A COMBINATION OF EARTH ORIENTATION DATA: SPACE92 JPL 93 C 01

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A combination of independently-determined Earth orientation data has been generated from space-geodetic observations spanning 1976-1992. The approach taken 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). The Kalman filter 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).

Information about the data that have been combined is given in Table 1. All publicly available, independent determinations of the Earth's orientation by the modern, space-geodetic techniques of very long baseline interferometry (VLBI), satellite laser ranging (SLR), lunar laser ranging (LLR), and the global positioning system (GPS) have been used. Since it was desirable to combine only independent determinations of the Earth's orientation, only one GPS data set was used, namely, that determined at JPL (Blewitt, private communication, 1993; note that only the GPS polar motion results were used), only one LLR data set was used, namely, that determined at JPL (Newhall, private communication, 1992) and only one SLR data set was used, namely, that determined at the University of Texas Center for Space Research (UTCSR; Eanes, private communication, 1992; note that the SLR UT1 results were not used herein 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). Three different data sets derived from independent VLBI observations have been used: the approximately twice-a-week single baseline measurements made using the radio telescopes of NASA's Deep Space Network (DSN; Steppe, private communication, 1992), the measurements made under the auspices of the International Radio Interferometric Surveying (IRIS) subcommission and analyzed at NOAA's Laboratory for Geosciences (IRIS Earth Orientation Bulletin No. 108, February, 1993; both their twice-a-week multibaseline results and their Intensive UT1 results at daily intervals have been used), and the UTPM determinations made by the VLBI group of the NASA Crustal Dynamics Project (CDP) at Goddard Space Flight Center (GSFC) from both their own CDP VLBI observations and from the CDP reduction of the IRIS multibaseline observations (Ma, private communication, 1993). Note that both the IRIS and CDP series used here include UTPM values determined by their own respective reductions of data taken by the United States Naval Observatory (USNO). Again, since it was desirable to combine only independent UTPM determinations, no series derived at the USNO was used (since the USNO data are reduced by, and the results included in, the IRIS and CDP series), and the results of the CDP reduction of the IRIS and USNO observations were used during 1979-1992.7, with the IRIS multibaseline series being used after 1992.7 (all of the IRIS Intensive results were used, however).

Before combining the series, the effect of the solid Earth tides upon UT1 was removed by using the model of Yoder *et al.* (1981). Also, the model of Dickman (1992) was used to remove the effect of the long period (fortnightly and longer) oceanic tides upon UT1 [the Dickman (1992) oceanic corrections to the Yoder *et al.* (1981) results were actually removed]. Finally, the empirical model of Herring (1992) was used to remove the effect of the semi- diurnal and diurnal oceanic tides upon those UT1 values that were determined from observations spanning a short enough time interval that these tidal effects should be present in them (namely, the LLR, DSN and IRIS Intensive series). The IRIS Intensive UT1 values are determined from observations spanning a short enough time interval that the semi-diurnal and diurnal oceanic tidal terms should be present at essentially full amplitude. However, the LLR and DSN observations span a long enough time interval that the semi-diurnal and diurnal oceanic tidal terms will be attenuated. Thus, for the LLR and DSN series, an attenuated version of the Herring (1992) semi-diurnal and diurnal oceanic tidal terms was removed. The attenuation factor applied depends upon the frequency (w) of the tidal term, as well as the duration time (T) of the observations (e.g. Guinot, 1970) and is given by [sin(wT/2)]/[wT/2].

Prior to combining the data, series-specific corrections were applied for bias and rate, and the stated uncertainties 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 type approach wherein each data set was compared to a combination of all other data sets (except for the GPS and IRIS multibaseline series which were treated separately as described below). First, a reference series (an extension of SPACE91) was used to initially correct the bias and rate of each series so that it agrees (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 series was iteratively adjusted 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 uncertainty of each series was adjusted by applying a multiplicative factor that made the residual of that 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 UTPM process contained in the Kalman filter. The incremental bias-rate corrections and uncertainty scale factors thus determined for the series were then applied 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 will have been determined that make the data sets agree with each other in bias and rate, and uncertainty scale factors will 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 (LAT), 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, a few round-robin iterations were completed in order to converge on initial values for the uncertainty scale factors. During subsequent iterations, those data points within 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 sigma. A total of 121 data points, or about two percent of the available data points, were thus deleted from all the series.

