A COMBINATION OF EARTH ORIENTATION MEASUREMENTS: SPACE94

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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 UT 1 –UTC values spanning October 6.0, 1976 to January 27.0, 1995 at l-day intervals.

INTRODUCTION

The modern, space-geodetic measurement techniques of lunar laser ranging, satellite laser ranging, very long baseline interferometry, and the global positioning system are each able to determine the Earth orientation parameters. But each technique has its own unique strengths and weaknesses in this regard. Not only is each technique sensitive to a different subset and/or linear combination 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 precision with which they can be determined. By combining the individual Earth orientation series determined by each technique, a polar motion and UT1 series can be obtained that is based upon all available independently determined measurements and that spans the greatest possible length of time.

Such combined Earth orientation series, like SPACE94, arc 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 non-rigid, Earth due to redistribution 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 (for reviews of Earth rotation studies see, e. g., *Munk and MacDonald,* 1960; *Lambeck, 1980,* 1988; *Hide and Dickey, 1991; Eubanks*, 1993; *Rosen, 1993),* Combined Earth orientation series, like SPACE94 whose generation is described in this report, enable such investigations by providing investigators with an observed Earth orientation series that, by incorporating all available independently determined measurements, has the highest possible data density and spans the greatest possible length of time.

GENERATION OF SPACE94

The approach taken in generating SPACE94 is based upon a Kalman filter that was developed at the Jet Propulsion Laboratory (JPL) for just 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 rigorously self-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 actually 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 UT 1 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 [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 approximate y 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" UT] measurements spanning January 4, 1995 to January 27, 1995 analyzed at the US Naval Observatory [USNO; *Eubanks,* personal communication, 1995]; and (4) the Earth orientation parameters (EOP) determined by the VLBI group of 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 UT] of the ocean tides at the *Mf*, *Mf'*, *Mm*, and *Ssa* tidal frequencies (the *Dickman [1993]* oceanic corrections to the *Yoder et al. [198* 1] 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 semi-diurnal and diurnal ocean tides from NOAA's IRIS "Intensive" UT1 values since these tidal terms had been added back and were included in the released UTl values. No subdaily ocean tidal terms were removed from any of the other series used in generating SPACE94 since none of the other series, including the USNO IRIS "Intensive" UT1 series, had these terms added back to them. Note that the particular NASA SGP series used in generating SPACE94 was a special solution that was generated just for inclusion in SPACE94 and did not have the subdaily tidal terms added back to the released UT1 and polar motion values *[Ma*, personal communication, 1995].

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" UT 1 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 that data, when difference 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 UT 1 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 difference 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), UTO 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 three 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 three times their adjusted uncertainties. A total of 196 data points, or about two percent 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 mot ion and the USNO IRIS "Intensive" UT 1 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 three 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) 90 C 04 [*Feissel and Essaïfi*, *1994*, p. H-75] for the years 1984–1 994 in order to obtain the additional bias-rate correction required to make it (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) 90 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 correct ions (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 arc no bias-rate entries in Table 2 for components that were either not used (e.g., the SLR UT 1 component), or not available (e.g., the IRIS 1 ntensive PM X and PMY components). Note that the same 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 could 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 2 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 2 for these series (shown in parentheses) are the formal errors in determining the relative corrections. The uncertainty scale factors given in Table 2 for these series are just'the scale factors determined for thcm as described above when separately comparing them to combinations of all the other, independent series.

SPACE94

All of the data sets (including the GPS and USNO IRIS "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 1-sigma 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 UT 1 (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', Mm,* and *Ssa* tidal frequencies. No diurnal or semi-diurnal ocean tidal terms were added back, however.

DISCUSSION AND AVAILABILITY

Because a Kalman filter was used in generating SPACE94, the resulting polar motion and UT1 values (Figure 1) 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 values is a function of time, with the earlier values being more heavily smoothed than the more recent values. However, the degree of smoothing applied to the SPACE94 polar motion and UT 1 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 homogeneous Earth orientation series, it is suggested that only the post-1 984 SPACE94 values be used.

Daily polar motion and UT1 values are reported in SPACE94 since the NOAA and USNO IRIS "Intensive" UT1 values arc 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 equi-spaced values. Thus, SPACE94 is an equi-spaced series of smoothed, interpolated polar motion and UT] values spanning 19761994 at daily intervals.

