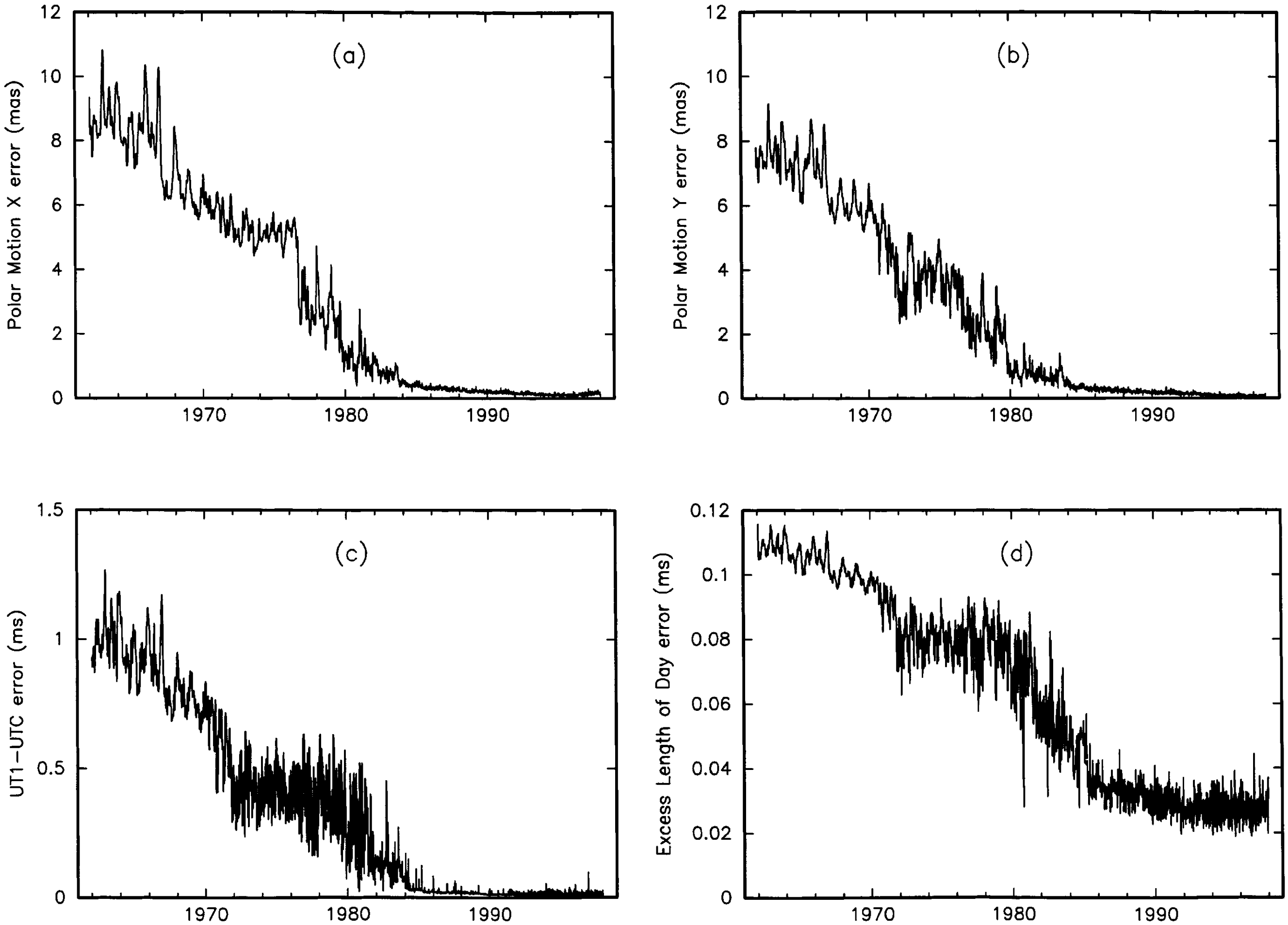

Fig. 4. Plots of the 1σ formal errors in the determination of **a** x component of polar motion, **b** y component of polar motion, **c** UT1–UTC, and **d** excess LOD as given by the combined Earth-orientation series COMB97

used in creating the BIH optical astrometric series that was used to generate COMB97 (Li 1985; Li and Feissel 1986). The ILS polar motion measurements (Yumi and Yokoyama 1980), which are based solely upon latitude observations made at the ILS stations, are therefore independent of those comprising COMB97 and have therefore been combined with them to form POLE97. Being based solely upon latitude observations, the ILS series contains no UT1 measurements but consists only of polar motion measurements spanning the period 1899.8 to 1979.0 at monthly intervals. Although no uncertainties are given with the individual polar motion values, the precision with which they have been determined is estimated to be 10–20 mas (Yumi and Yokoyama 1980, p. 27). An initial uncertainty of 15 mas was therefore assigned to each of the ILS polar motion values. Since this assigned measurement uncertainty will be adjusted later, its initial value is arbitrary, so long as it is not zero, and serves merely as an a priori estimate to be used in the series adjustment procedure described below.

