IERS TECHNICAL NOTE 14

Earth orientation reference frames and atmospheric excitation functions submitted for the 1992 IERS Annual Report

VLBI, LLR, GPS, SLR and AAM IERS Analysis Centres

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ERRATUM

IERS Technical Note No 13 - IERS Standards (1992)

p. 9 : GPS Block II dz = **0.9519** m vice 1.0229 m

p. 18 : Table 3.1, first line, last value should be **-0.0070** vice 0.0070.

p. 83 : Hobart Q1 EW tangential phase should be **160.4** vice -160.4.

p. 89 : Malibu M2 EW tangential phase should be **-142.4** vice 142.4.

p. 98 : Pearblossom M2 radial phase should be **-24.14** vice 24.1.

p. 137 : paragraph 3, read ...of the International **Astronomical** Union.

p. 137 : the formula reads

$$ds^2 = -c^2 d\tau^2$$

$$= -\left(1 - \frac{2U}{c^2}\right)(dx^0)^2 + \left(1 + \frac{2U}{c^2}\right)\left[(dx^1)^2 + (dx^2)^2 + (dx^3)^2\right].$$

(the "minus" sign was omitted in the second line)

p. 140, note 2: the formulas giving TCB-TCG, read

$$TCB - TCG = c^{-2}\left[\int_{t_0}^{t}(v_e^2/2 + U_{ext}(x_e))dt + v_e.(x - x_e)\right].$$

$$TCB - TCG = L_C \times (JD - 2443144.5) \times 86400 + c^{-2}v_e.(x - x_e) + P.$$

(the "." in the vector product V_e . $(x\text{-}x_e)$ was omitted)

1992 IERS ANNUAL REPORT

p. II-14, line 1 (title)

p. II-79, 80, 84, 86, Note 1

p. V-7, last table, lines 1, 3, 5

read ...SSC(IERS) 93 C **03**

IERS Technical Notes

This series of publications gives technical information related to the IERS activities, e.g. reference frames, excitation of the Earth rotation, computational or analysis aspects, models, etc. It also contains the description and results of the analyses performed by the IERS Analysis Centres for the Annual Report global analysis.

Back issues still available

No 1 : C. Boucher and Z.Altamimi. The initial IERS Terrestrial Reference Frame.

No 3 : D.D. McCarthy (ed). IERS Standards (1989)

No 4 : C. Boucher and Z. Altamimi. Evaluation of the realizations of the Terrestrial Reference System done by the BIH and IERS (1984-1988).

No 5 : Earth orientation and reference frame determinations, atmospheric excitation functions, up to 1989 (Annex to the IERS Annual Report for 1989). *[Superseded by T.N. No 8].*

No 6 : C. Boucher and Z. Altamimi. ITRF89 and other realizations of the IERS Terrestrial Reference System for 1989.

No 7 : E.F. Arias, M. Feissel and J.-F. Lestrade. The IERS extragalactic Celestial Reference Frame and its tie with HIPPARCOS.

No 8 : Earth orientation and reference frame determinations, atmospheric excitation functions, up to 1990 (Annex to the IERS Annual Report for 1990).

No 9 : C. Boucher and Z. Altamimi. ITRF90 and other realizations of the IERS Terrestrial Reference System for 1990.

No 10: C. Boucher and Z. Altamimi. The IERS GPS Terrestrial Reference Frame.

No 11: P. Charlot (ed.). Earth orientation, reference frames and atmospheric excitation functions submitted for the 1991 IERS Annual Report.

No 12: C. Boucher and Z. Altamimi. ITRF91 and other realizations of the IERS Terrestrial Reference System for 1991.

No 13: D.D. McCarthy (ed.). IERS Standards (1992).

No 14: P. Charlot (ed.) Earth orientation, reference frames and atmospheric excitation functions submitted for the 1992 IERS Annual Report.

No 15: C. Boucher and Z. Altamimi. ITRF92 and other realizations of the IERS Terrestrial Reference System for 1992.

Future issue

No 16: J.O. Dickey and M. Feissel (eds.). Results from the SEARCH'92 Campaign.

Table of contents

			page
	IERS Technical Notes		iii
VLBI	Earth Orientation Parameters from IRIS-S VLBI Measurements:	GIUB 93 R 01, 02	R-1
	Earth Orientation Parameters, site positions and velocities, and source positions from the NASA Space Geodesy Program-GSFC: Solution GLB 885	GSFC 93 R 01	R-7
	Solution GLB 885a	GSFC 93 R 02	R-11
	Solution GLB 886	GSFC 93 R 03	R-15
	Solution GLB 886a	GSFC 93 R 04	R-19
	Solution GLB 887	GSFC 93 R 05	R-23
	The JPL 1992-2 Reference Frame	JPL 92 R 02	R-31
	Earth Rotation Parameters from DSN VLBI: 1993	JPL 93 R 01	R-33
	The JPL 1993-2 Reference Frame	JPL 93 R 01	R-45
	NOAA Earth orientation time series and reference frames from VLBI observations:	NOAA 93 R 02, R 04, R 05, R 06	
	1- Description of analysis procedures		R-47
	2- Constraint algorithms		R-53
	3- Discussion of results		R-59
	Analysis of the IRIS VLBI intensive sessions	OPA 93 R 01	R-77
	Earth orientation parameters from IRIS VLBI measurements	SHA 93 R 01	R-81
	Earth orientation results from the U.S. Naval Observatory VLBI Program	USNO 93 R 01	R-83
LLR	Earth rotation (UT0-UTC and variation of latitude) from Lunar Laser Ranging	JPL 93 M 01	M-1
	Determination of universal time by Lunar Laser Ranging	SHA 93 M 01	M-7
	UT0 and variation of latitude determination from Lunar Laser Ranging observations for 1969-1992	UTXMO 93 M 01	M-11
GPS			
	FOREWORD		P-1
	Annual report of the CODE processing Center of IGS for 1992	CODE 92 P 01,	P-3
	Site coordinates from the Center for space research solution	CSR 92 P 03	P-15
	GPS data processing at the EMR analysis Centre	EMR 93 P 01, P 02, P 04	P-19

Table of contents (cont.)

	Daily Earth orientation parameters and ground station positions from routine IGS92-Campaign processing	ESOC 92 P 02, 93 P 01	P-25
	Earth orientation parameters from the JPL using GPS	JPL 92 P 02	P-33
	Geocentric site coordinates from the JPL using GPS	JPL 93 P 01	P-39
	1991-1993 SIO polar motion series	SIO 93 P 01	P-43
SLR	Earth orientation parameters and station coordinates from Central Laboratory for Geodesy	CLG 92 L 01, L 02, L 03, L 04	L-1
	Earth orientation and Site Coordinates from the Center for Space Research solution	CSR 93 L 01	L-7
	Earth rotation and station coordinates computed from SLR observations on LAGEOS-1	DUT 93 L 02	L-13
	Earth Orientation and station coordinates from LAGEOS SLR observations	GAOUA 93 L 01	L-19
	Earth rotation parameters and station coordinates by LAGEOS Laser Ranging data updated till mid-september, 1992	GFZ 93 L 01, L 02, L 03, L 04, L 05	L-23
	Earth orientation parameters from GSFC solution SL8.2	GSFC 93 L 01	L-31
Combination			
	A combination of Earth orientation data : SPACE 92	JPL 93 C 01	C-1
	Combination of precise observations of the orientation of the Earth	NEOS 93 C 01	C-9
AAM	Effective Atmospheric Angular Momentum functions and related parameters computed at the U.S. National Meteorological Center	NMC 87 * 01	*-1
	Effective Atmospheric Angular Momentum functions computed at the European Centre for Medium-range Weather Forecasts	ECMWF 87 * 01	*-5
	Effective Atmospheric Angular Momentum functions computed from the Japan Meteorological Agency data	JMA 87 * 01	*-7
	Effective Atmospheric Angular Momentum functions calculated at the U.K. Meteorological Office	UKMO 83 * 01	*-9

ALL RESULTS DESCRIBED IN THIS ISSUE ARE AVAILABLE ON REQUEST FROM THE CENTRAL BUREAU OF IERS.

VERY LONG BASELINE INTERFEROMETRY

EARTH ORIENTATION PARAMETERS FROM IRIS-S VLBI MEASUREMENTS

GIUB 93 R 01
GIUB 93 R 02

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Since 1990 the VLBI group at the Geodetic Institute of the University of Bonn (GIUB) regularly correlates and analyses VLBI experiments which are observed once per month under the acronym IRIS-S (International Radio Interferometric Surveying - South). The configuration of the IRIS-S network has undergone various changes in the recent past. Operations of the IRIS-S network started with five stations, i.e. Westford Observatory (Massachusetts, USA), Richmond Observatory (Florida, USA), Mojave Base Station (California, USA), Wettzell Geodetic Fundamental Station (Bavaria, Federal Republic of Germany) and Hartebeesthoek Radio Astronomy Observatory (South Africa). To date the IRIS-S network consists of Westford, Wettzell, Hartebeesthoek and a 12 m telescope near Santiago, Chile. The IRIS-S network configuration bears the invaluable advantage that it covers both the northern and the southern hemisphere within the individual experiments.

The data analysed consists of 34 sessions in quasi-monthly intervals from January 1990 to December 1992 (One session had to be canceled and one is still being analysed for unresolved phase instabilities). Two different terrestrial and celestial reference frames are used in two separate analyses. In the first analysis the IERS Celestial Reference Frame 1991 (ICRF) and the IERS Terrestrial Reference Frame 1991 (ITRF) (IERS, 1992) together with the NNR-NUVEL1 continental drift model (Argus and Gordon, 1991) are kept fixed. The respective Earth orientation parameters (EOP) and celestial pole offsets are estimated (GIUB 93 R 01). In a second solution the 34 IRIS-S measurements are adjusted in a single least squares adjustment solving for station coordinates and radio source positions as global parameters as well as EOP and celestial pole offsets for each measurement day (GIUB 93 R 02). The origin of the terrestrial reference frame is fixed through the Wettzell station coordinates which are kept at the ITRF 1991 values while continental drift effects are corrected using the NNR-NUVEL1 model for all stations. The origin of right ascension is fixed by the ICRF 1991 position of OJ287. The relative orientation of the frames is fixed on one IRIS-S measurement day (21. Dec. 1989) which is added to the input list. Here, the EOP of the USNO one-day concrete series are fixed and the IAU 1976 Precession and the IAU 1980 Theory of Nutation are applied.

All sessions are analysed using the CALC 7.6/SOLVE/GLOBL software system (Caprette *et al.*, 1990) which is based on the IERS 1989 Standards (McCarthy (ed.) *et al.*, 1989) and which is consistent with the IAU (1976) Resolution on Astronomical Constants, Time Scales and the Fundamental Reference Frame (Kaplan, 1981). The theoretical delays in the adjustment are calculated according to the Shapiro model (Ryan, 1989) and Hellings (1986) correction for relativistic bending. Horizontal and vertical ocean loading displacement effects of Scherneck (1991) are applied to the delay observables. The ionospheric refraction is dispersive and is calibrated by dual frequency observations. The hydrostatic component of atmospheric refraction is calibrated using the MTT model (Herring, 1992) based on surface meteorological data while the wet component is estimated with a 3-hour piecewiselinear function where surface meteorological data is available and 1-hour intervals where not. The station clocks are generally modelled with second order polynomials and only where the residuals show an abnormal behaviour a small number of additional clock parameters is introduced. Only delay observables are used in our analyses.

The one-sigma formal errors of the parameters are based on observation weights which are adjusted so that the Chi-square per degree of freedom ratio per baseline is close to unity. These contributions to the a priori variances should account for unmodelled effects in the data reduction (Herring *et al.*, 1986).

References

Argus, D.F., Gordon R.G., 1991: *Geoph. Res. Let.*, **18**, No. 11, 2039.

Caprette, D.S., Ma, C., Ryan, J.M., 1990: NASA Technical Memorandum 100765, NASA Goddard Space Flight Center, Greenbelt, MD. A-1.

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Kaplan, G.H., 1981: *USNO Circular No. 163*, Washington D.C.

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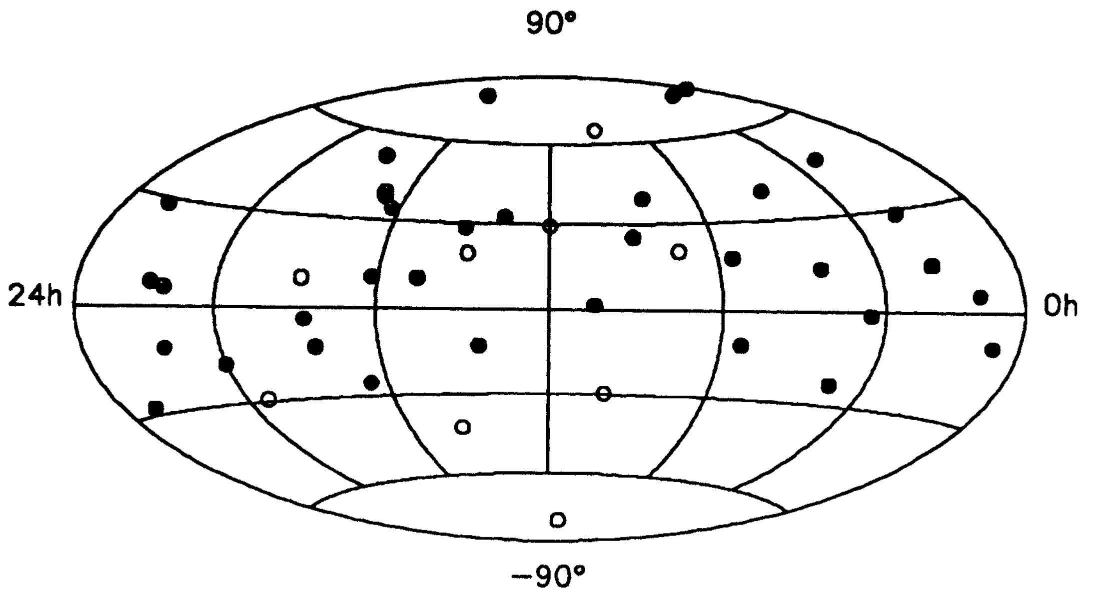
Ryan J.W., 1989: *CALC-7 Release Document*, GSFC.

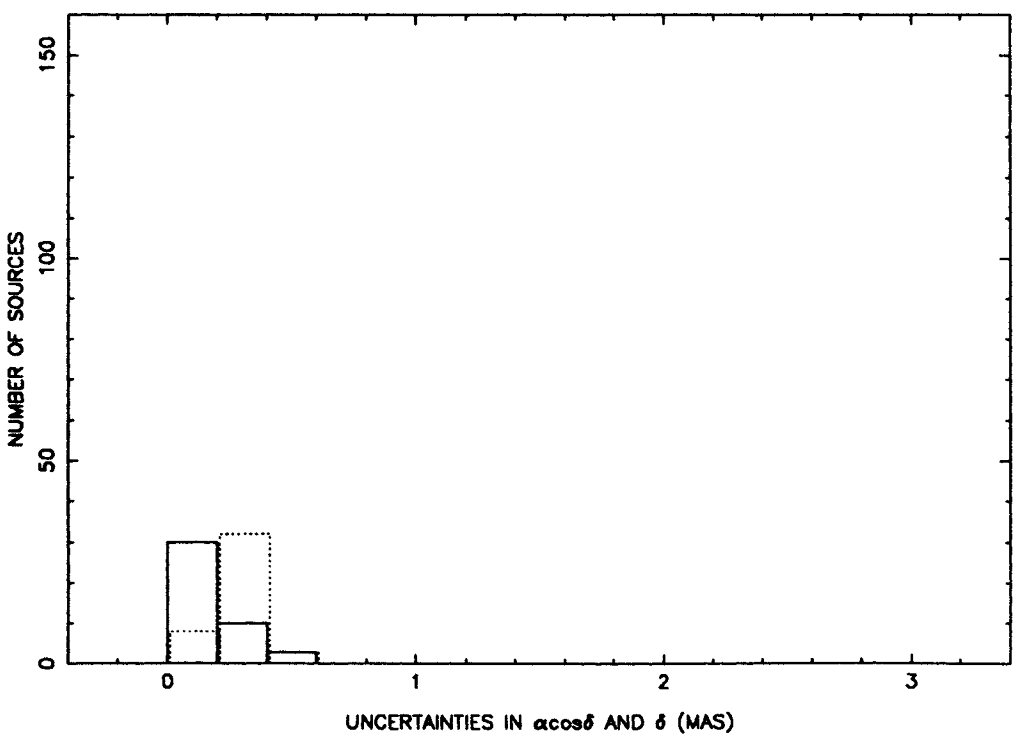
Scherneck, H.G., 1991: *Geophys. J. Int.*, **106**, 677.

Summary description of the terrestrial system attached to the set of station coordinates GIUB 93 R 02

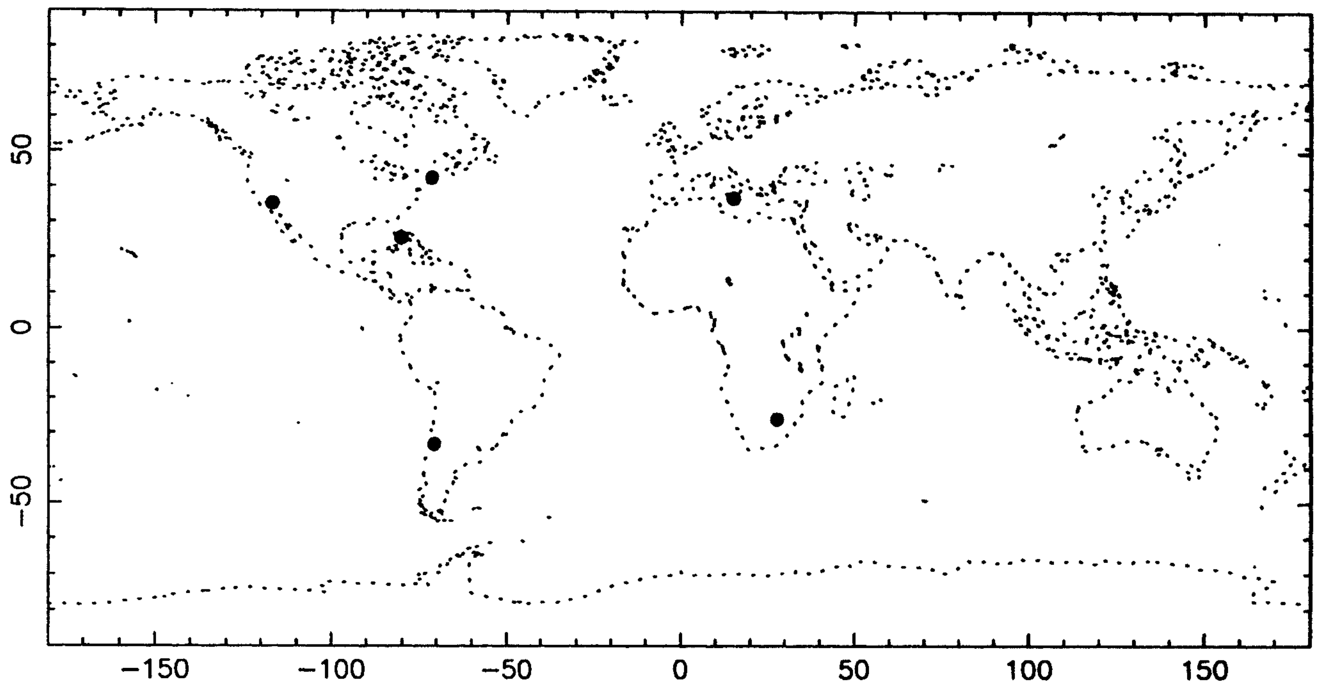
1 - Technique:		Mark III VLBI, Group delay observables
2 - Analysis Center:		GIUB
3 - Solution identifier:		SSC(GIUB) 93 R 02
4 - Software used:		CALC 7.6, SOLVE/GLOBL
5 -Relativity scale:		Solar System Barycenter
6 - Permanent tidal correction on station:		Not applied
7 - Tectonic plate model:		NNR-NUVEL1
8 - Velocity of light:		2.99792458 10^8 m/s
9 - Geogravitational constant:		Not applicable
10- Reference epoch:		1989 Dec. 21 for Earth orientation and nutation 1988 Jan. 01 for site coordinates J2000.0 for radio source positions
11- Adjusted parameters:		clock polynomials, wet troposphere parameters, EOP, celestial pole offsets, station coordinates, radio source positions
12- Definition of origin:	Terrestrial: Celestial:	Fixing Wettzell ITRF 1991 coordinates Fixing OJ287 ICRF 1991 right ascension
13- Definition of orientation:		Fixing USNO concrete EOP series and IAU 1980 Nutation for 1989 Dec. 21
14- Evolution in time:		Station coordinates move according to NNR-NUVEL1



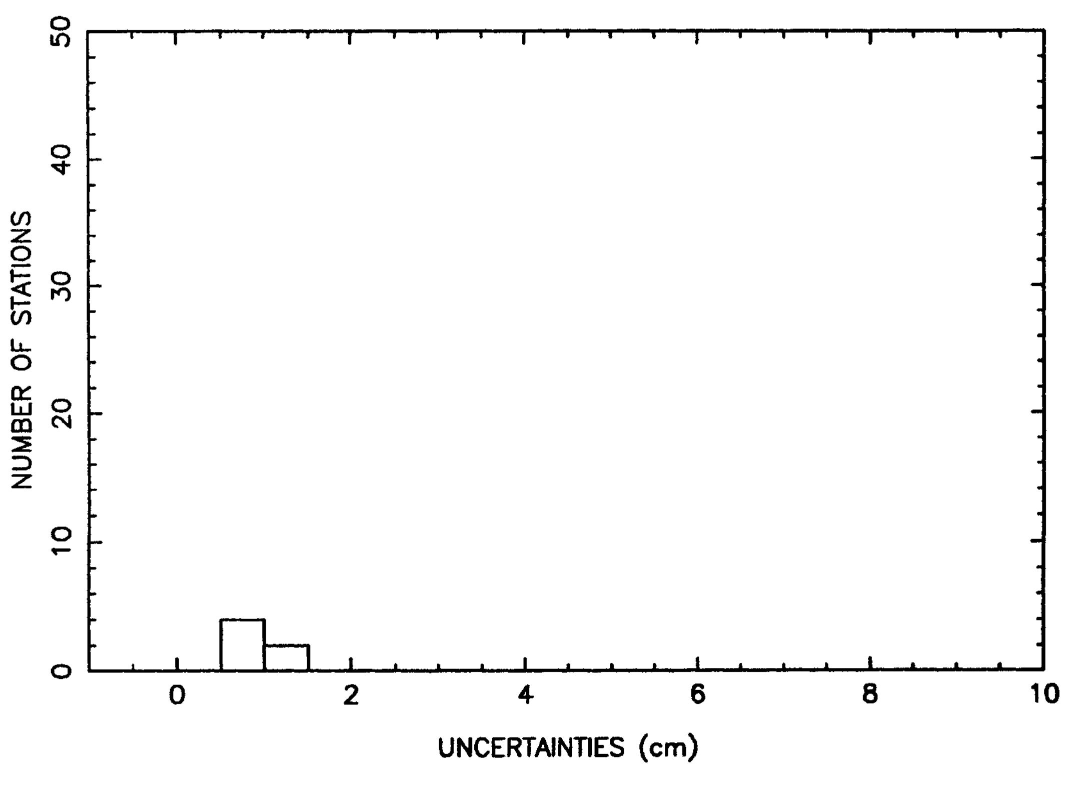
Distribution over the sky of the 44 extragalactic radio sources of the celestial frame RSC(GIUB) 93 R 01. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(GIUB) 93 R 01. 1 radio source with uncertainty larger than 0.003" is not shown.



Distribution of the 6 sites of the terrestrial frame SSC(GIUB) 93 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 6 stations of the terrestrial frame SSC(GIUB) 93 R 01.

EOP(GIUB) 93 R 01 From Jan 1990 to Dec 1992

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1990	11	0.21	11	0.14	11	0.12	11	0.29	11	0.13
1991	12	0.16	12	0.13	12	0.09	12	0.24	12	0.11
1992	11	0.15	11	0.11	11	0.11	11	0.23	11	0.10

EARTH ORIENTATION PARAMETERS, SITE POSITIONS AND VELOCITIES, AND SOURCE POSITIONS FROM THE NASA SPACE GEODESY PROGRAM-GSFC USING TWO-MONTH CONTINUOUS, PIECEWISE-LINEAR POSITIONS FOR HRAS 085: SOLUTION GLB885 GSFC 93 R 01

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Mark III VLBI delay data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for Earth orientation parameters. The observing sessions used in GLB885 are limited to those yielding useful EOP information, including all POLARIS one-baseline sessions.

A high frequency tidal EOP model, the MTT troposphere mapping model, NNR-NUVEL1, a constraint on vertical rates, and a nonlinear model for HRAS 085 are the major changes from our previous submissions.

The terrestrial reference frame origin is defined by the a priori position of the 18-m Westford antenna on 1988 Jan. 1, which is set to make the origin close to ITRF91. The right ascension origin is defined by the a priori position of 0420-014. The orientation of the terrestrial and celestial reference frames is defined by values from the USNO one-day concrete EOP series and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1985 Nov. 21, and by the position of WESTFORD and the direction of the WESTFORD-RICHMOND baseline, which evolve according to the NNR-NUVEL1 model.

Instantaneous EOP values were estimated at the middle of each observing session. No tidal terms in UT1 have been removed from the tabulated values of UT1-UTC. The pole and UT1 values include diurnal and semidiurnal tidal variations estimated from the complete set of Mark III VLBI geodetic data.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution. The other exceptions were WESTFORD, RICHMOND, and KAUAI, used to define the reference frame, and HRAS 085. The position of HRAS 085 was estimated as a continuous, piecewise-linear function with two-month intervals. Apart from the motion of the NNR-NUVEL1 model, the position of RICHMOND was constrained to change only in the a priori direction of WESTFORD. The vertical rate of KAUAI was constrained to be zero to provide a more robust geometry. The positions of six sites.

(YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, and MOJAVE12) each had one discontinuous change in position related to seismic events. The velocities of several sets of sites (FORT ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL, NRAO 140-NRAO85 1, SESHAN25-SHANGHAI) were constrained to be equal in order to strengthen the position or velocity estimates or to propagate more correctly the position of a site occupied only once.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB885 described below.

The basic models used to calculate the VLBI delays are generally consistent with the 1992 IERS standards and are contained in the Goddard CALC 7.6 program. These include IAU 1980 nutation with daily offsets in longitude and obliquity estimated, solid earth tides (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole tide, vertical and horizontal ocean loading, DE200 solar system ephemeris, and a modified Hellings (1986) VLBI time delay that agrees with the IERS standard model within 5 ps rms. The pole position for each observation was interpolated linearly from a one-day VLBI EOP series matching the USNO concrete series on the EOP reference date. The UT1 value for each observation was derived from the one-day VLBI EOP series by first removing the IERS standard tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from the complete set of Mark III geodetic data) were added to the interpolated pole and UT1 values. For each session a single reweighting constant computed for the particular day was added in quadrature to the data uncertainties derived strictly from SNR to reflect the actual data scatter. The dry troposphere effect was modeled from local meteorological data using the Saastamoinen zenith delay and the MTT dry troposphere mapping (Herring, 1992), while the residual wet troposphere was estimated using a continuous, piecewise-linear function with the MTT wet model (Herring, 1992). The behavior of the site clocks for each day was similarly estimated using a quadratic polynomial and a continuous, piecewise-linear function. For both estimates the variation in the continuous function was constrained to physically reasonable values except in the rare instances when the data dictated otherwise.

901623 dual-frequency Mark III delays and 0 delay rates from 1624 sessions using fixed stations and mobile sites were combined to estimate site positions and velocities, source positions, Earth orientation parameters, and troposphere and clock behavior from a least-squares solution with 1026 global parameters and 325710 arc parameters. There were 687757.6 degrees of freedom. A weak input covariance on polar motion and UT1 (X,Y - 45 mas, UT1 - 3 ms) was used so that all three components could be estimated for each session with more reliable indication of uncertainty and correlation. The weighted rms post-fit residual delay of the solution was 41.9 ps. The reduced chi-square was 0.968 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The complete Earth orientation time series is designated EOP(GSFC)93 R 01. Other results are source positions designated RSC(GSFC)93 R 01 and site coordinates at 1979-95 Jan 1.5 designated SSC(GSFC)93 R 01.

References

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Theil, H., 1963: *Amer. Stat. Ass. J.*, **58**, 401.

SUMMARY DESCRIPTION FOR SOLUTION GSFC 93 R 01 : SEE P. R-27

EOP(GSFC) 93 R 01 From Aug 1979 to Jan 1993

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1979	2	1.28	2	2.29	2	0.93	2	1.67	2	0.56
1980	20	0.66	20	0.65	20	0.30	20	1.02	20	0.30
1981	32	12.73	32	40.47	32	10.30	32	2.49	32	0.84
1982	55	12.74	55	40.48	55	10.31	55	2.56	55	0.86
1983	64	12.65	64	40.45	64	10.22	64	1.78	64	0.64
1984	87	0.69	87	0.66	87	0.34	87	0.90	87	0.33
1985	103	0.46	103	0.44	103	0.23	103	0.63	103	0.23
1986	123	0.46	123	0.41	123	0.23	123	0.62	123	0.22
1987	141	0.42	141	0.40	141	0.21	141	0.57	141	0.21
1988	156	0.38	156	0.37	156	0.18	156	0.52	156	0.20
1989	190	0.33	190	0.34	190	0.16	190	0.47	190	0.19
1990	238	0.27	238	0.32	238	0.14	238	0.42	238	0.17
1991	209	0.23	209	0.29	209	0.12	209	0.39	209	0.16
1992	203	0.23	203	0.31	203	0.12	203	0.38	203	0.15
1993	1	0.18	1	0.28	1	0.09	1	0.31	1	0.12

EARTH ORIENTATION PARAMETERS, SITE POSITIONS AND VELOCITIES, AND SOURCE POSITIONS FROM THE NASA SPACE GEODESY PROGRAM-GSFC USING LINEAR VELOCITY FOR HRAS 085: SOLUTION GLB885a GSFC 93 R 02

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Mark III VLBI delay data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for Earth orientation parameters. The observing sessions used in GLB885a are limited to those yielding useful EOP information, including all POLARIS one-baseline sessions.

A high frequency tidal EOP model, the MTT troposphere mapping model, NNR-NUVEL1, and a constraint on vertical rates are the major changes from our previous submissions.

The terrestrial reference frame origin is defined by the a priori position of the 18-m Westford antenna on 1988 Jan. 1, which is set to make the origin close to ITRF91. The right ascension origin is defined by the a priori position of 0420-014. The orientation of the terrestrial and celestial reference frames is defined by values from the USNO one-day concrete EOP series and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1985 Nov. 21, and by the position of WESTFORD and the direction of the WESTFORD-RICHMOND baseline, which evolve according to the NNR-NUVEL1 model.

Instantaneous EOP values were estimated at the middle of each observing session. No tidal terms in UT1 have been removed from the tabulated values of UT1-UTC. The pole and UT1 values include diurnal and semidiurnal tidal variations estimated from the complete set of Mark III VLBI geodetic data.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution. The other exceptions were WESTFORD, RICHMOND, and KAUAI, used to define the reference frame. Apart from the motion of the NNR-NUVEL1 model, the position of RICHMOND was constrained to change only in the a priori direction of WESTFORD. The vertical rate of KAUAI was constrained to be zero to provide a more robust geometry. The positions of six sites (YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, and MOJAVE12) each had one discontinuous change in position related to seismic events. The velocities of several sets of sites

(FORT ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL, HRAS 085-FTD 7900-MCD 7850-FD-VLBA, NRAO 140-NRAO85 1, SESHAN25-SHANGHAI) were constrained to be equal in order to strengthen the position or velocity estimates or to propagate more correctly the position of a site occupied only once.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB885a described below.