SPACE94 is available upon request either from the author or from NASA's Crustal Dynamics Data Information System (CDDIS). An ASCII version of it can be obtained from the CDDIS either by: (1) anonymous ftp to the internet address CDDIS.GSFC.NASA.G OV (128. 183,10,141) where it can be found in the 1994 subdirectory of the JPL directory, or (2) sending requests to Ms. Carey No]], Manager, CDDIS, NASA/Goddard Space Flight Center, Code 920,1, Greenbelt, Maryland 20771, USA; telephone: (301) 286-9283; facsimile: (301) 286-021 3; internet: noll@cddis.gsfc. nasa.gov.

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FIGURE CAPTIONS

Fig. 1. Plots of the x-component of polar motion (a), the y-component of polar motion (b), and UT 1 –UTC (c) 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 (c)is readily apparent.

Fig. 2. Plots of the 1-sigma formal uncertainties in the determination of the x-component of polar motion (a), the y-component of polar motion (b), and UT 1 –UTC (c) from SPACE94. The insert 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 (ins) 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 hereby 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 1. DATA SETS COMBINED TO FORM SPACE94

DATA SET NAME	DATA TYPE	ANALYSIS CENTER	DATA SPAN	NUMBER POINTS
LLR (JPL94M01; VOL, UTO)				
McDonald Cluster	LLR	JPL	05OCT76-27JUN94	398
CERGA	LLR	JPL	07APR84-13DEC94	471
Haleakala	LLR	JPL	10FEB85-11AUG90	66
UTCSR (CSR94L01; PMX, PMY)				
LAGEOS	SLR	UTCSR	02OCT76-31DEC93	1901
DSN (JPL94R01; T, V)				
CA-Spain Cluster	VLBI	JPL	26NOV79-08JAN95	533
CA-Australia Cluster	VLBI	JPL	28OCT78-05JAN95	541
NASA SGP (GLB973f)				
Multibaseline	VLBI	GSFC	04AUG79-28DEC94	1774
Westford-Ft. Davis	VLBI	GSFC	25JUN81-01JAN84	103
Westford-Mojave	VLBI	GSFC	21MAR85-06AUG90	13
NOAA (UT1MC 19JAN95; UT1)				
IRIS Intensive	VLBI	NOAA	02APR84-31DEC94	2355
....				
GPS (SIO93P01; PMX, PMY)				
Scripps	GPS	SIO	25AUG91-31MAY92	263
GPS (JPL95P01; PMX, PMY)				
JPL FLINN Analysis	GPS	JPL	01JUN92-27JAN95	814
USNO (N9403.EOP.INT 23FEB95; UT1)				
IRIS Intensive	VLBI	USNO	04JAN95-27JAN95	16

TABLE 2. ADJUSTMENTS TO DATA SETS PRIOR TO COMBINATION

DATA SET NAME	BIAS (mas)		RATE (mas/yr)		UNCERTAINTY SCALE FACTOR	
LLR (JPL94M01)	VOL	UTO	VOL	UTO	VOL	UTO
McDonald Cluster	2.296	0.903	-0.724	-0.111	1.379	1.189
	(0.237	(0.231)	(0.046)	(0.051)		
CERGA	-0.284	0.348	0.122	--0.060	1.799	1.301
	(0.179	(0.096)	(0.037)	(0.022)		
Haleakala	1.421	-0.627	-0.208	--0.065	1.530	1.788
	(0.275)	(0.235)	((1.180	(0.160)		
DSN (JPL94R01)	T	v	T	V	T	v
CA-Spain Cluster	0.942	-0.328	-0.009	0.020	1.417	1.186
	(0.072)	(0.171)	(0.016	(0.039)		
CA-Australia Cluster	0.356	0.701	-0.250	0.078	1.465	1.219
	(0.050)	(0.147)	(0.012	(0.035)		
NASA SGP (GLB973f)	T	v	T	v	T	v
Westford-Ft. Davis	4.664	0.330	0.723	-0.191	0.363	0.769
	(1.839)	(3.183)	(0.371)	(0.634)		
Westford-Mojave	0.443	0.723	-0.037	0.019	2.586	0.998
	(0.217)	(0.455)				

DATA SET NAME	BIAS PMX	BIAS PMY	BIAS UT1	RATE PMX	RATE PMY	RATE UT1	SCALE PMX	SCALE PMY	SCALE UT1
NASA SGP(973f)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-0.435	-1.690	1.074	-0.140	-0.060	-0.121	2.114	1.974	2.143
	(0.027	(0.023)	(0.031)	(0.007)	(0.005)	(0.007)			
UTCSR (94L01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Lageos	0.116	0.582	---	-0.058	-0.162	----	0.704	0.602	---
	(0.023)	(0.019)		(0.007)	(0.006)				
NOAA (19JAN95)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IRIS Inten.	---	---	1.110	---	---	-0.0'?5	---	---	0.947
			(0.027)			(0.007)			
GPS (SIO93P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Scripps	-0.818	-1.508	---	-0.040	-0.002	--	1.899	1.915	---
	(0.035)	(0.040)							
GPS (JPL95P01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
JPL FLINN	-0.246	0.455	---	0.028	-0.135	---	3.457	2.952	---
	(0.144)	(0.130)		(0.024)	(0.022)				
USNO (23FEB95)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
IRIS Inten.	---	---	-0.239	---	---	-0.010	---	---	1.578
			(0.042)						

