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Combinations of Earth orientation measurements: SPACE94, COMB94, and POLE94

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Abstract. A Kalman filter has been used to combine independent measurements of the Earth's orientation taken by the space-geodetic observing techniques of lunar laser ranging, satellite laser ranging, very long baseline interferometry, and the Global Positioning System. Prior to their combination, the data series were adjusted to have the same bias and rate, the stated uncertainties of the measurements were adjusted, and data points considered to be outliers were deleted. The resulting combination, SPACE94, consists of smoothed, interpolated polar motion and UT1-UTC values spanning October 6.0, 1976, to January 27.0, 1995, at 1-day intervals. The Kalman filter was then used to combine the space-geodetic series composing SPACE94 with two different, independent series of Earth orientation measurements taken by the technique of optical astrometry. Prior to their combination with SPACE94, the bias, rate and annual term of the optical astrometric series were corrected, the stated uncertainties of the measurements were adjusted, and data points considered to be outliers were deleted. The adjusted optical astrometric series were then combined with SPACE94 in two steps: (1) the Bureau International de l'Heure (BIH) optical astrometric series was combined with SPACE94 to form COMB94, a combined series of smoothed, interpolated polar motion and UT1-UTC values spanning January 20.0, 1962, to January 27.0, 1995, at 5-day intervals, and (2) the International Latitude Service (ILS) optical astrometric series was combined with COMB94 to form POLE94, a combined series of smoothed, interpolated polar motion values spanning January 20, 1900 to January 27, 1995 at 30.4375-day intervals.

Introduction

Optical astrometry and the modern, space-geodetic measurement techniques of lunar laser ranging, satellite laser ranging, very long baseline interferometry, and Global Positioning System interferometry are each able to determine the Earth orientation parameters. However, each technique has its own unique strengths and weaknesses in this regard. Not only are they sensitive to different subsets and/or linear combinations of the Earth orientation parameters, but the averaging times for the determination of these parameters are different, as are the intervals between observations and the precisions with which they can be determined. By combining the individual Earth orientation series determined by each technique, a polar motion and universal time (UT) series can be obtained that is based upon more data and spans a greater length of time than does any individual series.

Such combined Earth orientation series are useful as a priori series in data reduction procedures and for a variety of scientific studies. Since the observing stations are located upon the Earth's crust, successive Earth orientation observations measure changes in the orientation of the Earth's crust relative to a space-fixed, celestial reference frame. In general, the orientation of the solid Earth, and hence of the crust, changes due to (1) the action on the Earth of the gravitational forces of celestial bodies such as the Sun, Moon, and planets, (2) changes in the inertia tensor of the solid, but nonrigid, Earth due to redistributions of its mass, and (3) the effect of surface stresses on the solid Earth due to the actions of the Earth's atmosphere, hydrosphere, cryosphere, and, at the lower boundary of the solid Earth, the action of the Earth's liquid outer core. The analysis of Earth orientation observations therefore allows investigations into, for example, the exchange of angular momentum between the atmosphere, oceans, and solid Earth, the response of the solid Earth to imposed surface and gravitational body forces, and core-mantle boundary processes. Since changes in the Earth's orientation have been under observation by the technique of optical astrometry since the late 19th century, the optical astrometric observations are a valuable resource for (1) investigating Earth orientation changes that occurred prior to the start of the more accurate space-geodetic measurements, and (2) investigating decadal-scale changes in the Earth's orientation (for reviews of Earth rotation studies, see, e.g., *Munk and MacDonald* [1960], *Lambeck* [1980, 1988], *Hide and Dickey* [1991], *Eubanks* [1993], and *Rosen* [1993]). Combined Earth orientation series, like those whose generation are described in this report (an abbreviated version of which is given by *Gross* [1995a, b]) or those generated at the International Earth Rotation Service (IERS) Central Bureau [*IERS*, 1995, section II-4.1] or at the IERS Subbureau for Rapid Service and Predictions [*McCarthy and Luzum*, 1991; *IERS*, 1995, section III-1], enable such investigations by providing investigators with observed Earth orientation series that have a higher data density and/or span a greater length of time than does any individual, single-technique series.

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Generation of SPACE94

The approach taken in generating SPACE94 is similar to that employed previously at the Jet Propulsion Laboratory (JPL) when combining Earth orientation series [*Eubanks*, 1988; *Gross and Steppe*, 1991; *Gross*, 1992, 1993, 1994] and is based upon a Kalman filter that was developed at JPL for such a purpose [*Eubanks*, 1988; *Morabito et al.*, 1988; *Freedman et al.*, 1994]. JPL's Kalman Earth Orientation Filter (KEOF) is a sequential estimation technique that combines observations of the Earth's orientation in a rigorous and consistent manner producing smoothed, interpolated estimates of UT1 and the x and y components of polar motion (PMX and PMY, respectively).

Data Sets Combined to Form SPACE94

Table 1 lists the individual data sets that have been combined to form SPACE94, giving their identifiers, the number of measurements from each data set that were finally incorporated into SPACE94, and the time period spanned by those measurements. Since it was desirable to combine only independent determinations of the Earth's orientation, only one lunar laser ranging (LLR) data set was used, namely, that determined at JPL [*Newhall et al.*, 1994], and only one satellite laser ranging (SLR) data set was used, namely, that determined at the University of Texas Center for Space Research (UTCSR) [*Eanes and Watkins*, 1994]. Note that the SLR UT1 results were not used in generating SPACE94 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.

Two different data sets derived from Global Positioning System (GPS) measurements were used: (1) that determined at the Scripps Institution of Oceanography from daily measurements spanning August 25, 1991, to May 31, 1992 [*Bock et al.*, 1993] and (2) that determined at the Jet Propulsion Laboratory from daily measurements spanning June 1, 1992, to January 27, 1995 (*M. M. Watkins*, personal communication, 1995). Note that in both cases only the GPS polar motion results were used in generating SPACE94.

Four different data sets derived from independent very long baseline interferometry (VLBI) measurements were used: (1) the approximately twice-a-week single baseline measurements made using the radio telescopes of NASA's Deep Space Network (DSN [*Steppe et al.*, 1994]); (2) the single baseline "intensive" UT1 measurements spanning April 2, 1984, to December 31, 1994, made under the auspices of the International Radio Interferometric Surveying (IRIS) subcommission of the commission for International Coordination of Space Techniques for Geodesy and Geophysics (CSTG; a joint commission of the International Association of Geodesy (IAG) and the Committee on Space Research (COSPAR)) and analyzed at NOAA's Geosciences Laboratory [*IRIS*, 1994]; (3) the single baseline IRIS "intensive" UT1 measurements spanning January 4, 1995, to January 27, 1995, analyzed at the U. S. Naval Observatory (USNO (*T. M. Eubanks*, personal communication, 1995)); and (4) the Earth orientation parameters (EOP) determined by the VLBI group of

