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Combinations of Earth Orientation Measurements: SPACE2001, COMB2001, and POLE2001

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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, SPACE2001, consists of values and uncertainties for Universal Time, polar motion, and their rates that span from September 28.0, 1976 to January 19.0, 2002 at daily intervals. The space-geodetic measurements used to generate SPACE2001 have then been combined with optical astrometric measurements to form two additional combined Earth orientation series: (1) COMB2001, consisting of values and uncertainties for Universal Time, polar motion, and their rates that span from January 20.0, 1962 to January 15.0, 2002 at 5-day intervals, and (2) POLE2001, consisting of values and uncertainties for polar motion and its rate that span from January 20, 1900 to December 21, 2001 at 30.4375-day intervals.

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TABLE OF CONTENTS

Introduction 1

SPACE2001 2
Data Sets Combined to Form SPACE2001 2
Data Preprocessing and Treatment of Tide-Induced Rotational Variations 2
Adjustments Made to Space-Geodetic Series Prior to Combination 4
Combined EOP Series: SPACE2001...7

COMB2001..11
Data Preprocessing and Treatment of Tide-Induced Rotational Variations 11
Adjustments Made to BIH Series Prior to Combination..11
Combined EOP Series: COMB2001 12

POLE2001..15

Discussion..17

References 18

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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: SPACE2001, COMB2001, and POLE2001. 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 regarding the approach used at JPL to annually combine independent measurements of the Earth's orientation can be found in Gross (1996, 2000) and Gross et al. (1998).

SPACE2001

Data Sets Combined to Form SPACE2001

SPACE2001 is a combination of independent space-geodetic measurements of the Earth's orientation. Table 1 lists the space-geodetic series used in generating SPACE2001, giving their identifiers, the number of measurements from each series that were actually incorporated into SPACE2001, and the time interval spanned by those measurements. Note that the University of Texas Center for Space Research (UTCSR) satellite laser ranging (SLR) Universal Time (UT) values were not used in generating SPACE2001 due to problems associated with separating this component of the Earth's orientation from the effects of unmodeled forces acting on the satellite that cause the node of its orbit to drift (see Gross et al. 1998, p. 217 for further discussion about this point). Similarly, no global positioning system (GPS) or Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC) SLR length-of-day (LOD) values have been used in generating SPACE2001.

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 through May 31, 1992; measurements from the JPL GPS series were then used until the start of the International GPS Service (IGS) combined series EOP(IGS) 95 P 01 on January 1, 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 June 30, 1996; measurements from the IGS combined series EOP(IGS) 95 P 02 were used until the start of the accumulated IGS Software-Independent Exchange (SINEX) combined series EOP(IGS) 00 P 02 on February 27, 2000; and measurements from the accumulated IGS SINEX combined series EOP(IGS) 00 P 02 were used thereafter. Similarly, measurements from the National Oceanic and Atmospheric Administration (NOAA) International Radio Interferometric Surveying (IRIS) Intensive UT1 series were used until it ended on December 31, 1994; measurements from the USNO National Earth Orientation Service (NEOS) Intensive UT1 series were then used until it ended on December 4, 2000; and measurements from the GSFC NEOS Intensive UT1 series were used thereafter. In addition, measurements from the UTCSR SLR series EOP(CSR) 96 L 01 were used until it ended on February 4, 1996, with measurements from the JCET/GSFC SLR series used thereafter. Furthermore, due to systematic errors evident in the series of lunar laser ranging (LLR) measurements taken at the Observatoire de la Côte d'Azur (OCA) station starting in early 1997, only the OCA LLR measurements through December 17, 1996 were used.

Data Preprocessing and Treatment of Tide-Induced Rotational Variations

The Earth orientation series listed in Table 1 were first preprocessed by removing leap seconds from the UT1 values and, when necessary, by 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. I49). Since most of the series listed in Table 1 were

Table 1. Data Sets Combined to Form SPACE2001

Data Set Name	Data Type	Analysis Center	Reference	Data Span	Number
LLR (JPL98M01; VOL, UT0)					
McDonald Cluster	LLR	JPL	Williams et al. (1998)	Oct. 5, 1976 to Feb. 20, 1998	588
OCA	LLR	JPL	Williams et al. (1998)	April 7, 1984 to Dec. 17, 1996	633
Haleakala	LLR	JPL	Williams et al. (1998)	Feb. 10, 1985 to Aug. 11, 1990	70
UTCSR (CSR96L01)					
Lageos Polar Motion	SLR	UTCSR	Eanes and Watkins (1996)	Sep. 28, 1976 to Feb. 4, 1996	2220
JCET/GSFC (JCET02L12)					
Daily Lageos Polar Motion	SLR	JCET/GSFC	Pavlis (2002)	Feb. 7, 1996 to Jan. 18, 2002	2164
DSN (JPL97R01; T, V)					
California-Spain Cluster	VLBI	JPL	Steppe et al. (1997)	Nov. 26, 1979 to Dec. 10, 2001	760
California-Australia Cluster	VLBI	JPL	Steppe et al. (1997)	Oct. 28, 1978 to Sep. 30, 1997	697
NOAA (NOAA95R02)					
IRIS Intensive UT1	VLBI	NOAA	Ray et al. (1995)	April 2, 1984 to Dec. 31, 1994	2393
USNO (N9903)					
NEOS Intensive UT1	VLBI	USNO	Eubanks et al. (1999)	Jan. 4, 1995 to Dec. 4, 2000	1497
NASA/GSFC (GSFINT03)					
NEOS Intensive UT1	VLBI	GSFC	Petrov and Ma (2001)	Dec. 6, 2000 to Jan. 19, 2002	222
NASA/GSFC (GSF2001c)					
Multibaseline	VLBI	GSFC	Petrov and Ma (2001)	April 12, 1980 to Jan. 18, 2002	2829
NASA/GSFC (GSFC1122)					
Westford-Fort Davis	VLBI	GSFC	Ma and Gordon (1999)	June 25, 1981 to Jan. 1, 1984	105
Westford-Mojave	VLBI	GSFC	Ma and Gordon (1999)	March 21, 1985 to Aug. 6, 1990	18
GPS (SIO93P01; Polar motion)					
Scripps	GPS	SIO	Bock et al. (1993)	Aug. 25, 1991 to May 31, 1992	270
GPS (JPL 2001.8; Polar motion)					
Post-processed Flinn Analysis	GPS	JPL	Heflin et al. (2001)	June 1, 1992 to Dec. 31, 1994	867
GPS (IGS95P01; Polar motion)					
IGS Final Combination (ITRF93)	GPS	NRCan	Kouba and Mireault (1997)	Jan. 1, 1995 to June 29, 1996	545
GPS (IGS95P02; Polar motion)					
IGS Final Combination (IGS00)	GPS	CODE	Mireault and Kouba (2000)	June 30, 1996 to Feb. 26, 2000	1334
GPS (IGS00P02; Polar motion)					
IGS SINEX Comb. (IGS00)	GPS	NRCan	Ferland (2002)	Feb. 27, 2000 to Jan. 19, 2002	692