REFERENCE DATE FOR RATE ADJUSTMENT IS 1988.0

A COMBINED EOP SERIES: SPACE94

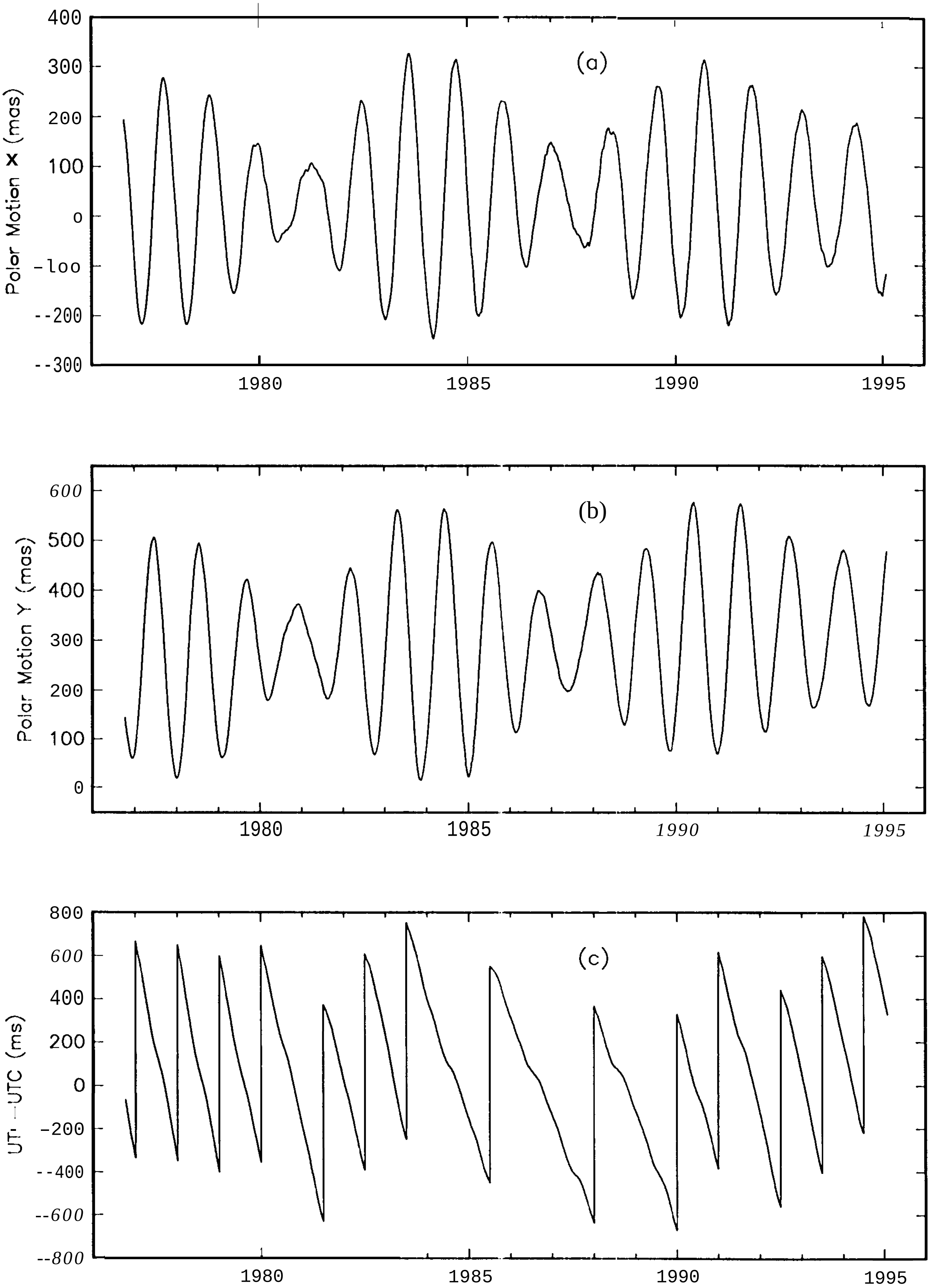

Fig. 1

A COMBINED EOP SERIES: SPACE94