The basic models used to calculate the VLBI delays are generally consistent with the 1992 IERS standards and are contained in the Goddard CALC 7.6 program. These include IAU 1980 nutation with daily offsets in longitude and obliquity estimated, solid earth tides (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole tide, vertical and horizontal ocean loading, DE200 solar system ephemeris, and a modified Hellings (1986) VLBI time delay that agrees with the IERS standard model within 5 ps rms. The pole position for each observation was interpolated linearly from a one-day VLBI EOP series matching the USNO concrete series on the EOP reference date. The UT1 value for each observation was derived from the one-day VLBI EOP series by first removing the IERS standard tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from the complete set of Mark III geodetic data) were added to the interpolated pole and UT1 values. For each session a single reweighting constant computed for the particular day was added in quadrature to the data uncertainties derived strictly from SNR to reflect the actual data scatter. The dry troposphere effect was modeled from local meteorological data using the Saastamoinen zenith delay and the MTT dry troposphere mapping (Herring, 1992), while the residual wet troposphere was estimated using a continuous, piecewise-linear function with the MTT wet model (Herring, 1992). The behavior of the site clocks for each day was similarly estimated using a quadratic polynomial and a continuous, piecewise-linear function. For both estimates the variation in the continuous function was constrained to physically reasonable values except in the rare instances when the data dictated otherwise.

901623 dual-frequency Mark III delays and 0 delay rates from 1624 sessions using fixed stations and mobile sites were combined to estimate site positions and velocities, source positions, Earth orientation parameters, and troposphere and clock behavior from a least-squares solution with 852 global parameters and 325710 arc parameters. There were 687922.2 degrees of freedom. A weak input covariance on polar motion and UT1 (X,Y - 45 mas, UT1 - 3 ms) was used so that all three components could be estimated for each session with more reliable indication of uncertainty and correlation. The weighted rms post-fit residual delay of the solution was 41.9 ps. The reduced chi-square was 0.970 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The complete Earth orientation time series is designated EOP(GSFC)93 R 02. Other results are source positions designated RSC(GSFC) 93 R 02 and site coordinates at 1979-95 Jan 1.5 designated SSC(GSFC) 93 R 02.

References

Hellings, R. W., 1986: *Astron. J.*, **91**, 1446.

Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36,** 157.

Theil, H., 1963: *Amer. Stat. Ass. J.*, **58,** 401.

SUMMARY DESCRIPTION FOR SOLUTION GSFC 93 R 02 : SEE P. R-27

SITE POSITIONS AND VELOCITIES, EARTH ORIENTATION PARAMETERS, AND SOURCE POSITIONS FROM THE NASA SPACE GEODESY PROGRAM-GSFC USING TWO-MONTH CONTINUOUS, PIECEWISE-LINEAR POSITIONS FOR HRAS 085: SOLUTION GLB886 GSFC 93 R 03

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Mark III VLBI delay data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the Geographical Survey Institute (Japan), the Communications Research Laboratory (Japan), the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for the terrestrial reference frame. The sessions used for GLB886 include all geodetic VLBI sessions available to the NASA Space Geodesy Program-GSFC. EOP information from solution GLB885 was applied to those sessions where the data or networks were inadequate to determine EOP well.

A high frequency tidal EOP model, the MTT troposphere mapping model, NNR-NUVEL1, a constraint on vertical rates, and a nonlinear model for HRAS 085 are the major changes from our previous submissions.

The terrestrial reference frame origin is defined by the a priori position of the 18-m Westford antenna on 1988 Jan. 1, which is set to make the origin close to ITRF91. The right ascension origin is defined by the a priori position of 0420-014. The orientation of the terrestrial and celestial reference frames is defined by values from the USNO one-day concrete EOP series and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1985 Nov. 21, and by the position of WESTFORD and the direction of the WESTFORD-RICHMOND baseline, which evolve according to the NNR-NUVEL1 model.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution. The other exceptions were WESTFORD, RICHMOND, and KAUAI, used to define the reference frame, and HRAS 085. The position of HRAS 085 was estimated as a continuous, piecewise-linear function with two-month intervals. Apart from the motion of the NNR-NUVEL1 model, the position of RICHMOND was constrained to change only in the a priori direction of WESTFORD. The vertical rate of KAUAI was constrained to be zero to provide a more robust geometry. The positions of six sites (YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, and MOJAVE12) each had one discontinuous change in position related to seismic events. The velocities of several sets of sites (FORT ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL, MOJAVE12-MOJ 7288, OVRO 130-OVR 7853-OV-VLBA, SESHAN25-SHANGHAI, NRAO 140-NRAO85 1, ONSALA60-MV2ONSLA) were constrained to be equal in order to strengthen the position or velocity estimates or to propagate more correctly the position of a site occupied only once.

Instantaneous EOP values were estimated at the middle of each observing session. No tidal terms in UT1 have been removed from the tabulated values of UT1-UTC. The pole and UT1 values include diurnal and semidiurnal tidal variations estimated from the complete set of Mark III VLBI geodetic data.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB886 described below.

The basic models used to calculate the VLBI delays are generally consistent with the 1992 IERS standards and are contained in the Goddard CALC 7.6 program. These include IAU 1980 nutation with daily offsets in longitude and obliquity estimated, solid earth tides (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole tide, vertical and horizontal ocean loading, DE200 solar system ephemeris, and a modified Hellings (1986) VLBI time delay that agrees with the IERS standard model within 5 ps rms. The pole position for each observation was interpolated linearly from a one-day VLBI EOP series matching the USNO concrete series on the EOP reference date. The UT1 value for each observation was derived from the one-day VLBI EOP series by first removing the IERS standard tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from the complete set of Mark III geodetic data) were added to the interpolated pole and UT1 values. For each session a single reweighting constant computed for the particular day was added in quadrature to the data uncertainties derived strictly from SNR to reflect the actual data scatter. The dry troposphere effect was modeled from local meteorological data using the Saastamoinen zenith delay and the MTT dry troposphere mapping (Herring, 1992), while the residual wet troposphere was estimated using a continuous, piecewise-linear function with the MTT wet model (Herring, 1992). The behavior of the site clocks for each day was similarly estimated using a quadratic polynomial and a continuous, piecewise-linear function. For both estimates the variation in the continuous function was constrained to physically reasonable values except in the rare instances when the data dictated otherwise.

1003763 dual-frequency Mark III delays and 0 delay rates from 1877 sessions using fixed stations and mobile sites were combined to estimate site positions and velocities, Earth orientation parameters, source positions, and troposphere and clock behavior from a least-squares solution with 1238 global parameters and 371603 arc parameters. There were 764930.9 degrees of freedom. A weak input covariance on polar motion and UT1 (X,Y - 45 mas, UT1 - 3 ms) was used so that all three components could be estimated for each session with more reliable indication of uncertainty and correlation. The weighted rms post-fit delay residual of the solution was 41.2 ps. The reduced chi-square was 0.974 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The site coordinates at 1979-95 Jan 1.5 are designated SSC(GSFC)93 R 03. Other results are the Earth orientation time series designated EOP(GSFC)93 R 03 and source positions designated RSC(GSFC)93 R 03.

References

Hellings, R. W., 1986: *Astron. J.*, **91**, 1446.

Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36,** 157.

Theil, H., 1963: *Amer. Stat. Ass. J.*, **58,** 401.

SUMMARY DESCRIPTION FOR SOLUTION GSFC 93 R 03 : SEE P. R-27

SITE POSITIONS AND VELOCITIES, EARTH ORIENTATION PARAMETERS, AND SOURCE POSITIONS FROM THE NASA SPACE GEODESY PROGRAM-GSFC USING LINEAR VELOCITY FOR HRAS 085: SOLUTION GLB886a GSFC 93 R 04

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Mark III VLBI delay data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the Geographical Survey Institute (Japan), the Communications Research Laboratory (Japan), the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for the terrestrial reference frame. The sessions used for GLB886a include all geodetic VLBI sessions available to the NASA Space Geodesy Program-GSFC. EOP information from solution GLB885a was applied to those sessions where the data or networks were inadequate to determine EOP well.

A high frequency tidal EOP model, the MTT troposphere mapping model, a constraint on vertical rates, and NNR-NUVEL1 are the major changes from our previous submissions.

The terrestrial reference frame origin is defined by the a priori position of the 18-m Westford antenna on 1988 Jan. 1, which is set to make the origin close to ITRF91. The right ascension origin is defined by the a priori position of 0420-014. The orientation of the terrestrial and celestial reference frames is defined by values from the USNO one-day concrete EOP series and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1985 Nov. 21, and by the position of WESTFORD and the direction of the WESTFORD-RICHMOND baseline, which evolve according to the NNR-NUVEL1 model.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution. The other exceptions were WESTFORD, RICHMOND, and KAUAI, used to define the reference frame. Apart from the motion of the NNR-NUVEL1 model, the position of RICHMOND was constrained to change only in the a priori direction of WESTFORD. The vertical rate of KAUAI was constrained to be zero to provide a more robust geometry. The positions of six sites (YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, and MOJAVE12) each had one discontinuous change in position related to seismic events. The velocities of several sets of sites

(FORT ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL, MOJAVE12-MOJ 7288, OVRO 130-OVR 7853-OV-VLBA, SESHAN25-SHANGHAI, NRAO 140-NRAO85 1, HRAS 085-FTD 7900-MCD 7850-FD-VLBA, ONSALA60-MV2ONSLA) were constrained to be equal in order to strengthen the position or velocity estimates or to propagate more correctly the position of a site occupied only once.

Instantaneous EOP values were estimated at the middle of each observing session. No tidal terms in UT1 have been removed from the tabulated values of UT1-UTC. The pole and UT1 values include diurnal and semidiurnal tidal variations estimated from the complete set of Mark III VLBI geodetic data.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB886a described below.

The basic models used to calculate the VLBI delays are generally consistent with the 1992 IERS standards and are contained in the Goddard CALC 7.6 program. These include IAU 1980 nutation with daily offsets in longitude and obliquity estimated, solid earth tides (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole tide, vertical and horizontal ocean loading, DE200 solar system ephemeris, and a modified Hellings (1986) VLBI time delay that agrees with the IERS standard model within 5 ps rms. The pole position for each observation was interpolated linearly from a one-day VLBI EOP series matching the USNO concrete series on the EOP reference date. The UT1 value for each observation was derived from the one-day VLBI EOP series by first removing the IERS standard tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from the complete set of Mark III geodetic data) were added to the interpolated pole and UT1 values. For each session a single reweighting constant computed for the particular day was added in quadrature to the data uncertainties derived strictly from SNR to reflect the actual data scatter. The dry troposphere effect was modeled from local meteorological data using the Saastamoinen zenith delay and the MTT dry troposphere mapping (Herring, 1992), while the residual wet troposphere was estimated using a continuous, piecewise-linear function with the MTT wet model (Herring, 1992). The behavior of the site clocks for each day was similarly estimated using a quadratic polynomial and a continuous, piecewise-linear function. For both estimates the variation in the continuous function was constrained to physically reasonable values except in the rare instances when the data dictated otherwise.

1003763 dual-frequency Mark III delays and 0 delay rates from 1877 sessions using fixed stations and mobile sites were combined to estimate site positions and velocities, Earth orientation parameters, source positions, and troposphere and clock behavior from a least-squares solution with 1064 global parameters and 371603 arc parameters. There were 765095.1 degrees of freedom. A weak input covariance on polar motion and UT1 (X,Y - 45 mas, UT1 - 3 ms) was used so that all three components could be estimated for each session with more reliable indication of uncertainty and correlation. The weighted rms post-fit delay residual of the solution was 41.3 ps. The reduced chi-square was 0.976 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The site coordinates at 1979-95 Jan 1.5 are designated SSC(GSFC)93 R 04. Other results are the Earth orientation time series designated EOP(GSFC)93 R 04 and source positions designated RSC(GSFC)93 R 04.

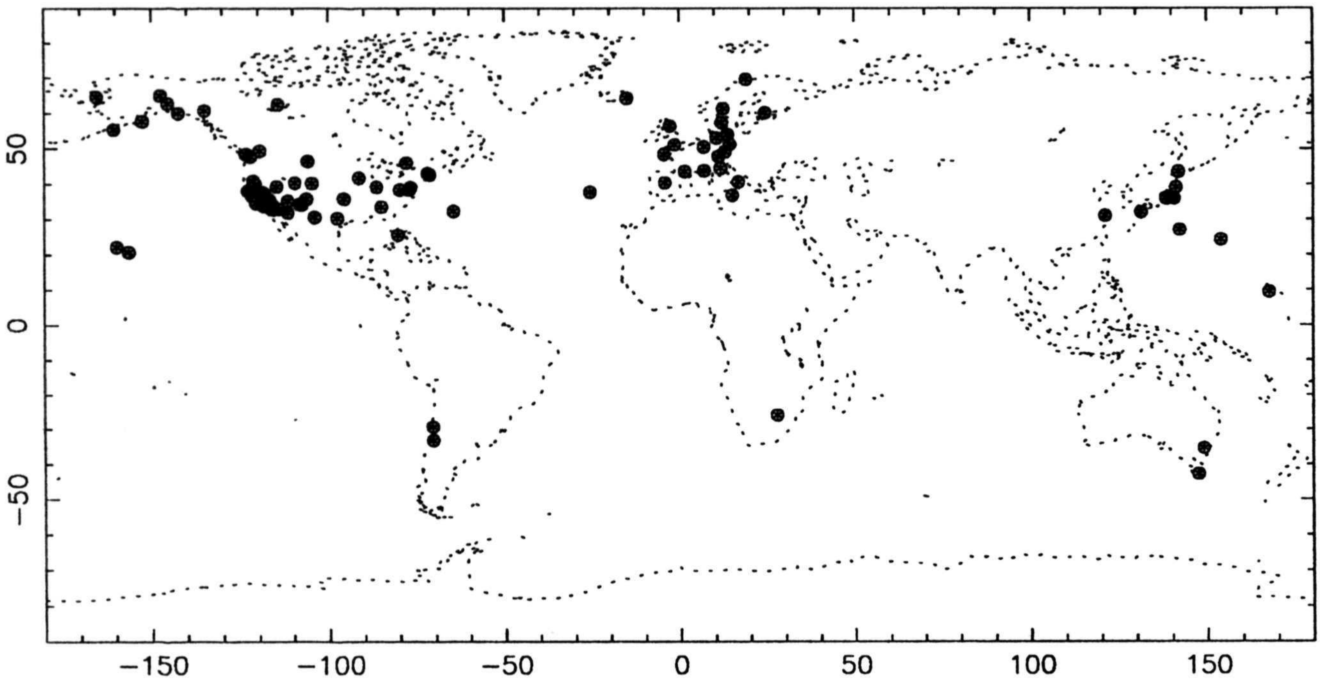
References

Hellings, R. W., 1986: *Astron. J.*, **91**, 1446.

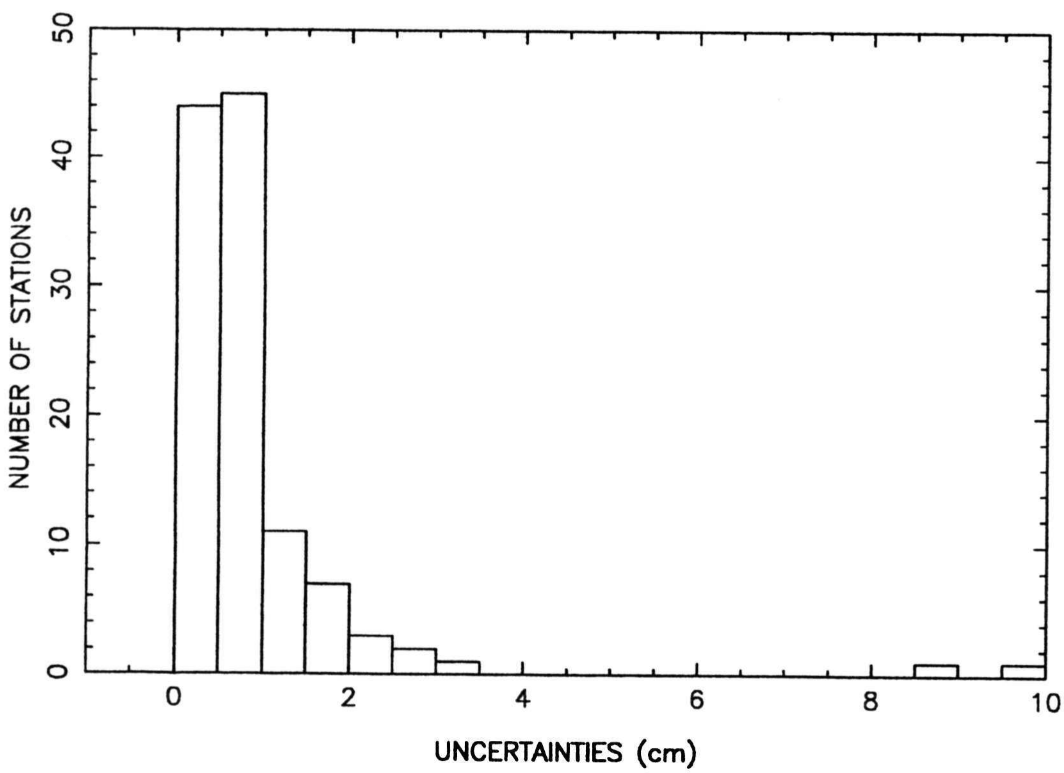
Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36,** 157.

Theil, H., 1963: *Amer. Stat. Ass. J.*, **58**, 401.

SUMMARY DESCRIPTION FOR SOLUTION GSFC 93 R 04 : SEE P. R-27



Distribution of the 92 sites of the terrestrial frame SSC(GSFC) 93 R 04.



Distribution of the uncertainties (quadratic mean of $\sigma_x, \sigma_y, \sigma_z$) for the 115 stations of the terrestrial frame SSC(GSFC) 93 R 04.

SOURCE POSITIONS, EARTH ORIENTATION PARAMETERS, AND SITE POSITIONS AND VELOCITIES FROM THE NASA SPACE GEODESY PROGRAM-GSFC USING LINEAR VELOCITY FOR HRAS 085: SOLUTION GLB887

GSFC 93 R 05

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Mark III VLBI delay and delay rate data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the US Naval Research Laboratory celestial reference frame program, the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for the celestial reference frame. Delay data from the geodetic sessions in solution GLB885a and both delay and delay rate data from the astrometric and survey sessions are included in solution GLB887.

A high frequency tidal EOP model, the MTT troposphere mapping model, a constraint on vertical rates and NNR-NUVEL1 are the major changes from our previous submissions.

The terrestrial reference frame origin is defined by the a priori position of the 18-m Westford antenna on 1988 Jan. 1, which is set to make the origin close to ITRF91. The right ascension origin is defined by the a priori position of 0420-014. The orientation of the terrestrial and celestial reference frames is defined by values from the USNO one-day concrete EOP series and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1985 Nov. 21, and by the position of WESTFORD and the direction of the WESTFORD-RICHMOND baseline, which evolve according to the NNR-NUVEL1 model.

About 100 sources used in the geodetic programs form the core of the celestial reference frame. These have ~100 to ~60000 observations each. About 320 sources have formal errors under 1 mas. The remaining sources include a number with very weak data.

Instantaneous EOP values were estimated at the middle of each observing session. No tidal terms in UT1 have been removed from the tabulated values of UT1-UTC. The pole and UT1 values include diurnal and semidiurnal tidal variations estimated from the complete set of Mark III VLBI geodetic data.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution.

The other exceptions were WESTFORD, RICHMOND, and KAUAI, used to define the reference frame. Apart from the motion of the NNR-NUVEL1 model, the position of RICHMOND was constrained to change only in the a priori direction of WESTFORD. The vertical rate of KAUAI was constrained to be zero to provide a more robust geometry. The positions of six sites (YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, and MOJAVE12) each had one discontinuous change in position related to seismic events. The velocities of several sets of sites (FORT ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL, SESHAN25-SHANGHAI, NRAO 140-NRAO85 1, HRAS 085-FTD 7900-MCD 7850-FD-VLBA) were constrained to be equal in order to strengthen the position or velocity estimates or to propagate more correctly the position of a site occupied only once.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB887 described below.

The basic models used to calculate the VLBI delays are generally consistent with the 1992 IERS standards and are contained in the Goddard CALC 7.6 program. These include IAU 1980 nutation with daily offsets in longitude and obliquity estimated, solid earth tides (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole tide, vertical and horizontal ocean loading, DE200 solar system ephemeris, and a modified Hellings (1986) VLBI time delay that agrees with the IERS standard model within 5 ps rms. The pole position for each observation was interpolated linearly from a one-day VLBI EOP series matching the USNO concrete series on the EOP reference date. The UT1 value for each observation was derived from the one-day VLBI EOP series by first removing the IERS standard tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from the complete set of Mark III geodetic data) were added to the interpolated pole and UT1 values. For each session a single reweighting constant computed for the particular day was added in quadrature to the data uncertainties derived strictly from SNR to reflect the actual data scatter. The dry troposphere effect was modeled from local meteorological data using the Saastamoinen zenith delay and the MTT dry troposphere mapping (Herring, 1992), while the residual wet troposphere was estimated using a continuous, piecewise-linear function with the MTT wet model (Herring, 1992). The behavior of the site clocks for each day was similarly estimated using a quadratic polynomial and a continuous, piecewise-linear function. For both estimates the variation in the continuous function was constrained to physically reasonable values except in the rare instances when the data dictated otherwise.

927990 dual-frequency Mark III delays and 26367 delay rates from 1702 sessions using fixed stations and mobile sites were combined to estimate site positions and velocities, source positions, Earth orientation parameters, and troposphere and clock behavior from a least-squares solution with 1476 global parameters and 336419 arc parameters. There were 733828.6 degrees of freedom. A weak input covariance on polar motion and UT1 (X,Y - 45 mas, UT1 - 3 ms) was used so that all three components could be estimated for each session with more reliable indication of uncertainty and correlation. The weighted rms post-fit residual of the solution was 42.1 ps for delays and 72.8 fs/s for rates. The reduced chi-square was 0.977 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The source positions are designated RSC(GSFC)93 R 05. Other results are the Earth orientation time series designated EOP(GSFC)93 R 05 and site coordinates at 1979-95 Jan 1.5 designated SSC(GSFC)93 R 05.

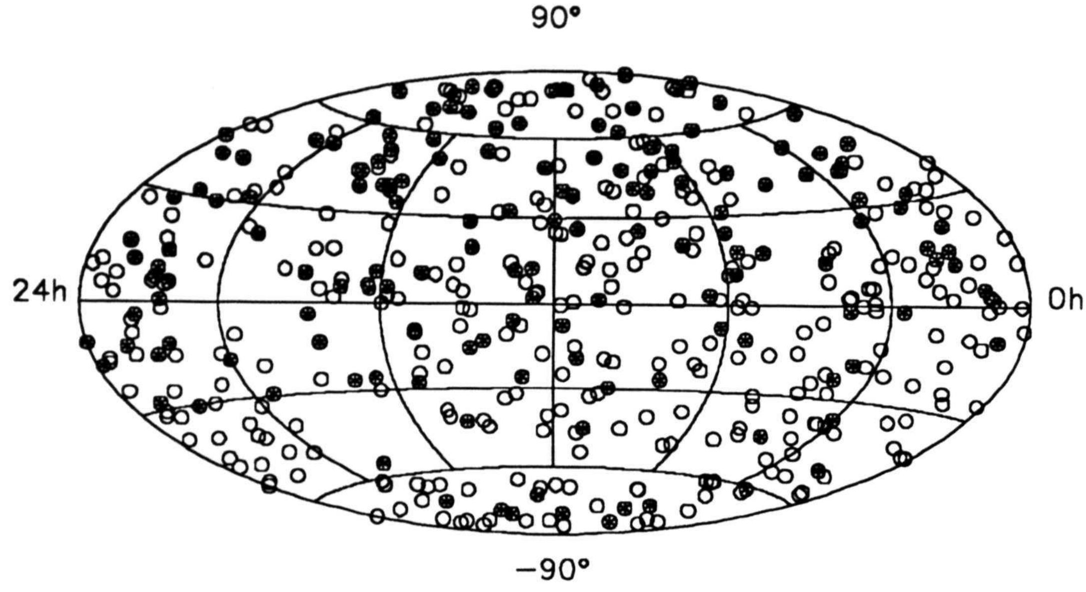
References

Hellings, R. W., 1986: *Astron. J.*, **91**, 1446.

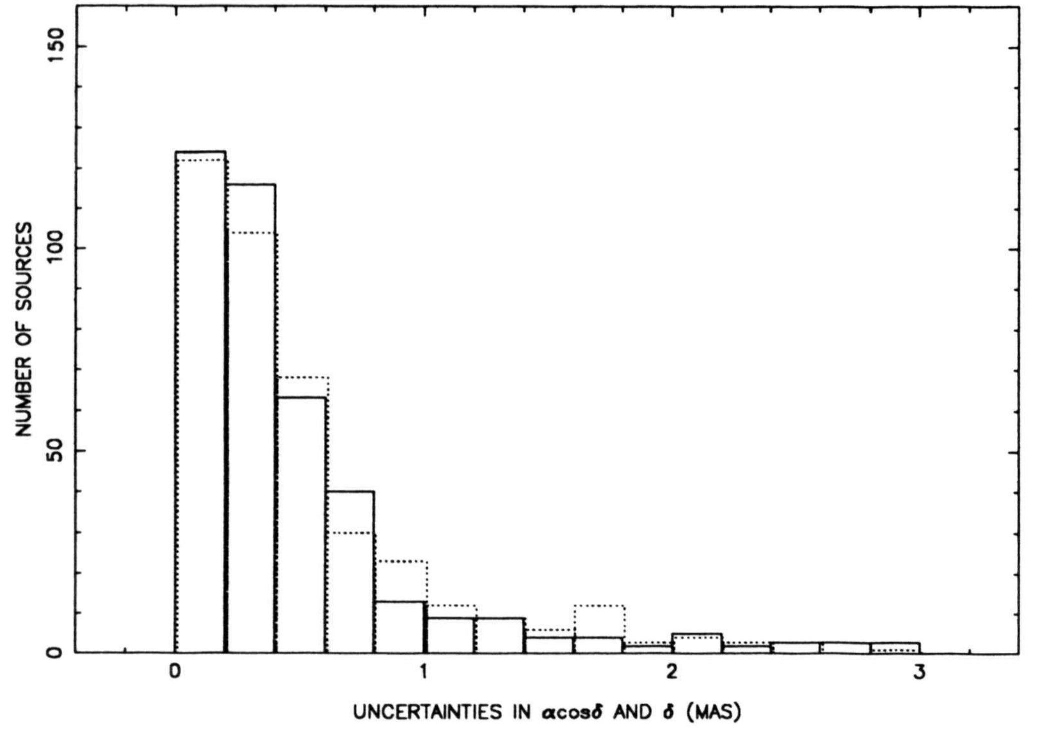
Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36**, 157.

Theil, H., 1963: *Amer. Stat. Ass. J.*, **58**, 401.

SUMMARY DESCRIPTION FOR SOLUTION GSFC 93 R 5 : SEE P. R-27



Distribution over the sky of the 449 extragalactic radio sources of the celestial frame RSC(GSFC) 93 R 05. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(GSFC) 93 R 05. 49 radio sources with uncertainties larger than 0.003" are not shown.

Summary description of the solutions GSFC 93 R 01, R 02, R 03, R 04 and R 05

1 - Technique: Mark III VLBI

Processed with the Mark-III Analysis System-CALC/GLOBL with the following

- Group delay observations used for geodetic data, group delays and phase delay rates used for astrometric data.
- Diurnal and semidiurnal tidal variations in polar motion and UT1 were estimated using all geodetic data (10 tidal components in UT1 and 12 in polar motion) that are consistent with those of Herring, Sovers and Watkins. The model below was applied in all solutions.

UT1 tidal terms (microseconds)

l	l'	F	D	Om	GST +pi	term	Cos value	Cos formal error	Sin value	Sin formal error
0	0	0	0	0	-1	K1	6.763	.36	16.39	.36
0	0	2	-2	2	-1	P1	-4.004	.34	-5.825	.34
0	0	2	0	2	-1	O1	-15.39	.34	-15.42	.33
1	0	2	0	2	-1	Q1	-3.287	.34	-3.888	.34
0	1	0	0	0	-1	S1	.9430	.32	3.542	.31
1	0	0	0	0	-1	M1	.7112	.31	2.953	.31
0	0	0	0	0	-2	K2	.1883	.30	3.503	.30
0	0	2	-2	2	-2	S2	-.7916	.29	8.867	.29
0	0	2	0	2	-2	M2	-7.990	.26	11.89	.27
1	0	2	0	2	-2	N2	-3.905	.23	1.754	.23

Polar motion tidal terms (milliarcseconds)

l	l'	F	D	Om	GST +pi	term	Cos value	Cos formal error	Sin value	Sin formal error
0	0	0	0	0	1	P K1	.1225	.0054	-.03364	.0055
0	0	-2	2	-2	1	P P1	-.05385	.0053	.02758	.0053
0	0	-2	0	-2	1	P O1	-.1338	.0053	.06768	.0053
-1	0	-2	0	-2	1	P Q1	-.03829	.0053	.01705	.0053
0	0	0	0	0	-2	R K2	-.01389	.0048	.01555	.0047
0	0	2	-2	2	-2	R S2	-.07437	.0043	.1033	.0043
0	0	2	0	2	-2	R M2	.01363	.0042	.2883	.0042
1	0	2	0	2	-2	P N2	-.02225	.0042	.05712	.0042
0	0	0	0	0	2	P K2	.01836	.0044	-.008648	.0045
0	0	-2	2	-2	2	P S2	-.006214	.0043	-.001571	.0043
0	0	-2	0	-2	2	P N2	.03178	.0041	-.07327	.0042
1	0	-2	0	-2	2	P	-.002796	.0035	.001874	.0036

P = Prograde, R = Retrograde

- Continuous, piecewise-linear position for HRAS 085 (for some solutions).
- Instantaneous EOP estimated at midpoint of observing sessions.
- A priori calibration of the 'dry' atmosphere via MTT dry mapping with either in situ measurements of pressure and temperature or site-dependent static values and the Saastamoinen zenith delay.

- No a priori calibration of the 'wet' atmosphere.
- Residual wet atmosphere estimated with the GSFC 'continuous piece-wise-linear function' technique with 60 minute intervals and 50 ps/hour constraint (except for a small subset of sessions using either shorter intervals or looser constraints) and the wet MTT partial derivative.
- Hydrogen maser clock errors modeled with the GSFC 'continuous piecewise-linear function' method using unconstrained 2nd order polynomials for the gross clock performance and continuous 60-minute interval segments with a clock rate constraint of 5 10^{-14} for the short term clock errors (except for a small subset of sessions using either shorter intervals or weaker constraints); a small number of actual clock epoch breaks and baseline-dependent constant clock errors also modeled.
- Observation weights adjusted by session-dependent constants derived so that the chi-square per degree of freedom was unity in individual session solutions.
- Quasar source positions estimated globally except for the right ascension of the quasar 0420-014, which is used to define the origin of right ascension of the celestial reference frame.
- Data to SHANGHAI (7226) and VLA (7619) lack ionosphere calibration.

2 - Analysis Center:

GSFC - the VLBI group of the NASA Space Geodesy Program at the Goddard Space Flight Center.

3 - Solution Identifier:

There are 5 solutions for this submission: GLB885, GLB885a, GLB886, GLB886a, and GLB887. The table below indicates the differences between them.

Solution ID	Type	HRAS 085	A priori EOP
GLB885	EOP	cpl	er877x = USNO concrete on 1985 Nov 21
GLB885a	EOP	pv	er877x
GLB886	TRF	cpl	er885
GLB886a	TRF	pv	er885a
GLB887	CRF	pv	er885a

EOP = Earth Orientation Parameter solution
TRF = Terrestrial Reference Frame solution
CRF = Celestial Reference Frame Solution

cpl = continuous, piecewise-linear positions estimated using two-month intervals
pv = position estimated at site position reference epoch, global velocity estimated

4 - Software used:
CALC 7.6, SOLVE/GLOBL, and DE200 ephemerides.

5 -Relativity Scale:
Set by the modified Hellings VLBI delay model described in the CALC 7 release documentation.

6 - Permanent tidal correction on station:
A solid earth tide model is used but the correction to remove the permanent tide (specified the IERS Standards) is not applied.

7 - Tectonic plate model:
No-Net-Rotation NUVEL-1 in all solutions.

8 - Velocity of light:
2.99792458 10^8 m/s

9 - Geogravitational constant:
Not applicable.

10 - Reference epoch:
1985 November 21 for both earth rotation and nutation, 1988 January 1 for site positions. Source coordinates are J2000.0.

