COMBINATION

A COMBINATION OF EARTH ORIENTATION DATA: SPACE90 JPL 90 C 01

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A combination of independently-determined Earth orientation data has been generated from space-geodetic observations spanning 1976-1990. 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), and lunar laser ranging (LLR) have been used. Since it was desirable to combine only independent determinations of the Earth's orientation, only one LLR data set was used, namely, that determined at JPL (Newhall *et al.* 1990) and only one SLR data set was used, namely, that determined at the Center for Space Research (CSR; Schutz *et al.* 1989). Four 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 *et al.* 1990), the approximately weekly multibaseline measurements made by the U.S. Naval Observatory's VLBI Network (NAVNET; Eubanks *et al.* 1990), the measurements made under the auspices of the International Radio Interferometric Surveying (IRIS) subcommission and analyzed at the National Geodetic Survey (NGS; IRIS Earth Orientation Bulletin No. 84, February, 1991; both their multibaseline results at 5-day intervals 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 *et al.* 1990; note that the actual CDP data set used herein is designated by the CDP VLBI group as EOP.629 and was determined by applying the Minster-Jordan plate tectonic motion model AM0-2 without adjustment (C. Ma, personal communication, 1990)]. Again, since it was desirable to combine only independent UTPM determinations, the results of the CDP reduction of the IRIS observations were used during 1979-1989, with the IRIS multibaseline results being used from 1990 onwards (all of the IRIS Intensive results were used, however).

The SLR data was first analytically corrected to be in the AM0-2 frame by applying a rate adjustment of -0.52 mas/yr to PMX and -0.24 mas/yr to PMY (IERS Annual Report for 1989, pp. II-26). 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.

Prior to combining the data, series-specific corrections were applied for bias and rate, and the stated uncertainties were adjusted by multiplying them by a series-specific scale factor. Values for these bias-rate corrections and uncertainty scale factors were determined in an iterative, round-robin fashion wherein each data set was compared to a combination of all other data sets (except for the IRIS data sets which were treated separately as described below). The bias and rate of each series was 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 a reliable rate determination could be made. The stated uncertainties of

each series were 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 each data set 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 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. The values for the relative bias-rate corrections and uncertainty scale factors thus determined have been previously reported by Gross and Steppe (1990) and are given here in Table 2. Except for the IRIS series (see below), the values for the bias- rate corrections given in Table 2 are the sum of all the incremental corrections and the values for the uncertainty scale factors given in Table 2 are the products of all the incremental scale factors. 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), not available (e.g., the IRIS Intensive PMX and PMY components), or for which reliable rate corrections could not be determined.

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 SLR and multibaseline VLBI measurements this is the usual UTPM (PMX, PMY, UT1) frame.

The IRIS data sets (both the multibaseline results and the Intensive UT1 results) were not included in the above iterative, round-robin scheme since they were determined in a somewhat different manner than were the other data sets. The IRIS series were determined by the NGS using a procedure in which the velocities of the observing stations were adjusted along with the station locations and the other model parameters (Carter and Robertson 1990). All of the other data sets used herein were determined by simply applying AM0-2 as a model for the motions of the stations, without adjustment. The IRIS data sets were therefore treated separately since it was desired to apply the iterative, round-robin procedure to only those data sets that were determined in as similar a manner as possible.

The incorporation of the IRIS data sets into the final UTPM combination is complicated by the desire to be able to update the combination (with a minimum of effort) as new data becomes available during the year. This updating of the combination is accomplished primarily with the IRIS Intensive and multibaseline data. The final combination being reported here is an updated version of an earlier combination that was originally generated using an earlier IRIS solution, namely, that given in the IRIS Earth Orientation Bulletin No. 80 of October, 1990. Values for the bias-rate corrections and uncertainty scale factors for the data sets of this earlier IRIS solution were obtained by comparing the uncorrected IRIS data to a combination of all the other data (after applying to all the other data the relative bias-rate corrections and uncertainty scale factors determined for them in the above iterative, round-robin procedure and given in Table 2). In this comparison, in order to get a reliable rate determination, all of the available IRIS results were used, including the multibaseline results for 1980-1989, even though only the corrected multibaseline results for 1990 were combined with the other data. The resulting bias-rate corrections and uncertainty scale factors thus determined for the earlier IRIS data sets are given in Table 2. The errors in these bias-rate corrections (given in parentheses in Table 2) are simply the formal errors in their determination. Note that the bias-rate corrections for these earlier IRIS data sets were determined prior to adjusting the uncertainties (it would have been more proper to have determined them after the uncertainties were adjusted). This is likely to have a small effect on the values for the bias-rate corrections, but could have a larger effect