The ILS series was combined with COMB97 to form POLE97 after first: (1) correcting the ILS series to have the same bias, rate, and annual term as COMB97; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the ILS series so that its residual, when differenced with COMB97, had a reduced chi-square of one; and (3) deleting those data points whose residual values were greater than three times their adjusted uncertainties. These adjustments were determined separately for the x and y components of the ILS polar motion series by fitting a bias, rate, and annual term to the difference of the ILS series with COMB97 during the period 1962.0 to 1979.0. The measurement uncertainties of the ILS polar motion values were adjusted by determining and applying a scale factor that made the residual of this fit have a reduced chi-square of one. During this procedure to determine uncertainty scale factors and bias, rate, and annual term corrections, four outlying ILS data points were detected and deleted. Tables 3 and 4 give the resulting uncertainty scale factors, and values and 1σ standard errors of the bias, rate, and annual term corrections thus determined for the ILS series.

A Kalman filter was then used to combine the ILS series with the adjusted BIH and space-geodetic series comprising COMB97 after applying to the ILS series the corrections for bias, rate, annual term, and measurement uncertainty given in Tables 3 and 4. The resulting combined Earth-orientation series, POLE97, consists of values (Fig. 5a, b) and 1σ standard errors (Fig. 5c, d) for

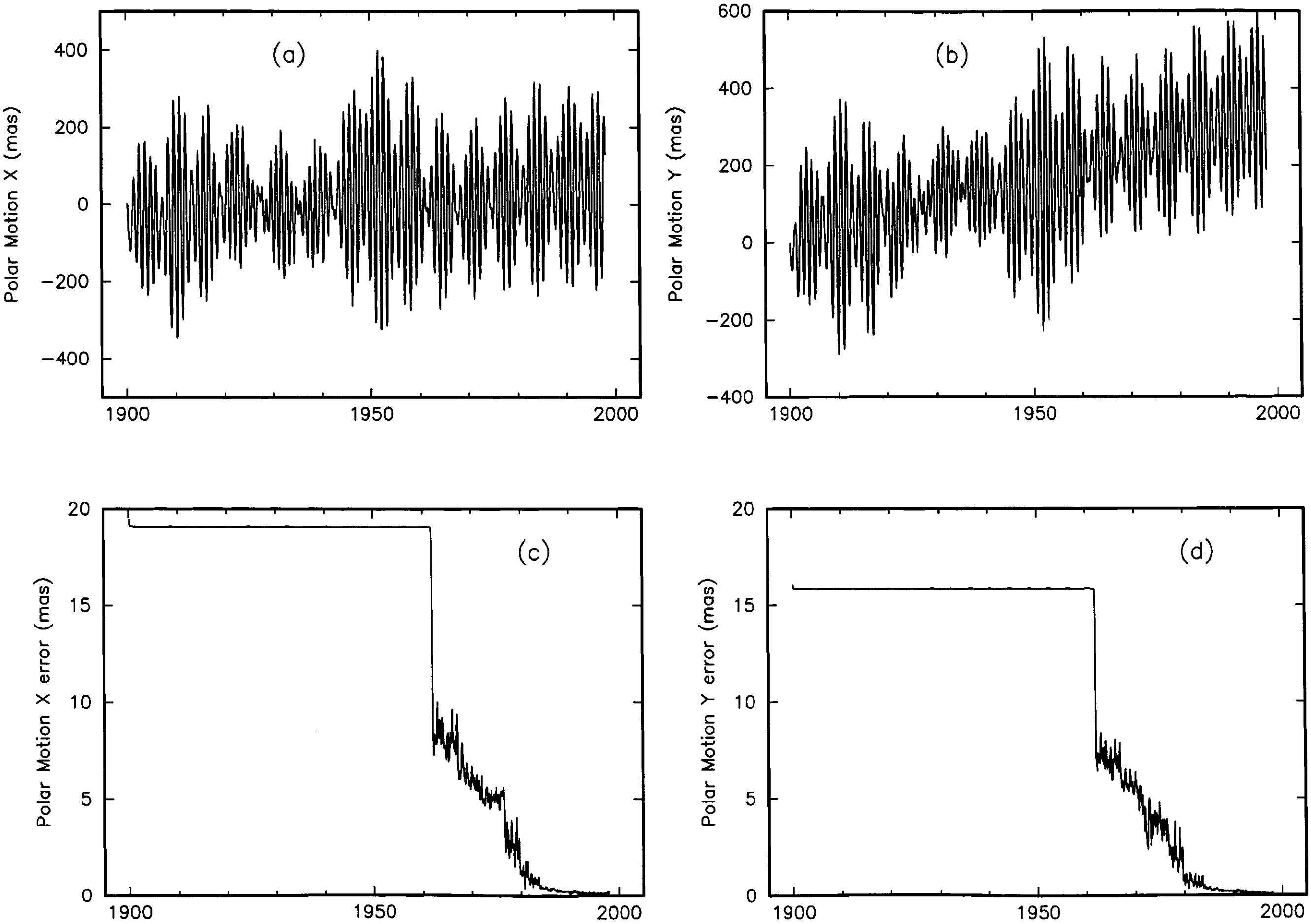

Fig. 5. Plots of **a** x component of polar motion, **b** y component of polar motion, **c** 1σ formal errors in the determination of the x component of polar motion, and **d** $1\ \sigma$ formal errors in the determination of the y component of polar motion as given by the combined polar motion series POLE97

polar motion and its rate spanning the period 20 January 1900 to 21 December 1997 at 30.4375-day intervals.