11 - Adjusted parameters:
Earth orientation, daily nutation offsets, global station positions and velocities, globally estimated source positions, and session-dependent clock and atmosphere parameters. Also continuous, piecewise-linear positions for HRAS 085 with 2-month intervals (for some solutions).

12 - Definition of the origin:
The origin of the terrestrial reference frame is fixed by the adopted position of the Westford antenna at 1988 January 1 and the NNR-NUVEL-1 model for all solutions. The origin is close to ITRF91 at the site position reference epoch.

13 - Definition of the orientation:
The orientation of the terrestrial reference frame is defined by the a priori EOP values on the reference day (1985 Nov 21) from the USNO concrete EOP series and by the direction of the WESTFORD to RICHMOND baseline, which evolves according to NNR-NUVEL1. The celestial reference frame is defined by the CEP pole position computed from the IAU 1980 nutation model and the J2000.0 precession model for the same reference day and the a priori right ascension of 0420-014.

14 - Evolution with time:

The stations with insufficient data are constrained to move with NNR-NUVEL-1. Westford's position and the direction from Westford to Richmond are constrained to evolve by the same model. The vertical rate at Kauai is constrained to zero. The vertical rates for stations which had uncertainties in their vertical rates in excess of 3mm/yr in an unconstrained solution are also constrained to zero. In GLB885 and GLB886, the motion of HRAS 085 is modeled with a continuous, piecewise-linear function due to its anomolous motion. The three-dimensional velocities of other stations with sufficient data are freely adjusted.

THE JPL 1992-2 REFERENCE FRAME JPL 92 R 02

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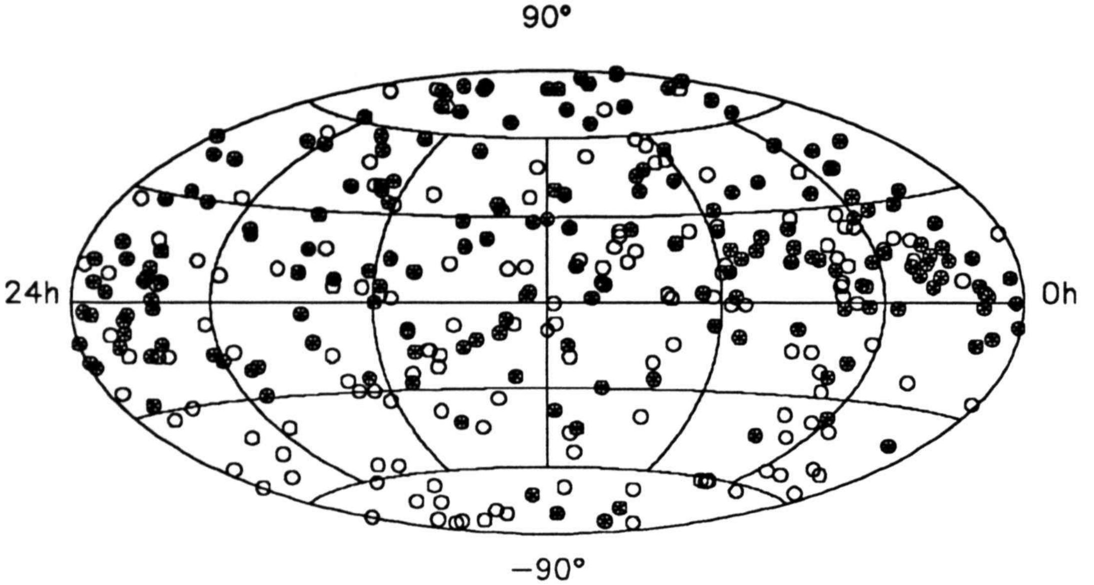
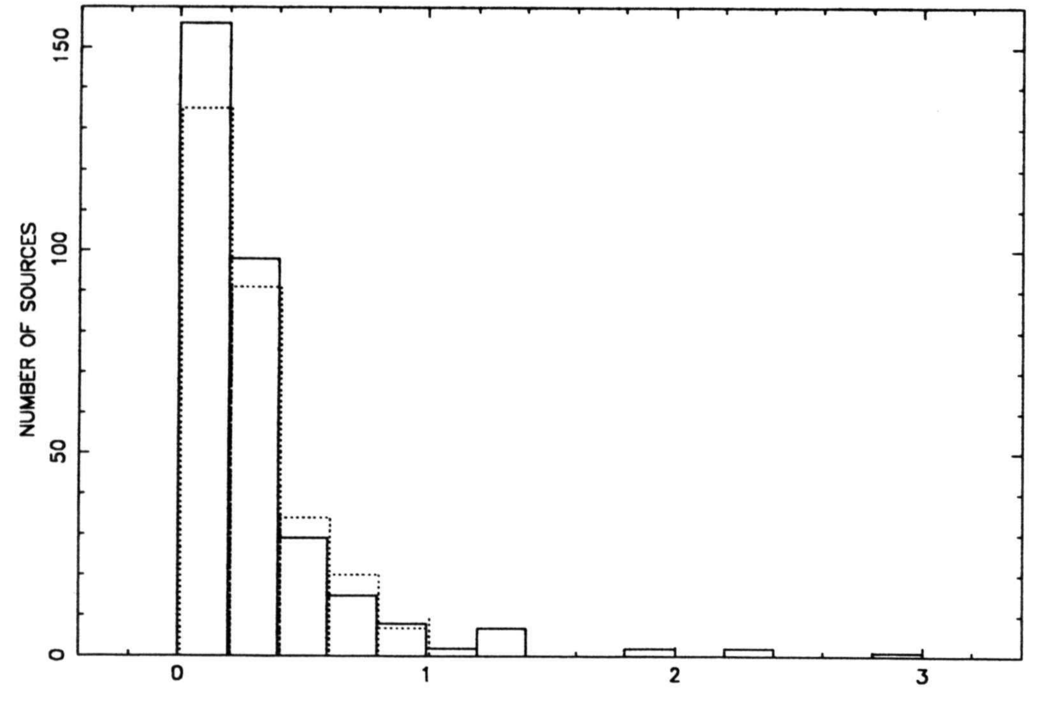
This set of radio source coordinates is based on a combination of all available VLBI data. It is the catalog that was generated in the analysis leading to the JPL model for short-period tidal UTPM variations (Sovers *et al.* 1993). Details of the fit can be found in that manuscript. The celestial frame was aligned with IERS 92C01 by constraints on three coordinates of two sources (OJ 287 and CTD 20). The ZMOA-2 nutation model was adopted with no further corrections. The data span is 1978-92; approximately 230,000 observation pairs each originate in the CDP and IRIS projects, 60,000 in NAVNET, and 27,000 are DSN observations. The catalog contains 333 sources with declination formal uncertainties ranging down to 20 microarcseconds. There are as many as 40,000 observations of a single source. For 45 infrequently observed sources, the declination sigmas exceed 1 mas. Quite obviously, this catalog suffers from systematic errors far in excess of the formal sigmas, due to time-variable source structure as well as other effects coming into play at the millimeter level. It should therefore be regarded as an example of formal precision that is achievable with large volumes of VLBI data.

Reference

Sovers, O.J., Jacobs, C.S., Gross, R.S., 1993: *J. Geophys. Res.* (in press).



Distribution over the sky of the 333 extragalactic radio sources of the celestial frame RSC(JPL) 92 R 02. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(JPL) 92 R 02. 13 radio sources with uncertainties larger than 0.003" are not shown.

EARTH ROTATION PARAMETERS FROM DSN VLBI: 1993 JPL 93 R 01

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This year we have introduced several modeling improvements, including estimating a parametric model for the nearly-diurnal and nearly-semidiurnal tidal frequency variations of UT1 and polar motion, and estimating site velocities.

In this report Earth Rotation Parameter (ERP) estimates have been obtained from an analysis of Deep Space Network (DSN) VLBI data that directly aligns its celestial and terrestrial reference frames with those of the International Earth Rotation Service (IERS). NASA's Deep Space Network operates radio telescopes for the primary purpose of communicating with interplanetary spacecraft. The DSN has three complexes: in California (stations DSS 12,13,14,15), in Spain (DSS 61,63,65), and in Australia (DSS 42,43,45). Two projects at JPL (called TEMPO and CAT M&E below) use these telescopes to make VLBI observations from which we have estimated earth rotation parameters. Each observing session uses antennas in two complexes, and usually exactly one antenna in each complex. This report describes a homogeneous reduction of currently available dual frequency (S and X band) VLBI data from both projects.

The Time and Earth Motion Precision Observations (TEMPO) project makes rapid turnaround VLBI measurements of station clock synchronization and earth orientation in support of spacecraft navigation, which needs extremely timely, moderate accuracy earth rotation information. In TEMPO observations the raw bit streams recorded at the telescopes are telemetered to JPL for correlation, so that no physical transportation of magnetic tapes is involved. TEMPO uses the JPL-developed Block I VLBI system, which has a 500,000 bits/second sampling rate, with time-division multiplexing of channels. This sampling rate permits the telemetry, and thus makes rapid turnaround possible. The reduced sensitivity caused by the relatively low sampling rate in comparison to other present-day VLBI systems is largely compensated by the very large antennas and very low system noise levels of the DSN telescopes. TEMPO uses two 70 meter DSN antennas (DSS 14, 43, 63) whenever possible and one 34 meter DSN antenna together with one 70 meter antenna when it is not possible to obtain simultaneous use of both of the larger antennas. Currently, TEMPO records 3 channels in S band (2285 MHz) and 3 channels in X band (8450 MHz). Since June 12, 1991, TEMPO has used a spanned bandwidth of 99 MHz at X band and 39 MHz at S band. Before that date, most TEMPO sessions used a spanned bandwidth of 40 MHz in each band. At present the DSN nominally schedules two TEMPO observing sessions per week, one on the Spain-California (SC) baseline, and the other on the Australia-California (AC) baseline. Each session is generally 3 hours in duration (occasionally less), and records a maximum of 20 sources. TEMPO observes most sources for 3 minutes and 18 seconds, a few for 6 minutes and 36 seconds. We plan to produce an operational series of ERP estimates from TEMPO sessions during 1993 that will be a continuation of the ERP series reported here.

The Catalog Maintenance and Enhancement (CAT M&E) project determines celestial coordinates of radio sources, and baseline vectors between DSN stations, for use in spacecraft navigation. In CAT M&E observations the raw bit streams are recorded on magnetic tapes for transportation to the correlator. Since June 1989 most CAT M&E observing sessions have used the Mark III VLBI system on stations DSS 15, 45, and 65, which support a 400 MHz spanned bandwidth capability. From late 1978 through 1988, CAT M&E used the Mark II VLBI system with a spanned bandwidth of 40 MHz in each band, and used two 70 meter DSN antennas (DSS 14, 43, 63) whenever possible. The DSN schedules CAT M&E observing sessions at irregular intervals, typically several times per year, with separate observing sessions on the SC and AC baselines. Each session is nominally 24 hours in duration and typically includes 100 to 330 observations of 50 to 134 radio sources.

Data from both the TEMPO and CAT M&E projects were used in the solution process for the ERP series reported here. In order that the TEMPO operational series of ERP estimates during 1993 can be an exact continuation of the ERP series reported here, the solution process consisted of two major steps. First, a "catalog solution" designated JPL 1993-1 (see below) determined radio source coordinates, station coordinates and site velocities, a parametric model for the celestial motion of the Celestial Ephemeris Pole, and a parametric model for the nearly-diurnal and nearly-semidiurnal tidal frequency variations of UT1 and polar motion. Then the second step, called the "ERP solution", used these results from the catalog solution to determine the earth rotation parameters in a manner that can be exactly continued in the operational series. In the ERP solution the data from each observing session were processed independently to provide an estimate of the UT0 and variation of latitude (DPHI) of the baseline VECTOR for that session. Except for the UT0 and variation of latitude, the relation between the earth-fixed reference frame and the radio-quasar reference frame was specified entirely by a priori data (which includes the results from the catalog solution). In addition to UT0 and DPHI, the other parameters estimated in the ERP solution were:

1 - A first degree polynomial clock model, including a term allowing for a bias in the phase-delay-rate data, with breaks as needed. Such clock breaks are rare in TEMPO sessions but more common in the longer duration CAT M&E sessions.
2 - Adjustments to the troposphere zenith delay at each station. In the CAT M&E sessions, new troposphere zenith parameters were introduced approximately every three hours (every two hours fordata after 1992.0). A priori estimates of the troposphere zenith delays, derived from tables of monthly average zenith delays for each station, were included in the solution with a 6 cm standard deviation. (For good quality observing sessions in recent years, the effect of these a prioris is negligible and the estimated troposphere zenith delays are essentially completely determined by the VLBI observables.)

Other properties of the ERP solution were:

1 - The reported earth rotation parameters include the nearly-diurnal and nearly-semidiurnal tidal frequency variations estimated in the catalog solution. (In other words, the effects in the table below headed "Short Period Tidal ERP Variations" have NOT been added back in producing EOP(JPL)93 R 01)
2 - Ocean loading effects were calculated from the model of Scherneck (1983; 1991).
3 - Pole tidal effects were included (Sovers, 1991).
4 - The Lanyi (1984) function was used for mapping zenith tropospheric delays to observed elevations.
5 - The effects of charged particles in the ionosphere and solar plasma on the single-band delay and delay rate observables were removed by using the appropriate linear combination of the S-band and X-band data to form "dual frequency" delay and delay rate observables.
6 - For recent years only sessions with 6 or more acceptable delay observations were included in the solution reported here.
7 - The effect on path lengths caused by moving ("slewing") the antenna subreflector, so as to maximize the antenna gain when its focal length changes as the elevation angle changes, has been modeled for the TEMPO data. No such model is needed for the CAT M&E data since CAT M&E does not slew the subreflector. (Apparent station coordinates estimated from VLBI data will be corrupted if the subreflector is slewed but the effect on path length is not modeled in the delay calculations. The station coordinates estimated by the JPL 1993-1 catalog solution and used in the ERP solution are appropriate both for the case where the subreflector is not slewed and no path length effect is modeled and also for the case where the subreflector is slewed and the resulting effect on path length is explicitly modeled in the calculations.)

The raw observable uncertainties have been modified by adding quadratically an uncertainty component, for each of the two stations, equal to a small fraction (0.002 or 0.003) of the total a priori tropospheric effect at that station on the observable. We further quadratically added an "additive noise" constant when needed so as to make the Chi Square of the postfit residuals approximately equal to the number of degrees of freedom in the solution. The delay and delay rate additive noise constants were adjusted separately for each CAT M&E observing session. For the TEMPO data, the additive noises were adjusted for each of several blocks of observing sessions.

Each Earth Rotation measurement here is a UT0-DPHI pair, and has an associated error ellipse in the UT0-DPHI plane. Each such error ellipse is completely specified by the reported standard errors and correlation coefficient between UT0 and DPHI. For single baseline VLBI measurements of ERP, such as those reported here, this error ellipse is typically quite elongated, with a ratio of major axis to minor axis of about 4:1. Therefore, for a proper interpretation of these data, it is CRUCIAL to make full use of the reported correlation coefficient.

For a single-baseline VLBI estimate of earth rotation, the orientation of the error ellipse in the UT0-DPHI plane is mostly determined by the global station geometry. The direction of the minor axis of the error ellipse in the UT0-DPHI plane as predicted by the station geometry is called the transverse rotation direction, and corresponds to the motion of the baseline in the local horizontal at each station or equivalently to a rotation about an axis through the center of the earth and the midpoint of the baseline. In addition to being relatively insensitive to random measurement errors, the transverse rotation component is also relatively free of errors introduced by tropospheric modeling errors, antenna deformations, and other sources of systematic local-vertical errors. The transverse rotation components for the DSN baselines are:

Baseline	Transverse Component
Australia-California	-1.000 DPHI + 0.00 (UT0-TAI)
Spain-California	+0.582 DPHI + 12.21 (UT0-TAI)
Spain-Australia	-0.972 DPHI + 2.77 (UT0-TAI)

These coefficients assume that UT0 and DPHI are expressed in seconds of time and in arcseconds, respectively; the units of the transverse components are arcseconds. We recommend that these linear combinations be used to take full advantage of the inherent accuracy of these data.

The ERP solution produced earth orientation results for a total of 938 observing sessions between October 28, 1978, and March 12, 1993.

During calendar year 1992, the TEMPO project produced earth rotation measurements from 96 dual frequency observing sessions, with a median standard error along the minor axis of the error ellipse of 0.3 milliarcseconds (mas), and along the major axis of 1.4 mas. During 1992 the median turnaround time for TEMPO measurements, from observation to availability of earth orientation parameters, was 50 hours.

The JPL 1993-1 Catalog

The JPL 1993-1 catalog was developed specifically for use in TEMPO operational ERP solutions during 1993. Since short duration VLBI determinations of the ERP are sensitive to errors in the celestial position of the Celestial Ephemeris Pole (CEP), and since the current IAU standards for the CEP are known to be in error by amounts significant to TEMPO, it is important that TEMPO use a CEP series that is corrected from the IAU standards and is consistent with the radio source coordinates (RSC) used. Current practicalities of TEMPO operations favor the use of a parametric model for the CEP that includes the long period motions. Therefore we have estimated such a model along with the RSC and set of station coordinates (SSC) in the JPL 1993-1 catalog solution. This year our CEP motion model consists of the ZMOA-1990-2 nutation model (Herring, 1991) plus adjustments to the coefficients of certain terms of the ZMOA-1990-2 model, along with the IAU precession model and adjustments to its coefficients. Our CEP motion model is intended only to permit processing of TEMPO data for the ERP during the period reported here and during 1993, and will presumably need revision in 1994. In particular, it may not include all significant components, not all its adjustments may be genuinely significant, and its parameters may not all be well separated, but we believe it is adequate for our purposes.

As part of the JPL 1993-1 catalog solution we estimated coefficients of a model of ERP variations at nearly-diurnal and nearly-semidiurnal tidal frequencies. Nearly-diurnal polar motion variations were constrained to have no retrograde part, thus allowing simultaneous estimation of nutations.

The JPL 1993-1 catalog solution had the following properties:

1. Except where otherwise noted, the catalog solution was essentially identical to the ERP solution described above.

2. All the available CAT M&E data through December 27, 1992, and most of the TEMPO data through January 17, 1993, were included.

3. Information from intra-complex radio interferometry was used to constrain the coordinate differences between stations within each complex. The uncertainties used for these intracomplex ties vary from station pair to station pair and from component to component (the local vertical uncertainty is typically three times the horizontal uncertainty). These uncertainties are our best estimates of the realistic one-standard-deviation uncertainties of these ties and range from 5 mm to 18 mm.

4. For each pair of observing sessions that used different pairs of DSN complexes (that is, California-to-Spain and California-to-Australia) with a time separation between the midpoints of the sessions of less than 15 hours, the adjustment (dX,dY,dUT1) to the initial values of earth orientation is the same for both members of the pair. (The initial-value ERP series was a version of the SPACE92 series (Gross, 1993) modified to not use DSN VLBI data; it is a smoothed, combination-of-techniques ERP series obtained by Kalman filtering.) This treatment of close-in-time pairs serves to determine the angle between the California-to-Spain and California-to-Australia baseline vectors (and thus also the length of the Australia-to-Spain vector). There were 65 such pairs of TEMPO sessions; there were 6 such pairs involving one TEMPO session and one CAT M&E session; and there were no such pairs involving two CAT M&E observing sessions.

5. The terrestrial frame of the JPL 1993-1 system was tied to the International Earth Rotation Service Terrestrial Reference Frame ITRF-91 (IERS, 1992, Table T-3) in the following way. The coordinates of all the DSN stations, including all those in California, were estimated in the catalog solution subject to six constraints applied to the nine coordinates of DSS 15, DSS 45, and DSS 65. These constraints are such that if a seven parameter transformation (3 translations, 3 rotations, 1 scale) between the JPL 1993-1 and ITRF-91 systems were estimated by unweighted least squares applied to the coordinates of DSS 15, 45, and 65, then

the resulting 3 translation and 3 rotation parts of the transformation would be zero while the scale could be nonzero and unknown in advance of computing the catalog. (When expressed as the dot product of a nine dimensional unit vector with the nine station coordinates, each constraint is assigned an a priori standard deviation of 5 mm; this does not affect the resulting coordinates but does affect the calculated formal errors, giving them a more spherical distribution than would result if either very large or very small a priori standard deviations were used.) These constraints serve to determine both the translation and the rotation of the terrestrial coordinate system. The station coordinates resulting from the solution apply at a reference time of 1988.0, in agreement with that of ITRF-91.

6. Three-dimensional site velocities were estimated for each of the three DSN complexes. All stations in each DSN complex were assumed to have the same site velocity. The velocities were constrained so as to produce no net translation rate and no net rotation rate, for the network composed of the three DSN complexes, relative to the net motion of this network of three sites as expressed in the ITRF-91 velocity field (IERS, 1992, Table T-5). Thus only three velocity parameters are actually being separately estimated; one way to describe these is as the rates of change of (1) the California-to-Australia length, (2) the California-to-Spain length, and (3) the angle between the California-to-Australia and California-to-Spain vectors. (When expressed as the dot product of a nine dimensional unit vector with the nine site velocity components, each constraint is assigned an a priori standard deviation of 1.0 mm/yr; this does not affect the resulting velocity components but does affect the calculated formal errors, giving them a more spherical distribution than would result if either very large or very small a priori standard deviations were used.)

7. The celestial frame of the JPL 1993-1 system was tied to the International Earth Rotation Service Celestial Reference Frame in the following way. The Right Ascension and Declination of OJ 287 (0851+202) and the Declination of CTD 20 (0234+285), which are among the best observed sources in the DSN catalog and are primary sources in the 1992 realization of the IERS Celestial Reference Frame, were held fixed at their values in that frame as specified in the set of radio source coordinates RSC(IERS)92 C 01 (IERS, 1992, Table C-4). The formal errors of these three source coordinates are properly zero, but in order to convey the quality of determination of these two sources we have replaced these three zeros in our source list RSC(JPL)93 R 01 by the formal errors for these three coordinates from a similar solution that had three coordinates of two different well-observed sources held fixed; we have similarly replaced the two correlation coefficients between Right Ascension and Declination for these two sources.

8. The reference epoch of the JPL 1993-1 celestial system was J2000, and the definition of sidereal time was a function of the estimated precession constant (Sovers, 1991, sections 2.6.1 and 2.9.3.3).

This year we have used the MODEST option to perform the general relativity calculations according to the "TDT spatial coordinates" convention (Sovers, 1991). This choice has a small effect on the length scale of the Set of Station Coordinates. The relativity model used is essentially equivalent to the "consensus model" described by Eubanks (1991). As a result, the estimated Set of Station Coordinates has the scale of a geocentric coordinate system using a time scale consistent with International Atomic Time.

The model of the celestial motion of the CEP obtained as part of the JPL 1993-1 catalog solution is presented below as adjustments to the IAU precession and ZMOA-1990-2 nutation coefficients along with two offset parameters which represent the estimated position of the (mean) CEP at epoch J2000 as expressed in the coordinate system of the radio sources. A positive X-offset represents a displacement of the CEP toward 18 hours Right Ascension, and a positive Y-offset represents a displacement of the CEP toward 0 hours Right Ascension. This year the CEP-motion model includes a term representing a secular rate in obliquity. Also included is an empirical term with a period of -429.8 days (for the origin of this particular value of period, see (Herring *et al.*, 1991; Herring, 1991)). Only those nutation terms listed below were adjusted in the catalog solution. Two sets of standard errors are presented; the "formal" errors are just the formal errors from the catalog solution, and the "generalized" errors are the formal errors from a similar solution which also estimated additional components with periods of 121.75, 27.55, 13.63, and 9.13 days as well as both out-of-phase nutations for all ten periods.

The parametric model for the nearly-diurnal and nearly-semidiurnal tidal frequency variations of UT1 and polar motion obtained as part of the JPL 1993-1 catalog solution is presented below. The argument conventions used here are those of Sovers et al. (1993). The formal errors of these parameters range from 14 to 56 microarc-seconds but realistic uncertainties are probably about 75 microarcseconds (one standard deviation).

Short Period Tidal ERP Variations

Term	Period (hours)	UT1 (microseconds) Cosine	UT1 (microseconds) Sine	Polar Motion Amplitude (microarcseconds) prograde	Amplitude (microarcseconds) retrograde	Phase (degrees) prograde	Phase (degrees) retrograde
K2	11.96724	- 0.1	5.2	40	77	54	243
S2	12.00000	2.6	12.9	49	151	42	310
M2	12.42060	-10.0	24.2	92	273	121	276
N2	12.65835	- 1.1	2.4	34	24	96	224
K1	23.93447	13.3	24.5	194	0	155	*
P1	24.06589	- 5.5	- 4.3	61	0	5	*
O1	25.81934	-14.4	-15.2	163	0	311	*
Q1	26.86836	1.9	- 2.7	15	0	297	*

Celestial Ephemeris Pole Motion Model
(nutations relative to ZMOA-1990-2)

IAU-Index	Period days	Phase	Component	Adjustment mas	Formal Error mas	Generalized Error mas
precession			Longitude	-3.30/yr	0.08/yr	0.18/yr
obliquity rate			Obliquity	-0.26/yr	0.07/yr	0.07/yr
Y-offset			L sin eps	-18.87	0.43	1.01
X-offset			Obliquity	+ 4.63	0.91	0.95
1	-6798.38	In	Longitude	- 1.35	0.36	0.93
			Obliquity	- 0.07	0.20	0.21
		Out	Longitude	+ 1.42	0.26	0.56
			Obliquity	- 0.05	0.33	0.35
2	-3399.19	In	Obliquity	- 0.18	0.10	0.10
		Out	Longitude	- 0.91	0.20	0.27
			Obliquity	+ 0.11	0.14	0.14
10	365.26	In	Longitude	- 0.54	0.09	0.11
			Obliquity	+ 0.01	0.03	0.04
		Out	Longitude	+ 0.66	0.09	0.10
			Obliquity	- 0.01	0.04	0.04
9	182.62	In	Longitude	+ 0.00	0.07	0.08
			Obliquity	- 0.05	0.03	0.03
		Out	Longitude	+ 0.20	0.07	0.07
			Obliquity	+ 0.05	0.03	0.03
31	13.66	In	Longitude	- 0.20	0.06	0.15
			Obliquity	+ 0.12	0.03	0.05
		Out	Longitude	+ 0.44	0.07	0.13
			Obliquity	+ 0.08	0.02	0.06
	-429.8	In	Longitude	+ 0.02	0.08	0.09
			Obliquity	- 0.02	0.04	0.04
		Out	Longitude	- 0.62	0.10	0.11
			Obliquity	- 0.14	0.03	0.03

For accurate interpretation of the UT0 and DPHI values reported here, one should use accurate values of the latitude and longitude of the baseline vector; these can be calculated for each station pair from the SSC estimated in the JPL 1993-1 catalog solution and reported here. Approximate values are:

Baseline	Latitude (°)	Longitude (°)
Australia-California	- 43.97	+106.05
Spain-California	+ 2.99	+ 30.73
Spain-Australia	+ 38.50	- 18.10

Acknowledgements. We would like to thank each and every one of the many people who contributed to the acquisition and analysis of the DSN VLBI data. The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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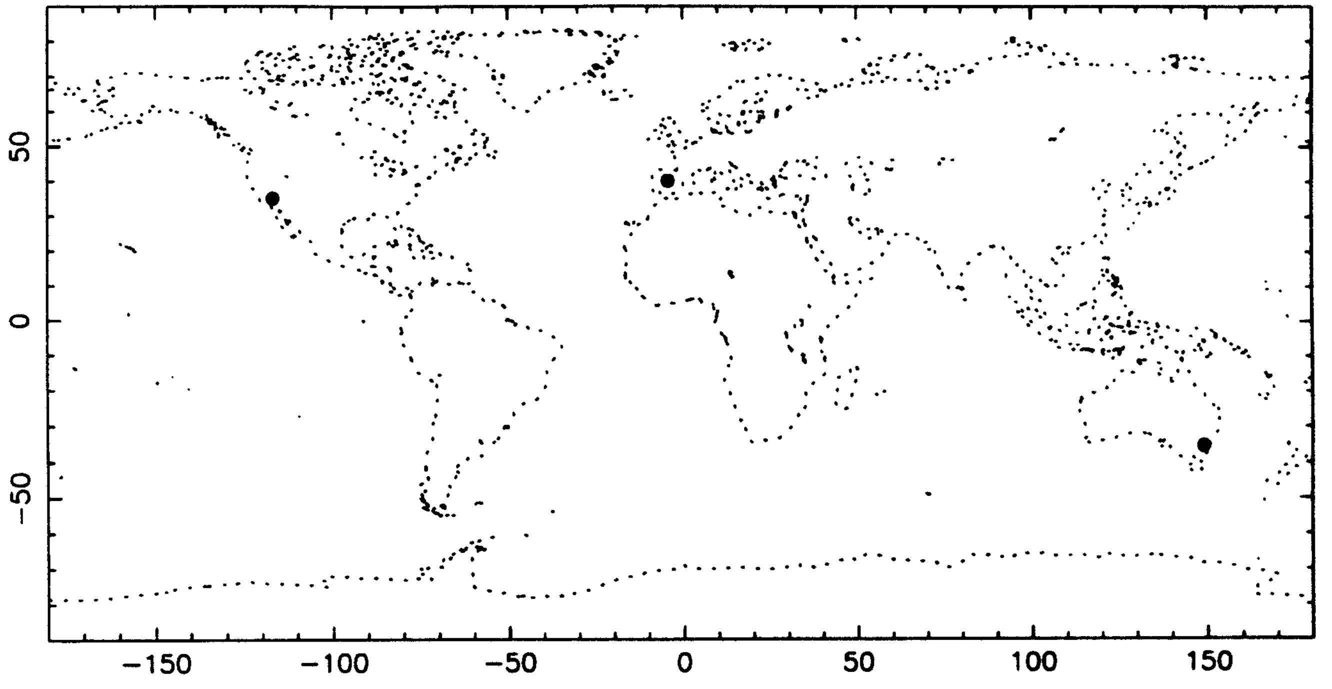
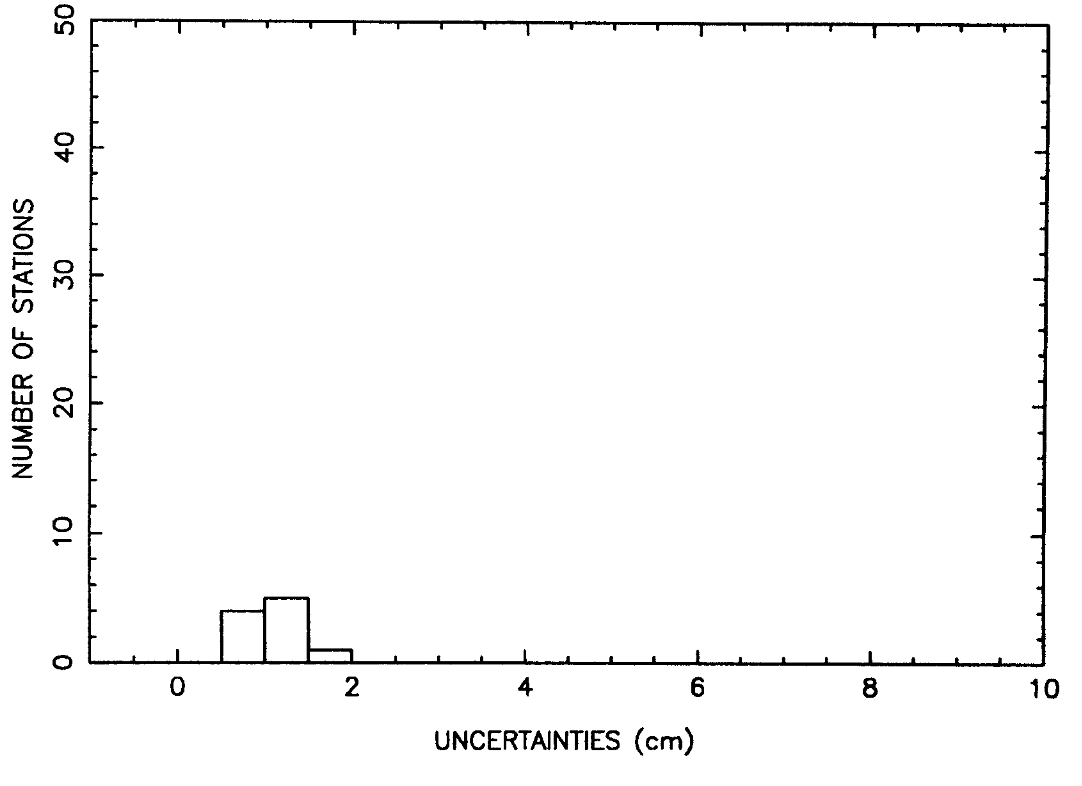
Summary description of the terrestrial system attached to the set of station coordinates SSC(JPL) 93 R 01

1 - Technique:	VLBI
2 - Analysis Center:	JPL
3 - Solution identifier:	1993-1
4 - Software used:	MODEST (nee Masterfit)
5 - Relativity scale:	LE (TDT = geocentric with IAT)
6 - Permanent tidal correction:	No
7 - Tectonic plate model:	ITRF-91 plus adjustments
8 - Velocity of light:	299 792 458 m/s
9 - Geogravitational constant:	3.9860 0448 10^{14} m^3 s^{-2}
10 - Reference epoch:	1 Jan 1988
11 - Adjusted parameters:	X0, Y0, Z0, $\dot{X}$, $\dot{Y}$, $\dot{Z}$
12 - 13 - Definition of the origin and orientation:	Six constraints were applied (with 5 mm uncertainty) to the nine coordinates (at epoch 1988.0) of DSS 15, DSS 45, and DSS 65, such that if a seven parameter transformation (3 translations, 3 rotations, 1 scale) between the JPL 1993-1 and ITRF-91 systems were estimated by unweighted least squares applied to the coordinates of DSS 15, 45, and 65, then the resulting 3 translation and 3 rotation parts of the transformation would be zero while the scale could be nonzero and unknown in advance of computing the catalog. See text for details.
14 - Constraint for time evolution:	Six constraints were applied (with 1.0 mm/yr uncertainty) to the nine site-velocity parameters of the DSN network so as to yield no-net-translation-rate and no-net-rotation-rate with respect to the net motion of the three sites Madrid, Goldstone, and Canberra as specified by the ITRF-91 velocity field. See text for details.