on the formal errors in their determination. Thus the formal errors of the IRIS bias- rate corrections given in Table 2 are likely to be smaller than if they had been determined after uncertainty adjustment. Also note that the uncertainty scale factors for the IRIS multibaseline data set are determined by comparing it to a combination of all the other data sets, including the CDP data set which includes the CDP reduction of the IRIS multibaseline observations. Therefore, the IRIS multibaseline data set is not completely independent of the combination to which it is being compared, and consequently the uncertainty scale factors that are determined for it are likely to be smaller than those that would be obtained if it were compared to a completely independent combination.

Each data set has been placed within an IERS reference frame by applying to it an additional bias-rate correction (in addition to the relative bias-rate corrections determined above and given in Table 2) that is common to all the data sets. This additional correction was determined by first combining all data (including the earlier IRIS data consisting of all the Intensive results along with the multibaseline results for 1990, and after applying to all the data the relative bias-rate corrections and uncertainty scale factors determined above and given in Table 2). This intermediate combination was then compared to the IERS combination EOP(IERS) 90 C 02 (IERS Annual Report for 1989, pp. II-29) for the years 1984-1989 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. The common bias-rate correction thus obtained is given in Table 3 along with the formal error in its determination (given in parenthesis in Table 3). This additional bias-rate correction is 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 UTPM series EOP(IERS) 90 C 02. The absolute bias-rate corrections (the sum of the relative and IERS corrections) that have been determined in this manner are given in Table 4 (except for the IRIS entries which are those applicable to the updated IRIS data - see below). The errors in the bias-rate corrections (given in parentheses in Table 4) are the square roots of the sum of the squares (rss) of the formal errors given in Tables 2 and 3 (after rotation to the appropriate natural reference frame). The values for the bias-rate corrections given in Table 4 are the sum of all the incremental corrections (given in Table 2) and the additional correction (given in Table 3) needed to place each series within the above IERS reference frame. Note that the same IERS rate correction is applied to all of the data sets, including those (such as NAVNET) for which no relative rate correction could be determined. Therefore, the rate correction (and its formal error) given inTable 4 for those data sets for which no relative rate correction could be determined is simply the IERS rate correction (and its formal error), but given, of course, in the natural reference frame for that data set.

The last step taken prior to generating the final combination being reported here was to extend the earlier combination by incorporating the IRIS Intensive and multibaseline results from the most recent IRIS solution available, which at the time was that solution reported in IRIS Earth Orientation Bulletin No. 84 of February, 1991. The values for the bias-rate corrections and uncertainty scale factors for these most recent IRIS data sets, and which are given in Table 4, were obtained by comparing the most recent uncorrected IRIS data to a combination of all the other data (excluding, of course, the earlier IRIS data) after applying the absolute bias-rate corrections and uncertainty scale factors given for them in Table 4. In this comparison, in order to again get a reliable rate determination, all of the available most recent IRIS results were used, including the multibaseline results for 1980-1989, even though only the corrected multibaseline results for 1990 were incorporated into the final combination. The errors in the bias-rate corrections for the most recent IRIS data sets (given in parentheses in Table 4) are simply the formal errors in their determination (and not the rss of the errors given in Tables 2 and 3). Also, as above for the earlier IRIS data sets, since the bias-rate corrections were determined prior to uncertainty adjustment, the errors given in Table 4 for them are likely to be smaller than if they had been determined after uncertainty adjustment. And since the uncertainty scale factors for the IRIS multibaseline data set are determined by comparison to a combination that is not completely independent of it, the uncertainty scale factors given in Table 4 for it are likely to be smaller than if they had been determined by comparison to a completely independent combination.