LLR, lunar laser ranging; JPL, Jet Propulsion Laboratory; VOL, variation of latitude; OCA, Observatoire de la Côte d'Azur; UTCSR, University of Texas Center for Space Research; SLR, satellite laser ranging; JCET, Joint Center for Earth Systems Technology; GSFC, Goddard Space Flight Center; DSN, Deep Space Network; T, transverse; V, vertical; VLBI, very long baseline interferometry; NOAA, National Oceanic and Atmospheric Administration; IRIS, International Radio Interferometric Surveying; USNO, United States Naval Observatory; NEOS, National Earth Orientation Service; NASA, National Aeronautics and Space Administration; GPS, Global Positioning System; SIO, Scripps Institution of Oceanography; IGS, International GPS Service; ITRF, International Terrestrial Reference Frame; NRCan, Natural Resources Canada; CODE, Center for Orbit Determination in Europe.

already consistent with the new definition of GST, this correction needed to be applied to only 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); the model of Kantha et al. (1998) 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, only the Kantha et al. (1998) oceanic corrections to the Yoder et al. (1981) model were actually removed. Also note that the Kantha et al. (1998) 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 that includes 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 them.

On Jnue 30, 1996 the IGS reference frame changed from the International Terrestrial Reference Frame ITRF93 to ITRF94; on March 1, 1998 it changed from ITRF94 to ITRF96; on August 1, 1999 it changed from ITRF96 to ITRF97; on February 27, 2000 it changed from ITRF97 to the IGS realization of ITRF97 known as IGS97; and on December 2, 2001 it changed from IGS97 to the IGS realization of ITRF2000, known as IGS00. These changes in reference frames potentially introduce discontinuities in the IGS combined Earth orientation series. However, the IGS Final combined series EOP(IGS) 95 P 02 and the accumulated IGS SINEX combined series EOP(IGS) 00 P 02 used here have had each of these segments aligned to IGS00. Thus, to within the uncertainty in determining the corrections required to align each segment to IGS00, the IGS combined series EOP(IGS) 95 P 02 and EOP(IGS) 00 P 02 used here should be reasonably homogeneous. They were, therefore, concatenated together; one set of bias-rate corrections and uncertainty scale factors were determined for them, as described below.

Adjustments Made to Space-Geodetic Series Prior to Combination

Prior to combining the series listed in Table 1 to form SPACE2001, 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. Also, both the bias-rate corrections and the uncertainty scale factors for all components of a given series were determined simultaneously in a multivariate approach using nonlinear weighted least squares. Using a multivariate approach allows the correlations between the components to be taken into account when determining the bias-rate corrections and uncertainty scale factors (see Gross et al. 1998, pp. 225). In addition, and just for the GPS series, the uncertainty scale factors were determined using just those GPS values whose epochs were within 12 hours of the epoch of a VLBI multibaseline measurement. Selecting the GPS values to be used in determining the uncertainty scale factors in this manner also helped to minimize the effects of interpolation error. The bias-rate corrections for the GPS series were, however, determined using all the values in the GPS series.

All the series listed in Table 1 were included in the iterative procedure except the NASA/GSFC NEOS Intensive UT1 series, which was treated separately, as described below. Details of the iterative procedure, including: (1) the use of a reference series, SPACE2000 (Gross