Distribution of the 3 sites of the terrestrial frame SSC(JPL) 93 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 10 stations of the terrestrial frame SSC(JPL) 93 R 01.

EOP(JPL) 93 R 01 From Oct 1978 to Jul 1993

Number of measurements per year and median uncertainties
Units : 0.001" for φ; 0.0001s for UT0

YEAR	φ		UTO	
	Nb	Sigma	Nb	Sigma
1978	3	0.43	3	1.15
1979	6	1.82	6	1.88
1980	21	4.04	21	5.78
1981	17	2.69	17	5.62
1982	43	3.57	43	4.44
1983	74	3.23	74	4.75
1984	71	3.43	71	5.35
1985	19	2.19	19	3.93
1986	71	2.55	71	3.38
1987	77	2.07	77	3.35
1988	93	1.54	93	2.22
1989	93	0.67	93	1.71
1990	108	0.90	108	1.81
1991	111	0.44	111	1.03
1992	115	0.41	115	0.70
1993	47	0.90	47	1.00

THE JPL 1993-2 REFERENCE FRAME JPL 93 R 01

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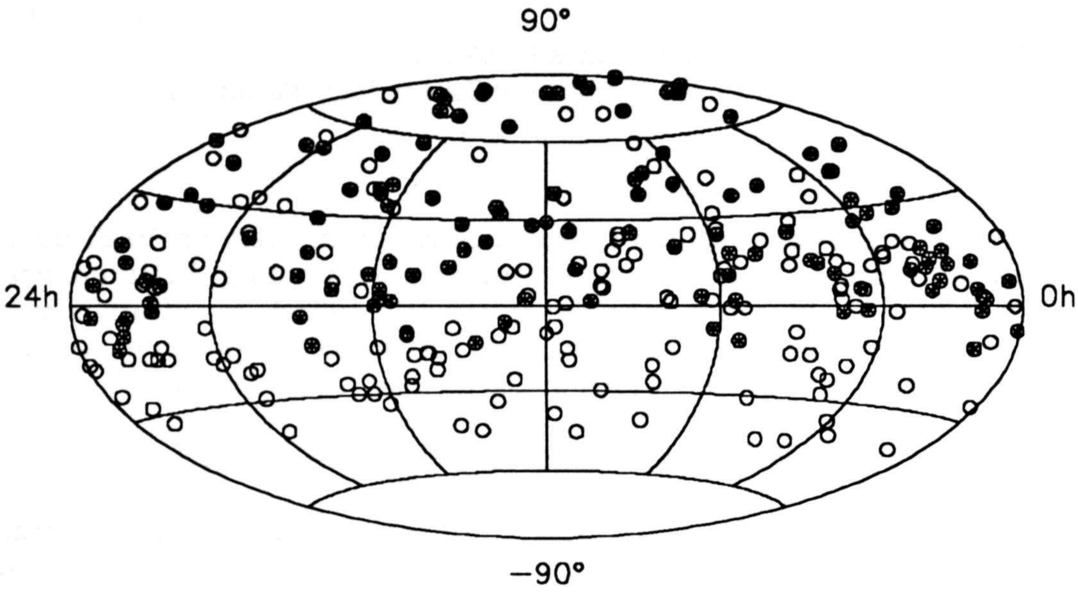
This collection of radio source coordinates is based solely on VLBI data from the JPL/DSN experiments performed in support of Catalog Maintenance and Enhancement (CM&E). In contrast to the frame JPL 1993-1, no effort is made to maintain continuity, for example by constraining certain source positions to values in the IERS reference frame. There are a total of 286 sources in JPL 1993-2.

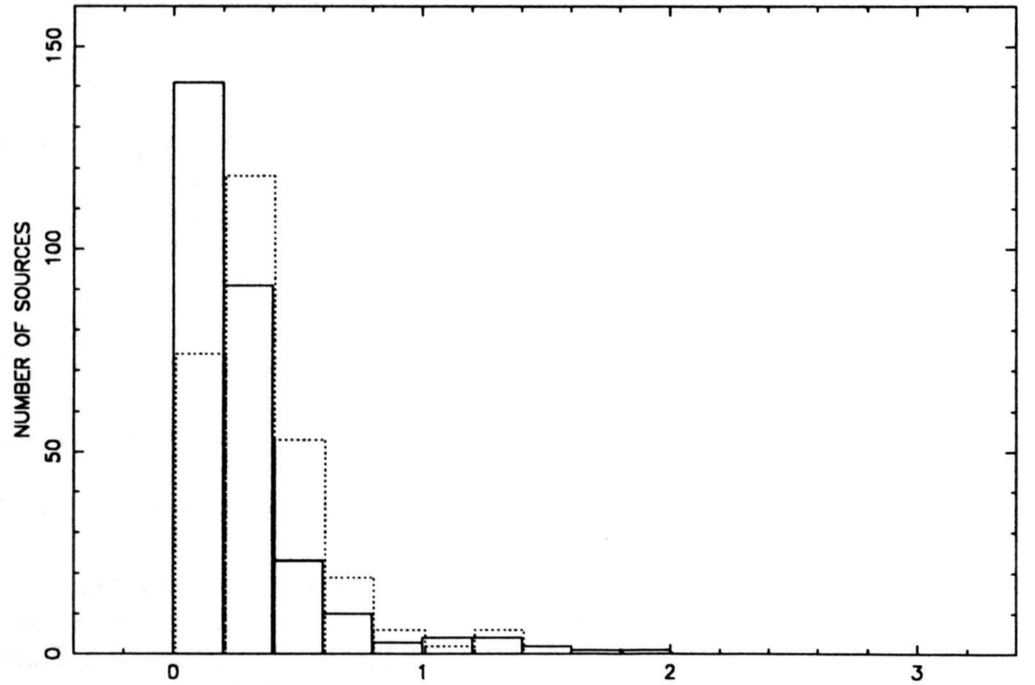
Some details of the analysis performed to generate JPL 1993-2 are:

1. 19,994 dual-frequency delay and delay rate pairs from observations spanning 1978 October to 1992 December are the basic observables. The single exception is the source 1955+335, which is a calibrator in radio star observations for the Hipparcos link, and which had no detectable S-band emission. There are roughly equal numbers of Mark II and Mark III observations.
2. Each observable error includes an additional contribution that is 0.2% of the tropospheric delay at each station. If needed, yet another constant is added in quadrature in order to make the reduced chi-square equal to 1 for each session.
3. The right ascension of 3C 273 is fixed.
4. The ZMOA-2 nutation series is used, but daily offsets in psi and epsilon are estimated, with a reference day of 1992 March 22-23.
5. A new set of station locations is estimated for each of 120 observing sessions. The Goldstone coordinates are kept fixed at ITRF91 values, with no corrections for the centimeter-order motion after the Landers earthquake in 1992 July.
6. Values of UT1 and polar motion are taken from the SPACE92ND series of Gross (this report).
7. Short-period tidal UTPM variations are modeled with the diurnal and semidiurnal amplitudes obtained by Sovers, Jacobs and Gross (J. Geophys. Res. 1993, in press).
8. Standard models are used for minor tidal effects: pole tide, K1 solid tide correction, and ocean loading.
9. New zenith tropospheric delays are estimated at each station every 2 to 3 hours.

The formal uncertainties in declination range upward from 0.1 mas. A total of 17 infrequently observed sources have declination sigmas exceeding 1 mas. Rotational offsets from the IERS 92C01 catalog are substantially larger than usual (e.g. 5 and 6 mas around the X and Y axes, respectively) due to the use of the ZMOA-2 nutation model.



Distribution over the sky of the 286 extragalactic radio sources of the celestial frame RSC(JPL) 93 R 02. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(JPL) 92 R 02. 6 radio sources with uncertainties larger than 0.003" are not shown.

NOAA EARTH ORIENTATION TIME SERIES AND REFERENCE FRAMES FROM VLBI OBSERVATIONS: 1. DESCRIPTION OF ANALYSIS PROCEDURES

EOP(NOAA) 93 R 04
EOP(NOAA) 93 R 05
EOP(NOAA) 93 R 06
RSC(NOAA) 93 R 02
SSC(NOAA) 93 R 02

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Estimated values for terrestrial site coordinates and velocities, celestial coordinates, and a time series of Earth orientation parameters (EOP) have been derived from a composite set of Mark III Very Long Baseline Interferometry (VLBI) data collected under the aegis of projects MERIT [Wilkins, 1984], POLARIS and IRIS [Carter *et al.*, 1985], the NASA Crustal Dynamics Project (CDP), and the US Naval Observatory (USNO). A total of 697,629 bandwidth-synthesis group delay observables amassed during 1183 one-day observing sessions between September 1980 and February 1993 were combined in a single least-squares adjustment to obtain an EOP time series (EOP (NOAA) 93 R 04 contains the results from 757 IRIS and USNO NAVNET sessions and EOP (NOAA) 93 R 05 contains results from the remaining 426 sessions, however both were produced from the same data reduction), coordinates for 107 radio sources (RSC (NOAA) 93 R 02), and coordinates and velocities for 55 VLBI reference points (SSC (NOAA) 93 R 02). In addition, a separate series of daily UT1 values for the period April - June 1984 and April 1985 through February 1993 has been produced (EOP (NOAA) 93 R 06 contains results from 1961 sessions). These UT1 values were determined from a special series of `Intensive' observing sessions using only the Westford-Wettzell baseline for about one hour each day [Robertson *et al.*, 1985], sufficient to determine only UT1. The EOP (NOAA) 93 R 06 Intensive UT1 time series is produced separately but is otherwise fully consistent with the UT1 values in the EOP (NOAA) 93 R 04 series from 24-hour EOP observing sessions.

The VLBI observations were analyzed at NOAA in general conformance with the latest *IERS Standards* [McCarthy, 1992]. Below, the specific approaches used in the NOAA solution to implement these standards are described with emphasis on areas of departure:

• The right ascension (RA) origin of the NOAA celestial reference frame at epoch J2000.0 is specified by constraining the sum of the adjusted RA values for 36 radio sources to be equal to the corresponding value obtained from the IERS Celestial Reference Frame (ICRF-91); see the companion report by Dillinger *et al.* [1993] for details of the constraint algorithm. The procedure is the same as used in the past except that the set of constraining sources differs from the nine used previously (some of which have substantial internal structures). The set of 36 constraining sources were selected on the following bases: having adequate numbers of VLBI observations (greater than 1000 in all cases except for three sources) distributed over the history of VLBI data; preferentially IERS primary sources (except for seven which are secondary in ICRF-91); forming a good distribution around the sky; being free of extended and time-varying brightness structures as much as possible. More than half of the constraining sources are observed in the regular IRIS-A and NAVNET EOP-monitoring sessions. The radio sources used for the RA constraint are:

0016+731	0953+254 (OK290)	1637+574
0048-097	1034-293	1642+690
0119+041	1055+018	1739+522
0229+131	1144+402	1741-038
0454-234	1308+326	1749+096
0528+134	1334-127	1921-293
0552+398	1354+195	1958-179
0727-115	1418+546	2121+053
0735+178	1548+056	2128-123
0823+033	1606+106	2145+067
0851+202 (OJ287)	1622-253	2234+282
0923+392 (4C39.25)	1633+382 (1633+38)	2255-282

• The geocentric origin of the NOAA terrestrial reference frame is specified for the epoch 1988.0 by requiring that the vector sum of the adjusted station coordinates be equal to the corresponding sum for the IERS Terrestrial Reference Frame (ITRF-91) for a set of 16 VLBI sites. This procedure differs from our previous submissions wherein the origin was defined by adopting without adjustment a set of coordinate values for Westford, MA, USA. The sites used for the terrestrial coordinate frame constraints were chosen on the following bases: having sufficiently long measurement histories to estimate reasonable site velocity values; forming a global distribution of sites, to the extent possible; avoiding sites in known deformation zones. The sites chosen for the terrestrial coordinate frame constraint are:

Westford, MA, USA *
Richmond, FL, USA *
Algonquin Park, Ont., Canada *
Gilcreek, Fairbanks, AK, USA *
NRAO85-3, Green Bank, WV, USA *
Platteville, CO, USA *
Pie Town, NM, USA
Onsala, Sweden *
Wettzell, Germany *
Shanghai, China
DSS-65, Madrid, Spain
Kauai, HI, USA *
Kwajalein Atoll, Marshall Islands
Hobart, Tasmania, Australia
DSS-45, Canberra, Australia
Hartebeesthoek, South Africa

Because the three-dimensional linear velocity of each VLBI site is estimated in the data analysis while the secular motions of the VLBI frame itself are indeterminant, it is necessary to impose additional constraints to define the translational and rotational motions of the entire terrestrial frame. This is done by requiring the vector sum of the translational velocities estimated for a set of nine VLBI sites be equal to the corresponding vector sum obtained assuming station velocities as predicted by the NNR-NUVEL1 global plate motion model [DeMets *et al.*, 1990; Argus and Gordon, 1991]. The angular velocity of the frame is constrained by requiring the vector sum of the rotational velocities formed from the cross products of each site velocity with its Earth radius vector be equal to the corresponding vector sum obtained from the NNR-NUVEL1 model for a set of nine sites. See the companion report by Dillinger *et al.* [1993] for details of the constraint equations. The nine sites used for the velocity constraints are indicated in the list above with asterisks. This particular subset was chosen to obtain as large a geographical extent as possible while retaining the closest possible match to rigid plate model motions and avoiding peculiar local site motions. The velocity values used to project station coordinate values to arbitrary epochs for those sites with brief data spans are adopted from the NNR-NUVEL1 model. (However, velocity parameters are adjusted in the data analysis for *all* sites, including those with brief data spans.) The velocity used to project coordinates for DSS-15 and Mojave (both in the Goldstone complex, CA, USA) after the Landers earthquake on 1992 June 28 is the velocity estimated for Mojave from data prior to the earthquake. The site name MOJAVE12 is used for pre-earthquake data while MOJAVEpq is used for data after the Landers earthquake. Altogether, coordinate projection has been done using model velocities for 20 of the sites in SSC (NOAA) 93 R 02, denoted by having velocity formal errors equal to zero.

• In the <u>transformation between the celestial and terrestrial systems</u>, the conventional formulation has been used except that the true obliquity of date is used in the equation of the equinox rather than the mean obliquity of date. Geodesic nutation is not taken into account. While the estimated nutation offset values reported here are with respect to the IAU 1980 model, the time variation of the nutation offsets between tabular points in the EOP *a priori* file used in our data analysis is assumed to follow the ZMOA-1990.2 model of Herring [1991]. The procedure used for the interpolation of *a priori* nutation offset values is analogous to the procedure describe below for tidal variations in the Earth's rotation. The orientation of the systems is specified by fixing the values for the EOP and nutation offsets to agree with those interpolated from the EOP (IERS) 90 C 04 series (corrected for the offsets and drift rates reported by the IERS to give consistency with the ITRF-91 and ICRF-91 frames) for the reference epoch 1991 August 12 19:49:50; the interpolation method is described below. This particular EOP reference epoch was chosen because two large, independent VLBI networks ran simultaneously that day: IRIS-A701 used Mojave (Goldstone, CA, USA), Richmond (FL, USA), Westford (MA, USA), and Wettzell (Germany) while Polar-N2 used Gilcreek (Fairbanks, AK, USA), DSS-13 (Goldstone, CA, USA), Haystack (Westford, MA, USA), Kashima (Japan), and Onsala (Sweden) and together the two sessions produced 2062 usable observations. The use of a single fixed reference epoch to relate the celestial and terrestrial systems, together with secular velocity constraints for the motion of the terrestrial frame, is a change from our previous procedure which used two fixed epochs and no secular velocity constraints.

• Solid Earth tide displacements are accounted for using the recommended correction to the K1 term without any correction to remove the zero-frequency "permanent tide" displacement. Values for the Love number h_2 and Shida number l_2 are 0.60967 and 0.0850, respectively. Rotational deformation due to polar motion, "pole tide", is also included.

• Radial and tangential displacements due to ocean loading are included but atmospheric loading effects are not. No adjustments were made to account for internal deformations of the VLBI antenna structures. Calibration data collected at each observing site have been applied to correct for variations in the electrical length of the cables between the radio receivers and the data acquisition systems.

• Tidal variations in the Earth's rotation are taken into account in forming *a priori* values for the EOPs in the VLBI data analysis. Since an offset adjustment to each EOP is made for each 24-hour observing session, the results are most sensitive to those tidal variations with periods shorter than about one day. The procedure used to form *a priori* EOP values at each VLBI observation epoch is: 1) tabulated EOP values are taken from a previous NOAA solution for the set of all IRIS and NAVNET observing sessions; 2) known tidal contributions based on models described below are removed; 3) a cubic spline interpolation is performed on the tidally corrected EOP values from the five nearest tabular epochs; 4) model tidal contributions are restored. The models used for the tidal contributions are: 1) UT1S tidal terms, including periods up to 18.6 years and corrections due to oceanic tides (see *IERS Standards*, McCarthy, 1992); 2) diurnal and semi- diurnal variations of X, Y, and UT1 derived by Herring [1992] based on analysis of 8.5 years of VLBI data. To minimize the effects of unmodelled Earth orientation variations, the VLBI adjustments of EOP values are made at the weighted mid-point epoch of each observing session rather than at the interior midnight, as was done in the past.

• Tropospheric refraction in the local zenith direction caused by the "dry" (hydrostatic) and "wet" components of the neutral atmosphere has been modelled *a priori* according to Saastamoinen [1972] using surface meteorological data (pressure, temperature, humidity) taken at each VLBI station during each observing session. The zenith delays are mapped to line-of-sight elevations with the CfA-2.2 model [Davis *et al.*, 1985] for the dry component and the Chao [1972] model for the wet part. Residual atmospheric delay, presumably due to the wet troposphere, is treated by adjusted parameters (see below) using the Chao "wet" elevation mapping function assuming a typical water vapor distribution. The dispersive portion of the atmospheric refraction due to the ionosphere is eliminated by the use of simultaneous dual-frequency (X- and S-band) observations.

• Shapiro's formulation for the general relativistic effects of signal propagation is used (see the previous edition of the *IERS Standards*, McCarthy, 1989) rather than the newer model recommended in the 1992 edition. We expect Shapiro's algorithm to agree within a few picoseconds (about 1 mm or better) with the newer algorithm.

The full set of group delay observations was processed at the NOAA VLBI Analysis Center in Rockville (MD, USA) using the CALC-7.6 program (see the appendix in Caprette *et al.*, 1990) to compute the theoretical delays and their partial derivatives, and using the SOLVE-3 program [Dillinger and Robertson, 1986] for the least-squares parameter adjustment. A single least-squares solution was performed using sparse-matrix handling techniques [Dillinger and Robertson, 1986] and constraint algorithms [Fallon and Dillinger, 1992; see also the companion report by Dillinger *et al.* 1993]. Delay rate observations are not included. The solution was done with a forward pass to reduce and combine all the data to determine values for the "global" parameters (those whose values are affected by all observing sessions) followed by a separate step to determine the "arc" parameters (those affected only by data from individual observing session). The geocentric coordinates and three-dimensional linear velocities of the stations and the J2000.0 celestial coordinates of the radio sources are determined globally. The only constraints applied in the estimation of the global parameters are those described above to remove inherent singularities associated with the right ascension origin of the celestial frame, the geocentric coordinate origin of the terrestrial frame, and the translational and rotational velocities of the terrestrial frame. The site coordinate parameters are adjusted at the weighted mean observation epoch for each site, rather than at an arbitrary epoch, in order to remove singularities that can arise when simultaneously adjusting coordinates and velocities for those sites with brief data spans. Site coordinate values are produced for arbitrary common epochs by projection of the mean-epoch coordinates using the estimated velocity values. Epoch projection of station coordinates for those with brief data spans is done with NNR-NUVEL1 velocities rather than with the estimated velocity values. The site coordinates refer to the intersection of the pointing axes of the fixed antennas (designated by a four-digit number and cataloged by the NASA CDP) or to reference ground monuments in the case of sites occupied by mobile VLBI systems.

Arc parameters are used to model both nuisance effects (clock and atmospheric delays) and the important EOP variations (X and Y pole position, UT1, offsets in nutation obliquity and longitude). Time variations in the station clock differences are treated by estimating coefficients of polynomials, usually one or two second-order polynomial segments per day per station. Residual ("wet") atmospheric delays are treated by estimating the values of a piece-wise linear, continuous function at break-points set every hour for each station of each observing session. A weak constraint is applied to the variation of the atmosphere parameters between break-points; see Dillinger *et al.* [1993]. One offset parameter is adjusted for each Earth orientation component per observing session. The EOP adjustments are computed at the weighted mean observation epoch of each observing session to minimize unmodelled effects in the *a priori* EOP variations. About 50 observing sessions are geometrically limited to such an extent that the estimation of all EOP components is singular or nearly so. These sessions include single-baseline data sets (Hartebeesthoek-Hobart) and relatively small networks, usually involving a mobile VLBI system involved in regional observing programs. For these cases, weak *a priori* constraints are applied (see Dillinger *et al.*, 1993). The constraints use EOP values interpolated from the tabulated *a priori* EOP series with weights equal to 50 times the *a priori* weight based on linear interpolation of the formal uncertainties of the tabulated EOP values. The effect of this constraint is that the formal uncertainties of estimated EOP values are never larger than about 3 mas since about 1985 when regular, high-quality VLBI data became routine.

The full solution included 697,629 group delay observations and 117,695 constraint equations to adjust a total of 156,408 parameters.

The standard errors quoted here are strictly the formal values obtained from the parameter adjustments by the propagation of the formal observational noise together with an added contribution calculated for each baseline of each observing session to give a normalized postfit residual of unity. These standard errors should be understood as lower limits on the actual uncertainty of the determinations, the limit that would be attained in the absence of unmodelled systematic errors. Based on comparisons with GPS determinations, we estimate that since the Wettzell observatory became operational in January 1984 the IRIS X and Y components of polar motion have had uncertainties no worse than 0.5 milliseconds of arc [Herring *et al.*, 1991]. Comparison of VLBI station coordinates with independent determinations using satellite laser ranging indicates that the formal standard errors are probably optimistic by a factor of about two [Ray *et al.*, 1991].

The Intensive UT1 observations use a single baseline from Wettzell, Germany to Westford, MA, USA. Through late 1991, eight observations were made of four different sources within each one-hour observing session conducted six days per week. Since that time, the observing mode has been upgraded to permit twice as many observations in each one-hour session. The observations are analyzed in a solution using the terrestrial and celestial reference frames and EOP values established by the 24-hour sessions described above. Only a UT1 offset, a clock offset, and a clock rate parameter are adjusted for each Intensive session.

A discussion of the results obtained from this solution set is presented by Ray *et al.* in a companion report.

On behalf of the International Radio Interferometric Surveying (IRIS) joint subcommission of the International Association of Geodesy (IAG) and the Committee on Space Research (COSPAR), NOAA distributes the monthly IRIS Bulletin A, *Earth Orientation Bulletin*, and maintains electronic files containing the same data on the NOAA computers which can be accessed by users who prefer a machine-readable form. Additional information or assistance concerning the data presented here, or the data available through INTERNET, IRIS Bulletin A, or the NOAA computer system may be obtained by contacting the authors.

References: see p. R-69.

NOAA EARTH ORIENTATION TIME SERIES AND REFERENCE FRAMES FROM VLBI OBSERVATIONS: 2. CONSTRAINT ALGORITHMS

EOP(NOAA) 93 R 04
EOP(NOAA) 93 R 05
EOP(NOAA) 93 R 06
RSC(NOAA) 93 R 02
SSC(NOAA) 93 R 02

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The methods and models used to analyze VLBI observations to extract geodetic information have evolved significantly in recent years [Robertson, 1987; Ray, 1991]. General descriptions of the analysis procedures used by NOAA have been given by Carter *et al.* [1985, 1989], Dillinger and Robertson [1986], and Fallon and Dillinger [1992]. The purpose of this report is provide further detail concerning the analysis results presented in the companion report by Carter *et al.* [1993], especially regarding the constraint algorithms employed.

The least-squares adjustment program used to process the VLBI data is called SOLVE-3, which was developed at the National Oceanic and Atmospheric Administration (NOAA) [Dillinger and Robertson, 1986]. SOLVE-3 uses efficient sparse-matrix handling techniques to perform a simultaneous least-squares adjustment of the nearly 1200 24-hour VLBI data sets collected over more than a decade. Formation of the individual observation equations follows usual practice [*e.g.*, Robertson, 1975] using the models described in Carter *et al.* [1993]. The theoretical delay values and their partial derivatives with respect to geophysical, astrometric, and various nuisance parameters are computed using the NASA-developed program CALC-7.6 (see the appendix in Caprette *et al.*, 1990). SOLVE-3 can provide linear corrections to the CALC-supplied theoretical delay values at the discretion of the user, for example to update *a priori* information. The VLBI analysis problem is complicated somewhat by the occurrence of rank deficiencies resulting largely from the fact that the observables measure pure differences. There is no sensitivity to the Earth's center of mass, for instance, to provide a "fixed" reference point for the origin of the terrestrial coordinate frame. Nor is there any absolute reference against which the velocities of the VLBI sites can be measured. One approach that can be used to avoid singularities in the least-squares adjustment is to reduce the number of degrees of freedom by not adjusting a sufficient number of parameters. Thus, the origin of the VLBI terrestrial frame can be specified by fixing the coordinates of one site to an adopted set of values and the motion of the frame can be set by fixing velocity values for two sites. Fixing more than a minimal set of parameters is an over-constraint of the system that can result in distortions of the results.

An alternative approach to eliminating the rank deficiencies is to introduce constraint equations, essentially additional observational equations containing enough *a priori* information to remove the singularities. SOLVE-3 has several methods for doing this. The primary reason for preferring constraint equations over fixing parameter values is to provide improved long-term stability for the reference frame by avoiding potential problems or peculiarities associated with individual sites or sources. The constraint procedures used for the analysis presented by Carter *et al.* [1993] are discussed below.

The right ascension origin of the celestial reference frame is specified by introducing a pseudo-observation equation which sets the sum of the right ascension adjustments for a selection of radio sources equal to a constant; that is

$$\sum \Delta\alpha_i = C_\alpha \tag{1}$$

where

$$\Delta\alpha_i = \text{Right Ascension adjustment for source i} = \alpha_i - \alpha_{i,prior} \tag{2}$$

Carter *et al.* [1993] have chosen the constant on the right-hand-side of Eqn. (1) to be equal to the sum of the right ascension differences between ICRF-91 and the NOAA *a priori* values for a set of 36 radio sources in order to bring these two celestial frames into close alignment:

$$C_\alpha = \sum (\alpha_{i,icrf} - \alpha_{i,prior}) \tag{3}$$

which means that the constraint in this case is equivalent to

$$\sum \alpha_i = \sum \alpha_{i,icrf} \tag{4}$$

When a pseudo-observation equation is used as a constraint in this manner a weight must be assigned as with any normal observation equation. The value of this weight, relative to the data weights, will determine the importance of the constraint in the least-squares adjustment. As large a weight value as possible is sought which does not introduce numerical instabilities. For the right ascension constraint, a weight has been used which corresponds to a standard error of .06 milliarcseconds (mas) for the right ascension adjustments.

The origin for the terrestrial coordinate reference frame is defined through the use of similar pseudo-observation equations. In this case, one equation is used for each of the three geocentric coordinates and the constants are chosen based on differences for 16 sites compared with the ITRF-91 values in order to bring the NOAA frame into close alignment. Thus, the constraint equations, applied at the epoch 1988.0, are

$$\sum \Delta \boldsymbol{R}_i = C_{xyz} \tag{5}$$

where

$$\Delta \boldsymbol{R}_i = \text{vector position adjustment for site i} = \boldsymbol{R}_i - \boldsymbol{R}_{i,prior} \tag{6}$$

and for the choice

$$C_{xyz} = \sum (\boldsymbol{R}_{i,itrf} - \boldsymbol{R}_{i,prior}) \tag{7}$$

is equivalent to

$$\sum R_i = \sum R_{i,itrf} \tag{8}$$

The weight assigned to each component constraint equation corresponds to a standard error of 0.32 mm.

Including velocity parameters as unknowns for each site introduces a requirement for six additional constraints. Three of these are necessary to define the translational velocity of the terrestrial frame. This requirement can be accommodated by fixing a linear combination of site velocity vectors $\mathbf{V}_i$ such that

$$\sum V_i = C_t \tag{9}$$

with the components of the constant vector selected to be equal to the sum of site velocities predicted by the NNR-NUVEL1 global plate motion model [DeMets *et al.*, 1990; Argus and Gordon, 1991]. Thus, the frame will have no translational velocity relative to the plate model except to the extent that the observed VLBI motions for the constraint sites deviate from the predicted velocities. By using more than one site in the constraint, the effect of such local peculiar motions will be reduced. Carter *et al.* [1993] have selected nine VLBI sites, six of which are on the North American plate, to minimize non-plate effects and have used a constraint weight which corresponds to a standard error of .032 mm/yr.

Another set of three constraints must be supplied to remove the perfect correlation between $\mathbf{V}_i$ and the secular change in the Earth orientation parameters, corresponding to an ambiguity in the rotational velocity of the terrestrial frame. This is accomplished by setting the net rotation of a group of sites equal to a constant by [Fallon and Dillinger, 1992]

$$\sum (V_i \times R_i) = C_r \tag{10}$$

where the constant vector $\mathbf{C}_r$ is chosen equal to the corresponding vector cross-product using velocities from the NNR-NUVEL1 plate motion model for the same set of nine VLBI sites used for the translational velocity constraint. Expansion of the above constraint equations gives a sum of terms all of which are of the form of components of $\mathbf{V}$ times components of $\mathbf{R}$. Using the relationship for the variance of a product to describe the elements of the variance of this equation gives

$$\sigma^2 = \sigma_v^2 r^2 + 2 v r \sigma_{vr} + \sigma_r^2 v^2 \tag{11}$$

where

$$\begin{aligned} v &= \text{a component of } V \\ r &= \text{a component of } R \\ \sigma_v^2 &= \text{variance of v} \\ \sigma_r^2 &= \text{variance of r} \\ \sigma_{vr} &= \text{correlation of v,r} \end{aligned} \tag{12}$$

The first term of this sum is of order $(.002)^2(6378137.)^2$ in units of $(m^2/yr)^2$ while the last term is of order $(.005)^2(.01)^2$. At the mean epoch of the observations of each site, the epoch at which the site coordinates are computed (see below), the correlation between **V** and **R** is zero and the second term vanishes. Clearly the first term dominates this equation, so the weight assigned is controlled by the uncertainty in the velocity parameters. For this analysis, the weight used corresponds to a standard error of .016 mm/yr.