Table 1. Data Sets Combined to Form SPACE94

Data Set Name	Data Type	Analysis Center	Data Span	Number
LLR (JPL94M01; VOL UT0)				
McDonald Cluster	LLR	Jet Propulsion Laboratory	Oct. 5, 1976 to June 27, 1994	398
Cerga	LLR	Jet Propulsion Laboratory	April 7, 1984 to Dec. 13, 1994	471
Haleakala	LLR	Jet Propulsion Laboratory	Feb. 10, 1985 to Aug. 11, 1990	66
[illegible]				
Lageos Polar Motion	SLR	University of Texas Center for Space Research	Oct. 2, 1976 to Dec. 31, 1993	1901
DSN (JPL94R01; T, V)				
California-Spain Cluster	VLBI	Jet Propulsion Laboratory	Nov. 26, 1979 to Jan. 8, 1995	533
California-Australia Cluster	VLBI	Jet Propulsion Laboratory	Oct. 28, 1978 to Jan. 5, 1995	541
NASA SGP (GLB9 [illegible])				
Multibaseline	VLBI	Goddard Space Flight Center	Aug. 4, 1979 to Dec. 28, 1994	1774
Westford-Fort Davis	VLBI	Goddard Space Flight Center	June 28, 1981 to Jan. 1, 1984	103
Westford-Mojave	VLBI	Goddard Space Flight Center	March 21, 1985 to Aug. 6, 1990	13
NOAA (UT1MC Jan. 19, 1995)				
IRIS intensive UT1	VLBI	National Oceanic and Atmospheric Administration	April 2, 1984 to Dec. 31, 1994	2355
GPS ([illegible]; Polar motion)				
Scripps	GPS	Scripps Institution of Oceanography	Aug. 25, 1991 to May 31, 1992	263
GPS (JPL95P01; Polar motion)				
JPL FLINN analysis	GPS	Jet Propulsion Laboratory	June 1, 1992 to Jan. 27, 1995	814
USNO (N9403 Feb. 23, 1995)				
IRIS intensive UT1	VLBI	United States Naval Observatory	Jan. 4, 1995 to Jan. 27, 1995	16

LLR, lunar laser ranging; VOL, variation of latitude; UTCSR, University of Texas Center for Space Research; SLR, satellite laser ranging; DSN, Deep Space Network; T, transverse; V, vertical; VLBI, very long baseline interferometry; NASA, National Aeronautics and Space Administration; SGP, Space Geodesy Program; NOAA, National Oceanic and Atmospheric Administration; IRIS, International Radio Interferometric Surveying; GPS, Global Positioning System; JPL, Jet Propulsion Laboratory; FLINN, Fiducial Laboratories for an International Natural science Network; USNO, United States Naval Observatory.

the NASA Space Geodesy Program (SGP) at Goddard Space Flight Center (GSFC) from measurements taken under the auspices of a number of observing programs including the multibaseline measurements of the IRIS, USNO, and Crustal Dynamics Project (CDP) [*Ma et al.*, 1994]. Since it was desirable to combine only independent determinations of the Earth's orientation and since the NASA SGP data set used here includes Earth orientation parameters determined from the multibaseline measurements taken by both IRIS and the USNO, no separate NOAA or USNO multibaseline VLBI data sets were used in generating SPACE94.

Treatment of Rotational Variations Caused by Solid Earth and Ocean Tides

Before combining the Earth orientation series, leap seconds were removed, the effect upon UT1 of the solid Earth tides was removed by using the model of *Yoder et al.* [1981], and the model of *Dickman* [1993] was used to remove the effect upon UT1 of the ocean tides at the *Mf*, *Mf'*, *Mm*, and *Ssa* tidal frequencies (the *Dickman* [1993] oceanic corrections to the *Yoder et al.* [1981] results were actually removed). Finally, the empirical model of *Herring* [1993] (also see *Herring and Dong* [1994]) was used to remove the effect of the semidiurnal and diurnal ocean tides from NOAA's IRIS "intensive" UT1 values. It was not necessary to remove subdaily ocean tidal terms from any of the other series used in generating SPACE94 since these terms had already been removed from them during the processing procedures used in their determination.

Adjustments Made to Series Prior to Their Combination

Prior to combining the data, series-specific corrections were applied for bias and rate, and the stated uncertainties of the measurements were adjusted by multiplying them by series-specific scale factors. Values for these bias-rate corrections and uncertainty scale factors were determined in an iterative round-robin approach wherein each data set was compared, in turn, to a combination of all other data sets (except for the two GPS polar motion series and the USNO IRIS "intensive" UT1 series which were treated separately as described below). A reference series, SPACE93 [*Gross*, 1994], was first used to initially adjust the bias and rate of the individual series so that they were all in agreement (in bias and rate) with the reference series. This was done for the sole purpose of initially aligning the series with each other in an attempt to reduce the required number of round-robin iterations. The stated uncertainties of the series were not adjusted at this time. Any inconsistencies introduced by using a reference series for this initial bias-rate alignment should be removed during the subsequent iterative round-robin procedure.

After initial bias-rate alignment, the round-robin procedure was performed wherein the bias and rate of each individual series was iteratively adjusted so as to be in agreement with the bias and rate exhibited by a combination of all the other series, with rate adjustments being determined only for those series whose overlap with all the other series was great enough that reliable rate determinations could be made. The stated measurement uncertainty of each series was adjusted by applying a multiplicative factor that made the residual of the data, when differenced with a combination of all other data, have a reduced chi-square of one. Note that the formal error associated with the residual in calculating the reduced chi-square accounts for the error of interpolation between the time of the residual and the times of other data points by using the stochastic model of the polar motion and UT1 process contained in KEOF. The incremental bias-rate corrections and uncertainty scale factors thus determined for each of the individual series were then applied to the series and the process repeated until convergence was achieved (convergence being indicated by the incremental bias-rate corrections approaching zero and the incremental uncertainty scale factors approaching one). At the completion of this iterative, round-robin process, relative bias-rate corrections have been determined that make the data sets agree with each other in bias and rate, and uncertainty scale factors have been determined that make the residual of each data set (when differenced with a combination of all others) have a reduced chi-square of one.

When performing this iterative, round-robin procedure to determine bias-rate corrections and uncertainty scale factors, each data type is analyzed (and results reported) in the natural reference frame for that data type. For single-baseline VLBI measurements this is the transverse (T), vertical (V) frame [*Eubanks and Steppe*, 1988]; for single-station LLR measurements this is the variation of latitude (VOL), UT0 frame; and for GPS, SLR, and multibaseline VLBI measurements this is the usual UTPM (PMX, PMY, UT1) frame.

For the purpose of determining bias-rate corrections and uncertainty scale factors, the LLR observing stations at McDonald were clustered, so that a common bias-rate correction and uncertainty scale factor was determined for all the McDonald LLR series. This was done so that rate adjustments could be made to these series. There is not enough overlap with the other, independent Earth orientation series to allow a reliable rate correction to be determined for any individual McDonald station-derived LLR series. Thus, without clustering the McDonald stations, it would only be possible to make bias corrections to the McDonald LLR series, with consequent deleterious effects on the rate of the UT1 values prior to about 1982 in the final, combined series. Similarly, the individual DSN radio telescopes in California were clustered, as were those in Spain and, separately, in Australia, so that a common bias-rate correction and uncertainty scale factor was determined for all the California-Spain single baseline Earth orientation series, as well as for all the California-Australia series.