Table 2. Adjustments to Space-Geodetic Series

Data Set Name	Bias, mas			Rate, mas/yr			Uncertainty Scale Factor		
LLR (JPL98M01)		VOL	UT0		VOL	UT0	VOL		UT0
McDonald Cluster		–0.276 ± 0.110	0.085 ± 0.106		–0.182 ± 0.033	–0.064 ± 0.031	1.627		1.406
OCA		0.471 ± 0.062	0.033 ± 0.039		0.205 ± 0.024	0.053 ± 0.014	2.587		1.847
Haleakala		–2.437 ± 1.124	–1.386 ± 0.701		–0.608 ± 0.219	–0.173 ± 0.147	2.719		2.395
DSN (JPL97R01)		T	V		T	V	T		V
California-Spain Cluster		–0.665 ± 0.023	–0.191 ± 0.054		0.166 ± 0.005	0.120 ± 0.012	1.502		1.248
California-Australia Cluster		0.756 ± 0.018	0.483 ± 0.051		0.036 ± 0.007	–0.016 ± 0.021	1.499		1.164
NASA GSFC (1122)		T	V		T	V	T		V
Westford-Fort Davis		10.887 ± 3.997	5.571 ± 5.946		0.991 ± 0.401	0.520 ± 0.595	1.547		0.884
Westford-Mojave		1.131 ± 1.158	–0.091 ± 1.592		0.007	–0.008	2.461		0.654
NASA GSFC (2001c)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multibaseline	0.238 ± 0.008	–0.132 ± 0.007	0.159 ± 0.011	–0.026 ± 0.002	–0.039 ± 0.002	–0.038 ± 0.003	1.660	1.640	1.664
NOAA (95R02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IRIS Intensive	-----	-----	0.337 ± 0.023	-----	-----	–0.008 ± 0.007	-----	-----	1.035
USNO (N9903)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
NEOS Intensive	-----	-----	0.076 ± 0.042	-----	-----	–0.007 ± 0.008	-----	-----	1.325
GSFC (GSFINT03)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
NEOS Intensive	-----	-----	0.313 ± 0.066	-----	-----	–0.061 ± 0.010	-----	-----	1.386
UTCSR (96L01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Lageos	–0.155 ± 0.011	0.810 ± 0.009	-----	0.057 ± 0.004	0.114 ± 0.003	-----	0.891	0.784	-----
JCET (JCET02L12)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Daily Lageos	0.131 ± 0.025	0.251 ± 0.025	-----	–0.018 ± 0.004	–0.114 ± 0.004	-----	2.176	2.122	-----
GPS (SIO93P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Scripps	–1.266 ± 0.192	–1.034 ± 0.254	-----	–0.057 ± 0.218	–0.325 ± 0.294	-----	1.892	2.160	-----
GPS (JPL 2001.8)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
JPL	–0.052 ± 0.021	0.248 ± 0.017	-----	–0.023 ± 0.020	–0.068 ± 0.016	-----	1.442	1.094	-----
GPS (IGS95P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IGS ITRF93	–0.077 ± 0.084	0.525 ± 0.079	-----	0.247 ± 0.030	0.197 ± 0.028	-----	1.446	1.014	-----
GPS (IGS95P02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IGS IGS00	0.105 ± 0.025	–0.069 ± 0.023	-----	–0.015 ± 0.004	–0.010 ± 0.003	-----	1.930	1.285	-----
GPS (IGS00P02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
SINEX IGS00	0.105 ± 0.025	–0.069 ± 0.023	-----	–0.015 ± 0.004	–0.010 ± 0.003	-----	1.930	1.285	-----

Reference date for bias-rate adjustment is 1993.0. See Table 1 footnotes.

2001), 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, Australia, and Spain; (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, 2000) 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 near one; and outlying data points (those whose residual values are greater than four times their adjusted uncertainties) have been deleted. A total of 40 data points, or about 0.2% of those combined, were thus deleted.

The NASA/GSFC NEOS Intensive UT1 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. This reference series was 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 NASA/GSFC NEOS Intensive UT1 series, all of its data points after January 1, 1997 were used for this purpose, even though only those after December 6, 2000 ultimately get incorporated into SPACE2001. Thus, in order for the reference series to be completely independent of the NASA/GSFC NEOS Intensive UT1 series, only that portion of the USNO NEOS Intensive UT1 series before January 1, 1997 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 NASA/GSFC NEOS Intensive UT1 series to its complementary smoothing. However, no such outlying data points were found in that portion of the NASA/GSFC NEOS Intensive UT1 series that is ultimately incorporated into SPACE2001: that is, in that portion after December 6, 2000.

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 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) C 04 (IERS 2000, pp. 38–39 and p. 125) during the interval 1987–2001 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. The values of the bias-rate corrections given in Table 2 are the sum of: (1) all the incremental corrections applied during the iterative procedure, (2) the corrections applied to initially align the series with each other, and (3) 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) 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 of the incremental bias-rate corrections determined 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 Westford-Mojave single baseline VLBI 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 correction, but given, of course, in the natural reference frame of that series. In these cases, no uncertainties for the rate corrections are given. Also note that the entries in Table 2 for the two IGS combined series EOP(IGS) 95 P 02 and EOP(IGS) 00 P 02 are they same. Because these series were initially given within the same

IGS00 reference frame, they were concatenated together and only one set of bias-rate corrections and uncertainty scale factors were determined for them, as discussed above.

Combined EOP Series: SPACE2001

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, SPACE2001, consists of values (Figure 1) and 1σ standard errors (Figure 2) for polar motion, Universal Time, and their rates spanning September 28.0, 1976 to January 19.0, 2002 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 Kantha et al. (1998) model for the ocean tides. However, semidiurnal and diurnal ocean tidal terms have not been added to and are, therefore, not included in the SPACE2001 UT1 values.

Figure 3 is a plot of the difference between the SPACE2001 polar motion, UT1, and LOD values and those of the IERS combined Earth orientation series EOP(IERS) C 04. As can be seen, these two series are very consistent with each other, especially after 1987 when the root-mean-square (rms) of their difference is only 0.218 mas for the *x*-component of polar motion, 0.187 mas for the *y*-component, 0.025 ms for UT1, and 0.018 ms for LOD. Prior to 1984, the difference between these two series exhibits greater variability and even some systematic behavior, particularly in the *x*-component of polar motion. This systematic behavior is due to differences in the approaches used here and by the IERS to correct the bias and rate of the individual series before they are combined.