Adopting a rotational constraint of this form forces the secular drift of the Earth orientation parameters to adjust in a way that preserves the velocity constraint. Using this constraint along with the corresponding velocity translation constraint in a minimally constrained adjustment allows us to relate the VLBI results to the framework of any general model for "absolute" site motions, as closely as the data will allow without distorting the relative motions of the sites as determined by the VLBI data. Adopting a particular global plate motion model and set of sites for the constraint constants dictates the resulting secular Earth orientation rates. Different realizations of the VLBI reference frames using different choices of constraint sites will result in differing secular rates for the Earth orientation parameters depending on the extent of peculiar, non-plate motion at the sites used in the constraints.

Two practical numerical difficulties can occur when simultaneously adjusting site coordinates and velocities: 1) When adjusting all site coordinates at a common epoch, those sites having observational data over short time spans can produce singularities in the velocity parameters, particularly if the observations are distant from the epoch of the adjustment. 2) If constraints are applied to the velocities of those sites to remove the singularities, undesirable distortions of the remaining network can occur. To avoid these problems, we solve for the coordinates of each site at the weighted mean epoch, T_{mean}, of the observations for that site as defined by

$$T_{mean} = \frac{\sum w_i t_i}{\sum w_i} \tag{13}$$

where w_i is the weight of each VLBI observation involving the site and t_i is the epoch of the observation. Having site coordinates at different epochs is inconvenient for many other purposes. Mathematically, the problem of projecting the coordinates **R** and their associated variances in time is not difficult. For a given site using the definition **X** = [**RV**], the projected coordinate values are computed by

$$R(t_1) = X(t_0)\ F^T \tag{14}$$

$$Q(t_1) = F\ Q(t_0)\ F^T \tag{15}$$

where

$$F = \begin{vmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t \\ \multicolumn{6}{c}{\Delta t = t_1 - t_0} \end{vmatrix} \tag{16}$$

where t_0 is set equal to the mean observation epoch for the site and Q is the covariance matrix associated with X.

Another problem arises for those data sets lacking adequate geometric strength to determine reasonable values for the Earth orientation parameters (EOPs). For these cases, we have elected to provide the adjustment with *a priori* information in the form of weighted constraint equations for the EOPs. The values used in the constraint equations are interpolated from the tabular *a priori* EOP series in a manner described by Carter *et al.* [1993]. The EOP constraint equations have the simple form $x = c$, where x is the EOP being constrained and c is the interpolated value. The weight assigned to this pseudo-observation equation is the linearly interpolated variance from the *a priori* EOP series, multiplied by a user-specified scale factor here set to 50.

The atmosphere zenith delay parameters are treated as a series of equally spaced, continuous linear segments. The unknowns in the adjustment are the endpoint values of each segment. Given that data gaps and variable amounts of data occur in some parameter segments, this procedure, by itself, is insufficient. To overcome this problem, constraints are applied requiring the slopes of adjacent segments be equal. Denoting A_i as the atmosphere offset parameter at epoch t_i, the constraint can be expressed as

$$A_{i+1} - A_i = A_{i+2} - A_{i+1}$$

or in the equivalent form actually used in SOLVE-3

$$A_i - 2A_{i+1} + A_{i+2} = 0\ .$$

If the constraint equations were rigidly enforced the result would be a simple linear model for the atmospheric variation with time. To achieve a model which permits greater variability, the constraints are enforced with a weight based upon a variance considered appropriate for the actual behavior of the atmosphere here taken to behave as a random walk process:

$$\text{weight} = (\sigma^2\, t)^{-1}$$

where σ is the standard deviation of the atmospheric variation and t is the length of each time segment. One constraint is applied for each segment except the last one, which is already included in the previous segment. The weights used in this analysis assumed a standard deviation for the atmosphere of 50 $ps/hr^{1/2}$.

References: see p. R-69.

NOAA EARTH ORIENTATION TIME SERIES AND REFERENCE FRAMES FROM VLBI OBSERVATIONS: 3. DISCUSSION OF RESULTS

EOP(NOAA) 93 R 04
EOP(NOAA) 93 R 05
EOP(NOAA) 93 R 06
RSC(NOAA) 93 R 02
SSC(NOAA) 93 R 02

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A number of important changes have been made in the data analysis procedures used by NOAA for the current submission. Most of these changes are designed to bring the NOAA system into closer agreement with the standards and reference frames of the IERS. Apart from simple consistency, the changes are also expected to improve the long-term stability of the NOAA results as new data and observing sites are incorporated. One very significant change is an extension to the *IERS Standards* [McCarthy, 1992]: use of Herring's [1992] model for diurnal and semi-diurnal variations of X and Y polar motion and UT1 in the *a priori* modelling of Earth orientation variations. This report discusses the motivations for the changes made and evaluates the results as presented in the accompanying report by Carter *et al.* [1993].

Celestial Reference Frame The current NOAA celestial reference frame consists of 107 radio sources, versus 84 sources reported last year, approximately uniformly distributed about the sky. Of these sources, 50 are designated "primary" in the IERS Celestial Reference Frame, ICRF-91. The right ascension origin of the NOAA frame is defined by a constraint to match ICRF-91 for a subset of 36 sources; see Carter et al. [1993]. By distributing the origin constraint over as many different sources as possible, it is expected that systematic errors associated with individual objects, such as time-varying brightness structures and variations in the history of VLBI observing, will be significantly reduced affording enhanced long-term stability of the system. The mean and root-mean-squared (rms) differences between the RSC (NOAA) 93 R 02 celestial frame reported by Carter *et al.* [1993] and the ICRF-91 are shown in Table 1 for two subsets of radio sources. These rms differences are consistent with the level of scatter expected for the ICRF-91 primary sources themselves.

Table 1. Differences between RSC (NOAA) 93 R 02 and ICRF-91

	ΔRA (μas)	ΔRA cos(dec) (μas)	Δdec (μas)
50 primary sources in common:			
mean	-30.6	-39.7	129.9
rms	298.0	228.5	382.4
36 constraint sources:			
mean	1.2	-22.3	88.5
rms	323.3	213.6	342.8

Terrestrial Reference Frame The motivation and procedure for defining the coordinate origin of the NOAA terrestrial reference frame is completely analogous to the celestial reference frame discussed above. As described by Carter *et al.* [1993], the NOAA site positions are adjusted so that the origin matches the IERS Terrestrial Reference Frame, ITRF-91, for a subset of 16 out of the full set of 55 VLBI sites. Primarily, improved long-term stability is expected by reducing the sensitivity to data problems, peculiarities, and coverage associated with a single fixed site. In addition, connection of each VLBI station's position to the origin constraint is improved by distributing the constraint over as large a network as possible. This is particularly beneficial considering the distribution of observational data in time at individual sites is generally not uniform and there is no single station that has regularly observed with all the other stations. Unlike the celestial origin constraint, however, the realization of the terrestrial origin constraint is severely limited by the available geographic distribution of VLBI sites. A roughly uniform, global distribution of constraint sites would be preferred but the actual distribution, especially for sites with lengthy observing histories, is highly restricted. For these reasons, together with the fact that terrestrial points move with respect to one another, we do not expect the long-term stability of the terrestrial reference frame to rival that of the celestial frame.

The use of the new coordinate origin constraint produces a change in the distribution of formal errors for the station positions. Previously, when the position of Westford was fixed to define the coordinate origin, station position uncertainties increased with distance from Westford. Using a distribution of sites for the origin constraint removes this effect and produces a more nearly uniform error distribution among sites with similar data spans. Furthermore, the error ellipses for individual station positions are less eccentric rather than being elongated in the direction of the local vertical, at least for stations with mature histories.

The overall translational and rotational velocities of the NOAA terrestrial reference frame are specified through a set of constraints similar to the specification of the coordinate origin except that only nine VLBI sites are used in the velocity constraints and the defining motions are adopted from the NNR-NUVEL1 global plate motion model (see Carter *et al.*, 1993 and Dillinger *et al.*, 1993). There are two important distinctions in the application of these constraints compared with the celestial and terrestrial coordinate origin constraints: 1) The estimated site velocity values are unavoidably coupled to the secular drifts in the Earth orientation parameters (EOPs) which produces a small, but significant non-linear dependence on the *a priori* EOP series used in the data analysis. If the *a priori* EOP time series is not already consistent with the reference frames, iteration of the solution is required to produce a fully self-consistent, stable solution. 2) The external *a priori* information used in the frame velocity constraints -- the NNR-NUVEL1 model for rigid plate motions [DeMets *et al.*, 1990; Argus and Gordon, 1991] -- is an idealized representation of relative terrestrial motions that is totally independent of VLBI results. On the other hand, the ICRF-91 and ITRF-91 coordinate values used in the origin constraints are combinations which include previous VLBI results. Thus, the match of the observational results to the constraint is unlikely to be as close for velocities.

These distinctions make the analysis results somewhat more sensitive to the selection of VLBI sites used for the velocity constraints than is true for the origin constraints. In general, one set of velocity constraint sites will produce a frame with significantly different translational and rotational rates compared with a different set of constraint sites. The resulting secular rates for the EOPs will also differ (typically, by 100-200 μas/yr). While the specification of these rates is arbitrary, some choices are preferred for practical reasons. For one, the NOAA frames are designed to match the IERS frames as closely as possible, partly to better maintain long-term stability. Also, since the coordinates for sites with brief VLBI occupations are projected in time using NNR-NUVEL1 model velocities, we prefer to match the plate motions most closely over those portions of the Earth's surface where these sites are concentrated, primarily N. America and Europe. (However, for the same reason, coordinate values for sites projected to an epoch far from the observation epoch should be regarded with some suspicion, particularly since the projection is done assuming no uncertainty in the velocity values.) Empirically we have found that these objectives are reasonably well satisfied by our choice of nine velocity constraint sites with six in N. America, two in Europe, and one in Hawaii. When testing a velocity constraint with the 16 sites used for the coordinate origin specification, for instance, we have found that the resulting terrestrial frame translated with respect to ITRF-91 by about 4-5 mm/yr.

Table 2 shows the topocentric velocities for the 35 VLBI sites having sufficient data spans, relative to the velocities predicted from the NNR-NUVEL1 plate motion model. The nine sites used to constraint the terrestrial frame velocity components are indicated by asterisks. The rms velocity residual for the constraint sites is 2.0 mm/yr for the horizontal components and 1.7 mm/yr for the vertical. The residual velocities in Table 2 illustrate the difficulty encountered in attempting to select a set of velocity constraint sites whose motions are consistent with the plate motion model. The more global the distribution of constraint sites, generally the more difficult it becomes to satisfy consistency. There are several other aspects of the results in Table 2 worth noting. There appear to be indications of departures from NUVEL motions for Australia and Africa relative to N. America if DSS45, HOBART26, and HARTRAO are representative of their plates. Likewise, sizable vertical motions are observed, contrary to the assumption of rigid, non-deforming plates. The most significant examples are PIETOWN (-22.4 ± 1.4 mm/yr), WETTZELL (-2.9 ± 0.4 mm/yr), LA-VLBA (-14.5 ± 2.1 mm/yr), DSS45 (17.4 ± 2.5 mm/yr), MATERA (-14.4 ± 2.2 mm/yr), ONSALA (2.3 ± 0.4 mm/yr), and HATCREEK (-10.6 ± 2.1 mm/yr). Note that WETTZELL and ONSALA are used in the frame velocity constraint. Whether these vertical determinations represent systematic VLBI errors, local motions of the VLBI antennas, regional motions (for example, due to subsidence), or geophysical motions (for example, due to post-glacial rebound) remains to be understood. It is likely that a combination of factors is responsible. Some indication of the level of systematic velocity error can be had by comparing determinations for the three pairs of antennas located very near one another: HAYSTACK and WESTFORD agree within one standard deviation for all three velocity components; NRAO-140 and NRAO85-3 disagree by 4 σ in the east but agree well in north and up; GOLDVENU and MOJAVE12 disagree by 3.4 σ in the north and east but are consistent in up.

Table 2. Differences between NOAA Site Velocities and NNR-NUVEL1 (all units mm/year)

		ΔV_n	ΔV_e	ΔV_u	σV_n	σV_e	σV_u
Eurasia:							
DSS65		-1.2	3.5	3.6	0.5	0.6	3.1
EFLSBERG		0.8	2.4	-4.4	0.3	0.4	1.1
MATERA		3.9	4.2	-14.4	0.5	0.6	2.2
MEDICINA		1.8	4.0	-5.7	0.3	0.4	1.2
NOTO		5.2	1.5	-6.4	0.5	0.7	2.4
ONSALA60	*	0.1	0.4	2.3	0.2	0.3	0.4
SESHAN25		-6.0	7.0	-0.8	1.2	1.4	4.1
TROMSONO		-1.9	12.3	-4.1	1.0	1.0	5.8
WETTZELL	*	0.3	1.8	-2.9	0.2	0.3	0.4
N. America, stable:							
ALGOPARK	*	-0.8	1.6	2.5	0.2	0.2	1.0
GILCREEK	*	0.3	-0.6	-1.0	0.2	0.3	0.6
GORF7102		3.5	4.0	-7.3	1.1	0.9	5.9
HAYSTACK		0.0	1.9	0.4	0.2	0.3	0.8
WESTFORD	*	0.1	1.5	1.1	0.2	0.2	0.7
HRAS 085		0.2	0.3	0.2	0.4	0.2	1.1
LA-VLBA		3.3	0.8	-14.5	0.7	0.7	2.1
MARPOINT		1.0	-1.0	0.6	0.9	0.6	4.6
NRAO 140		-0.1	0.8	-1.0	0.3	0.2	1.0
NRAO85 3	*	-0.8	-0.7	-0.4	0.4	0.3	1.2
PIETOWN		-1.6	-1.8	-22.4	0.5	0.3	1.4
PLATTVIL	*	-3.1	-0.7	1.1	0.8	0.5	5.0
RICHMOND	*	0.3	1.5	1.5	0.4	0.3	0.9
YLOW7296		-3.0	-3.7	25.4	1.8	1.7	6.9
N. America, California:							
GOLDVENU		5.7	-2.8	-6.5	0.5	0.4	2.5
MOJAVE12		7.7	-4.3	-4.8	0.3	0.2	1.0
HATCREEK		5.7	-7.4	-10.6	0.5	0.4	2.1
OVRO 130		6.3	-6.4	1.4	0.4	0.3	1.5
VNDNBERG		-3.2	-0.6	-2.5	0.5	0.5	2.0
Pacific:							
KAUAI	*	0.1	-3.8	0.9	0.5	0.8	0.9
KWAJAL26		-2.5	-2.0	-1.9	1.7	1.6	6.1
Australia:							
DSS45		6.8	-3.6	17.4	1.7	2.3	2.5
HOBART26		8.7	-2.9	9.5	1.8	2.4	2.5
S. Africa:							
HARTRAO		-10.7	-3.5	-1.9	1.6	1.5	1.9
Japan:							
KASHIMA		2.5	-22.6	-1.2	0.5	0.9	1.0
KASHIM34		4.0	-22.8	-9.7	1.0	1.3	2.8

* Sites used in the velocity constraints for frame translation and rotation.

Table 3. Comparison of VLBI Up Rates with Post-Glacial Rebound

	--- Up Component of Local Velocity (mm/yr) ---			
	VLBI Rate	Adj. VLBI Rate[a]	VLBI Sigma	PGR[b]
		Northern Europe		
ONSALA	+2.3	+0.9	0.4	+1.3
WETTZELL	-2.9	-4.2	0.4	+0.3
		North America		
ALGOPARK	+2.5	+0.2	1.0	+3.2
HAYSTACK	+0.4	-1.9	0.8	-1.2
WESTFORD	+1.1	-1.2 a	0.7	-1.2
NRAO 140	-1.0	-3.3	1.0	-1.2
NRAO85 3	-0.4	-2.7	1.2	-1.2
RICHMOND	+1.5	-0.7	0.9	+0.1
GILCREEK	-1.0	-2.6	0.6	-0.8

[a] VLBI Up rates adjusted for net translational motion of the frame so that Westford. Up rate agrees with ICE-3G post-glacial rebound model.
[b] Post-glacial rebound (PGR) rates from ICE-3G model by Tushingham and Peltier [1991].

In Table 3, our observed VLBI vertical rates are compared with the expected rates due to post-glacial rebound (PGR) for a set of well-measured sites surrounding the retreated Fennoscandian and Laurentide ice sheets. The PGR rates are from the ICE-3G model of Tushingham and Peltier [1991]. Because of the inherent ambiguity in the net translational motion of the VLBI terrestrial frame, an adjustment has been applied to the observed velocities to facilitate comparison. All vertical rates are adjusted so that the rate for WESTFORD agrees with the ICE- 3G rate. In this framework, all of the listed sites except WESTFORD have uplift rates smaller than predicted but the largest discrepancy is for WETTZELL. The relative uplift between ONSALA and WETTZELL, which is independent of the frame translational ambiguity and is determined at a 10-σ level of significance, is fives times as large as the predicted uplift. The discrepancies among the N. American stations are smaller and less significant but uniformly favor lower uplift rates than predicted. This could indicate that the predicted rate for WESTFORD should be greater than the -1.2 mm/yr value from ICE-3G. In any event, the VLBI results have certainly approached a level which should be useful in refining models for the PGR effect provided that possible local motions are properly accounted for.

Two sets of coordinate values are reported for the Mojave (Goldstone, CA,USA) VLBI reference point 7222. The site name MOJAVE12 refers to data collected prior to the Landers earthquake on 1992 June 28 while MOJAVEpq refers to the much more limited data collected after that time. The coordinates for MOJAVEpq have been projected to epoch 1988.0 using the MOJAVE12 velocity. Thus, the difference in the coordinate values gives a direct measure of the displacement detected by VLBI at that site. The displacement vector, a little more than 2cm in magnitude, is given in Table 4.

Table 4. Landers Earthquake Displacement Observed at Mojave 7222

Component	Value (mm)	Error (mm)
X	-20.6	3.6
Y	-5.8	4.5
Z	-1.9	4.7
N	-9.9	3.5
E	-15.8	3.3
U	+10.7	5.4

Earth Orientation Results The two most significant changes made in the analysis procedures for EOP results are: 1) A new reference epoch was selected for which EOP values are fixed to establish the relative orientations of the terrestrial and celestial reference frames. 2) Herring's [1992] model for diurnal and semi-diurnal variations in the polar X and Y coordinates and in UT1 is now applied in the modelling to interpolate *a priori* EOP values. The consequences of these changes are considered below.

The new EOP reference epoch (1991 August 12 19:49:50) was selected because two large, independent VLBI networks ran simultaneously that day; see Carter *et al.* [1993]. A total of nine VLBI antennas were used producing 2062 usable observations. Six of the stations are (or have been) elements of the regular EOP-monitoring networks and most of the stations routinely produce high-quality data. The combined data set should yield EOP estimates of unsurpassed quality. This factor is important because the formal errors of the reference day propagate throughout the solution to influence the formal error determinations on all other days. Likewise, the network interconnectability is important to ensure that all stations and networks are adequately related to the EOP values at the reference epoch. The particular choice for fixed EOP reference day is better in these respects than any other that we are aware of.

Figure 1 shows the evolution of the EOP formal standard errors for UT1, X pole position, and the nutation offset in obliquity from the combined EOP (NOAA) 93 R 04 and 05 data sets. The trends are similar in all the EOP components. The dense band of points corresponds largely to measurements by the regular IRIS-A and NAVNET EOP-monitoring networks together with NASA global sessions. There is a dramatic drop in the uncertainties during 1984 with the establishment of the four-station IRIS-A EOP network, which operated at five-day intervals, and with the installation of cryogenically cooled FET-amplifier receivers. After that, the decline in formal uncertainties is gradual but steady until mid-1989 when HRAS-085 was replaced by MOJAVE12 in IRIS-A, expanding the geometric extent of the network. Since the drop in 1989, the errors have declined only slightly. Throughout the period there have been occasional observation sessions with smaller networks that are not robust for EOP determinations, primarily involving the mobile VLBI systems engaged in regional measurement campaigns. There is also a set of points forming the lower envelope of the trend (especially evident in the plot of UT1 formal errors), beginning

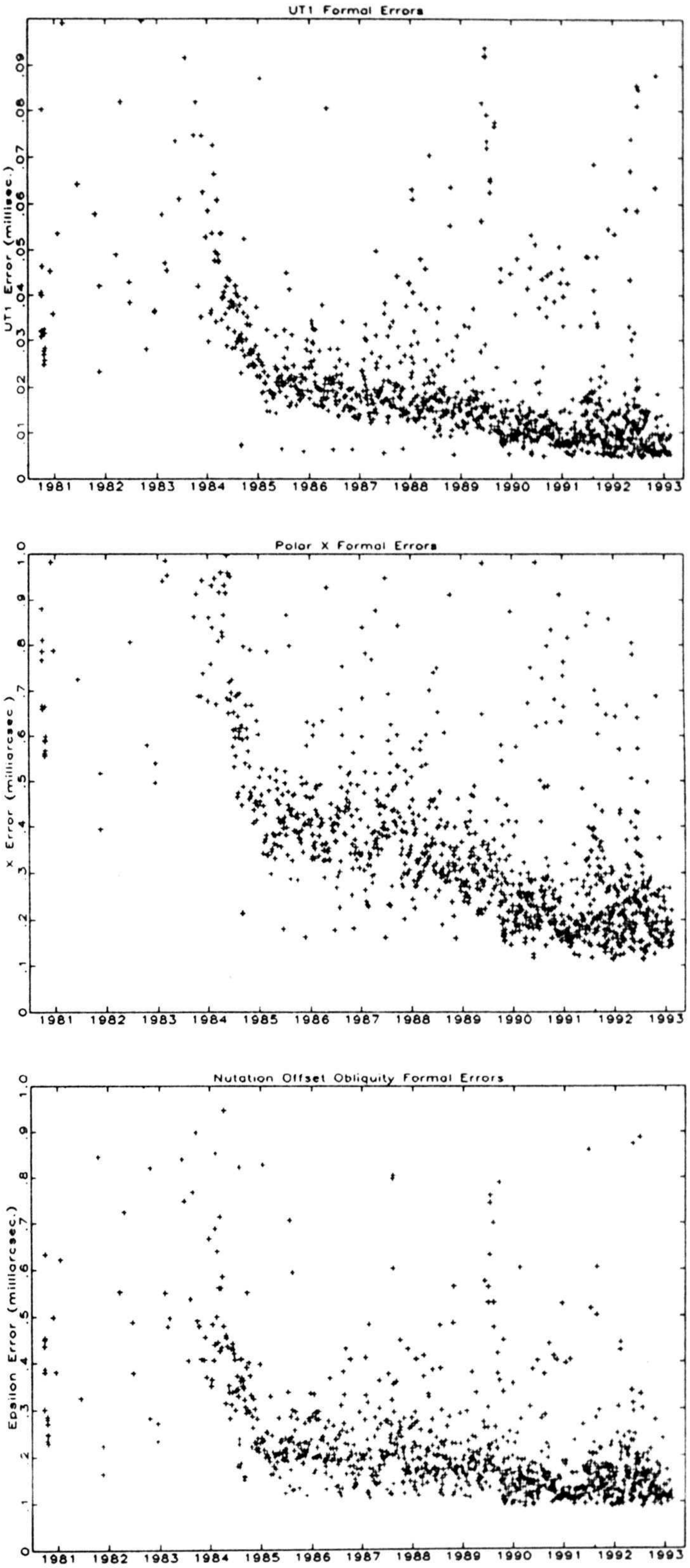

Fig. 1. EOP formal errors for UT1 (top), X (middle), and nutation obliquity (bottom).

in 1984, that comes from the NASA POLAR series, which uses a circum-polar network of northern hemisphere stations. The fact that the POLAR results are constant over the entire period implies that the overall declining trend of the other networks is not likely to be an artifact of increasing proximity to the EOP reference date, shown in Figure 1 by a small tic mark along the time axis. The current routine EOP precisions are about 150-250 μas for X and Y pole position, 5-10 μs for UT1, and 100-150 μas for obliquity.

Given measurement precisions of this level, it is expected that accounting for diurnal and semi-diurnal tidal EOP variations, which have amplitudes of 0.5-1 mas [Herring, 1992], should produce small but noticable improvements. Our analysis includes Herring's model for these effects as part of the interpolation procedure used to form *a priori* EOP values, in addition to the tidal models recommended in the *IERS Standards* (see Carter *et al.*, 1993). We observe an improvement in the global fit of the VLBI delay data by 2.4% using that model. In addition, we have found in test solutions that aliased UT1 power is removed when Herring's model is applied. The tests were done with and without the addition of a UT1-rate (or length-of-day) parameter (the adjustments being done at conventional midnight epochs) and the spectrum of the resulting UT1 differences was analyzed. Distinct peaks show up in the difference spectrum near fortnightly (~14 μs amplitude), weekly (~10 μs), and annual (~7 μs) periods. Applying Herring's model removes these peaks when the difference test is repeated.

The NOAA EOP values report total quantities (except for the nutation offsets which are relative to the IAU 1980 model for nutation). Having accounted for the diurnal and semi-diurnal EOP variations, together with adjusting the EOP offsets at the weighted mean observation epoch of each session, these time series should fully preserve tidally coherent components with periods down to about 12 hours. Residual unmodelled variations will occur, primarily due to exchange of angular momentum with the atmosphere. These incoherent variations are very effectively averaged out in our analysis for those components with time dependencies proportional to t^n for n odd over the 24-hour observing sessions; such variations will be attenuated but not fully average out for those components having time dependencies proportional to t^n with n even over 24-hour periods. Thus, there is no advantage to using EOP rate parameters in addition to the offset parameters already included. Indeed, such parameters will degrade the precision of the results significantly.

<u>Intensive UT1 Results.</u> Early studies of the UT1 results obtained from the 1-hour single-baseline IRIS Intensive sessions estimated their accuracy to be about 100 μs [Robertson *et al.*, 1985]. A major portion of the error was attributed to inaccuracies in the *a priori* values for X and Y pole position. (The Intensives themselves were not intended to provide independent estimates of the pole position.) It is now possible to evaluate the accuracy of the Intensives in a more direct way than was possible then by comparing UT1 determinations with estimates from coincident VLBI observing sessions. Altogether there are 320 Intensive sessions between 1985.5 and 1993.0 that overlap with a 24-hour multi-baseline VLBI session. The time series of UT1 differences obtained from these coincident sessions is shown in Figure 2. The weighted rms (wrms) UT1 difference is 65.1 μs with a weighted mean of 6.3 μs. To quantify the magnitude of errors induced by interpolation of X and Y values, we have also examined the subset of 60 Intensives coincident with USNO NAVNET sessions (between 1991.4 and 1993.0). In this comparison, X and Y interpolation errors are negligible because the NAVNET sessions themselves are contained in our *a priori* EOP series, which is not true of the remaining comparison set. The wrms difference in UT1 values for this subset is 56.4 μs with a mean of 12.4 μs. Since the precision of the NAVNET UT1 determinations is about 10 μs or better, we infer that the intrinsic accuracy of the Intensive UT1 determinations is about 55 μs. Errors in the interpolation of X and Y values contribute roughly 30-40 μs of additional (quadratic) uncertainty in the typical case.

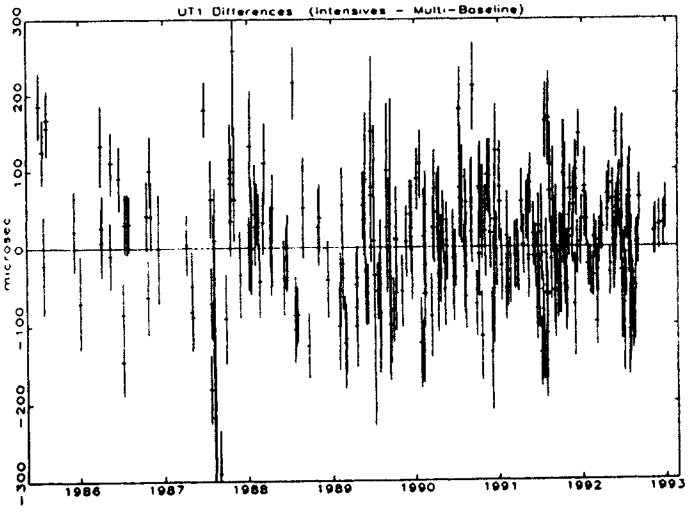

Fig. 2. Differences in UT1 from IRIS Intensives and coincident multi-baseline VLBI sessions.

Systematic Errors. There are two basic approaches used to assess the accuracy of VLBI results: 1) examination of the consistency of repeated determinations of geodetic quantities; 2) comparison of VLBI determinations with those from independent techniques. Repeatability studies are especially well suited to estimating the VLBI performance for terrestrial position determinations. MacMillan and Ray [1991] have taken this approach to infer long-term repeatabilities for various types of observing sessions. Their results are shown in Table 5 for three subsets of observing sessions. The full set of Mark III VLBI data includes many mobile VLBI baselines from small regional networks which are severely limited in low-elevation angle coverage. This factor accounts for the poorer vertical performance for the full data set. Since relatively few mobile VLBI sessions are included in our analysis, the IRIS-A values in Table 5 should be roughly representative of our results. The formal errors for the station positions underestimate the observed repeatabilities by a factor of 2.5 for the vertical components of the NASA R&D sessions, known as the ATD series, but by only about 35% for the horizontal components. This is consistent with the general view that uncalibrated errors in modelling the tropospheric propagation effect, which primarily degrade vertical determinations, dominate the VLBI error budget. In their comparison of independent determinations of geocentric station coordinates for 18 pairs of VLBI and satellite laser ranging stations, Ray *et al.* [1991] found wrms differences of 15-22 mm per component (after a seven-parameter frame adjustment). Their results are consistent with the overall formal errors of both techniques being too small by a factor of about 2.

Table 5. VLBI Position Repeatabilities by Session Type[a]

	σ_V (mm)	σ_H (mm)	σ_L 1000 km (mm)	σ_L 5000 km (mm)
Average of all Mark III data	26.4	4.9	7.5	16.0
IRIS-A (1990)	13.3	3.5	5.1	8.6
NASA R&D (ATDs)	11.0	2.3	3.5	6.8

[a]Long-term repeatabilities of station vertical and horizontal position components and of baseline length for two distances, from MacMillan and Ray [1991].

Using a three-dimensional station position accuracy of 15 mm from the operational VLBI EOP-monitoring networks, the associated accuracy for the EOP estimates is about 480 μas, approximately 2-3 times the formal uncertainty level. This level is consistent with comparisons of independent determinations of X and Y pole position made using GPS observations [Herring *et al.*, 1991]. There are reasons to expect poorer performance in some cases, however. For example, we have observed that when one or more VLBI stations of a three-station network (the minimum number needed to determine all EOP components independently) suffers a sustained loss of data, the EOP values can be in error by more than 1 mas (based on comparison with GPS estimates) even though the formal uncertainties are affected only slightly. In practical terms, this situation can be largely avoided by designing observing networks with sufficient redundancy to minimize the effects of data outages. Nevertheless, it is clear that a better understanding of the systematic errors is needed. One particularly well documented example of a long-term systematic error is the non-linear motion of the HRAS85-3 VLBI site at Ft. Davis, TX, USA [*e.g.*, Herring and Dong, 1991]. Since our data analysis assumes linear site motions, the deviations (up to several cm at the Ft. Davis site, mostly in the local vertical) will be partially absorbed into the EOP estimates. Unfortunately, the effect of the Ft. Davis motion is especially pronounced because that site was the westernmost element in the IRIS-A network for about eight years. While this appears to be the most obvious case, smaller non-linear motions are likely at other sites [Herring and Dong, 1991].

We appreciate the cooperation and assistance of the IERS/Central Bureau staff in evaluating earlier NOAA test solutions.