During the iterative, round-robin procedure, outlying data points were deleted. Before deleting any data points, four round-robin iterations were completed in order to converge on initial values for the uncertainty scale factors. During subsequent iterations, those data points of a given series were deleted whose residual values were greater than 3 times their adjusted uncertainties, where the residual values were those resulting from fitting a bias and rate to the difference of that series with a combination of all other series. During the final round-robin iteration, no series contained data points whose residual values were greater than 3 times their adjusted uncertainties. A total of 196 data points, or about 2% of those combined, were thus deleted from the data sets.

Bias-rate corrections and uncertainty scale factors were determined for the two GPS polar motion series and the USNO IRIS "intensive" UT1 series by separately comparing them to a combination of all other, independent series after the other series had had the bias-rate corrections and uncertainty scale factors applied to them that had been previously determined for them as described above. Only bias corrections were determined and applied to the Scripps GPS polar motion and the USNO IRIS "intensive" UT1 series since their overlap with the other, independent series was not great enough to allow reliable rate corrections to be determined. During this comparison, outlying data points (i.e., those whose residual values were greater than 3 times their adjusted uncertainties) were also deleted.

Finally, each data set was placed within an International Earth Rotation Service (IERS) reference frame by applying to it an additional bias-rate correction that is common to all the data sets. This additional correction was determined by first combining all the data (including the two GPS and the USNO IRIS "intensive" series, and after applying to all the data the relative bias-rate corrections and uncertainty scale factors determined above). This intermediate combination was then compared to the IERS combination EOP(IERS) C 04 [IERS, 1995, p. II-58] for the years 1984–1994 in order to obtain the additional bias-rate correction required to make (and therefore each individual data set) agree in bias and rate with the IERS combination. This additional bias-rate correction was then applied to each data set, along with the relative bias-rate corrections determined above, in order to make the data sets agree with each other and be in that IERS reference frame defined by the Earth orientation series EOP(IERS) C 04.

The total bias-rate corrections (the sum of the relative and IERS corrections) that have been determined for the data sets are given in Table 2. Except for the two GPS and the USNO IRIS "intensive" series (see below), the values for the bias-rate corrections given in Table 2 are the sum of all the incremental corrections, the corrections applied to initially align the series with each other, and the additional, common correction applied in order to place each series within the IERS reference frame. The values for the uncertainty scale factors given in Table 2 are the products of all the incremental scale factors determined during the iterative, round-robin procedure. The errors in the bias-rate corrections (given in parentheses in Table 2) are the formal errors in the determination of the incremental bias-rate corrections during the last iteration of the iterative, round-robin procedure. There are no bias-rate entries in Table 2 for components that were either not used (e.g., the SLR UT1 component) or not available (e.g., the IRIS "intensive" PMX and PMY components). Note that the same

Table 2. Adjustments to Space-Geodetic Series Prior to Their Combination

Data Set Name	Bias, mas			Rate, mas/yr			Uncertainty Scale Factor		
	VOL	UT0		VOL	UT0		VOL	UT0	
LLR (JPL94M01)									
McDonald Cluster	2.296 ± 0.237	0.903 ± 0.231		-0.724 ± 0.046	-0.111 ± 0.051		1.379	1.189	
Cerga	-0.284 ± 0.179	0.348 ± 0.096		0.122 ± 0.037	-0.060 ± 0.022		1.799	1.301	
Haleakala	1.421 ± 0.275	-0.627 ± 0.235		-0.208 ± 0.180	0.065 ± 0.160		1.530	1.788	
Data Set Name	Bias, mas			Rate, mas/yr			Uncertainty Scale Factor		
	T	V		T	V		T	V	
DSN (JPL 94R01)									
California-Spain Cluster	0.942 ± 0.072	0.378 ± 0.017		0.002 ± 0.016	0.020 ± 0.039		1.417	1.186	
California-Australia Cluster	0.361 ± 0.050	0.701 ± 0.011		0.250 ± 0.012	0.078 ± 0.035		1.465	1.219	
NASA SGP (GLB973f)									
Westford-Fort Davis	4.664 ± 1.839	0.330 ± 3.183		0.723 ± 0.371	-0.191 ± 0.634		0.363	0.769	
Westford-Mojave	0.443 ± 0.217	0.723 ± 0.455		[illegible] 0.037	[illegible] 0.015		2.586	0.998	
Data Set Name	Bias, mas			Rate, mas/yr			Uncertainty Scale Factor		
	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
NASA SGP (973f)									
Multibaseline	0.435 ± 0.027	-1.690 ± 0.023	[illegible] ± 0.031	[illegible] ± 0.007	-0.060 ± 0.005	0.121 ± [illegible]	2.114	1.974	2.143
UTCSR (94L01)									
Lageos	0.116 ± 0.023	0.582 ± 0.019		[illegible]	0.162 ± 0.006		0.701	0.602	
NOAA									
IRIS intensives	----	----	110 ± 0.027			0.075 ± [illegible]			0.947
USNO									
IRIS intensives		----	-0.239 ± 0.012		----	0.010		....	1.578
GPS (SIO93P01)									
Scripps	-0.818 ± 0.035	-1.508 ± 0.040		[illegible] 0.04	-0.002		1.899	1.915	.....
GPS (JPL95P01)									
JPL FLINN	-0.246 ± 0.144	0.455 ± 0.130		0.02[illegible] ± [illegible]	-0.135 ± 0.022		3.457	2.952	.....

Reference date for rate adjustment is 1988.0. See Table 1 footnotes.

IERS rate correction is applied to all the data sets, including those (such as the USNO IRIS "intensive" series) for which no relative rate correction multi be determined. Therefore the rate correction given in Table 2 for those data sets for which no relative rate correction could be determined is simply the IERS rate correction but given, of course, in the natural reference frame for that data set, In these cases, no errors for the rate corrections are given.

Since the GPS and USNO IRIS "intensive" series were not included in the iterative, round-robin procedure, the bias rate corrections given in Table ? for them are just the sum of the relative corrections that were separately determined for them (see above) and the additional, common correction needed to place them within the IERS reference frame. The errors in the bias rate corrections given in Table ? for these series (shown in parentheses) are the formal errors in determining the relative corrections. The uncertainty scale faders given in Table 2 for these series are just the scale factors determined for them as described above when separately comparing them to combinations of all the other, independent series.