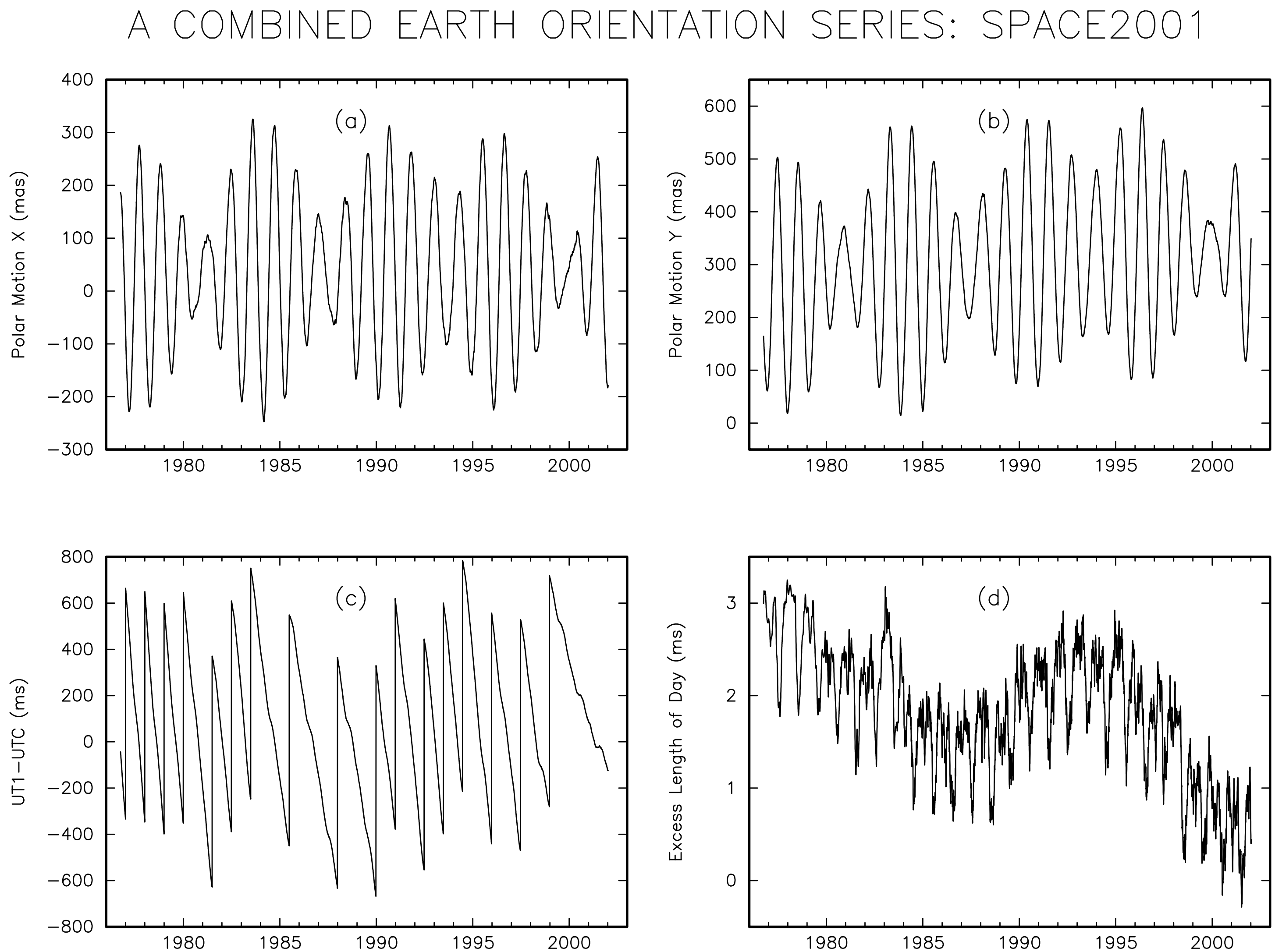

Figure 1. Plots of the *x*-component of polar motion (1a), *y*-component of polar motion (1b), UT1–UTC (1c), and excess length-of-day (1d) as given by the combined Earth orientation series SPACE2001. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Note that the UT1–UTC values displayed in 1c include the tidal variations, whereas the excess length-of-day values shown in 1d do not.