The final UTPM combination was generated by combining all of the data (including the most recent IRIS data consisting of all the Intensive results along with the multibaseline results for 1990) after adjusting their biases, rates, and uncertainties by the amounts given in Table 4. This final combination, spanning June 21.0, 1976 to January 18.0, 1991, is designated SPACE90 and is given in Table 5 as daily values at midnight of PMX, PMY, UT1- UTC, their formal errors (1 sigma), and correlations. No tides have been removed from the UT1 values and 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 SPACE90 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 0.4 mas in polar motion and 0.05 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 (L1707; VAR LAT, UT0)					
McDonald 2.7m	LLR	JPL	5/22/76 - 6/29/85	375	AM0-2
McDonald LRS	LLR	JPL	3/2/85 - 1/27/88	35	AM0-2
McD LRS (New Site)	LLR	JPL	3/28/88 - 12/9/89	20	AM0-2
CERGA	LLR	JPL	4/7/84 - 12/20/89	271	AM0-2
Haleakala	LLR	JPL	11/14/84 - 12/17/89	105	AM0-2
DSN (90 R 01; T, V)					
CA(12)-Spain(63)	VLBI	JPL	7/18/82 - 8/25/84	57	AM0-2
CA(14)-Spain(61)	VLBI	JPL	9/19/82 - 8/1/87	42	AM0-2
CA(14)-Spain(63)	VLBI	JPL	11/26/79 - 12/10/89	142	AM0-2
CA(15)-Spain(63)	VLBI	JPL	10/4/87 - 7/8/90	42	AM0-2
CA(12)-Australia(43)	VLBI	JPL	7/2/82 - 7/22/84	58	AM0-2
CA(14)-Australia(42)	VLBI	JPL	2/15/83 - 9/20/87	34	AM0-2
CA(14)-Australia(43)	VLBI	JPL	10/28/78 - 3/3/90	170	AM0-2
CA(15)-Australia(43)	VLBI	JPL	11/8/87 - 7/9/90	36	AM0-2
CDP (EOP.629)					
Multibaseline	VLBI	GSFC	8/4/79 - 12/29/89	700	AM0-2
Westford-Ft. Davis	VLBI	GSFC	6/25/81 - 1/1/84	103	AM0-2
NAVNET (NAVY 1990-2)					
Multibaseline	VLBI	USNO	9/11/88 - 2/21/90	38	AM0-2
CSR (89 L 02; PMX, PMY)					
LAGEOS	SLR	Texas	5/15/76 - 1/3/89	970	AM1-2
.....					
IRIS (30JAN91)					
Multibaseline	VLBI	NGS	1/3/90 - 1/18/91	82	Adjusted
Intensive (UT1)	VLBI	NGS	4/2/84 - 1/16/91	1467	Adjusted