5 Discussion

An individual series of Earth-orientation parameters is determined from a series of measurements taken at a particular set of observing stations. By definition, the locations and velocities of those observing stations determine the terrestrial reference frame within which that individual Earth-orientation series is given. Different Earth-orientation series, being based upon measurements taken at different sets of observing stations, will therefore be given within different terrestrial reference frames. Since each set of observing stations is likely to be located on a different subset of the tectonic plates, and since the model of tectonic plate motions is not perfectly accurate, then the solution-specific terrestrial reference frames can be expected to be offset from each other (thereby causing the EOP series to differ in bias) and to drift away from each other (thereby causing the EOP series to differ in rate) even though each analysis center has followed the procedures and standards recommended by the IERS (McCarthy 1996). These differences in the bias and rate of the individual Earth-orientation series must be removed before the series are combined. Furthermore, since the international terrestrial reference frame (currently ITRF96) within which each EOP solution is nominally given changes from year to year, then the values for the bias-rate corrections determined for a particular EOP series can be expected to change from year to year. Thus, for example, the bias-rate corrections determined for the EOP series used to generate SPACE97 (given in Table 2) are somewhat different from those determined for the EOP series used to generate SPACE95 (Gross et al. 1998, Table 7). These differences are likely to be due to differences in the underlying terrestrial reference frames within which each EOP series is given and to year-to-year differences in the analysis procedures used to determine the EOP series.

The accuracy of any combined Earth-orientation series is primarily a function of the accuracy of the individual series being combined. As the accuracies of the individual series change with time, so will the accuracy of the combined series. This is particularly evident in the x component of the SPACE97 polar motion values, where from Fig. 2a it is seen that the uncertainties of the post-1996.5 values are somewhat larger than those of the 1995.0–1996.5 values. From Table 2 it is seen that the uncertainty scale factor (8.833) applied to the x component of the GPS polar motion series used after 30 June 1996 [the IGS combined series EOP(IGS) 95 P 02] is much larger than that (2.420) applied to the x component of the GPS series used during the period 1995.0–1996.5 [the IGS combined series EOP(IGS) 95 P 01], reflecting the larger scatter (not shown) in its residual series. Since the adjusted uncertainties of the x component of the GPS polar motion series used after 1996.5 are much larger than those used during the period 1995.0–1996.5, the uncertainties of the x component of the SPACE97 combined series are greater after 1996.5 than they are during the period 1995.0–1996.5. This is not evident in the y component of the SPACE97 polar motion values since the uncertainty scale factors applied to the y components of the two GPS polar motion series are more nearly equal, being 1.244 for the series used during the period 1995.0–1996.5 versus 1.041 for that used after 1996.5. Since the adjusted uncertainties of the y components of the two GPS polar motion series are more nearly equal, the uncertainties of the y component of the corresponding SPACE97 polar motion values are also more nearly equal.

Since a Kalman filter has been used in generating SPACE97, COMB97 and POLE97, the resulting polar motion and UT1 values are smoothed to a degree depending upon both the spacing between the measurements being combined and the uncertainties that have been assigned to them. Since improvements to the observing systems, both in the hardware and software, and in the number of systems, have led to increasingly precise determinations of the Earth's orientation, and since the time resolution of the measurements has generally increased in concert with the measurement precision, the degree of smoothing applied to the SPACE97, COMB97, and POLE97 values is a function of time, with the earlier values being more heavily smoothed than the more recent values.

Daily EOP values are reported in SPACE97 since the NOAA IRIS and USNO NEOS Intensive UT1 values are given at daily intervals, as are the GPS polar motion values, although gaps exist in each of these data sets. However, prior to the start of these data sets, the measurements combined to form SPACE97 are given less frequently, and so the Kalman filter used to combine these measurements also interpolates them in order to produce a series of equally spaced values. Thus, SPACE97, COMB97, and POLE97 are equally spaced series of smoothed, interpolated Earth-orientation parameters.

The combined Earth-orientation series SPACE97, COMB97, and POLE97 are available upon request from the author. They can also be obtained from NASA's Crustal Dynamics Data Information System (CDDIS) by anonymous ftp to cddisa.gsfc.nasa.gov (128.183.102.102), where they can be found in the pub/jpl/1997 directory.

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