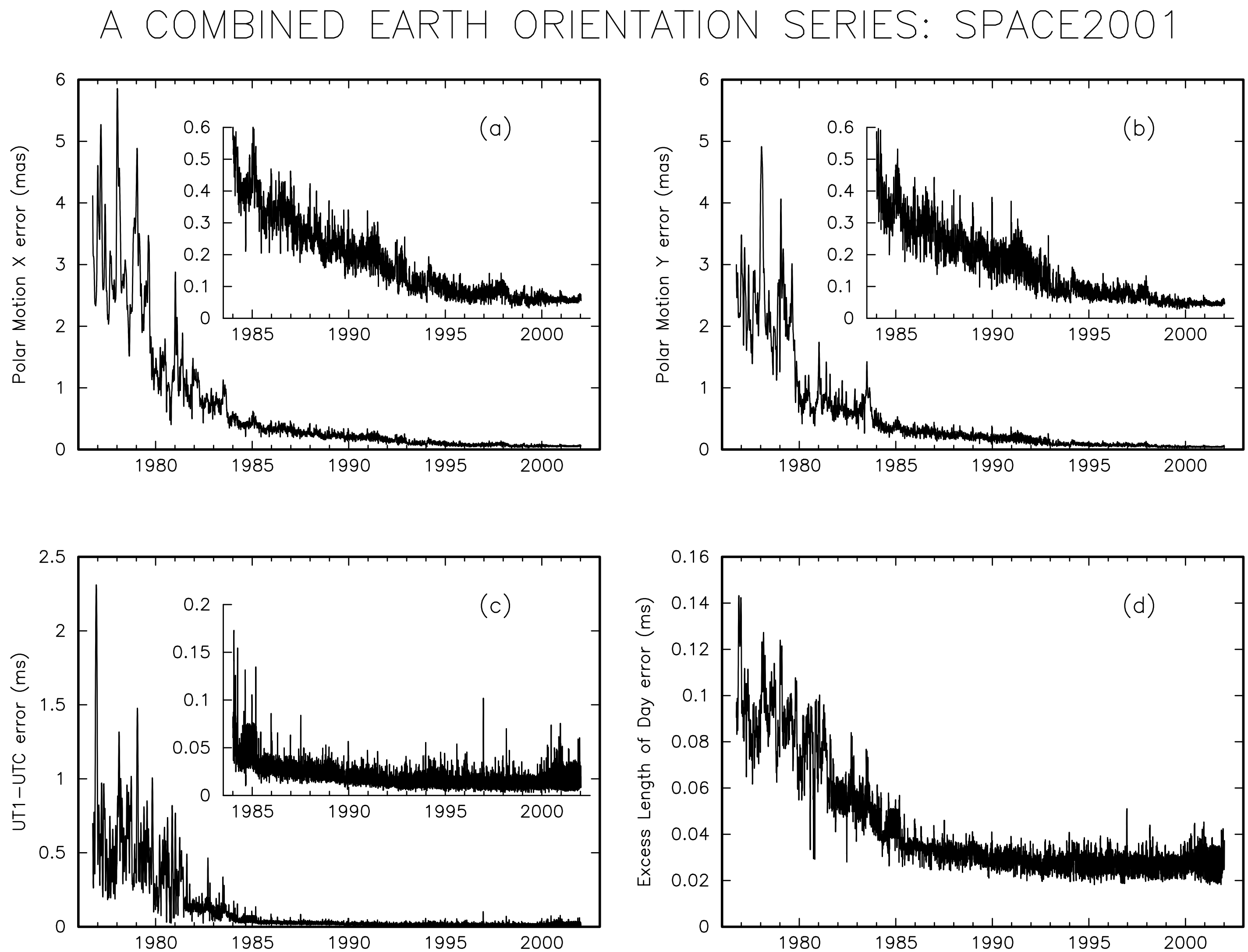

Figure 2. Plots of the 1σ formal errors of the *x*-component of polar motion (2a), *y*-component of polar motion (2b), UT1–UTC (2c), and excess length-of-day (2d) as given by the combined Earth orientation series SPACE2001. The insert within panels 2a, 2b, and 2c shows that component's post-1984 uncertainties on an expanded scale with the same units: milliarcseconds (mas) for polar motion, milliseconds (ms) for UT1-UTC.

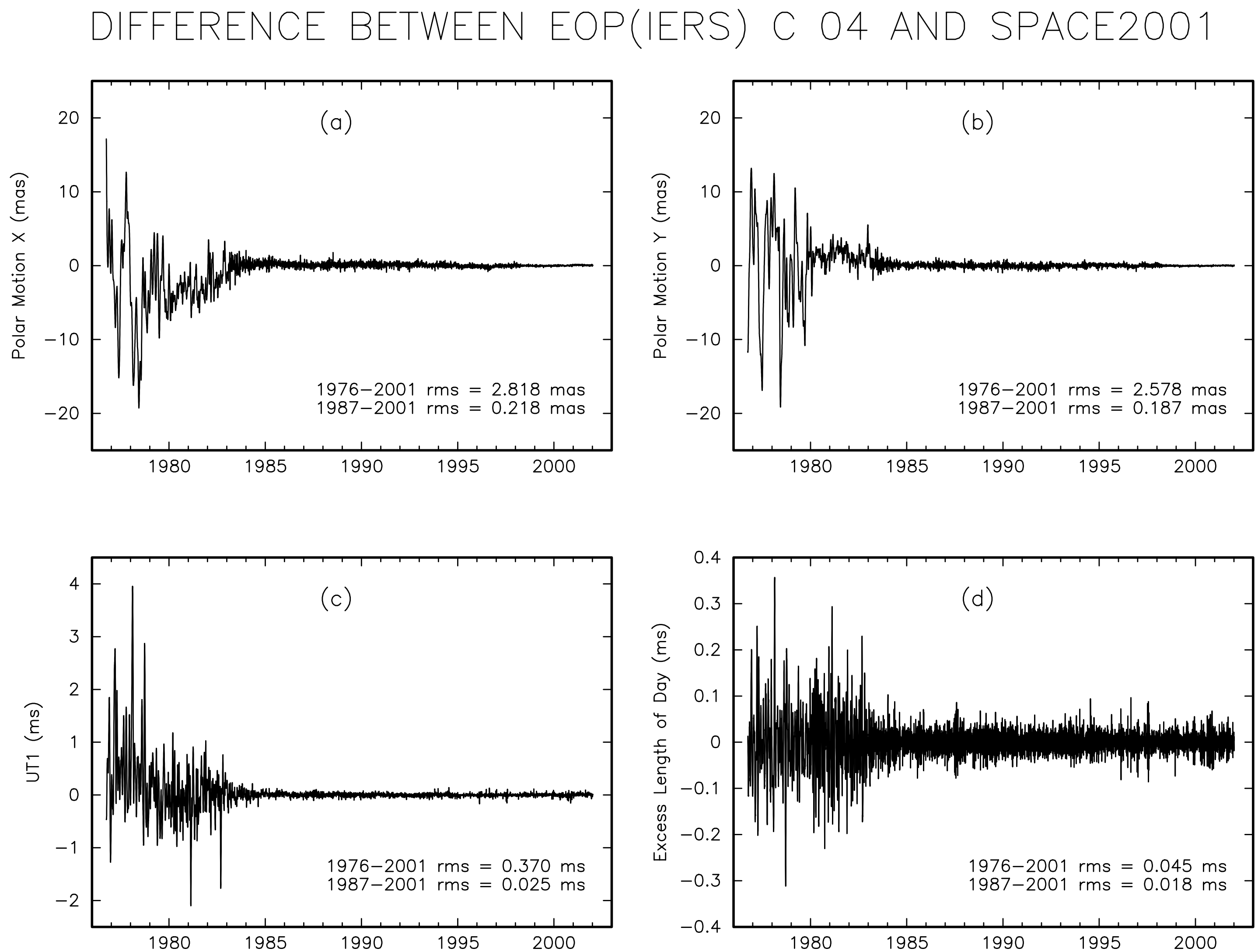

Figure 3. Plots of the difference between the IERS combined Earth orientation series EOP(IERS) C 04 and SPACE2001 formed by subtracting the SPACE2001 values from those of the IERS series. The difference between the *x*-component of polar motion is shown in 3a. The difference between the *y*-component is shown in 3b. The difference between UT1–UTC is shown in 3c. The difference between the excess length-of-day is shown in 3d.

COMB2001

COMB2001 extends SPACE2001 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 that span from January 5.0, 1962 to December 31.0, 1981 at 5-day intervals.