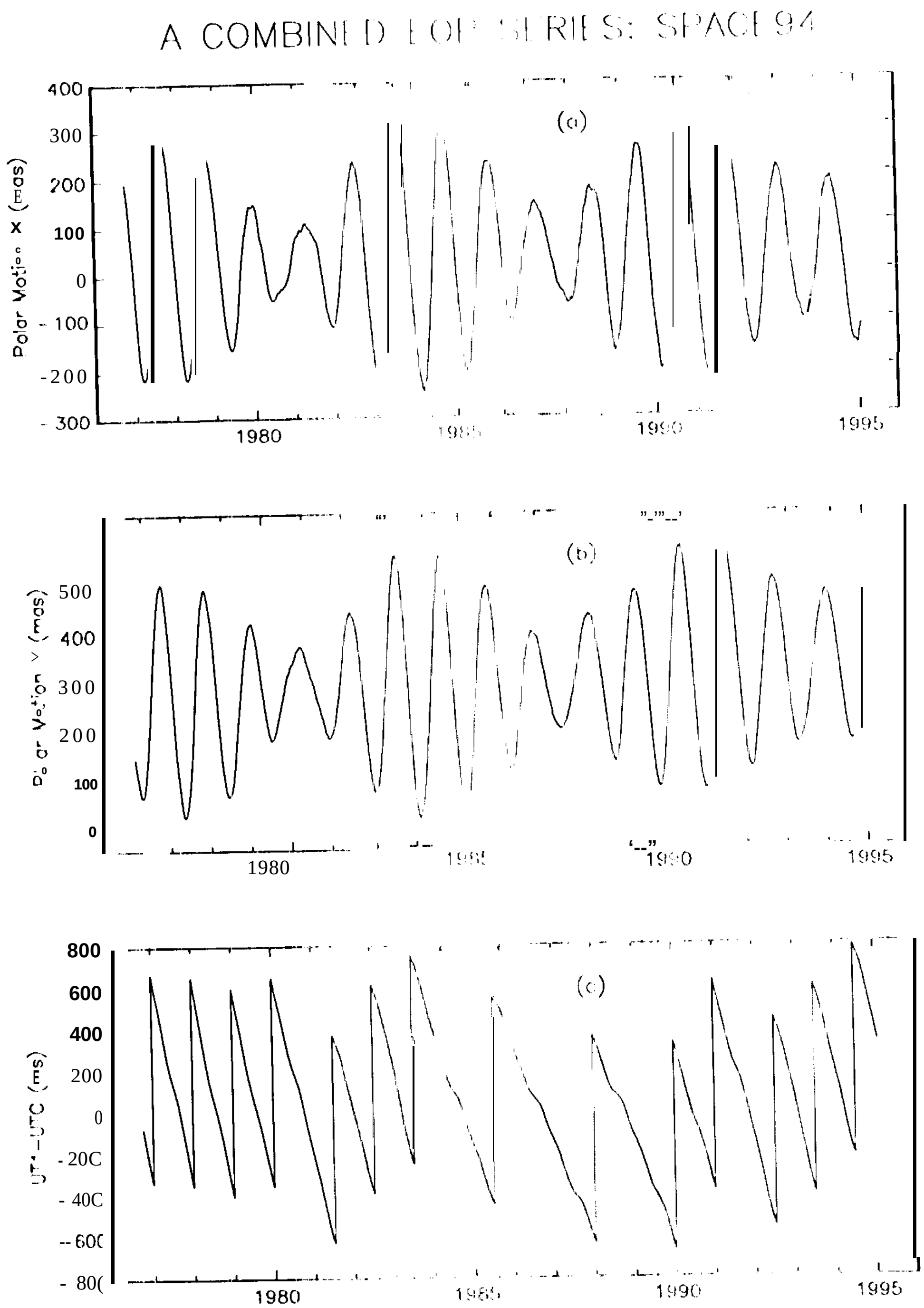

Figure 1. Plots of (a) the x component of polar motion, (b) the y component of polar motion, and (c) UT1-UTC from the combined Earth orientation series SPACE94. SPACE94 is a series of smoothed, interpolated Earth orientation parameters spanning October 6.0, 1976, to January 27.0, 1995, at daily intervals. The occurrence of leap seconds in the UT1-UTC component (Figure 1c) is readily apparent.

SPACE94

All of the data sets (including the GPS and TSNOIRIS "intensive" series) were then combined after adjusting their biases, rates, and measurement uncertainties by the amounts given in Table 2. The resulting combination, spanning October 6.0, 1976, to January 27.0, 1995, is designated SPACE94 and consists of daily values at midnight of PMX, PMY, and UT1-UTC (Figure 1), their 1σ formal uncertainties (Figure 2), and correlations. Leap seconds have been restored, the model of *Yoder et al.* [1981] was used to add back the effect of the solid Earth tides upon UT1 (the full amplitude of the tidal effect at the epoch of the time tag was added back), and the model of *Dickman* [1993] was used to add back the ocean tidal corrections to the *Yoder et al.* [1981] model at the *Mf*, *Mf'*,