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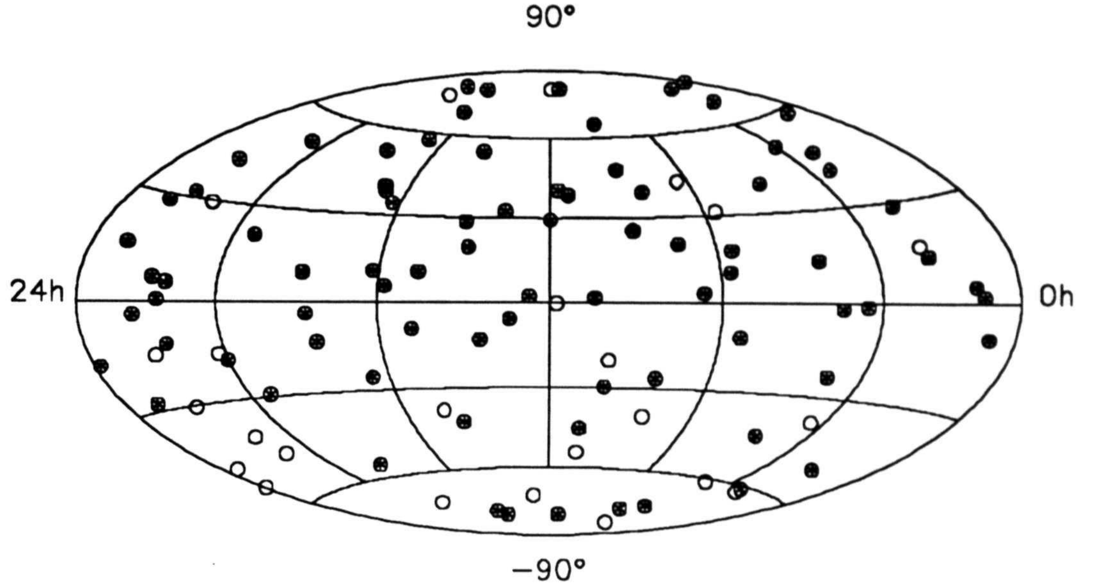
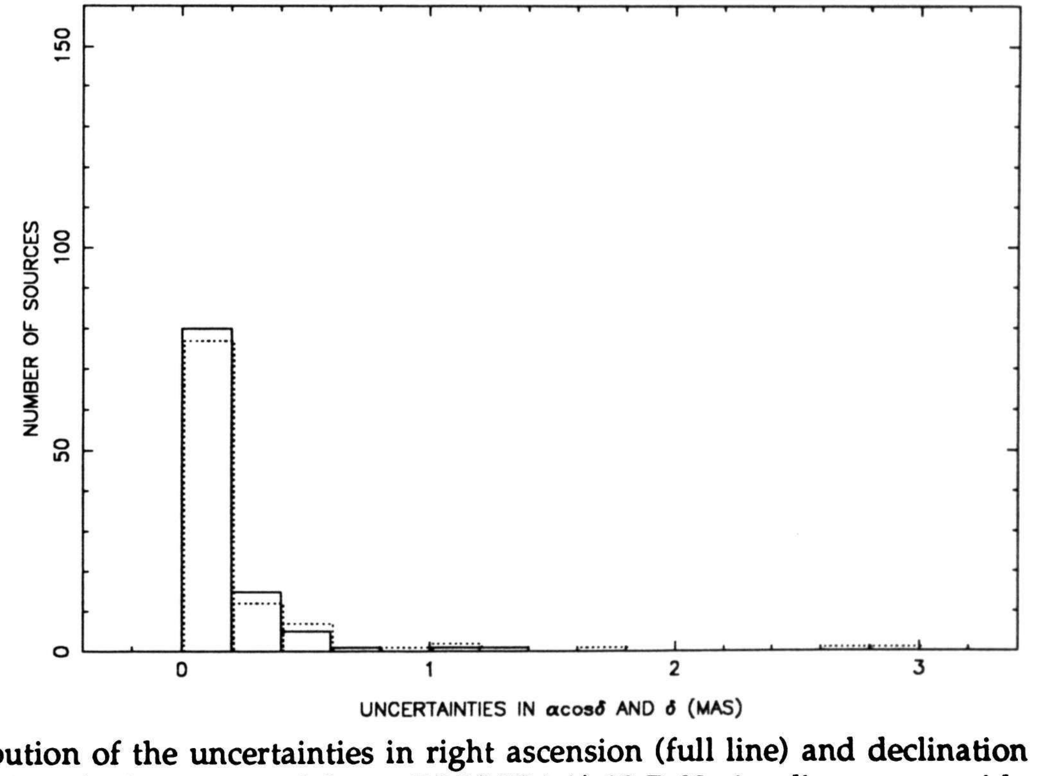
Summary description of the terrestrial system attached to the set of station coordinates SSC(NOAA) 93 R 02

1 - Technique:	Bandwidth-synthesis Mark III VLBI
2 - Analysis Center:	NOAA VLBI Analysis Center, N/OES13 11400 Rockville Pike Rockville, MD, USA 20852
3 - Solution Identifier:	solution rundate = 09/03/93 17:23:57
4 - Software Used:	COREL and FRNGE for the Mark III data correlation; DE200 ephemerides, CALC-7.6, and SOLVE-3 for data analysis
5 - Relativity Scale:	Radio source coordinates are in solar system barycentric system; Terrestrial site coordinates are geocentric (ignoring the local gravitational potential of the Earth)
6 - Permanent Tidal Correction on Station:	No correction is applied to remove the zero-frequency displacement introduced by the solid Earth tide model.
7 - Tectonic Plate Model:	NNR-NUVEL1 is used to specify the large-scale motion of the entire terrestrial reference frame in both translational and rotational senses for nine VLBI sites (see text for details); the same model is also used to propagate the relative positions of sites with data spans too brief to permit reliable determinations of VLBI velocities.
8 - Velocity of Light:	299792458. m/s
9 - Geogravitational Constant:	not applicable
10 - Reference Epochs: Station coordinates	1988 January 01
Source coordinates	J2000.0
EOP fixed epoch	1991 August 12 19:49:50 UT

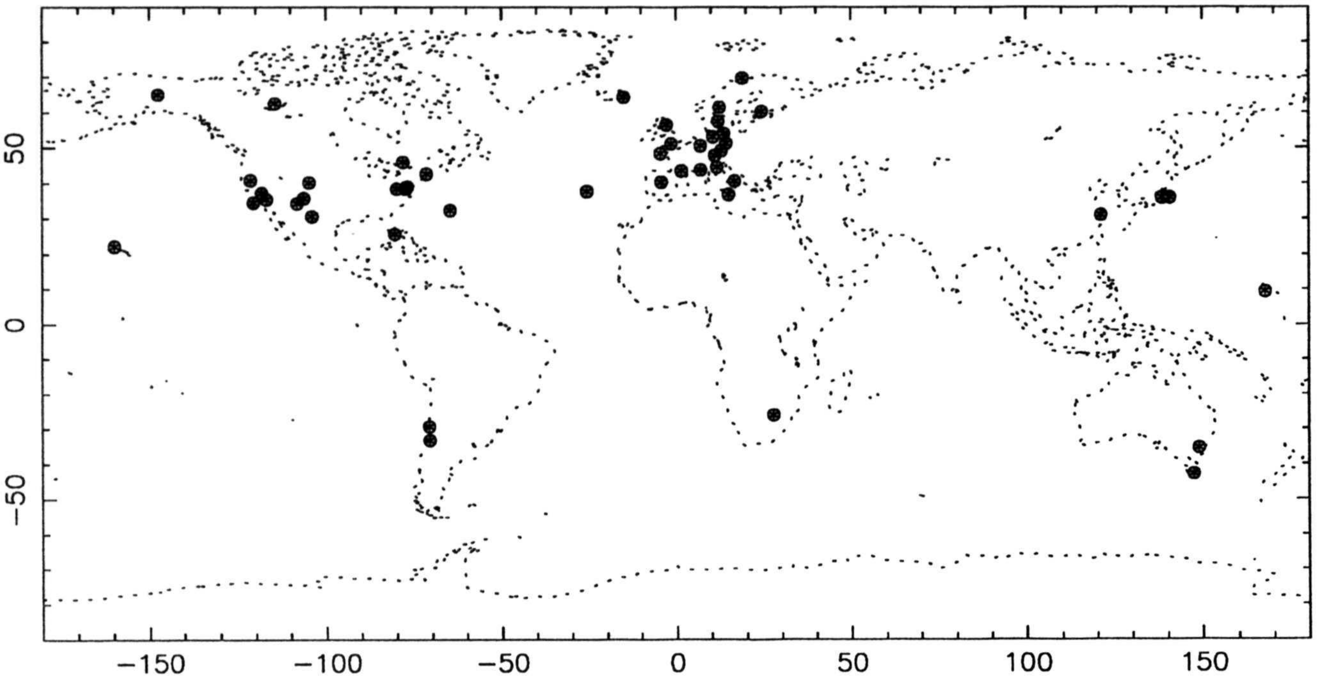
11 - Adjusted Parameters:	XYZ geocentric station coordinates and linear station velocities adjusted globally for all sites at their mean observation epochs; radio source coordinates adjusted globally for all sources; pole X and Y coordinates, UT1, nutation longitude and obliquity offsets adjusted for each 24-hour observing session; UT1 is the only EOP adjusted for 1-hour Intensive sessions; clock polynomial coefficients adjusted for all but one station in each observing session; atmosphere offset parameters for each hour interval for each station for each 24-hour observing session (no atmosphere parameters are included in the analysis of the 1-hour Intensive sessions)
12 - Definition of the Origin:	The coordinate origin of the terrestrial reference frame is specified by setting the vector sum of the adjusted coordinates for 16 VLBI sites equal to the corresponding vector sum for ITRF-91 (see text); the right ascension origin of the celestial reference frame is specified by setting the sum of the adjusted right ascensions for 36 radio sources equal to the corresponding sum for ICRF-91 (see text)
13 - Definition of the Orientation:	The relative orientation of the terrestrial and celestial reference frames is specified by fixing the EOP values to those interpolated from the EOP (IERS) 90 C 04 series (corrected for the offsets and drift rates reported by the IERS to give consistency with the ITRF-91 and ICRF-91 frames) for the reference epoch 1991 August 12 19:49:50; the interpolation method is described in the text.
14 - Constraint for Time Evolution:	The secular translational velocity and rotational velocity of the terrestrial reference frame are specified through constraints; see item 7 above and text.



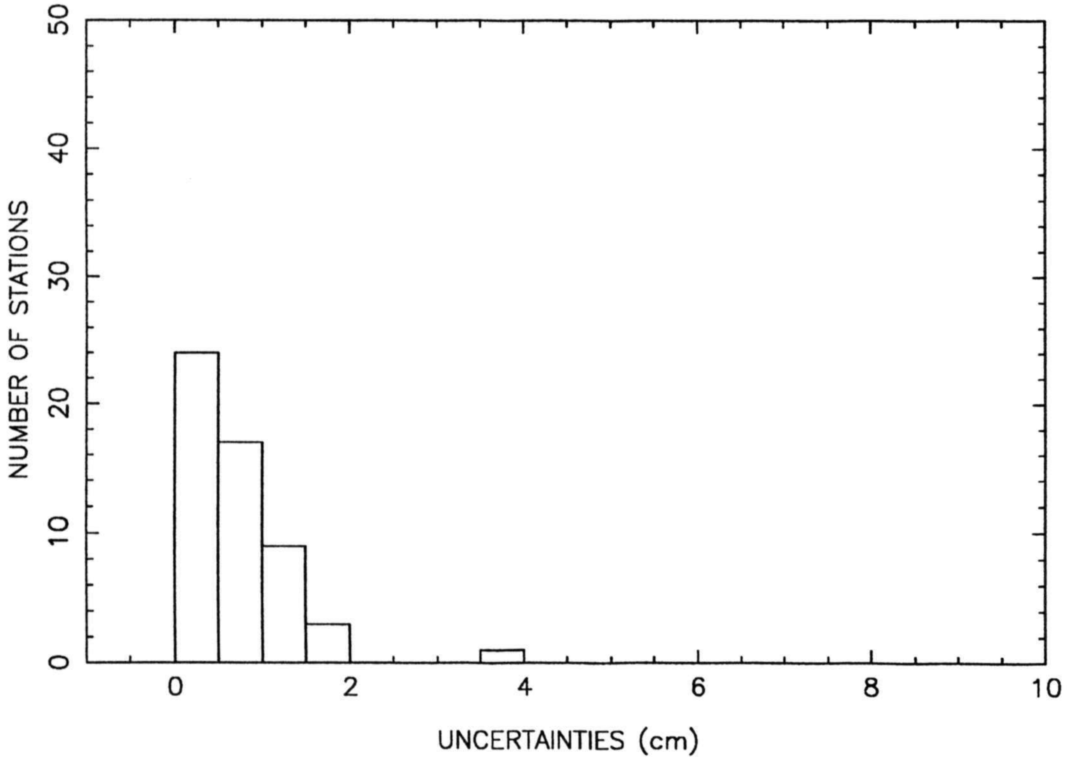
Distribution over the sky of the 107 extragalactic radio sources of the celestial frame RSC(NOAA) 93 R 02. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(NOAA) 93 R 02. 4 radio sources with uncertainty larger than 0.003" are not shown.



Distribution of the 48 sites of the terrestrial frame SSC(NOAA) 93 R 02.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 54 stations of the terrestrial frame SSC(NOAA) 93 R 01.

EOP(NOAA) 93 R 04 From Sep 1980 to Jul 1993

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1980	16	0.67	16	0.70	16	0.32	16	1.00	16	0.34
1981	6	1.03	6	1.14	6	0.56	6	1.32	6	0.47
1982	10	1.13	10	1.00	10	0.46	10	1.79	10	0.52
1983	17	0.98	17	1.77	17	0.73	17	1.60	17	0.50
1984	70	0.68	70	0.73	70	0.36	70	1.03	70	0.36
1985	71	0.42	71	0.44	71	0.21	71	0.60	71	0.22
1986	73	0.41	73	0.39	73	0.19	73	0.59	73	0.21
1987	73	0.40	73	0.39	73	0.18	73	0.57	73	0.21
1988	73	0.34	73	0.34	73	0.16	73	0.50	73	0.19
1989	72	0.30	72	0.28	72	0.14	72	0.43	72	0.17
1990	72	0.22	72	0.23	72	0.10	72	0.35	72	0.15
1991	89	0.21	89	0.22	89	0.10	89	0.33	89	0.13
1992	100	0.22	100	0.23	100	0.10	100	0.34	100	0.14
1993	46	0.16	46	0.17	46	0.06	46	0.28	46	0.12

EOP(NOAA) 93 R 05 From Jul 1984 to Dec 1992

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	8	0.47	8	0.50	8	0.30	8	0.56	8	0.18
1985	12	0.34	12	0.32	12	0.16	12	0.42	12	0.15
1986	19	0.33	19	0.28	19	0.17	19	0.40	19	0.16
1987	34	0.35	34	0.32	34	0.25	34	0.50	34	0.17
1988	38	0.35	38	0.34	38	0.18	38	0.40	38	0.17
1989	67	0.31	67	0.30	67	0.17	67	0.44	67	0.20
1990	80	0.26	80	0.23	80	0.12	80	0.36	80	0.14
1991	75	0.19	75	0.17	75	0.09	75	0.32	75	0.14
1992	93	0.22	93	0.24	93	0.09	93	0.39	93	0.16

EOP(NOAA) 93 R 06 From Apr 1984 to Aug 1993

Number of measurements per year and median uncertainties
Units : 0.001" for UT1

YEAR	UT1	
	Nb	Sigma
1984	64	0.73
1985	159	0.41
1986	237	0.42
1987	245	0.41
1988	255	0.41
1989	234	0.43
1990	261	0.42
1991	247	0.40
1992	222	0.29
1993	151	0.27

ANALYSIS OF THE IRIS VLBI INTENSIVE SESSIONS

EOP(OPA) 93 R 01

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The VLBI observations obtained over 1985-1992 on the Wettzell-Westford baseline in the frame work of the IRIS project have been analysed. The latitudes of the two stations are respectively 49° and 43° N. The observations consist of two scans of each of the four radio sources in the program (four scans since October 1991), repeated on all days when no 24 h routine IRIS-A is scheduled. The observation list includes two high declination sources (0212+735, 1803+784), and two lower declination sources which are changed about every three months. This scheduling results in three-month batches with constant geometry and sidereal time of observation. It was conceived as a compromise between constraints on tropospheric propagation errors, monitoring of the station clocks and practicability of daily observations. It is optimised for the determination of universal time. Figure 1 shows the distribution on the sky of the program sources over 1985-1992.

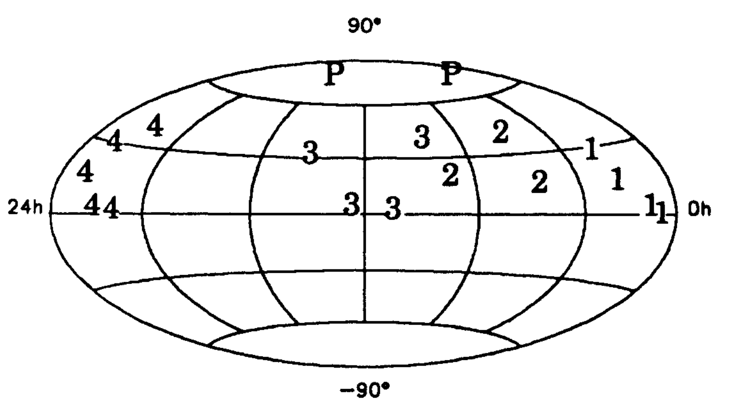

Figure 1. Program sources in the IRIS intensive observations. P : permanently observed, 1, 2, 3, 4 : observed during the corresponding trimester.

With the observations available, the only parameters which can be estimated together with UT1-UTC from one session are the clock difference and the clock difference rate between the two stations. The three parameters are assumed to be constant over the 45 minutes of observation. The space-time structure of the scans result in a high negative correlation between UT1-UTC and the clock difference (-0.8 in the best cases), and a satisfactory decorrelation (smaller than 0.6 in absolute value) for the other pairs of parameters.

As a result of the yearly return of a similar source program (see Fig. 1), the correlation scheme is roughly reproduced with a yearly cycle.

The data analysis includes the adoption of fixed values for the coordinates of stations and sources, for the pole coordinates (x, y) and the celestial pole offsets ($d\psi$, $d\varepsilon$). All values where adopted from homogeneous IERS results: SSC(IERS) 92 C 01 and the NNR-NUVEL1 model for the terrestrial frame, RSC(IERS) 92 C 01 for the celestial frame, and EOP(IERS) 90 C 04 for the terrestrial and celestial coordinates of the pole (corrected for the bias recommended in the 1991 IERS Annual Report, p. II-13). Considering an accuracy of ±0.5 mas on each of the *a prioris*, Hefty and Gontier (1993), have studied the error propagation and the effect of the quarterly structured program. They conclude that the highest sensitivity of UT1-UTC is with respect to the source positions and the celestial pole offsets, at the level of 0.03 ms to 0.05 ms.

Modelling of observations is made with the French-developped software GLORIA (Global Radio-Interferometry Analysis, see Gontier 1992), which follows generally the IERS Standards (McCarthy, 1992), with the following peculiarities:

- the transformation between the terrestrial frame and the celestial frame makes use of Guinot's (1979) non-rotating origin (or departure point) concept (Gontier 1991, Capitaine and Gontier 1993),

- the tropospheric correction is based on Saastamoinen (1972) zenith delay using the CFA 2.2 mapping function (Davis *et al*, 1985) for the dry component and the Chao (1974) mapping function for the wet component (see the references in the IERS Standards ,McCarthy, 1992).

- the BDL2000 ephemeris (Chapront-Touzé and Chapront 1983, Bretagnon 1982).

Editing of observations was performed by using an L_1 norm analysis of each session to detect outliers. This estimation technique (minimizing the sum of absolute values of residuals) is known to be less sensitive to outliers than the least-squares (L_2 norm) technique when the degree of freedom of an estimation is low (Bougeard 1992).

The results include 1837 individual determinations of UT1-UTC with 95% of formal uncertainties smaller than 0.07 ms. The actual existence of discontinuities corresponding to the quarterly change of the observing program was investigated by comparison with EOP(GSFC) 93 R 01 (Ma *et al.*, 1993). The quarterly differences found are listed in Table 1. Most of the changes are significant at the 3σ level, their rms value is ±0.03 ms, consistent with the Hefty and Gontier (1993) expectation.

Acknowledgements. We are thankful to J. Morrison (NOAA) for providing the past and current observation data sets, and to J. Souchay (Paris Observatory) for the L_1 norm estimation software.

Table 1. Quarterly UT1 differences of EOP(OPA) 93 C 01 with EOP(GSFC) 93 R 01
Unit: 0.0001 s

Date	bias	rms resid	Date	bias	rms resid
			1989.13	-1.64 ± 0.08	0.63
1985.36	-0.92 ± 0.14	0.94	1989.38	-0.91 ± 0.03	0.27
1985.64	-0.58 ± 0.09	0.72	1989.62	-1.25 ± 0.07	0.54
1985.91	-0.51 ± 0.10	0.70	1989.88	-2.09 ± 0.12	0.79
1986.13	-1.74 ± 0.08	0.56	1990.16	-1.42 ± 0.05	0.48
1986.37	-0.63 ± 0.07	0.57	1990.41	-1.09 ± 0.06	0.43
1986.66	-0.95 ± 0.09	0.84	1990.62	-0.73 ± 0.11	0.89
1986.91	-0.50 ± 0.11	0.77	1990.88	-1.26 ± 0.09	0.72
1987.12	-1.34 ± 0.12	0.89	1991.13	-1.32 ± 0.06	0.46
1987.37	-0.89 ± 0.08	0.63	1991.39	-1.19 ± 0.09	0.65
1987.65	-2.24 ± 0.07	0.62	1991.62	-0.87 ± 0.09	0.77
1987.90	-0.62 ± 0.06	0.42	1991.87	-1.31 ± 0.09	0.62
1988.13	-1.45 ± 0.08	0.65	1992.13	-1.40 ± 0.06	0.44
1988.37	-1.00 ± 0.05	0.43	1992.37	-0.41 ± 0.07	0.52
1988.62	-2.11 ± 0.08	0.67	1992.62	-0.89 ± 0.08	0.55
1988.88	-1.69 ± 0.11	0.81	1992.89	-1.20 ± 0.08	0.55

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EOP(OPA) 93 R 01 From April 1985 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.001" for UT1

YEAR	UT1	
	Nb	Sigma
1985	157	0.34
1986	236	0.31
1987	245	0.32
1988	255	0.28
1989	233	0.27
1990	261	0.27
1991	239	0.25
1992	211	0.21

EARTH ORIENTATION PARAMETERS FROM IRIS VLBI MEASUREMENTS

SHA 93 R 01

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In 1992 the VLBI analysis center at the Shanghai Observatory of Chinese Academy of Sciences regularly correlated and analysed the data of VLBI experiments which are observed once per five-day interval before August 1991 and at seven-day interval after September 1991 under the IRIS-A(International Radio Interferometric Surveying-Atlantic project). The standard configuration of the IRIS-A VLBI network consists of 7 stations, i.e. Westford, HRAS, Richmond, Wettzell, Mojave, Onsala, and Algopark Observatory. The geodetic VLBI data since 1984 have been kept in archives. However, only the data since October 1989 (including the data of VLBI experiments of some other VLBI network) can be read out by the main computer (sun470) of Shanghai Observatory. It is impossible to calculate the celestial and terrestrial frames by using only these data with the adequate accuracies. Therefore, in this analysis, the celestial frame was taken from the results of a global VLBI solution of the VLBI group at NASA Goddard Space Flight Center which contains all Mark III S/X experiments from August 1979 to July 1990 (Ma *et al.*, 1990). The station positions were also taken from these results which include continental drift parameters for each station.

The data of dual-frequency Mark III delays were used to estimate the coordinates of the pole and UT1 from October 1989 to June 1992 with the CALC 7.1 SOLVK software system. In addition to the Earth Orientation Parameters, the estimations of nutation angles and the dry atmospheric zenith time delay for each site were also obtained. The behavior of the site clocks for each day was similarly estimated using Kalman Filtering.

The basic models used to calculate the VLBI delays are consistent with the IERS standards which include IAU (1980) nutation, solid earth tide (h2 = 0.60967, l2 = 0.085) correcting the K1 term but not the zero frequency displacement, pole-tide, vertical ocean loading but not horizontal terms, Chao dry and wet troposphere mapping, DE200 solar system ephemerides, and a modified Yang and Zhao (1992) VLBI time delay with 1 ps accuracy, which differ from Shapiro *et al* (1989) and Hellings (1986) time delay in some additional terms caused by the geocentric velocity V. The NNR-NUVEL1 plate model was adopted instead of AM0-2 and no model for atmospheric loading is used. The *a priori* pole position for each observation was interpolated with a spline method from the five-day GLB621 series. The *a priori* UT1 value for each observation was derived from the five-day IERS concrete series by first removing the IERS standard tidal model, interpolating with a spline to the epoch of observation, and then restoring the standard tidal model.

The complete Earth Orientation Parameters and adjustment of nutation angles time series is designated SHA 93 R 01.

Acknowledgments. The geodetic VLBI data from December 1992 to August 1992 is supplied by Dr. S. Manabe, National Astronomical Observatory, Mizusawa-shi, Japan.

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EOP(SHA) 93 R 01 From Oct 1989 to Jun 1992

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

YEAR	X		Y		UT1		$\delta\psi$		$\delta\varepsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1989	15	0.21	15	0.20	15	0.12	15	0.35	15	0.16
1990	70	0.16	70	0.17	70	0.09	70	0.28	70	0.13
1991	36	0.15	36	0.16	36	0.08	36	0.29	36	0.11
1992	31	0.18	31	0.19	31	0.09	31	0.31	31	0.13

EARTH ORIENTATION RESULTS FROM THE U.S. NAVAL OBSERVATORY VLBI PROGRAM USNO 93 R 01

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As part of its participation in the National Earth Orientation Service (NEOS) the U.S. Naval Observatory (USNO) operates a program in Very Long Baseline Interferometry (VLBI) to monitor changes in the orientation of the Earth on a regular basis. NEOS is a joint cooperative effort of the USNO and the National Oceanic and Atmospheric Administration (NOAA), and this VLBI program is designed to complement the observations coordinated by the NOAA as part of the International Radio Interferometric Surveying (IRIS) subcommission. The Naval Research Laboratory (NRL) and the Crustal Dynamics Project VLBI group at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) also assisted in the development of the program. The Navy VLBI Network (NAVNET) measures the orientation of the Earth in space from Mark III VLBI observations. Current NAVNET operations consist of one 24-hour duration observing session per week, a two-hour duration NAVNET INTensive (NAVINT) observing session on another day of the week, and special NAVNET EXperimental (or NAVEX) sessions on an irregular basis. These data are used to estimate UT1, polar motion and nutation for inclusion in the International Earth Rotation Service (IERS) combined solutions. All of the currently available 24-hour-duration NAVNET and NAVEX data are provided in this report in a uniform reduction using the Navy 1993-9 reference frame, which will also be described.

The USNO VLBI program began observations in June, 1987, with a series of 8-hour GNUT (Goddard-Navy UT) experiments. Routine NAVNET observations began on January 5, 1989, on a weekly basis using the Maryland, Alaska, Hawaii and Florida antennas. One 24-hour GNUT was observed in September, 1988; monthly 24-hour NAVNETs commenced in April, 1989, and all of the weekly NAVNETs have been nominally 24 hours in duration since June 27, 1989. The operational NAVNET currently includes the VLBI stations at Gilmore Creek, Alaska, Kokee Park, Hawaii, and Green Bank, West Virginia. In the past, the stations at Richmond, Florida and Maryland Point, Maryland, participated in the operational NAVNET, and the stations at Wettzell, Germany, and Matera, Italy, have been used operationally when one or more of the regular stations were unavailable. At present, one 24-hour NAVNET experiment is scheduled every week; starting in May, 1991, the NAVNET schedules were coordinated with the schedules of the IRIS-A experiments arranged by NOAA so that the IRIS-A observing sessions nominally start on the Monday, and the NAVNET sessions on the Thursday, of each week. The NAVNET data are reduced and released to NEOS and the IERS on a regular basis; typical processing times are now on the order of 5 days from the acquisition of data to release of the final results for the regular NAVNET data.

Until August, 1992, operational NAVNET observing sessions routinely included the Richmond, Florida, station. Shortly after NAVNET-190 (20-21 August) the Richmond telescope was destroyed by Hurricane Andrew, reducing the operational NAVNET to 3 stations. Shortly after NAVNET 193 (10-11 September) the island of Kauai was struck by Hurricane Iniki. Although the VLBI antenna was not seriously damaged in this Hurricane, all commercial power was lost, and the Kauai station did not resume operations until NAVNET 202 (12-13 November). During this extended period NAVNET operations continued using the Matera and Wettzell VLBI stations together with the regular West Virginia and Alaska NAVNET stations.

In cooperation with the Agenzia Spaziale Italizana, Centro di Geodesia Spaziale, the NAVNET program initiated in October, 1991, a series of monthly NAVNET experimental (NAVEX) observing sessions using the new geodetic antenna in Matera, Italy, along with the Alaska, Hawaii and West Virginia NAVNET stations. Radio telescopes in Wettzell, Germany, Noto, Italy, Algonquin Park, Canada, Hartebeesthoek, South Africa, Santiago, Chile, and Kashima, Japan, have also participated in NAVEX observations. The major goals of these experiments are to study the sources of systematic error in VLBI Earth orientation measurements and to investigate the observed sub-diurnal variations in orientation. To facilitate these goals these experiments are performed simultaneously with IRIS-A or IRIS-P experiments conducted by the U.S. National Geodetic Survey. During the EPOCH'92 campaign (July 27th - August 11th, 1992) the USNO complemented the nearly continuous Extended Research and Development sessions conducted by the NASA/GSFC VLBI group by organizing at set of 4 NAVEX-Global sessions using Green Bank, Matera, Algonquin Park, Hartebeesthoek, Santiago and Kashima. All of these NAVEX results are included with the other NAVNET Earth orientation data provided to IERS.

The NAVNET VLBI data are acquired using Mark III VLBI data acquisition terminals with a nominal 8 X band and 6 S band channels, each with a 2 MHz bandwidth, measuring group delay and phase delay rate. The accuracy of the group delay estimates is greatly improved by using the technique of band width synthesis. Until the beginning of 1992 normal operation used channels are spread across 85 MHz at S band and 350 MHz at X band, using the "Narrow" channel frequencies shown in Table 1. In 1991 the potential spanned bandwidth was nearly doubled and a series of tests were performed to prepare for the operational use of this upgrade using the "Wide" channel frequencies shown in Table 1. These tests (on 8/26/91, 9/24/91, 1/14/92, 1/21/92 and 1/28/92) were successful, and operational use of the wider spanned bandwidth began on February 1, 1992. At present, the operational NAVNET observing sessions mostly use the Wide bandwidth setup, and the NAVEX sessions, the Narrow bandwidth setup.

The NAVNET VLBI data are correlated at the Washington Correlator, which is located at the Naval Observatory and run by a consortium among the USNO, NOAA, NRL, and NASA. The correlator provides estimates of the band-width-synthesis group delay and the phase delay rate from the radio noise recorded at the stations, together with estimates of the random (thermal) noise associated with each measurement and a quality factor describing the reliability of the measurement. Only observations with quality factors of 5 or higher are used in the USNO reduction of the NAVNET data.

Observations with letter quality factors of A through F, which indicate serious problems with the correlated data, are also not used in the USNO reduction.

Table 1 : NAVNET Channel Frequencies

Channel Number	Band	Narrow Band Frequency Setup, MHz	Wide Band Frequency Setup, MHz
1	S	2217.99	2220.99
2	S	2222.99	2230.99
3	S	2237.99	2250.99
4	S	2267.99	2305.99
5	S	2292.99	2340.99
6	S	2302.99	2345.99
1	X	8210.99	8212.99
2	X	8220.99	8252.99
3	X	8250.99	8352.99
4	X	8310.99	8512.99
5	X	8420.99	8732.99
6	X	8500.99	8852.99
7	X	8550.99	8912.99
8	X	8570.99	8932.99

After correlation, fringe fitting, and the removal of any remaining bandwidth synthesis delay ambiguities, data from the NAVNET, NAVEX and GNUT multi-baseline sessions with durations of 16 hours or longer are used in a series of weighted least-squares solutions to define a USNO VLBI reference frame and to estimate the Earth orientation within that reference frame. The data are processed with IERS standard models to the maximum extent possible. The GSFC CALC 7.6 software is used in the data reduction process. The Nuvell plate motion model is used without adjustment to describe the tectonic motions of the stations. The CFA 2.2 tropospheric mapping function is used to relate line of sight tropospheric propagation delays to the tropospheric zenith delay. Due to a solution set-up error, previous NAVNET solutions did not model ocean tidal loading; starting with the Navy 1993-9 reference frame solutions, and the operational Earth orientation solutions based on that frame, the NAVNET data reduction applies the IERS standard model for both horizontal and vertical deformations due to ocean tidal loading. Ground deformations due to atmospheric loading are currently not modeled.