Data Preprocessing and Treatment of Tide-Induced Rotational Variations

The BIH optical astrometric series was first preprocessed by removing leap seconds from the UT1 values and by correcting the UT1 values to be consistent with the new definition of GST, as adopted by the IERS (IERS 1997, p. I49). 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 that were combined to form SPACE2001 were also used to remove them from the BIH series: namely, the Yoder et al. (1981) model for the solid Earth tides and the Kantha et al. (1998) 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 measurements. (See Gross 1996, p. 8735 and Gross et al. 1998, pp. 226–227 for further discussion about this point.)

Adjustments Made to BIH Series Prior to Combination

The preprocessed BIH optical astrometric series was combined with the space-geodetic series that comprise SPACE2001 after first: (1) correcting the BIH series to have the same bias, rate, and annual term as SPACE2001; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the BIH series so that its residual, when differenced with SPACE2001, had a reduced chi-square of one; and (3) deleting those data points, if any, whose residual values were greater than four times their adjusted uncertainties. Due to software limitations associated with the need to correct the annual term of the BIH series, the above adjustments were determined separately for each component of the BIH series in a univariate approach rather than simultaneously in a multivariate approach as was done for the series combined to form SPACE2001. 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 SPACE2001 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 standard errors of the bias, rate, and annual term corrections thus determined for the BIH series. When determining these uncertainty scale factors and the bias, rate, and annual term

Table 3. Adjustments to Bias, Rate, and Stated Uncertainty of Optical Astrometric Series

Data Set	Bias, mas			Rate, mas/yr			Uncertainty Scale Factor		
	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
BIH	-1.000 ± 0.855	-0.650 ± 0.724	-8.923 ± 0.769	1.201 ± 0.480	0.956 ± 0.193	5.439 ± 0.318	1.820	1.689	1.937
ILS	-50.706 ± 2.360	-0.809 ± 1.740	-----	0.569 ± 0.483	-0.285 ± 0.355	-----	2.177	1.589	-----

Reference date for bias-rate adjustment of BIH series is 1980.0. Reference date for bias-rate adjustment of ILS series is 1970.0.

Table 4. Adjustment to Annual Term of Optical Astrometric Series

Data Set	Coefficient of Sine Term, mas			Coefficient of Cosine Term, mas		
	PMX	PMY	UT1	PMX	PMY	UT1
BIH	-5.806 ± 1.021	-6.155 ± 0.692	5.469 ± 0.813	-2.976 ± 1.083	9.419 ± 0.764	-0.970 ± 0.871
ILS	-2.321 ± 3.297	9.047 ± 2.426	-----	7.763 ± 3.329	-10.697 ± 2.452	-----

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.

corrections, no outlying BIH data points were deleted since no data points had residual values greater than four times their adjusted uncertainties.

Combined EOP Series: COMB2001

A Kalman filter was used to combine the BIH series with the adjusted space-geodetic series that comprise SPACE2001 after first 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, COMB2001, consists of values (Figure 4) and 1σ standard errors (Figure 5) for polar motion, Universal Time, and their rates that span from January 20.0, 1962 to January 15.0, 2002 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 Kantha et al. (1998) model for the ocean tides. The full amplitude (i.e., no tidal terms 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 COMB2001 UT1 values.