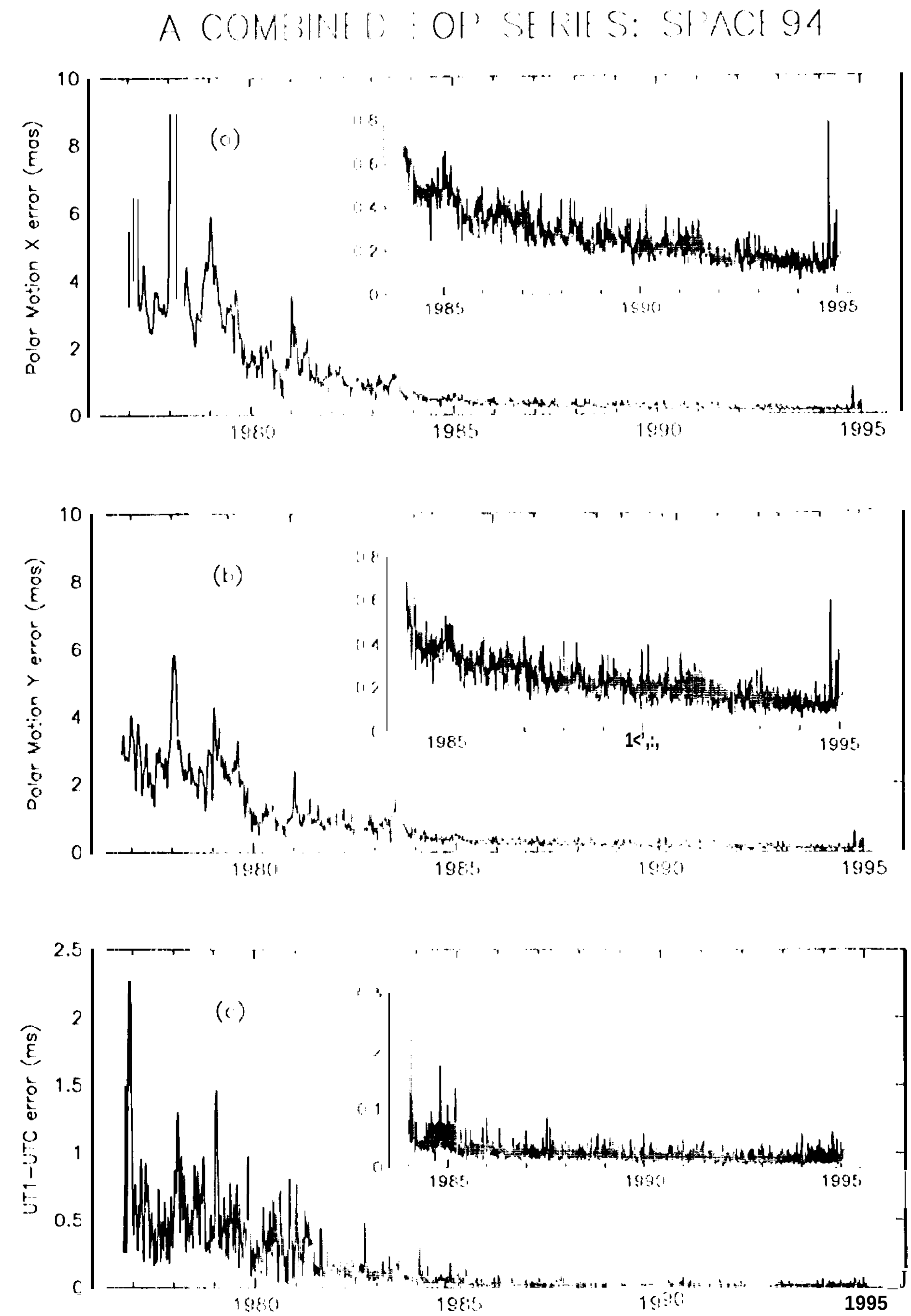

Figure 2. Plots of the 1σ formal uncertainties in the determination of (a) the x component of polar motion, (b) the y component of polar motion, and (c) UT1-UTC from SPACE94. The inset within each panel shows that component's post-1984 uncertainties on an expanded scale with the same units (milliarcseconds (mas) for PMX and PMY, milliseconds (ms) for UT1-UTC). Improvements to the observing systems have led to increasingly precise determinations of the Earth's orientation. The effects of these improvements are reflected here by the reduction in the formal uncertainties from about 2 mas in polar motion and 0.5 ms in UT1 - UTC during the late 1970s to their current values of about 0.2 mas in polar motion and 0.02 ms in UT1 - UTC.

Table 3. Adjustments to Bias, Rate, and 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	7.993 ± 4.280	6.035 ± 1.893	[illegible]	[illegible] ± 0.483	0.41[illegible] ± 0.180	[illegible] ± 0.316	1.830	1.601	1.865
ILS	49.540 ± 22.177	7.389 ± 1.747		[illegible]	0.876 ± 0.356		[illegible]	1.599	. . .

Reference date for rate adjustment of BIH series is 1988.0, and reference date for rate adjustment of ILS series is 1970.0. See Table 1 footnotes.

Mm, and *Ssa* tidal frequencies. No diurnal or semidiurnal tidal terms were added back, however.

Generation of COMB94

The particular optical astrometric polar motion and UT1 series used in generating COMB94 was that determined by the Bureau International de l'Heure (BIH) from an analysis of time and latitude observations [*Li*, 1985; *Li and Feissel*, 198[illegible]]. This BIH optical astrometric series, consisting of values of PMX, PMY, and UT1 spanning 1962.0–1982.0 at 5-day intervals, was combined with the space-geodetic series comprising SPACE94 after first (1) correcting the BIH series to have the same bias, rate, and annual term as SPACE94, (2) applying a constant multiplicative scale factor to the measurement uncertainties of the BIH series so that its residual, when differenced with SPACE94, had a reduced chi-square of one, and (3) deleting those data points whose residual values were greater than 3 times their adjusted uncertainties.

Treatment of Rotational Variations Caused by Solid Earth and Ocean Tides

Before combining the BIH optical astrometric series with the previously adjusted space-geodetic series comprising SPACE94, leap seconds were removed, and the effect of solid Earth tides upon the BIH UT1 measurements was removed by using the model of *Yoder et al.* [1981]. Also, the model of *Dickman* [1993] was used to remove the effect upon UT1 of the ocean tides at the *Mf*, *Mf'*, *Mm*, and *Ssa* tidal frequencies (the *Dickman* [1993] oceanic corrections to the *Yoder et al.* [1981] results were actually removed). 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 period of the fortnightly and monthly tides, the amplitudes of these tidal terms were attenuated prior to their removal from the BIH UT1 measurements. The attenuation factor that was applied to the amplitude of each fortnightly and monthly tidal term is a function of both the averaging interval (5 days) as well as the period of the individual tidal term [e.g., *Guinot*, 1970] and was about 0.80 for a fortnightly tidal term of period 14 days and about 0.95 for a monthly tidal term of period 28 days. The amplitudes of the longer period (semiannual and longer) tidally induced rotational variations were not attenuated prior to their removal from the BIH UT1 measurements.

Adjustments Made to the BIH Series

Prior to combining the BIH optical astrometric series with the space-geodetic series comprising SPACE94, corrections were made to its bias, rate, and annual term, and the stated uncertainties of the BIH measurements were adjusted by multiplying them by scale factors. First, the measurement uncertainties were adjusted by determining and applying scale factors that made each component of the residual series, obtained upon fitting a bias, rate and annual term to the difference of the BIH series with SPACE94, have a reduced chi-square of one. During this comparison for determining the measurement uncertainty scale factors, five outlying data points (those whose residual values were greater than 3 times their adjusted uncertainties) were deleted. The measurement uncertainty scale factors thus determined for the BIH series are given in Table 3.

After adjusting the measurement uncertainties, corrections to the bias, rate, and annual term of the BIH series were determined by comparing the BIH series to two different reference series: (1) the adjusted McDonald lunar laser ranging series that was incorporated into SPACE94, consisting of values for UT0 and the variation of latitude (VOL) at the McDonald station, was used as a reference series to determine bias rate and annual term corrections for these two components of the BIH series (i.e., the McDonald UT0 and VOL components), and (2) SPACE94 was used as a reference series to determine the bias-rate and annual term corrections to the third orthogonal BIH component that is not determinable

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	-5.627 ± 1.017	[illegible]	[illegible] ± 0.781	2.79[illegible] ± 1.0[illegible]	9.8[illegible] ± 0.683	-0.922 ± 0.832
ILS	-0.406 ± 3.059	8.055 ± 2.453	-	10.03[illegible] ± 3.0[illegible]	-10.9[illegible] ± 2.457	-----

Reference date for rate adjustment of BIH series is 1988.0, and reference date for rate adjustment of ILS series is 1970.0 See Table 1 footnotes