Unmodeled variations in the tropospheric propagation delays and the relative time offset between the station clocks are a significant source of error in geodetic VLBI. The surface pressure, temperature and relative humidity are recorded at each station and used to estimate the variations in the hydrostatic zenith tropospheric propagation delay. Further variations in these quantities are treated by the estimation of piecewise linear models directly in the least squares solutions. A new piecewise linear function is introduced every 60 minutes for the zenith tropospheric propagation and every 90 minutes for the relative station clocks.

NAVNET data reduction depends on a reference frame, which is derived from the NAVNET data and is intended to align the NAVNET Earth orientation results as closely as is possible with both the terrestrial and celestial reference frames maintained by the IERS. Due to software limitations, the NAVNET reference frame is obtained from the USNO VLBI data in a two solution process. In the first solution, the IERS Rapid Service (Bulletin A) estimates of the UT1 and polar motion are treated as a priori measurements and the nutation in longitude and obliquity is fixed at the IERS Rapid Service values. The mean of the Right Ascensions of the 49 radio sources given in Table 2 is held fixed at the value given in the IERS combined celestial reference frame for 1991 (RSC(IERS) 91 C 01). All other source coordinate parameters, and all of the station coordinates except for those of the Green Bank NRAO85 3 station, are adjusted in this solution. The purpose of this first solution is to align the celestial reference frame with the celestial pole implied by the IERS Rapid Service nutation series. The declinations of two sources, 0202+149 and 0742+103, are then fixed in a second solution to the values obtained in the first solution. This second solution globally adjusts the coordinates of all of the other sources (subject to the same Right Ascension constraint as before) and all of the station coordinates except for the NRAO85 3 together with an adjustment for UT1, Polar Motion, both components of nutation plus the piecewise linear clock and troposphere models separately for each experiment. The IERS Rapid Service estimates of the UT1 and polar motion are treated as a priori measurements in this solution. The position of the NRAO85 3 station at the epoch 1980 October 17 is fixed at the value given by the ITRF-90 adjusted to that epoch using the Nuvell model, and all stations are allowed to move at the Nuvell rate. The Mojave12 VLBI station does not move at the Nuvell rate, and its position components were treated as "arc" parameters in the solution, with a separate position being estimated for each experiment in which they were observed. Four radio sources (3C84, 3C273B, 3C345 and 3C454.3) were judged to have too much source structure to be usable for geodetic work and are no longer observed; the coordinates of these "removed" sources were also treated as "arc" parameters in the solution.

Table 2 : Sources used to constrain Right Ascension in the Navy 92-3 reference frame :

0016+731	0048-097	0106+013	0119+041	0133+476	0201+113
0229+131	0234+285	0235+164	0300+470	0420-014	0434-188
0528+134	0552+398	0727-115	OJ287	4C39.25	0814+425
1055+018	1123+264	1144+402	1222+037	1308+326	1334-127
OQ208	1418+546	1502+106	1510-089	1519-273	1548+056
1611+343	1633+38	NRAO530	1739+522	1741-038	1749+096
2121+053	2145+067	2216-038	2234+282	2253+417	2345-167
3C279	3C418	CTA26	CTA102	NRAO140	2128-123
2243-123					

The new NAVNET reference frame, Navy 1993-9, was prepared using 100,533 delay and delay rate observation pairs from 221 observing sessions (complete through December 30, 1992), with a weighted rms residual scatter of ± 38.5 picoseconds for the delay observations and ± 107.2 femtoseconds per second for the delay rate data. Table 3 describes the stations used in NAVNET operations. The station coordinates for the epoch 1980 October 17, as well as the source positions, are available on request from the Central Bureau of IERS. The "Source Type" describes the quality of the position with Reference ("R") sources being 0202+149 and 0742+103, the Primary ("P") sources having the most accurate positions and the Secondary ("S") sources having position formal errors larger than a miliarcsecond.

Table 3 : Stations Participating in the U.S. Navy VLBI Program

Station	Location	Station ID Code
GILCREEK	Fairbanks, Alaska	AL
KAUAI	Kokee Park, Kauai, Hawaii	KU
RICHMOND	Richmond, Florida	RI
NRAO85 3	Green Bank, West Virginia	GB
MARPOINT	Maryland Point, Maryland	MD
MOJAVE12	Mojave, California	MO
WESTFORD	Westford, Massachussetts	WF
ALGOPARK	Algonquin Park, Canada	AP
MEDICINA	Medicina, Italy	ME
NOTO	Noto, Italy	NO
MATERA	Matera, Italy	MA
HARTRAO	Hartebeesthoek R.A.O., South Africa	HT
WETTZELL	Wettzell, Germany	WZ
SANTIA12	Santiago, Chile	ST
KASHIM34	Kashima, Japan (34 meter)	KB
KASHIMA	Kashima, Japan (26 meter)	KA

The NAVNET 24-hour experiments are nominally performed on Thursday and Friday of each week. Earth orientation results from these data are generally available within five days after the end of the experiment, by the Thursday of the week after the experiment. The NAVNET Earth orientation results are obtained from the 24-hour experiments in a multi-parameter least squares adjustment for UT1, polar motion and both components of nutation, together with the piecewise linear clock and troposphere models. Additional baseline dependent clock offsets are added whenever the non-closure of the clock estimates around station triangles is judged to be significant. We have discovered that errors in the a priori UT1 rate during an observing session can be significant, especially given the typical rapid turn around of the NAVNET data, as experiments are frequently processed using UT1 predictions. The operational NAVNET solutions now estimate the rate of change of the UT1 averaged over the entire observing session. The solution used a total of 103,723 observation pairs (delay and delay rate) and produced weighted rms residual scatters of ± 38.0 picoseconds for the delay observations and ± 106.4 femtoseconds per second for the delay rate data. (This solution included some experiments from 1993 which were not used in the reference frame solution.) The station coordinates and source positions are fixed at the a priori values given by the Navy 1993-9 reference frame; the positions of the secondary sources and the removed sources are treated as arc parameters, with a separate position being estimated for each experiment in which they were observed. The tie to the 1993-9 reference frame is thus obtained by the fixed station coordinates and source positions; this method avoids week to week variations in the reference frame used in the reduction of the NAVNET data. Although the Earth orientation parameter formal errors thus do not fully reflect errors introduced by uncertainties in the station coordinates and source positions, solutions performed without these constraints indicate that inclusion of these errors would not significantly increase the resulting Earth orientation parameter formal errors.

NAVNET Earth orientation results submitted to the IERS Central Bureau includes the Earth orientation parameter values and their formal errors together with the weighted root mean square delay error, the experiment duration, the number of delay observations, and a subset of the Earth orientation parameter correlation matrix. The full covariance matrix for each 24-hour experiment in the form of parameter sigmas and all ten correlation coefficients between the five Earth orientation parameters is also available. Note that the parameter formal errors have all been scaled to milliseconds of arc on the ground or in the sky, so that the relative ability to determine these parameters can be ascertained easily.

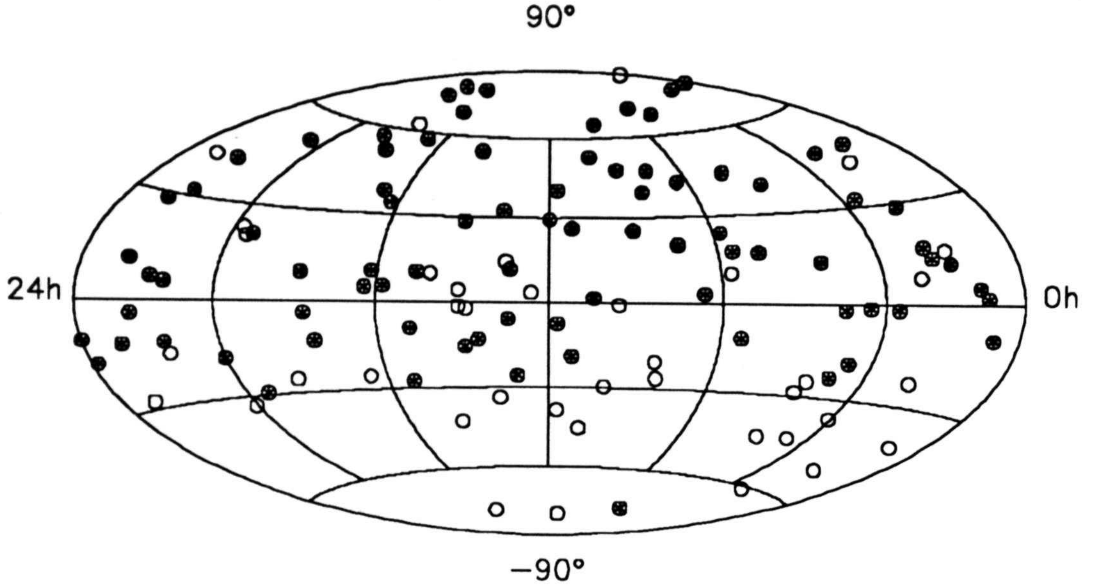
The errors presented in this report are formal errors obtained from the covariance matrix of the least squares adjustment. The post fit residual scatter is always larger than would be expected given the formal error estimates for the delay and delay rate observables provided by the correlator. The total residual scatter is made to agree with that expected given the observable error estimates through addition of empirically determined "noise" additive variances to the square of the correlator formal error estimates. These additive variances are determined separately for each experiment; different constants are used for the delay and delay rate data from each baseline used in an experiment.

The operational NAVNET solutions now estimate the rate of change of the UT1 during each experiment. These UT1 rate estimates converted to estimates of the Length of the Day (LOD) during the observing session (the LOD is minus the UT1 rate in milliseconds/day) are available on request from the IERS Central Bureau. They are comparable in accuracy to those obtainable through differencing of successive UT1 offset estimates, and thus make an interesting data product in themselves.

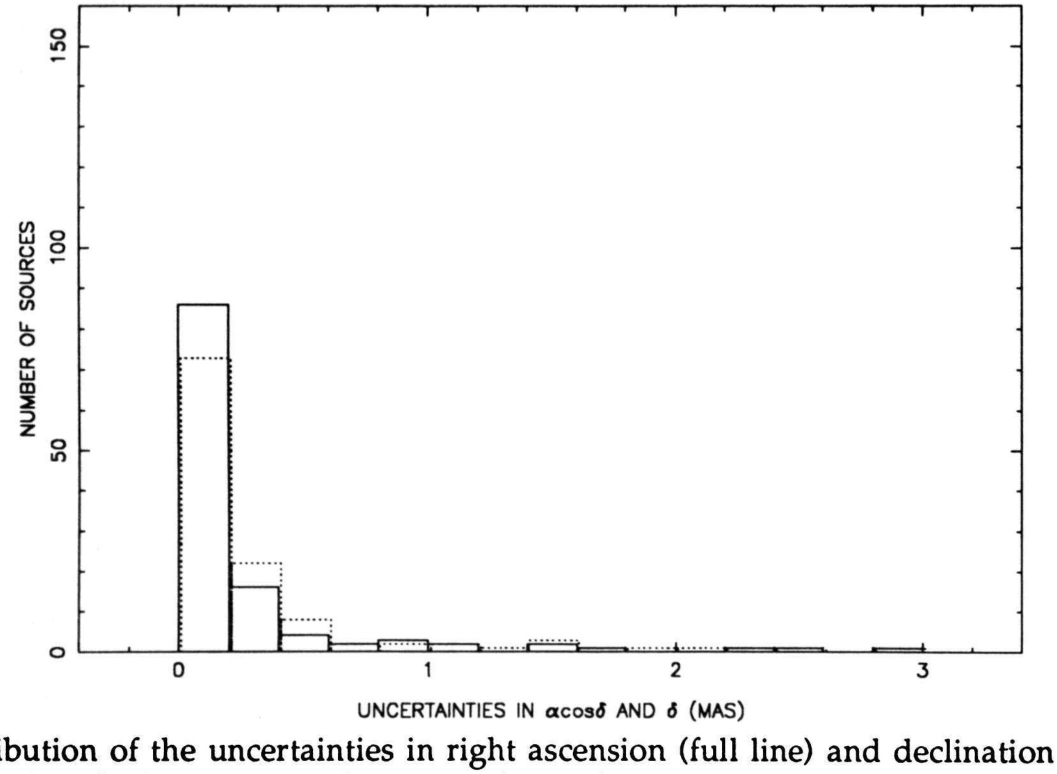
Questions, comments or requests to be placed on the NAVNET distribution list should be directed to T.M. Eubanks, Code TSEO, U.S. Naval Observatory, Washington D.C. 20392-5100, by phone at (202) 653-1501, on SPAN at CDDIS::USNO or USNO01::TME, and on Internet at tme@casa.usno.navy.mil or tme@usno01.usno.navy.mil.

Summary description of the terrestrial system attached to the set of station coordinates SSC(USNO) 93 R 01 (USNO 1993-9)

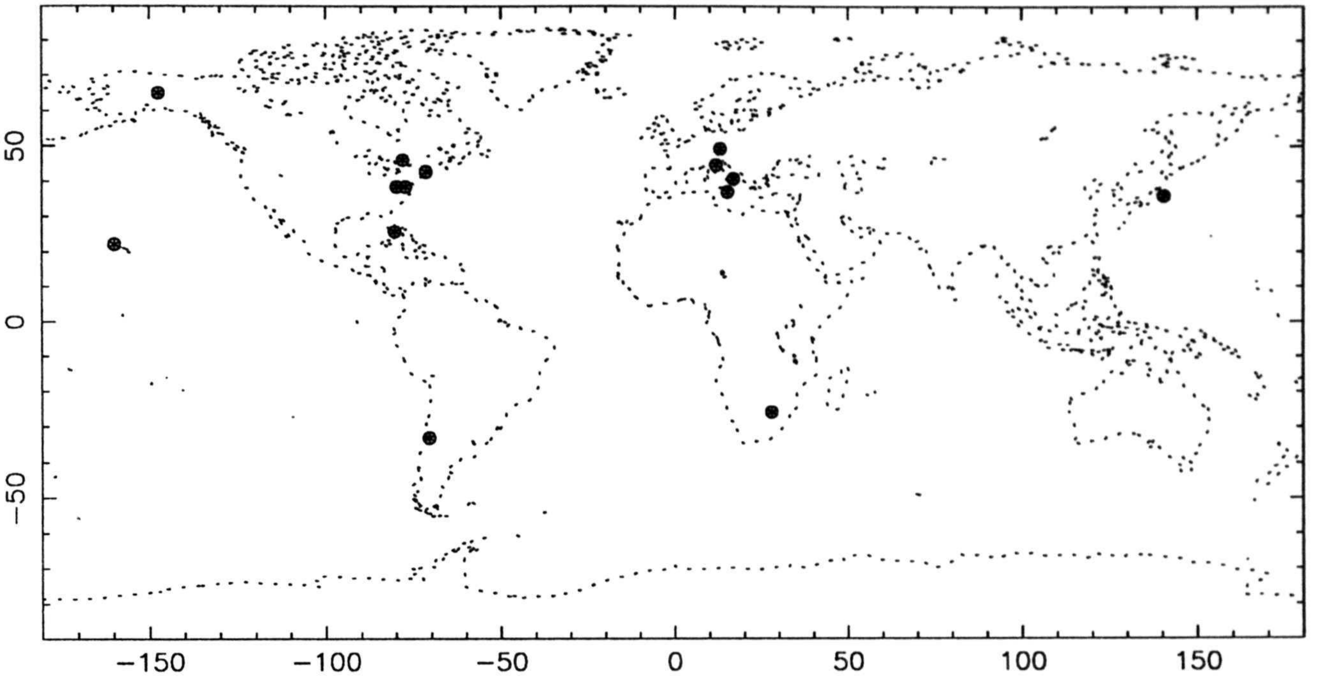
1 - Technique:	VLBI
2 - Analysis Center:	USNO
3 - Solution identifier:	1993-9
4 - Software used:	Calc 7.6
5 - Relativity scale:	Geocentric
6 - Permanent tidal correction:	No
7 - Tectonic plate model:	Nuvell
8 - Velocity of light:	299 792 458 m/s
10 - Reference epoch:	17 October 1980
11 - Adjusted parameters:	see text
12 - Definition of the origin:	NRAO85 3 station position in ITRF-90
13 - Definition of the orientation:	Mean 49 sources in Right Ascension Mean IERS Bull. A values for UT1, Polar and (indirectly) Nutation
14 - Constraint for time evolution:	Nuvell model



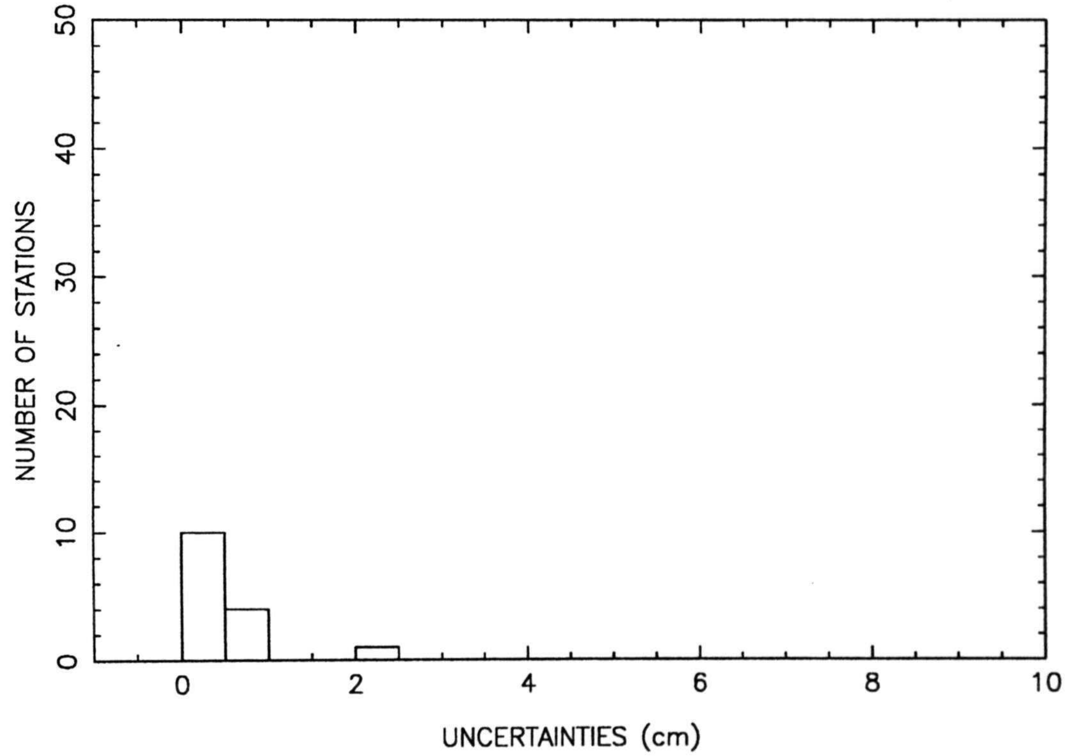
Distribution over the sky of the 123 extragalactic radio sources of the celestial frame RSC(USNO) 93 R 01. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(USNO) 93 R 01. 4 radio sources with uncertainty larger than 0.003" are not shown.



Distribution of the 14 sites of the terrestrial frame SSC(USNO) 93 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 15 stations of the terrestrial frame SSC(USNO) 93 R 01.

EOP(USNO) 93 R 01 From Sep 1988 to Jul 1993

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1988	2	1.80	2	2.17	2	0.89	2	1.42	2	0.55
1989	28	0.51	28	0.71	28	0.30	28	0.61	28	0.24
1990	53	0.26	53	0.26	53	0.16	53	0.41	53	0.18
1991	66	0.23	66	0.23	66	0.15	66	0.39	66	0.16
1992	71	0.16	71	0.17	71	0.10	71	0.28	71	0.12
1993	33	0.14	33	0.14	33	0.08	33	0.23	33	0.09

LUNAR LASER RANGING

EARTH ROTATION (UT0-UTC AND VARIATION OF LATITUDE) FROM LUNAR LASER RANGING

JPL 93 M 01

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Lunar Laser Ranging (LLR) data have been acquired and analyzed between April, 1970 and February, 1993. These data are used to estimate station locations, reflector locations, and lunar gravity and orbit parameters. Beginning in 1970, data acquisition was sufficiently dense to permit determinations of Earth rotation UT0 and variation of latitude (VOL). Values of UT0-UTC and VOL through 1991 have been submitted previously; 50 such values were derived from data acquired in 1992.

The full range data set comprises 7998 normal points taken from five sites: the McDonald Observatory 2.7-meter telescope; the McDonald Laser Ranging Station (MLRS, situated in separate locations before and after a move in early 1988); the Haleakala Observatory on Maui, Hawaii; and the CERGA system in Grasse, France. These normal points are used to estimate the set of lunar and Earth-related parameters. The post-fit residuals are analyzed by the daily-decomposition method (Dickey *et al.*, 1985) to obtain estimates of UT0-UTC and variation of latitude for each station-reflector pair on every day for which sufficient data are available. This set of values is designated EOP(JPL) 93 M 01.

The IAU expression has been used for Greenwich mean sidereal time (Aoki *et al.*, 1982). The planetary and lunar ephemeris used in the fit was DE210/LE210. The lunar librations were integrated simultaneously with the ephemeris.

Plate motion has been applied to the station coordinates using the NNR-NUVEL1 model of Argus and Gordon (1991). The base epoch for plate motion is January 1, 1991 (Julian Date 2448257.5).

The tidally driven diurnal and semidiurnal UT1 variations (M2, S2, N2, K1, O1, and P1), from the theoretical results in Wunsch and Busshoff (1992), have been added to the input UT1 file when fitting the ranges. Consequently, the output table of UT0 has these fast variations removed according to that theoretical model.

A correction to the IAU luni-solar precession constant (Lieske *et al.*, 1977; Lieske, 1979) has been taken as -3.3 mas/yr (Williams *et al.*, 1993). The correction has been made so as not to cause a rate change in UT (Williams and Melbourne, 1982; Zhu and Mueller, 1983).

To the IAU nutations (Seidelmann, 1982) we have added the ZMOA corrections (Herring *et al.*, 1991*a*; 1991*b*) for the in-phase 9 yr, 1 yr, and half-month terms and for the in-phase and out-of-phase corrections for the half-year terms. Corrections to the 18.6 yr nutation coefficients were estimated, yielding

$$\Delta\epsilon = 2.2 \cos\Omega + 1.0 \sin\Omega \quad \text{mas}$$
$$\sin\epsilon\, \Delta\psi = -2.2 \sin\Omega + 0.8 \cos\Omega \quad \text{mas}$$

The constraint of the two in-phase terms (Williams *et al.*, 1991) includes a correction for the precession change and a connection between the changes of the two components. The two out-of-phase components are constrained to be in the ratio of 0.78. Subject to the constraint, the uncertainty in the nutation coefficients is about 1.3 mas, and the precession uncertainty is 0.4 mas/yr. Without the constraint these uncertainties would be larger.

With the production of the 1992 values of UT0-UTC and VOL a set of geocentric station locations has been established and provided to the IERS Central Bureau. Its designation is SSC(JPL) 93 M 01.

The separation between the Haleakala transmitter and receiver conforms to a survey. A range bias is estimated for Haleakala beginning in January, 1990. The separations between the McDonald sites were constrained to survey values.

The approximate uncertaintities in each of the cylindrical coordinates for all stations are: spin radius, 3 cm; longitude, 1.5 mas (4 cm); and z, 7 cm. Each of the three cylindrical coordinates of the five sites has significant correlation with the corresponding coordinate of the remaining four sites; these correlations are positive, implying that the coordinates shift together in the estimation process.

It should be noted that the McDonald 2.7 m telescope ceased LLR activity in June, 1985.

The station locations were derived using the formulation of the relativistic solar-system barycentric frame of reference. The transformation to the relativistic geocentric formulation requires the application of a scale factor.

Acknowledgments. We wish to acknowledge and thank the staffs of CERGA, Haleakala, the University of Texas McDonald Observatory, and the Lunar Laser Ranging associates. Normal points were constructed from individual photon returns by R. Ricklefs, P. Shelus, A. Whipple, and J. Ries at the University of Texas for the MLRS and for Haleakala data. D. O'Gara produced Haleakala normal points independently. C. Veillet provided normal points for the CERGA data. The planetary ephemeris was produced by E. M. Standish. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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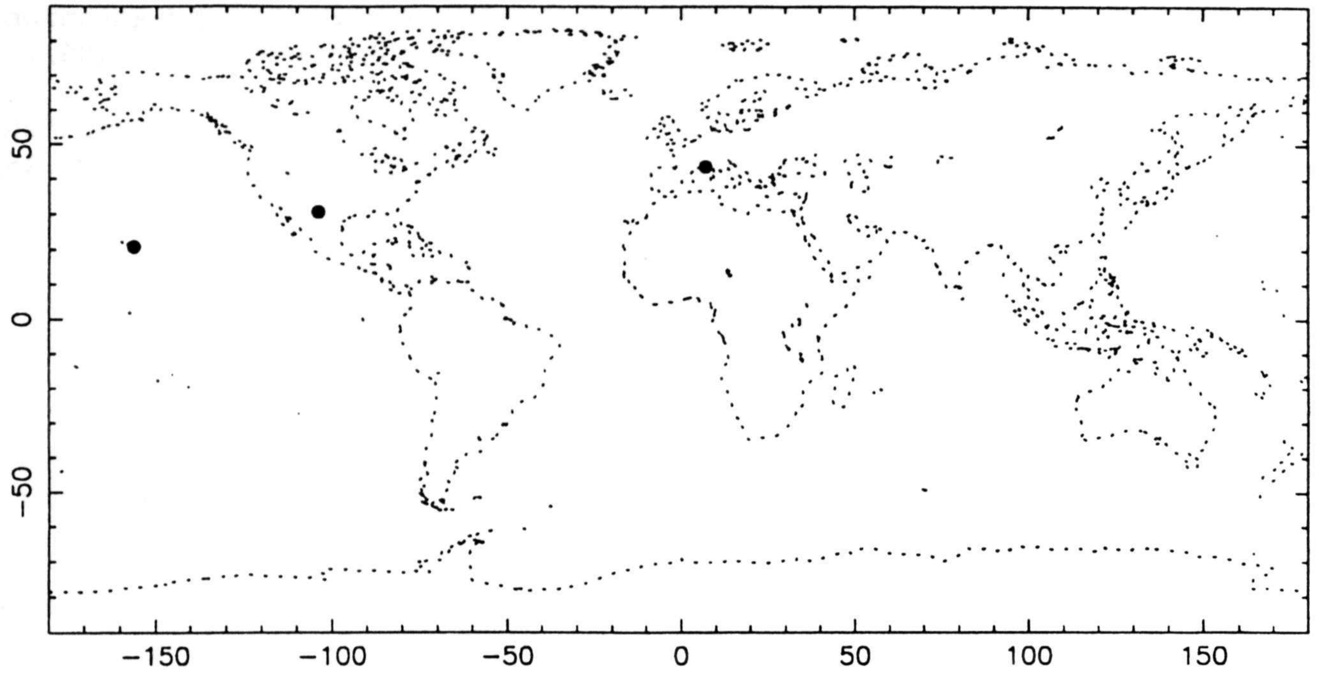
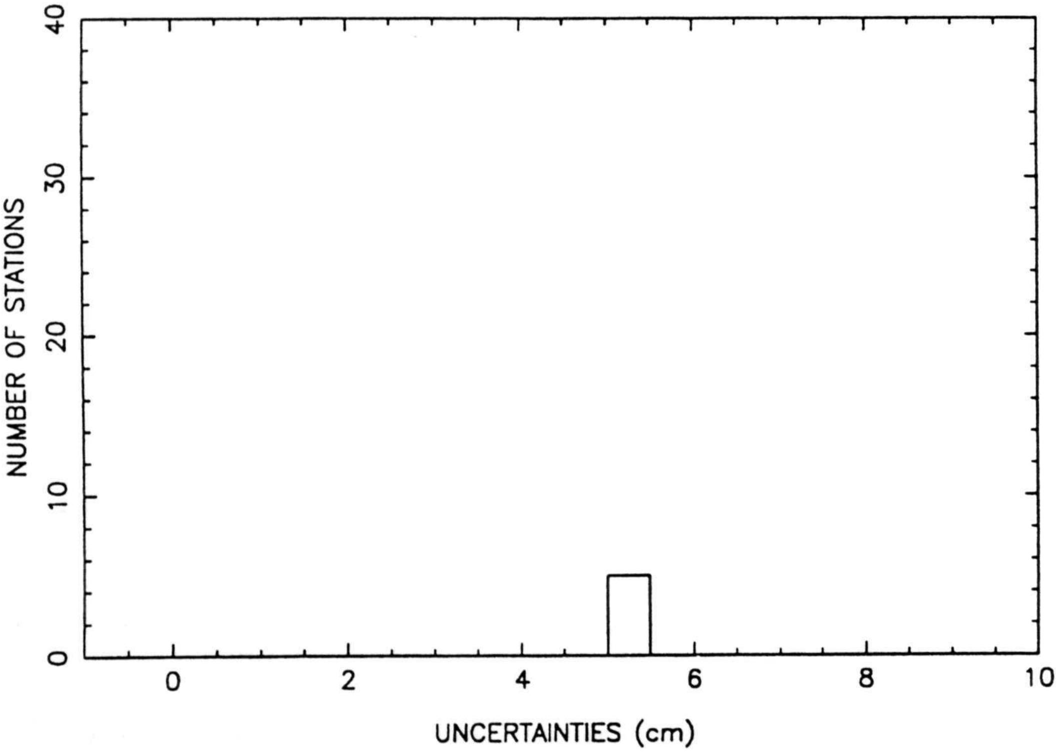


Distribution of the 3 sites of the terrestrial frame SSC(JPL) 93 M 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 5 stations of the terrestrial frame SSC(JPL) 93 M 01.

EOP(JPL) 93 M 01 From Apr 1970 to Feb 1993

Number of measurements per year and median uncertainties
Units : 0.001" for φ; 0.0001s for UT0

YEAR	φ		UTO	
	Nb	Sigma	Nb	Sigma
1970	15	19.86	15	10.64
1971	35	18.16	35	8.43
1972	72	11.70	72	5.47
1973	106	22.70	106	8.15
1974	69	15.99	69	6.94
1975	87	14.71	87	7.44
1976	64	12.01	64	5.53
1977	68	9.35	68	4.33
1978	49	10.33	49	5.49
1979	66	8.48	66	4.55
1980	68	7.40	68	3.89
1981	45	10.30	45	4.07
1982	6	10.40	6	4.75
1983	0		0	
1984	26	5.20	26	2.73
1985	111	6.96	111	2.88
1986	28	5.48	28	2.05
1987	19	4.68	19	1.34
1988	71	2.50	71	1.16
1989	42	2.44	42	1.08
1990	89	1.76	89	1.01
1991	56	1.44	56	0.81
1992	50	1.24	50	0.73
1993	23	1.56	23	1.15

DETERMINATION OF UNIVERSAL TIME BY LUNAR LASER RANGING

SHA 93 M 01

Jin Wenjing, Xu Huaguan, Huang Chengli, Shanghai Observatory, China

Lunar Laser Ranging (LLR) data have been analyzed during JD 2447187.5 - JD 2448989.5. These data set of McDonald (71111, 71112), Grasse (1910) and Haleakala (56610) contain 2726 normal points reflected from four reflectors.

Theoretical models and astronomical constants solid Earth tide and ocean tide, etc were adopted from IERS Standards (McCarthy, 1992). The influence of plate motion is taken into account with NUVEL model. The base epoch for plate motion is January 1, 1988.