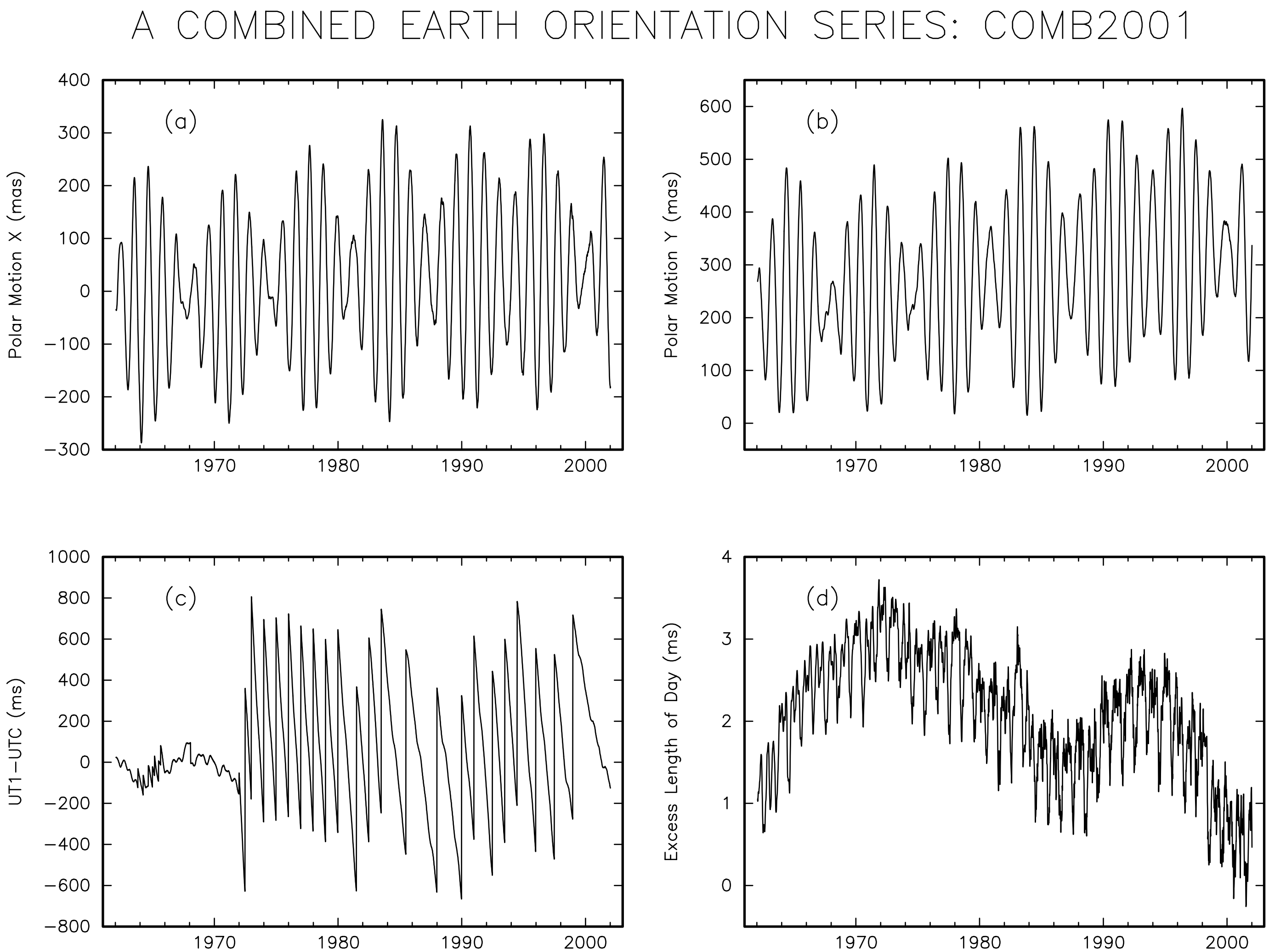

Figure 4. Plots of the *x*-component of polar motion (4a), *y*-component of polar motion (4b), UT1–UTC (4c), and excess length-of-day (4d) as given by the combined Earth orientation series, COMB2001. The discontinuous changes in the plot of UT1–UTC are caused by the presence of leap seconds. Prior to 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 2000, Table IV-3), the effect of which is also readily apparent in 4c. Note that the UT1–UTC values displayed in 4c include the tidal variations, whereas the excess length-of-day values shown in 4d do not.

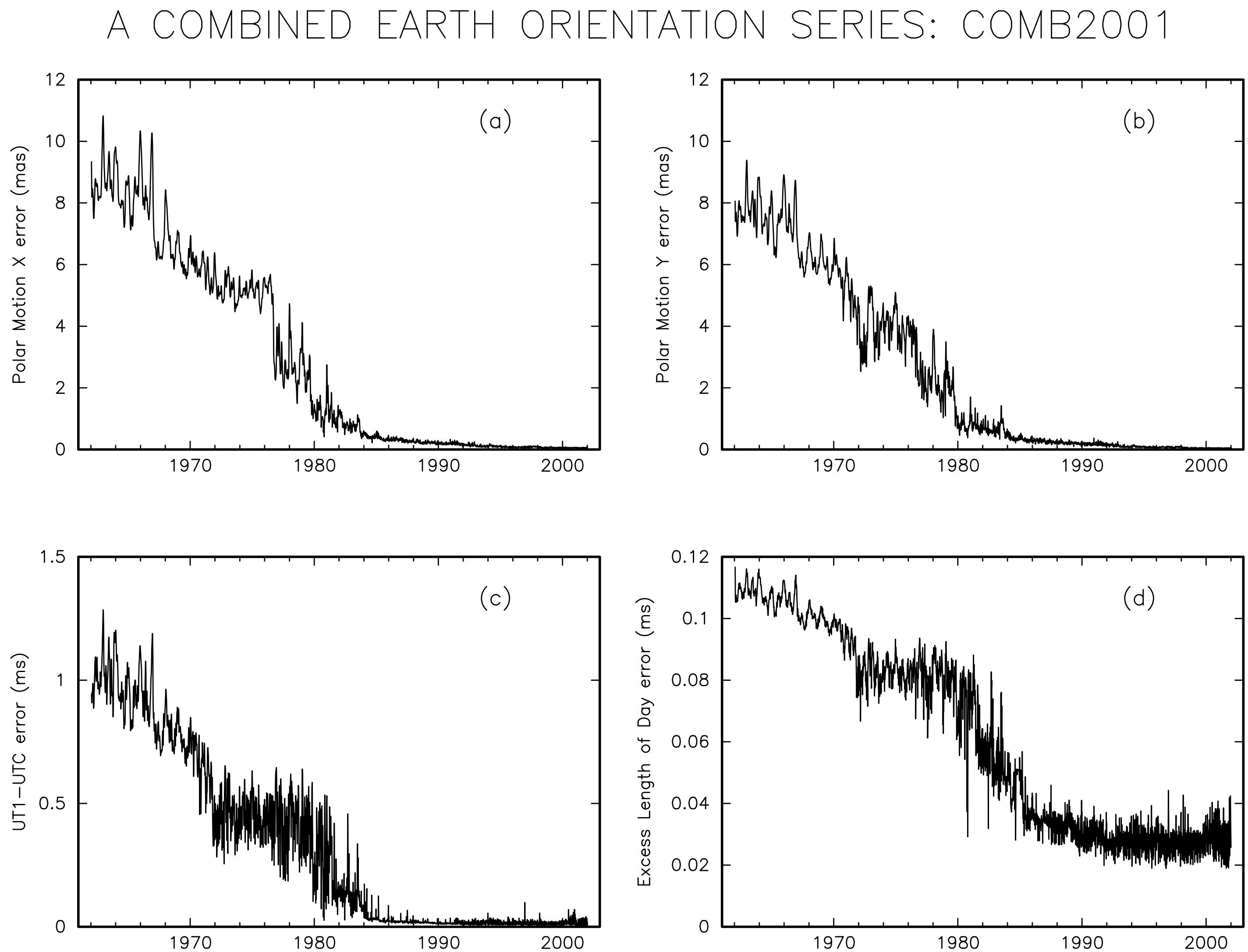

Figure 5. Plots of the 1σ formal errors of the *x*-component of polar motion (5a), *y*-component of polar motion (5b), UT1–UTC (5c), and excess length-of-day (5d) as given by the combined Earth orientation series COMB2001.