Table 2: Relative adjustments to data sets

DATA SET NAME	BIAS (mas)		RATE (mas/yr)		UNCERTAINTY SCALE FACTOR	
LLR (L1707)	LAT	UT0	LAT	UT0	LAT	UT0
McDonald 2.7m	-1.954	3.994	---	---	1.086	1.199
	(0.601)	(0.751)				
McDonald LRS	0.170	0.634	---	---	0.917	1.687
	(0.482)	(0.869)				
McD LRS (New Site)	-0.260	3.822	---	---	0.716	1.001
	(0.441)	(0.495)				
CERGA	0.479	2.998	0.328	0.650	1.204	1.104
	(0.201)	(0.138)	(0.125)	(0.086)		
Haleakala	-1.308	3.262	0.801	0.269	1.204	1.192
	(0.400)	(0.276)	(0.279)	(0.202)		
DSN (90 R 01)	T	V	T	V	T	V
CA(12)-Spain(63)	-1.877	4.293	---	---	1.240	1.181
	(0.553)	(0.876)				
CA(14)-Spain(61)	-0.123	2.827	---	---	1.196	0.991
	(0.549)	(1.024)				
CA(14)-Spain(63)	-0.344	2.109	0.258	-0.524	1.295	1.144
	(0.151)	(0.377)	(0.073)	(0.133)		
CA(15)-Spain(63)	-0.879	1.193	---	---	1.021	1.130
	(0.231)	(0.744)				
CA(12)-Australia(43)	-2.495	-4.004	---	---	1.142	1.160
	(0.222)	(0.744)				
CA(14)-Australia(42)	-1.842	-3.651	---	---	1.168	1.143
	(0.250)	(0.872)				
CA(14)-Australia(43)	-1.767	-2.529	0.103	-0.014	1.456	1.114
	(0.113)	(0.273)	(0.042)	(0.110)		
CA(15)-Australia(43)	-1.085	-4.028	---	---	1.139	0.852
	(0.184)	(0.409)				
CDP (EOP.629)	T	V	T	V	T	V
Westford-Ft. Davis	-0.947	-4.687	---	---	1.649	1.021
	(0.329)	(0.558)				

CDP (EOP.629)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	1.402	-1.465	-1.616	0.009	0.775	0.559	1.567	1.540	2.181
	(0.051)	(0.047)	(0.099)	(0.027)	(0.025)	(0.060)			
NAVNET (1990-2)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	0.971	-0.569	-1.475	---	---	---	1.278	1.436	1.274
	(0.168)	(0.187)	(0.204)						
CSR (89 L 02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
LAGEOS	-2.176	3.512	---	-0.025	0.412	---	0.838	0.835	---
	(0.059)	(0.055)		(0.032)	(0.029)				

Table 2 (cont.) : Relative adjustments to data sets

DATA SET NAME	BIAS (mas)			RATE (mas/yr)			UNCERTAINTY SCALE FACTOR		
IRIS (28SEP90)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-7.421	4.442	-2.821	0.161	0.840	0.331	1.357	1.250	1.913
	(0.030)	(0.028)	(0.038)	(0.016)	(0.016)	(0.020)			
Intensive	---	---	-2.857	---	---	0.445	---	---	1.308
			(0.037)			(0.025)			

Reference time for rate adjustment is 1988.0

Table 3: Common bias-rate correction applied to each series to place it within an IERS Reference frame

BIAS (mas)			RATE (mas/yr)		
PMX	PMY	UT1	PMX	PMY	UT1
-2.627	-0.591	4.244	-0.044	-0.588	-0.439
(0.031)	(0.029)	(0.040)	(0.017)	(0.016)	(0.025)

Reference time for rate adjustment is 1988.0

Table 4: Adjustments to data prior to final combination

DATA SET NAME	BIAS (mas)		RATE (mas/yr)		UNCERTAINTY SCALE FACTOR	
LLR (L1707)	LAT	UT0	LAT	UT0	LAT	UT0
McDonald 2.7m	-1.891	9.017	-0.559	-0.284	1.086	1.199
	(0.602)	(0.752)	(0.016)	(0.023)		
McDonald LRS	0.232	5.657	-0.559	-0.284	0.917	1.687
	(0.483)	(0.870)	(0.016)	(0.023)		
McD LRS (New Site)	-0.197	8.845	-0.559	-0.284	0.716	1.001
	(0.442)	(0.496)	(0.016)	(0.023)		
CERGA	-2.057	5.450	0.355	-0.074	1.204	1.104
	(0.203)	(0.142)	(0.127)	(0.088)		
Haleakala	0.858	7.797	0.605	0.053	1.204	1.192
	(0.401)	(0.279)	(0.279)	(0.203)		
DSN (90 R 01)	T	V	T	V	T	V
CA(12)-Spain(63)	0.349	0.294	-0.226	0.486	1.240	1.181
	(0.554)	(0.876)	(0.022)	(0.020)		
CA(14)-Spain(61)	2.110	-1.172	-0.227	0.484	1.196	0.991
	(0.550)	(1.024)	(0.022)	(0.020)		
CA(14)-Spain(63)	1.889	-1.890	0.031	-0.039	1.295	1.144
	(0.155)	(0.379)	(0.076)	(0.135)		