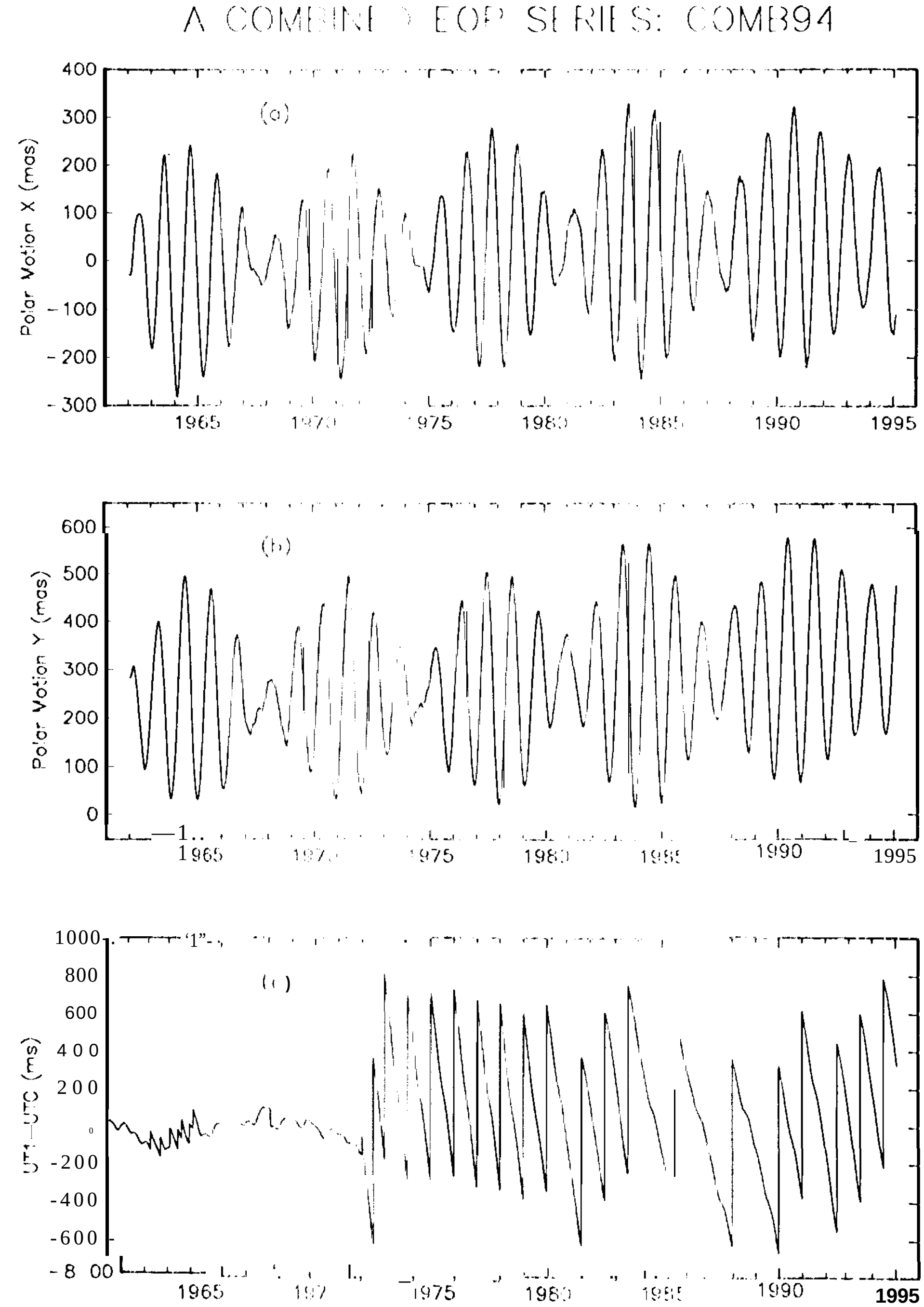

Figure 3. Plots of (a) the *x* component of polar motion, (b) the *y* component of polar motion, and (c) UT1-UTC from the combined Earth orientation series, COMB94. COMB94 is a series of smoothed, interpolated polar motion and UT1-UTC values spanning January 20.0, 1962, to January 27.0, 1995, at 5-day intervals. The occurrence of leap seconds in the UT1-UTC component (Figure 3c) is readily apparent. 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 [illegible] [e.g., [illegible], 1995, Table [illegible]], the effect of which is also readily apparent in (Figure 3c).

from single-station lunar laser ranging observations. The advantage of using the adjusted McDonald LLR series for the purpose of determining corrections to the BIH series is that the McDonald LLR series spans 1970-1994, whereas SPACE94 spans only 1976-1994. Thus more reliable determinations of the needed BIH corrections can be made using the adjusted McDonald LLR series as a reference than can be done using SPACE94 because the interval of overlap between the BIH series and the McDonald LLR series is greater than it is with SPACE94. The formal uncertainties of the fit for the bias-rate and annual term corrections to the BIH series are found to be of comparable size for both the UT0 and V(?)] components but are

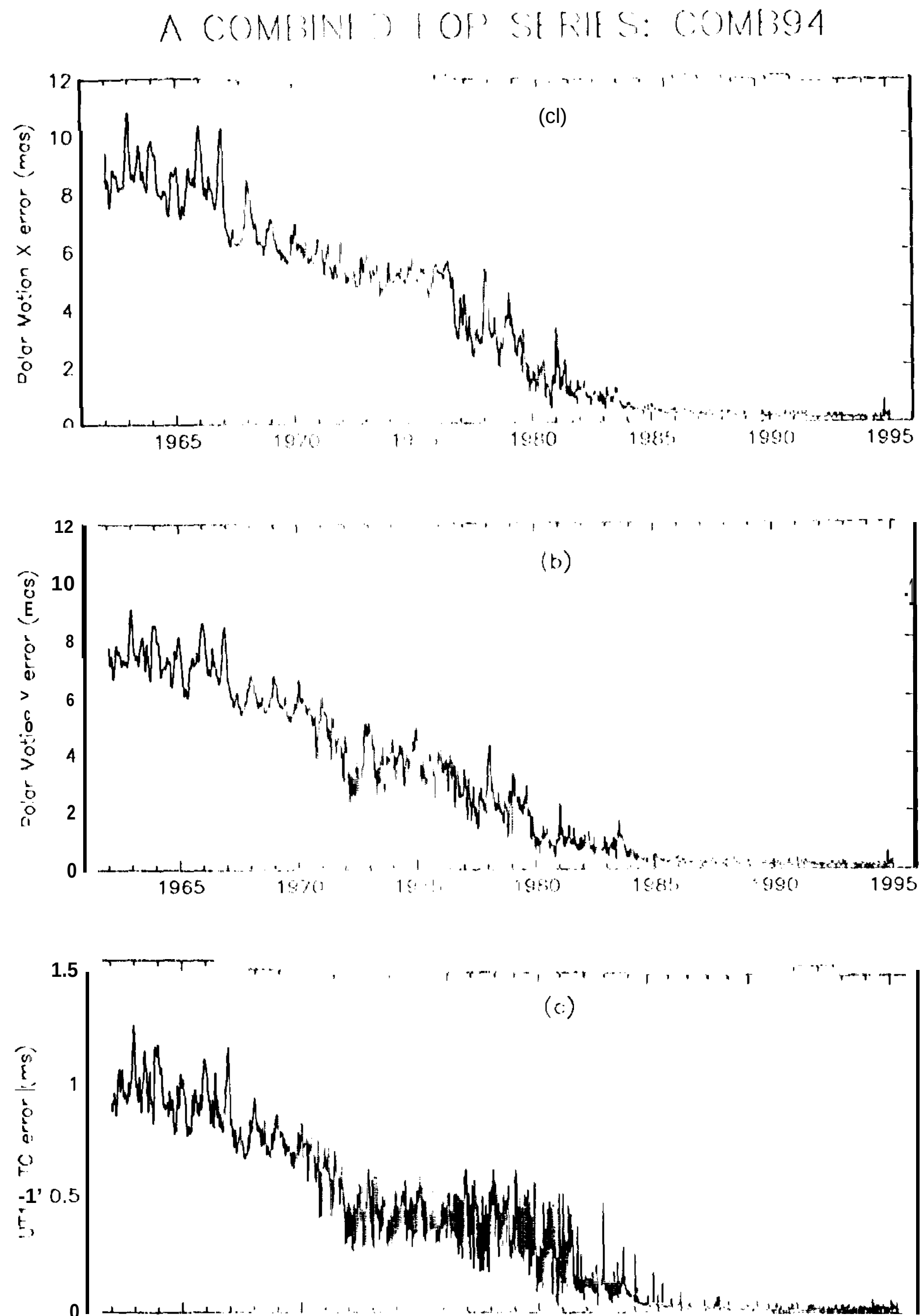

Figure 4. Plots of the 1σ formal uncertainties in the determination of (a) the x component of polar motion, (b) the y component of polar motion, and (c) UT1-UTC from COMB94.

much larger (by a factor of 2 to 4 depending upon the particular term being fit) for the indeterminable component. This supports the approach of using the McDonald LLR series as reference for determining the corrections to both the UT0 and VOL components of the BIH series and only using the shorter-duration SPACE94 series for determining the corrections to the indeterminable component. Note that an annual term of the BIH series was corrected, in addition to a bias and rate, because optical astrometric observations are known to be susceptible to seasonally varying systematic errors.