POLE2001

No optical astrometric observations taken at the stations of the International Latitude Service (ILS) were used when creating the BIH optical astrometric series that was used to generate COMB2001 (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 COMB2001 and have, therefore, been combined with them to form POLE2001. Being based solely upon latitude observations, the ILS series contains no UT1 measurements, but consists solely of polar motion measurements that span 1899.8–1979.0 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 as 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 COMB2001 to form POLE2001 after: (1) correcting the ILS series to have the same bias, rate, and annual term as COMB2001; (2) applying a constant multiplicative scale factor to the measurement uncertainties of the ILS series so that its residual, when differenced with COMB2001, had a reduced chi-square of one; and (3) deleting those data points, if any, whose residual values were greater than four times their adjusted uncertainties. Again, due to software limitations associated with the need to correct the annual term, 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 COMB2001 during 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, no outlying ILS data points were deleted since no data points had residual values greater than four times their adjusted uncertainties. 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 that comprise COMB2001; this was done 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, POLE2001, consists of values (Figure 6a and 6b) and 1σ standard errors (Figure 6c and 6d) for polar motion and its rate that span from January 20, 1900 to December 21, 2001 at 30.4375-day intervals.

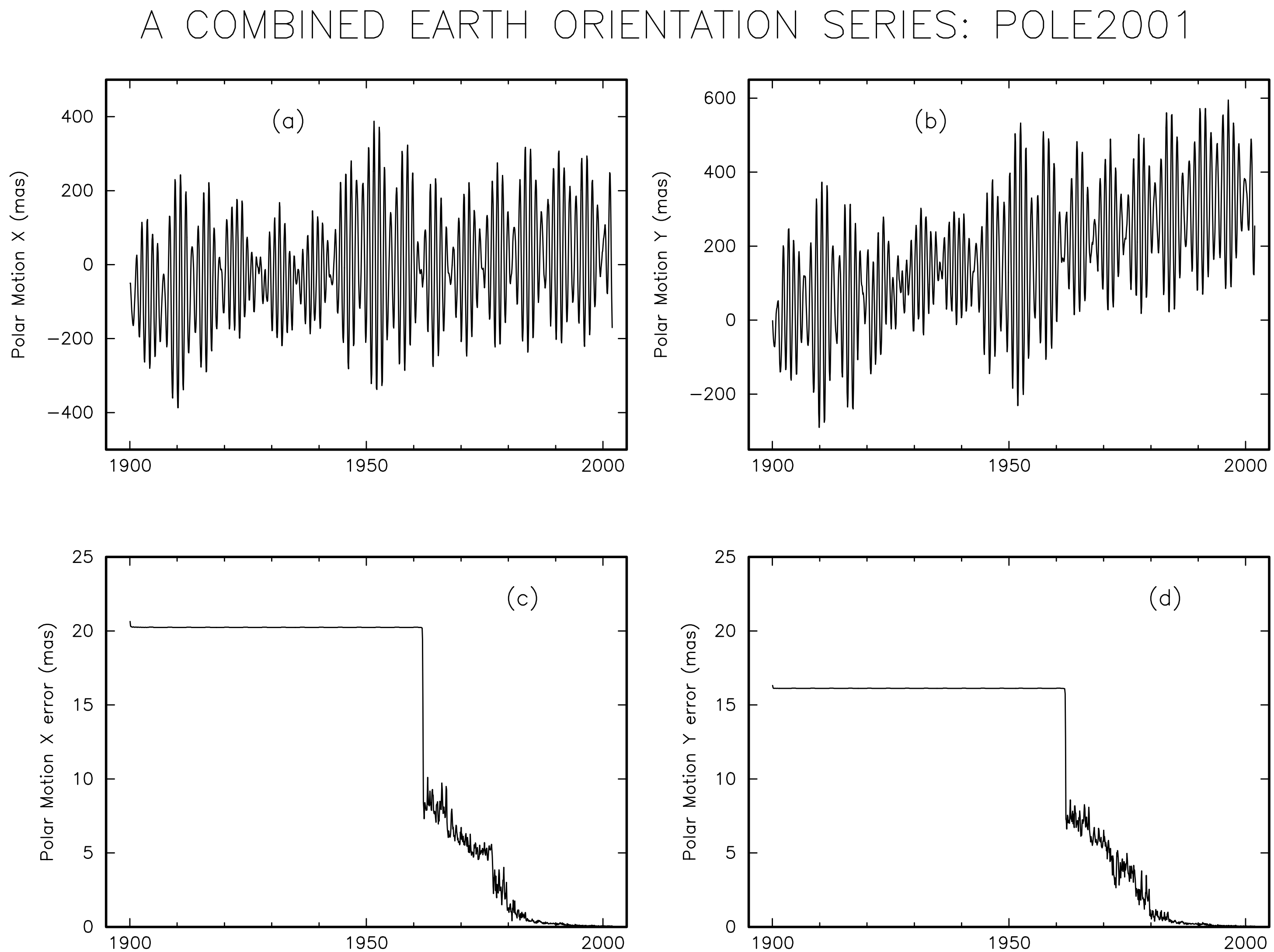

Figure 6. Plots of the *x*-component of polar motion (6a), the *y*-component of polar motion (6b), the 1σ formal errors of the *x*-component of polar motion (6c), and the 1σ formal errors of the *y*-component of polar motion (6d) as given by the combined polar motion series POLE2001.

DISCUSSION

Since a Kalman filter has been used in generating SPACE2001, COMB2001, and POLE2001, the resulting polar motion and UT1 values are smoothed to a degree that depends 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 SPACE2001, COMB2001, and POLE2001 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 SPACE2001 since the NOAA IRIS, USNO NEOS, and GSFC NEOS Intensive UT1 values are given at daily intervals, as are the GPS and JCET/GSFC SLR 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 SPACE2001 are given less frequently; therefore, the Kalman filter used to combine these measurements also interpolates them in order to produce a series of equally spaced values. Thus, SPACE2001, COMB2001, and POLE2001 are equally spaced series of smoothed, interpolated Earth orientation parameters.

The combined Earth orientation series SPACE2001, COMB2001, and POLE2001 are available from: (1) JPL's Space Geodetic Science and Applications Group by anonymous ftp to <ftp://euler.jpl.nasa.gov/keof/combinations/2001>, (2) NASA's Crustal Dynamics Data Information System (CDDIS) by anonymous ftp to <ftp://cddisa.gsfc.nasa.gov/pub/jpl/2001>, or (3) the author upon request to Richard.Gross@jpl.nasa.gov.

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