A bias-rate correction and uncertainty scale factor was determined for the IRIS multibaseline series by comparing this series to a combination of all other, independent series (but not including the GPS series -- see below) after the other series had had the bias-rate corrections and uncertainty scale factors applied to them that had been determined for them in the above iterative, round-robin procedure. For the purpose of this comparison, only the non-IRIS results contained in the CDP multibaseline series were selected and used. Also, for the purpose of this comparison, the entire IRIS multibaseline series, starting in 1980, was used so that a rate correction could be determined for it. Thus, a bias-rate correction and uncertainty scale factor was determined for the IRIS multibaseline series based upon the entire data set, even though just the corrected values since 1992.7 ultimately get combined with the other series. During this comparison, outlying data points (i.e. those whose residual values were greater than three times their adjusted uncertainties) were also deleted.

Similarly, a bias correction and uncertainty scale factor was determined for the GPS series by comparing it to a combination of all other, independent series (including the IRIS multibaseline 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 a bias correction was determined and applied to the GPS series since its overlap with the other, independent series was not great enough to allow a reliable rate correction to be determined. After the stated uncertainties of the GPS series were adjusted, no data points were found to be outliers (i.e., no data points had residual values greater than three times their adjusted uncertainties), and hence no data points were deleted from the GPS series.

Finally, each data set was placed within an 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 IRIS multibaseline data since 1992.7, 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 (e.g., 1991 IERS Annual Report) for the years 1984-1993.1 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 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 correction (the sum of the relative and IERS corrections) that has been determined for each data set is given in Table 2. Except for the GPS and IRIS multibaseline 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 IERS rate correction is applied to all the data sets, including those (such as the GPS 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 IRIS multibaseline 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 parentheses in Table 2) are the formal errors in determining the relative corrections. The uncertainty scale factors given in Table 2 for the GPS and IRIS multibaseline series are just the scale factors determined for them as described above when separately comparing them to combinations of all the other, independent series.

Note that the entries in Table 2 should not be used as a measure of the relative accuracy of the Earth orientation series. No attempt was made to place the series within a common reference frame prior to determining bias-rate corrections for them. Thus, the values for the bias-rate corrections given in Table 2 include the effects upon the Earth orientation series of reference frame differences.

The final UTPM combination was generated by combining all of the data (including the IRIS multibaseline results since 1992.7) after adjusting their biases, rates, and uncertainties by the amounts given in Table 2. This final combination, spanning May 20.0, 1976 to January 21.0, 1993, is designated SPACE92 and is given as daily values at midnight of PMX, PMY, UT1-UTC, their formal errors (1 sigma), and correlations. 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). Similarly, the model of Dickman (1992) was used to add back the oceanic tidal corrections to the Yoder *et al.* (1981) results. No diurnal or semi-diurnal oceanic tidal terms were added back, so the UT1 values given in SPACE92 can be properly considered to be UT1-UTC. The three correlations given at each time tag are the correlations between the UTPM values at that time tag. Improvements to the observing systems (both in the hardware and software, and in the number of systems) have led to more precise determinations of the Earth's orientation. This improvement is reflected in SPACE92 by the reduction of the UTPM formal errors from about 2 mas in polar motion and 0.5 ms in UT1 during the late 1970's to their current values of about 0.3 mas in polar motion and 0.03 ms in UT1.

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Table 1. Data Combined

DATA SET NAME	DATA TYPE	ANALYSIS CENTER	DATA SPAN	NUMBER POINTS	PLATE MODEL
LLR (92M01; VAR LAT, UT0)					
McDonald Cluster	LLR	JPL	22MAY76-15DEC91	383	AM0-2
CERGA	LLR	JPL	07APR84-27JAN92	317	AM0-2
Haleakala	LLR	JPL	10FEB85-11AUG90	68	AM0-2
UTCSR (92L01; PMX, PMY)					
LAGEOS	SLR	UTCSR	19MAY76-30DEC91	1693	Adjusted
DSN (92R01; T, V)					
CA-Spain Cluster	VLBI	JPL	26NOV79-27DEC92	433	AM0-2
CA-Australia Cluster	VLBI	JPL	28OCT78-24DEC92	445	AM0-2
CDP (GLB869b)					
Multibaseline	VLBI	GSFC	04AUG79-04SEP92	1235	Adjusted
Westford-Ft. Davis	VLBI	GSFC	25JUN81-01JAN84	103	Adjusted
Westford-Mojave	VLBI	GSFC	21MAR85-06AUG90	18	Adjusted
IRIS (UT1MC03FEB93; UT1)					
Intensive	VLBI	NOAA	02APR84-21JAN93	1911	Adjusted
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IRIS (IRIS27JAN93)					
Multibaseline	VLBI	NOAA	04SEP92-22JAN93	38	Adjusted
GPS (PMX, PMY)					
JPL FLINN Analysis	GPS	JPL	21JUN92-23JAN93	185	Adjusted