The bias, rate, and annual term corrections to the BIH series were determined by (1) transforming the BIH polar motion and UT1 components to the McDonald UT0, VOL, and indeterminable components, (2) comparing these transformed BIH components to the adjusted McDonald LLR series (for the UT0 and VOL components) and to the similarly transformed SPACE94 series (for the indeterminable component), and (3) transforming the corrections thus determined back to the usual UTPM (PMX, PMY, UT1) frame. The bias, rate, and annual term corrections thus determined for the BIH series are given in

Tables 3 and 4 in the UTPM frame. The errors in the bias, rate, and annual term corrections are the formal errors in determining these corrections in the McDonald UT0–VOL indeterminable frame but are given in Tables 3 and 4 after the transformation back to the usual UTPM frame.

COMB94

The BIH series was then combined with the adjusted space-geodetic series comprising SPACE94 after applying to it the corrections for bias, rate, annual term, and measurement uncertainty given in Tables 3 and 4. The resulting combination, spanning January 20.0, 1962, to January 2[illegible], 1995, is designated COMB94 and consists of values at 5-day intervals of PMX, PMY, and UT1–UTC (Figure 3), their formal uncertainties (Figure 4), and correlations. Leap seconds were restored to the UT1 component, and the model of *Yoder et al.* [1981] was used to add back the effect of the solid Earth tides upon UT1 (the full amplitude, with no terms being attenuated, of the tidal effect at the epoch of the time tag was added back), and the model of *Dickman* [1993] was used to add back the ocean tidal corrections to the *Yoder et al.* [1981] model at the *Mf*, *Mf'*, *Mm*, and *Ssa* tidal frequencies. No diurnal or semidiurnal ocean tidal terms were added back.

Generation of POLE94

No optical astrometric observations made at the stations of the International Latitude Service were used in creating the particular BIH series that was used above in generating COMB94 [*Li*, 1985; *Li and Feissel*, 1986]. The ILS polar motion measurements, which are based solely upon latitude observations made at the ILS stations, are therefore independent of those comprising COMB94 and have been subsequently combined with them to form POLE94. Being based solely upon latitude observations, the ILS series contains no UT1 measurements but consists solely of polar motion measurements spanning 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, so long as it is not zero, and serves merely as an a priori estimate for the series adjustment procedure described below.

The ILS series was combined with COMB94 to form POLE94 after first (1) correcting the ILS series to have the same bias,

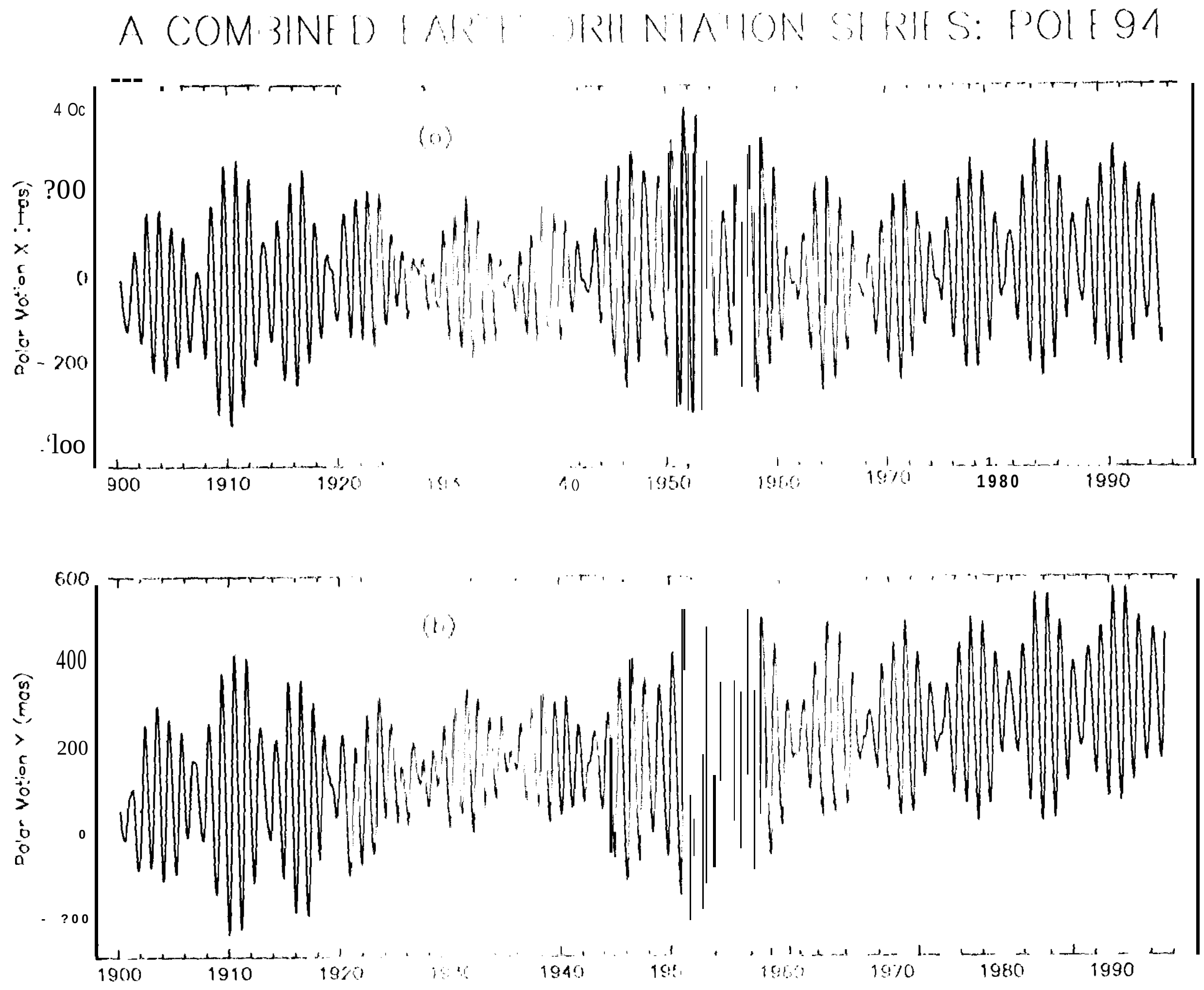

Figure 5. Plots of (a) the x component of polar motion and (b) the y component of polar motion from the combined Earth orientation series POLE94. POLE94 is a series of smoothed, interpolated polar motion values spanning January 20, 1900, to January 21, 1995, at 30.4375 day intervals.

rate, and annual term as COMB94, (2) applying a constant multiplicative scale factor to the measurement uncertainties of the ILS series so that its residual, when differenced with COMB94, had a reduced chi-square of one, and (3) deleting those data points whose residual values were greater than 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 COMB94. The measurement uncertainties of the ILS polar motion values were adjusted by determining and applying a scale factor to them such that 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, three outlying ILS data points (those whose residual values were greater than three times their adjusted uncertainties) were deleted. Tables 3 and 4 give the values of the corrections thus determined and applied to the ILS series along with their 1σ formal uncertainties.