Table 4 (cont.) : Adjustments to data prior to final combination

DATA SET NAME	BIAS (mas)		RATE (mas/yr)		UNCERTAINTY SCALE FACTOR	
CA(15)-Spain(63)	1.354	-2.806	-0.227	0.484	1.021	1.130
	(0.234)	(0.745)	(0.022)	(0.020)		
CA(12)-Australia(43)	-3.799	0.689	-0.576	-0.401	1.142	1.160
	(0.224)	(0.745)	(0.016)	(0.021)		
CA(14)-Australia(42)	-3.134	1.043	-0.577	-0.399	1.168	1.143
	(0.251)	(0.873)	(0.016)	(0.021)		
CA(14)-Australia(43)	-3.060	2.165	-0.474	-0.413	1.456	1.114
	(0.117)	(0.275)	(0.045)	(0.112)		
CA(15)-Australia(43)	-2.378	0.666	-0.577	-0.399	1.139	0.852
	(0.186)	(0.411)	(0.016)	(0.021)		
CDP (EOP.629)	T	V	T	V	T	V
Westford-Ft. Davis	-0.429	-0.482	-0.294	-0.548	1.649	1.021
	(0.331)	(0.559)	(0.020)	(0.021)		

CDP (EOP.629)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-1.225	-2.056	2.628	-0.035	0.187	0.120	1.567	1.540	2.181
	(0.060)	(0.055)	(0.107)	(0.032)	(0.030)	(0.065)			
NAVNET (1990-2)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-1.656	-1.161	2.769	-0.044	-0.588	-0.439	1.278	1.436	1.274
	(0.171)	(0.190)	(0.208)	(0.017)	(0.016)	(0.025)			
CSR (89 L 02)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
LAGEOS	-4.802	2.921	---	-0.069	-0.176	---	0.838	0.835	---
	(0.067)	(0.062)		(0.036)	(0.033)				
IRIS (30JAN91)	PMX	PMY	UT1	PMX	PMY	UT1	PMX	PMY	UT1
Multi	-10.014	3.791	1.383	0.133	0.255	-0.115	1.364	1.254	1.916
	(0.030)	(0.028)	(0.038)	(0.016)	(0.016)	(0.020)			
Intensive	---	---	1.340	---	---	0.002	---	---	1.305
			(0.037)			(0.025)			

Reference time for rate adjustment is 1988.0

Table 5:

EOP(JPL) 90 C 01 Available from 1976 to 1991

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

YEAR	X		Y		UT1	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1976	194	3.79	194	2.85	194	10.43
1977	365	2.59	365	2.07	365	5.44
1978	365	2.23	365	1.85	365	6.23
1979	365	1.77	365	1.55	365	5.83
1980	366	0.99	366	0.77	366	3.75
1981	365	1.08	365	0.82	365	3.11
1982	365	0.90	365	0.74	365	1.70
1983	365	0.75	365	0.78	365	1.48
1984	366	0.51	366	0.47	366	0.91
1985	365	0.47	365	0.43	365	0.62
1986	365	0.44	365	0.41	365	0.50
1987	365	0.42	365	0.38	365	0.46
1988	366	0.40	366	0.37	366	0.43
1989	365	0.45	365	0.43	365	0.41
1990	365	0.45	365	0.41	365	0.47
1991	18	0.45	18	0.40	18	0.46

COMBINATION OF PRECISE OBSERVATIONS OF THE ORIENTATION OF THE EARTH
NEOS 91 C 01

[The procedure for obtaining this series is described in the IERS Annual Report for 1990, part. III.]

EOP(NEOS) 91 C 01 Available from 1990 to 1990

Number of measurements and RMS uncertainty per year
Units : 0.001" for X,Y,$d\psi$,$d\varepsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$d\psi$		$d\varepsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1990	365	0.48	365	0.66	365	0.58	365	0.89	365	0.33