Table 2. Adjustments to data sets

DATA SET NAME	BIAS (mas)			RATE (mas/yr)			UNCERTAINTY SCALE FACTOR		
LLR (92M01)	LAT	UT0		LAT	UT0		LAT	UT0	
McDonald Cluster	1.399	0.453		-0.800	-0.102		1.030	1.046	
	(0.419)	(0.272)		(0.091)	(0.078)				
CERGA	-0.408	0.728		0.232	-0.144		1.203	1.147	
	(0.206)	(0.127)		(0.071)	(0.047)				
Haleakala	1.854	-0.813		0.279	-0.352		1.210	1.220	
	(0.372)	(0.261)		(0.246)	(0.182)				
DSN (92R01)	T	V		T	V		T	V	
CA-Spain Cluster	1.508	-0.906		0.240	0.170		1.195	1.099	
	(0.085)	(0.195)		(0.026)	(0.059)				
CA-Australia Cluster	-3.073	1.591		-0.350	-0.068		1.221	1.113	
	(0.056)	(0.161)		(0.018)	(0.050)				
CDP (GLB869b)	T	V		T	V		T	V	
Westford-Ft. Davis	3.842	-0.927		0.696	-0.181		1.028	0.912	
	(1.975)	(3.262)		(0.396)	(0.648)				
Westford-Mojave	0.421	0.088		0.012	0.004		1.680	1.050	
	(0.204)	(0.404)							
CDP (GLB869b)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	0.569	-1.769	-0.380	-0.077	-0.053	-0.165	1.434	1.317	1.464
	(0.029)	(0.025)	(0.033)	(0.011)	(0.010)	(0.012)			
UTCSR (92L01)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
LAGEOS	-0.078	-0.057	---	0.033	-0.081	---	0.899	0.888	---
	(0.025)	(0.022)		(0.011)	(0.010)				
IRIS (03FEB93)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Intensive	---	---	1.068	---	---	-0.154	---	---	0.982
			(0.028)			(0.011)			

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IRIS (27JAN93)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-9.894	3.714	1.091	0.127	0.226	-0.121	1.365	1.349	1.290
	(0.037)	(0.037)	(0.036)	(0.014)	(0.014)	(0.012)			
GPS	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
JPL FLINN	-0.507	-1.441	---	0.007	0.017	---	1.779	2.036	---
	(0.047)	(0.057)							

Reference date for rate adjustment is 1988.

EOP(JPL) 93 C 01 From May 1976 to Jan 1993

Number of measurements per year and median uncertainties
Units : 0.001" for X,Y; 0.0001s for UT1

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1976	226	5.01	226	3.85	226	6.85
1977	365	3.07	365	2.54	365	4.40
1978	365	3.29	365	2.25	365	5.31
1979	365	2.65	365	2.15	365	4.00
1980	366	1.52	366	1.05	366	2.69
1981	365	1.30	365	1.08	365	1.82
1982	365	0.99	365	0.90	365	1.25
1983	365	0.83	365	0.85	365	0.97
1984	366	0.51	366	0.45	366	0.56
1985	365	0.43	365	0.37	365	0.35
1986	365	0.38	365	0.33	365	0.31
1987	365	0.31	365	0.28	365	0.29
1988	366	0.27	366	0.26	366	0.28
1989	365	0.27	365	0.25	365	0.27
1990	365	0.24	365	0.24	365	0.23
1991	365	0.25	365	0.25	365	0.23
1992	366	0.28	366	0.30	366	0.24
1993	21	0.22	21	0.29	21	0.26