The result of combining the corrected ILS optical astrometric polar motion measurements with COMB94 is designated POLE94, spans January 20, 1900, to January 1, 1995, and consists of values at 30.4375-day intervals of PMX and PMY (Figure 5), their 1σ formal uncertainties (Figure 6), and correlations.

Discussion and Availability

Since a Kalman filter has been used in generating SPACE94, COMB94, and POLE94, the resulting polar motion and UT1 values (Figures 1, 3, and 5) 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 SPACE94, COMB94, and POLE94 values is a function of time, with the earlier values being more heavily smoothed than the more recent values. Generally speaking, this change in the degree of applied smoothing should be taken into account when analyzing these data sets. However, the degree of smoothing applied to the SPACE94 polar motion and UT1 values since 1984 can be expected to be relatively uniform since the measurement uncertainty since 1984 has been relatively uniform (Figure 2). Thus for applications requiring a reasonably homogeneous Earth orientation series based solely upon space-geodetic measurements, it is suggested that only the post-1984 SPACE94 values be used.

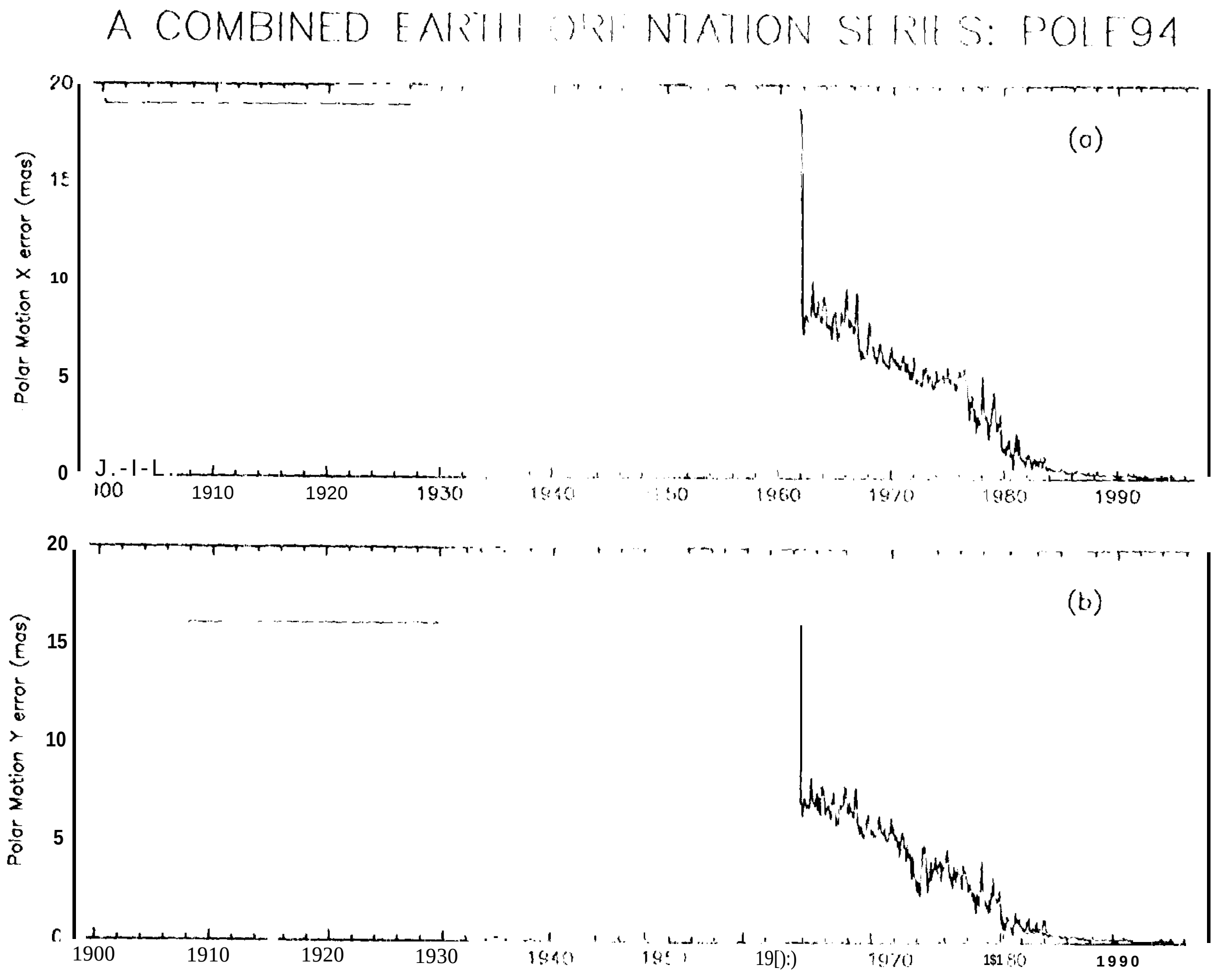

Figure 6. Plots of the 1σ formal uncertainties in the determination of (a) the x component of polar motion and (b) the y component of polar motion from POLE94. In deriving POLE94, a constant uncertainty was assigned to the ILS polar motion measurements resulting in a constant uncertainty for the POLE94 polar motion values prior to the incorporation into POLE94 of the other Earth orientation series starting in 1962.

Daily polar motion and UT1 values are reported in SPACE94 since the NOAA and USNO IRIS "intensive" UT1 values are given at daily intervals, as are the Scripps and JPL GPS polar motion values (although gaps exist in each of these four data sets). However, prior to the start of these data sets, the measurements combined to form SPACE94 are given less frequently, and so the Kalman filter used to combine these measurements (KEOF) also interpolates them in order to produce a series of equally spaced values. Thus SPACE94, as are COMB94 and POLE94, is an equally spaced series of smoothed, interpolated Earth orientation parameters.

SPACE94, COMB94, and POLE94 are available upon request either from the author or from NASA's Crustal Dynamics Data Information System (CDDIS). ASCII versions of these files can be obtained from the CDDIS either by (1) anonymous ftp to the internet address CDDIS.GSFC.NASA.GOV (128.183.10.141) where it can be found in the 1995 subdirectory of the JPL directory, or (2) sending requests to Carey Noll, Manager, CDDIS, NASA/Goddard Space Flight Center, Code 920.1, Greenbelt, Maryland 20771, USA, telephone: (301) 286-9283; facsimile: (301) 286-9283; internet: noll@cddis.gsfc.nasa.gov.

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