The relativistic effects (propagation correction, scale factor and Lorentz effect) are considered. The planetary ephemeris DE303/LE303 and the lunar librations integrated simultaneously with the ephemeris were used for calculating the theoretical distances from the observing stations to the reflectors on the Moon. In this global solution, more than 50 parameters like station and retro-reflector coordinates, lunar potential, and orbit parameters of the Earth-Moon system were estimated.

The post-fit residuals are analyzed to obtain 313 values of UT0-UTC during this period. Due to the need of solving, the normal time between the first and last normal points should be greater than 1.5 hour and more than two points per day are needed. The cylindrical station coordinates are designated SSC(SHA) 93 M 01.

The mathematical model is described in Jin *et al.* (1985). UT0 is calculated in one day interval. The precision of the normal point is taken for the weight of observational equation.

Acknowledgments. The planetary ephemeris DE303/LE303 is supplied by Jet Propulsion Laboratory, California Institute of Techology. The global data of lunar laser ranging are obtained from Dr.Veillet, CERGA.

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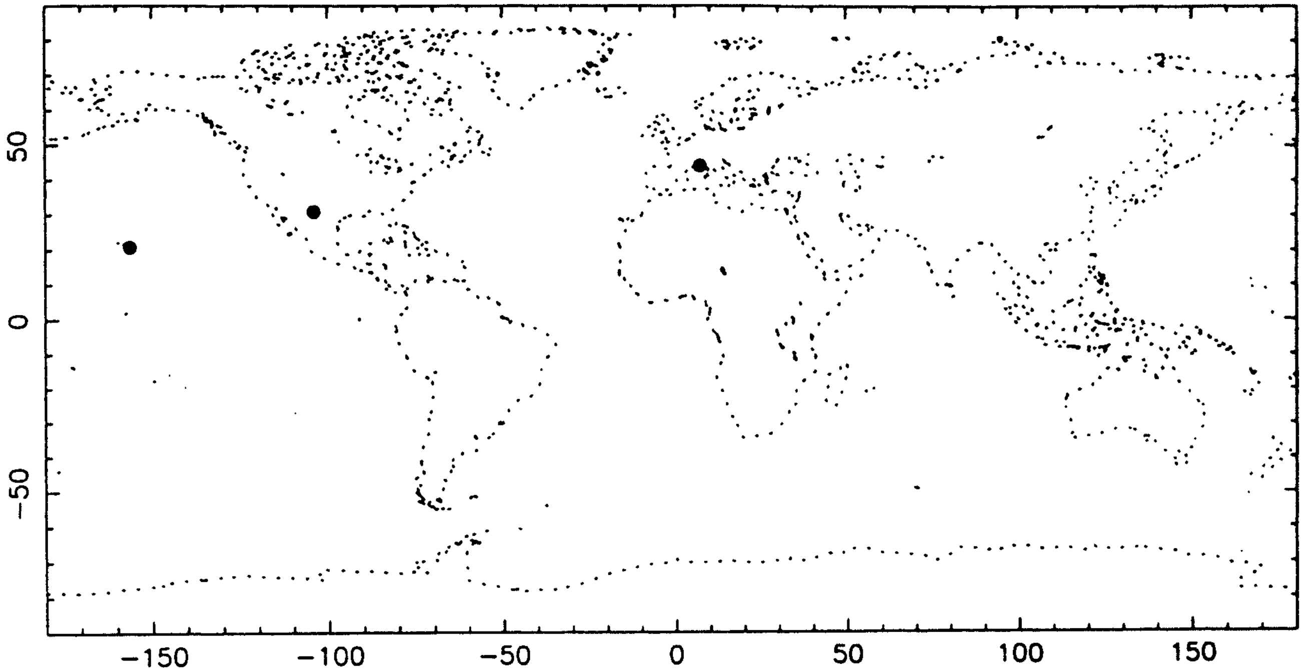
Jin Wenjing, Wang Qiangguo, 1985: Determination of ERP with lunar laser ranging and discussion of the influence of the adopted parameters, *Proceedings of the international conference on earth rotation and the terrestrial reference frame* p. 287-285.

Summary description of the terrestrial system attached to the set of station coordinates SSC(SHA) 93 M 01

1 - Technique	LLR
2 - Analysis Center	SHA
3 - Solution identifier	EOP(SHA) 93 M 01
4 - Software used	SHA LLR software
5 - Relativity scale	SSB
6 - Permanent tidal correction on station	No
7 - Tectonic plate model	NUVEL
8 - Velocity of light	299792458
9 - Geogravitational constant(GM)	3.986004418 10^{14}
10 - Reference epoch	1988.0
11 - Adjusted parameters	Cylindrical coordinate of stations (rates fixed)
12 - Definition of the origin	Geocenter (center of mass)
13 - Definition of orientation	EOP from 1988 to 1992 taken from IERS circular B
14 - Contraint for time evolution	Contrained to NUVEL



Distribution of the 3 sites of the terrestrial frame SSC(SHA) 93 M 01.

EOP(SHA) 93 M 01 From Jan 1988 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.0001s for UT0

YEAR	UTO Nb	UTO Sigma
1988	62	1.40
1989	54	1.40
1990	88	1.50
1991	56	1.60
1992	46	1.45

UT0 AND VARIATION OF LATITUDE DETERMINATION FROM LUNAR LASER RANGING OBSERVATIONS FOR 1969-1992 UTXMO 93 M 01

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We have analyzed the total set of lunar laser ranging data available to us to determine UT0-UTC. These data were acquired between September, 1969 and March, 1993. A total of 8252 normal points, from the McDonald Observatory 2.7m telescope (which ceased operation in 1985), the McDonald Laser Ranging Station (saddle site and Mt. Fowlkes site) near Fort Davis, Texas, the Haleakala Observatory on Maui, Hawaii (which ceased operation in 1990) and the CERGA station in Grasse, France were used in this solution. The data were edited and weighted using an automated and objective scheme which identifies suspected outliers and adjusts station assigned weights to yield consistent distributions of the weighted residuals for all stations. There were sufficient data for 877 station/reflector pair estimations of UT0-UTC including 78 UT0 estimates, on 63 nights, in 1992. This is an increase of approximately 35% over last year.

Our method of analysis was similar to that described by Langley *et al.* (1981). We first used the MIT Planetary Ephemeris Program (PEP) to estimate corrections to the global parameters. The IERS standards were used with corrections made to the mass of the Earth-Moon system, the constant of precession, obliquity of the ecliptic, and the 18.6 year, annual, semi-annual, and fortnightly nutation terms. Adjustments to the MIT ITR-78 solution were made for the Earth-Moon barycenter orbit, lunar orbit, and lunar libration. The node of the Earth-Moon barycenter orbit was fixed to tie the longitude of the celestial reference frame. The AM0-2 plate motion model was used without adjustment. Our a priori Earth orientation series was the MIT UT1COM42/WOBCOM29 until 2 April 1988 (MJD 47253.0) followed by the University of Texas Center for Space Research (CSR) LGN7692. We have biased the UT1COM42/WOBCOM29 series to the LGN7692 series to reduce the arbitrary bias between our UT0 series and the IRIS VLBI 5-day and CSR SLR 3-day series. We estimated a piecewise linear spline for the polar motion components and UT1 to model long period deficiencies in the series. The orientation of the terrestrial reference frame was tied by fixing the zero point of the a priori ERP adjustments at 11 January 1985 (MJD 46076.0). A full correlation matrix for these station coordinates has been provided to the IERS Terrestrial Frame Section. We also estimated a third degree and order lunar potential, lunar love number, and lunar dissipation parameter along with the selenocentric retroreflector coordinates. Lastly, we estimated time delay biases, relative to MLRS, for the McDonald 2.7m, Maui and CERGA data.

Following the global solution, we analyzed the post-fit residuals in the usual fashion (e.g., Stolz *et al.*, 1976) to determine nightly corrections to UT0 and variation of latitude. The nightly corrections were then added to the ERP corrections contained in the splines, and the a priori ERP series to obtain the final values of UT0-UTC and variation of latitude. A minimum of three normal points for each station/reflector pair and at least a 1.5 hour span of coverage were the criteria we adopted for the nightly UT0 estimations. The weighted root mean square of the final postfit range residuals, for the entire span of data, was 5.1 cm. The weighted rms of the postfit residuals for the 508 normal points obtained by the two active stations during 1992 was 3.6 cm.

We have compared our UT0 and variation of latitude series with the IRIS/NAVNET VLBI series. We calculated the bias, slope and weighted rms about the linear fit of the differences between our UT0R and variation of latitude estimates and those implied by the IRIS/NAVNET UT1 and polar motion values. Interpolation of the IRIS series was performed using a four point Newton interpolation scheme. Table 1 gives the results of this comparison for the period where all stations operated with short pulse lasers (1986.5 to 1993.2).

Table 1. Comparison between University of Texas McDonald Observatory LLR UT0R and variation of latitude (DPhi) and IRIS VLBI 5-day values. The period of comparison is 1986.5 to 1993.2. The epoch of the linear fit is 1989.85.

Station		Bias (mas)	Slope (mas/yr)	WRMS (mas)	N
CERGA	DUT0R:	2.29 ± 0.13	-1.46 ± 0.08	2.18	249
	DPhi:	-11.05 ± 0.13	0.69 ± 0.08	2.71	
MLRS	DUT0R:	4.93 ± 0.74	-0.97 ± 0.41	2.18	15
	DPhi:	2.80 ± 0.70	2.03 ± 0.38	2.98	
Maui	DUT0R:	4.85 ± 0.82	1.84 ± 0.42	2.33	20
	DPhi:	9.96 ± 0.80	0.58 ± 0.43	3.52	

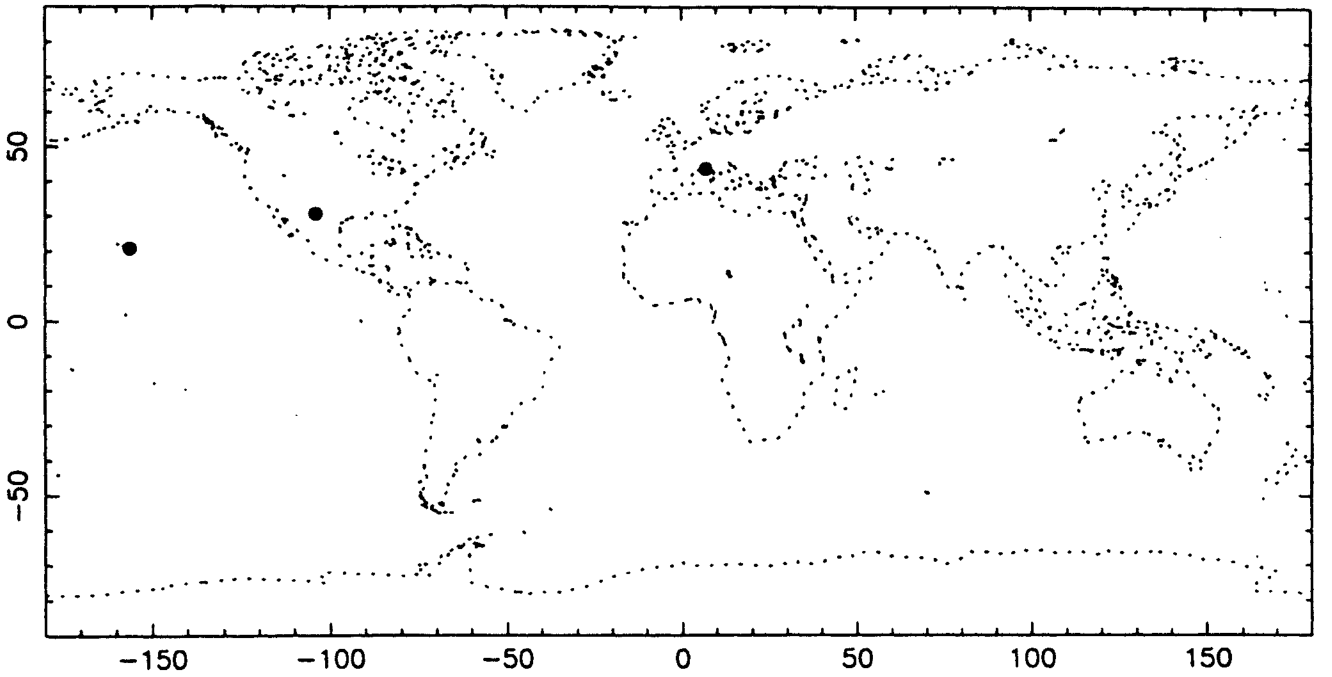
References

Langley, R. B., King, R.W., Shapiro, I.I., 1981: Earth Rotation from Lunar Laser Ranging, *J. Geophys. Res.*, **86**, 11913-11918.

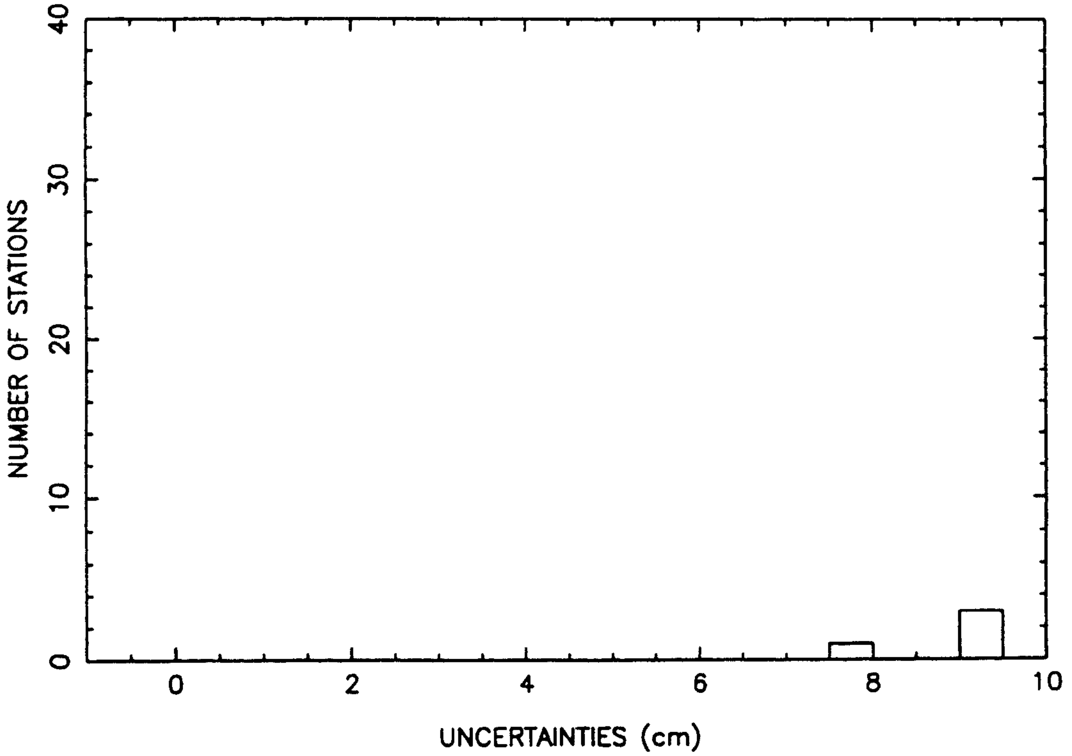
Stolz, A., Bender, P. L., Faller, J. E., Silverberg, E. C., Mulholland, J. D., Shelus, P.J., Williams, J. G., Carter, W. E., Gurnie, D. G., Kaula, W. M., 1976: Earth Rotation Measured by Lunar Laser Ranging, *Science,* **193**, 997-999.

Summary description of the terrestrial system attached to the set of station coordinates SSC(UTXMO) 93 M 01

1 - Technique:	LLR
2 - Analysis Center:	UT/McD
3 - Solution identifier:	UTXMO 93 M 01
4 - Software used:	PEP
5 - Relativity scale:	SSB
6 - Permanent tidal correction on station:	No
7 - Tectonic plate model:	AM0-2
8 - Velocity of light (C):	299792458
9 - Geogravitational constant (GM):	$3.98600444 \ 10^{14}$ (geocentric)
10 - Reference epoch:	1984.0
11 - Adjusted parameters:	λ, φ, h
12 - Definition of the origin:	Geocenter
13 - Definition of the orientation:	Fixed to CSR LGN7692 series at 11 Jan 1985
14 - Constraint for time evolution:	Constrained to AM0-2



Distribution of the 3 sites of the terrestrial frame SSC(UTXMO) 93 M 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 5 stations of the terrestrial frame SSC(UTXMO) 93 M 01. 1 station with uncertainty larger than 10 cm is not shown.

EOP(UTXMO) 93 M 01 From Oct 1970 to Dec 1992

Number of measurements per year and median uncertainties
Units : 0.001" for φ; 0.0001s for UT0

YEAR	φ		UTO	
	Nb	Sigma	Nb	Sigma
1970	5	46.90	5	6.61
1971	11	15.30	11	5.39
1972	48	8.50	48	5.61
1973	56	16.20	56	5.53
1974	28	7.60	28	4.59
1975	41	8.10	41	5.54
1976	41	7.60	41	5.20
1977	29	7.10	29	4.42
1978	22	8.30	22	4.70
1979	27	7.20	27	4.43
1980	33	6.50	33	3.90
1981	3	5.00	3	4.21
1982	0		0	
1983	6	5.60	6	3.89
1984	45	5.90	45	4.09
1985	104	8.25	104	4.06
1986	24	6.50	24	3.22
1987	26	10.05	26	3.10
1988	57	5.00	57	2.70
1989	46	4.10	46	2.91
1990	89	4.10	89	2.60
1991	58	3.65	58	2.31
1992	52	3.90	52	2.57

GLOBAL POSITIONING SYSTEM

FOREWORD

In 1990 the IERS Directing Board set up an interim Technique Coordinating Centre for GPS to evaluate its potential for EOP applications and to encourage broader participation in the use of the technique. The GIG'91 Campaign (see 1991 IERS Annual Report) was a first attempt at coordinating on an international basis the efforts of a number of participants in deploying a globally distributed network of GPS tracking stations. The campaign was executed over three-week period in Jan-Feb 1991. Its primary purpose was to collect tracking data with sufficient strength to evaluate the accuracy of the GPS ephemeris products, the tracking station locations and the EOP information.

As a result of these IERS activities and partially out of recognition of the enormous potential of GPS, if properly coordinated, a small working group was formed in early 1990 with the goal of establishing a permanent GPS service operated through the cooperative efforts of a number of organizations and agencies under IAG auspices. The objectives of the International GPS Geodynamics Service (IGS) are to provide to the scientific community GPS data products with the highest accuracy, reliability and integrity that is economically feasible. The working group organized a three-month campaign, IGS'92, which started in June 1992. This campaign initiated the effective operation of the IGS, including the setting up of a close cooperation between IERS and IGS.

Since the IGS'92 campaign the network of GPS stations has largely remained intact and continued to make continuous observations; it also has grown considerably. As a result there is a continuing effort by a number of analysis centers to process the data on an ongoing basis and to generate GPS satellite ephemerides, station locations and velocities, and EOP results. A total of eight GPS Analysis Centers have contributed their Earth orientation and terrestrial frame results to the IERS Central Bureau and sub-Bureau for Rapid Service and Predictions.

In parallel, the future cooperation of IERS with the International GPS Geodynamics Service (IGS) was discussed in detail by the two services. The final agreement is that the IERS will rely on IGS for the GPS observations and their organisation, and that in turn the IGS rules will make provision for the interfacing of its participants with IERS, including direct interaction of the GPS Analysis Centres with the IERS Central Bureau and Sub-bureau for Rapid Service and Predictions.

The global Earth rotation and terrestrial frame results described in this section are based on observations collected since 1991 and analysed during 1992 in this context.

Several sets of station coordinates have been computed by the Terrestrial Frame Section of the IERS Central Bureau, at IGN, and proposed to the IGS analysis centers to be used in their orbit computation. They are referred to in some of the analysis descriptions published in these volume. These sets are:

1) SSC(IERS) 92 C 02 (epoch 1992.5): 1st version sent in IGS Mail #33 on 1 July 1992. This set has been computed by referring the ITRF91 coordinates to epoch 1992.5 using its velocity field and adding the local ties between GPS and SLR-VLBI reference points. These local ties concern only GPS points which are not originaly in the ITRF91.

2) SSC(IERS) 92 C 03 (epoch 1992.5): 2nd version sent in IGS Mail #65 on 12 August 1992. This set has been computed using the same procedure as in 1. Some stations have been added or updated.

3) SSC(IERS) 92 C 04 (epoch 1992.5): 3rd version sent in IGS Mail #90 on 9 September 1992. This set has been computed using the same procedure as in 1. Some stations have been added or updated.

4) SSC(IERS) 93 C 01 (epoch 1992.6): 4th version which was presented at the IGS Workshop in Bern and is published in the proceedings of this Workshop. This set has been computed in two steps. In the first step a global combined GPS solution has been computed using five GPS solutions provided by five analysis centers: JPL, SIO, CSR, CODE and EMR. In the second step the global combined GPS solution has been combined with the ITRF91 at epoch 1992.6.

5) SSC(IERS) 93 C 02 (epoch 1993.06): 5th version (included in IGS Mail #236, 5 April 1992). It is extracted from SSC(IERS) 93 C 01, containing the 12 selected sites as decided at the IGS Workshop in Bern. It is shifted to 1993.06 epoch using the ITRF91 velocity field.

W.G. Melbourne
GPS Coordinator

ANNUAL REPORT OF THE CODE PROCESSING CENTER OF IGS FOR 1992

EOP(CODE) 92 P 04
SSC(CODE) 92 P 01, 02

G. Beutler, M. Rothacher, W. Gurtner, T. Springer, E. Brockmann, S. Fankhauser, S. Botton, L. Mervart, U. Wild, A. Wiget

1. INTRODUCTION

General Remarks

Today we are looking back to about eight months of processing the observations of the IGS Core network (IGS=International GPS Geodynamics Service). Our contribution to this service started around 21 June 1992, the start of the 1992 IGS Test Campaign, and it was never stopped since. In the initial phase the emphasis had to be put on the development and perfection of the routine processing. Data flow, automatic (pre-)processing, and routine quality control were set up, program bugs had to be fixed, human interactions were minimized. In the second priority the physical modeling was improved and checked parallel to the routine processing. This first phase is over about now. The emphasis in the second phase will lie on the critical analysis of the used models and on the development of long-term analysis capabilities.

It is worth mentioning that in this first phase we developed the mental and technical capacity of processing on a very high accuracy standard permanent GPS tracking data. The same is true for the six other IGS processing centers that were active since 21 June 1992. This fact undoubtedly is of highest importance for fundamental astronomy, global and regional geodynamics in future.

The CODE Processing Center

CODE (Center for Orbit Determination in Europe) is one of the processing centers of the International GPS Geodynamics Service (IGS). Four institutions are collaborating under this label :

- The Swiss Federal Office of Topography (L+T)
- The French Institut Geographique National (IGN)
- The German Institute for Applied Geodesy (IfAG)
- The Astronomical Institute of the University of Berne (AIUB)

All mentioned institutions are supporting CODE either by manpower or financially. It was agreed within CODE that only a long term committment makes sense in this field of science. Therefore, after having seen during the 1992 IGS Test Campaign (21 June - 23 September 1992) that the human, hard- and software resources were about adequate, CODE continued operating after the official end of the 1992 IGS

Test Campaign (21 June - 23 September 1993). Today CODE is one of the processing centers of the IGS Pilot Service (intermediary IGS Service starting on 1 November 1992 and ending when the "final" IGS Service will be established by IAG).

The processing center is located at the AIUB, where the computations are done on a cluster of VAX computers. The Bernese GPS Software Version 3.4+ is used. The "+" indicates that the official version of the Bernese Software had to be gradually updated to meet the requirements of the routine processing.

In IGS terminology Processing Centers are meant to produce orbits on a regular, preferably daily, basis. The delay between observation and availability of orbits should essentially be driven by the time it takes to make observations available at the IGS network centers (CDDIS, the Crustal Dynamics Data Information System of NASA, IGN, the Institut Geographique National, and SIO, Scripps Institution of Oceanography).

This was exactly the understanding of the task at CODE : Since 21 June 1992 an uninterrupted series of orbits, earth rotation parameters, coordinates, and miscellaneous results is being generated. It is worth mentioning that CODE results were delivered to CDDIS and IGN for every day (non-AS days and AS days, AS = Anti-Spoofing) since 21 June 1992. The results were sent on a weekly basis, the delay so far was on the order of 7-10 days.

In 1992 the accuracy of CODE results was significantly deteriorated under AS, which could be attributed to a mal-functioning of the ROGUE receiver under AS. This was disappointing for us, because processing and pre-processing schemes at CODE should give results of comparable quality independent of AS (see below).

It is remarkable how the understanding of the project was developing at CODE since the beginning of the operations : In the proposal to IGS we wrote (May 1991) :

- the main purpose is the computation of GPS orbits for the entire system.
- the emphasis will lie on regional orbits over Europe.

Side issues will be :

- earth rotation parameters
- regional ionosphere models for Europe
- satellite clock parameters

It was planned to process the observations of about 12-15 stations, where more than half of them should lie in Europe.

This original concept had to be modified rather quickly : It became evident that highest quality orbits could only be produced, if earth rotation parameters with 1 mas accuracy or better were generated together with the orbits; it was not possible to rely on predictions stemming from other space techniques. Due to these facts and due to the circumstance that the ERPs were analysed very rapidly by IERS agencies (Central Bureau and the IERS Rapid Service), ERPs became of primary interest already in the routine operations. Also it became clear that 12-15 stations were not enough; today the data of about 30 stations are routinely analyzed. Even now we feel that the scarcity of stations in South America, Africa, former Soviet Union, and India is one of the most important accuracy-limiting factors of our (and other centers) analyses.

Although we will not discuss all aspects mentioned in our original proposal, we would like to point out that we are still following these topics :

- during the 1992 Test Campaign we were producing free-network solutions for Europe. The results were handed over to the IERS.
- we were and are producing local ionosphere models for Europe. We could demonstrate that these models together with our CODE orbits allow ambiguity-resolution baseline by baseline (Mervart *et al.*, 1993). Analyses of this kind demonstrate the usefulness of the IGS concept for the "normal" user.

2. ANALYSIS CHARACTERISTICS

The summary given here is based on the papers (Rothacher *et al.*, 1992) and (Gurtner *et al.*, 1992) presented at the IAG Symposium No 112 in Potsdam.

Automated Data Flow, Processing Scheme, and Technical Aspects

The incoming data are sent to CODE via FTP by IGN and IfAG. In a first step data files are decompressed, the a priori orbits are generated (based on broadcast orbits), the receivers are synchronized to GPS time (using either C/A- or P-code), single difference files are formed, then the phase single difference files are screened. It is important to know that it is not necessary to use the P-code in our pre-processing scheme. If it is available we usually run a program which cleans the wide-lane on the zero-difference level using the Melbourne/Wuebbena linear combination of phase and code. If (under AS) the P-code is not available, this pre-processing part is simply skipped. Afterwards the single difference phase observations are screened, where the ionosphere-free linear combination L3 and the wide-lane L5 are checked for discontinuities. If the code/phase linear combinations were screened previously, we may use a program switch which will assume that L5 is clean already. If discontinuities are encountered, it is checked whether they can be safely removed by adding integer numbers of cycles in the individual carriers. If this is not the case, new ambiguities are set up. Through this procedure we perhaps set up too many ambiguities, but we have the advantage that the procedure may be used under AS too.

In a second step one-day solutions are computed. During the first few months we used these solutions for pure data quality checks. Later on we became aware that these solutions already are of a remarkable quality. Therefore, since 25 July 1992 we are keeping track of the earth rotation parameters x and y. It is planned to compare them to our 3-days series in future.

In the third step 3-days solutions are produced. All results leaving CODE are based on these 3-days solutions. We generate one such solution for each day, which means that we are working with overlapping orbits. The principle is shown in Figure 1.

```
I----IxxxxI----I                           3-days arc No 1
     I----IxxxxI----I                      3-days arc No 2
          I----IxxxxI----I                 3-days arc No 3
                 .....                           ....

-------IxxxxIxxxxIxxxxIxxxxIxxxxIxxxxI-->  Released CODE Orbits

      day 1                                from arc No 1
           day 2                           from arc No 2
                day 3                      from arc No 3
                      ...                        ...
```

Figure 1: Processing in Overlapping Intervals at AIUB (Official CODE orbits)

During the 1992 IGS Test Campaigns steps 2 and 3 of our analysis were done separately for the European sites and for the Global sites. With the beginning of the IGS Pilot Service the separate European solution was discontinued, but all European stations were incorporated into the Global solution. We are now routinely producing two different solutions : one solution with fixing a certain number of stations (among them are 5 European sites, see Table 2) to their official ITRF coordinates, in a second program run we are processing exactly the same observations, but we are leaving all European sites (apart from Wettzell) unconstrained. In this way we are still producing "free" European solutions.

The force model

Earth's Potential and related Information :

- GEM-T3 (8,8) model (including the non-zero terms C21, S21 (!)) as specified in the IERS standards (Mc Carthy, 1992)
- GM=398.6004415 10^{12} m^2/s^2
- Equatorial Radius of the earth a = 6378137.0 m

Gravitation by sun/moon :

at present we are using analytical approximations for the recommended JPL DE-200 series. The differences to the DE-series are not important for the arc-lengths (maximum of three days) which we are using at present. For long term analyses (a few months) the differences might become relevant. This is why we will incorporate the DE-200 in the near future into our routine processing scheme too.

Radiation Pressure Modelling

We use the Rock4, Rock42 models according to Fliegel (1992). In this model the satellite masses must be used. In Table 1 we give the masses we use at present as a priori values. These a priori models are left unchanged in our processing.

We may solve, however, for a direct radiation pressure parameter dp0 (pointing from the sun to the satellite) and for a y-bias parameter p2.

Table 1 also contains the input parameters for the Rock models and other satellite specific data which are used in our processing.

Table 1. Satellite Specific Data

SATELLITE SPECIFIC DATA

PRN	BLOCK NO.	ANTENNA OFFSETS (M) DX	DY	DZ	MASS (KG)	DP0 (1.E-8)	P2 (1.E-9)	ROCK MODEL (T=1,S=2)	
1	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	ok
2	2	0.2794	0.0000	1.0259	878.2	-0.8596	0.8249	2	ok
3	1	0.2100	0.0000	0.8540	521.8	-0.1098	0.2328	2	ok
6	1	0.2100	0.0000	0.8540	453.8	-0.1600	0.7385	2	off
8	1	0.2100	0.0000	0.8540	440.9	0.0000	0.0000	2	off
9	1	0.2100	0.0000	0.8540	462.6	0.0000	0.0000	2	off
11	1	0.2100	0.0000	0.8540	522.2	-0.2749	-0.5216	2	ok
12	1	0.2100	0.0000	0.8540	519.8	-0.1856	0.2371	2	ok
13	1	0.2100	0.0000	0.8540	520.4	-0.4206	-0.6902	2	ok
14	2	0.2794	0.0000	1.0259	887.4	-0.8120	0.8043	2	ok
15	2	0.2794	0.0000	1.0259	885.9	-0.7188	0.6608	2	ok
16	2	0.2794	0.0000	1.0259	883.2	-0.7046	0.4846	2	ok
17	2	0.2794	0.0000	1.0259	883.2	-0.6821	0.6294	2	ok
18	2	0.2794	0.0000	1.0259	883.2	-0.7657	0.0000	2	ok
19	2	0.2794	0.0000	1.0259	883.2	-0.8262	0.4905	2	ok
20	2	0.2794	0.0000	1.0259	887.4	-0.9558	0.3691	2	ok
21	2	0.2794	0.0000	1.0259	883.9	-0.7674	0.3047	2	ok
22	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	new
23	3	0.2794	0.0000	1.0259	972.9	0.3138	0.3932	2	ok
24	3	0.2794	0.0000	1.0259	975.	-0.7518	1.0852	2	ok
25	3	0.2794	0.0000	1.0259	975.	-1.0015	0.9704	2	ok
26	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	new
27	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	new
28	3	0.2794	0.0000	1.0259	975.	-0.1438	0.1147	2	new
29	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	new
30	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	next
31	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	next
32	3	0.2794	0.0000	1.0259	975.	0.0000	0.0000	2	new

BLOCK NUMBER: BLOCK I = 1, BLOCK II = 2, BLOCK IIA = 3, BLOCK IIR = 4

Light <--> Shadow Changes

We assume instantaneous light <--> shadow transits. The corresponding transit times are computed by indirect interpolation, the numerical integration is initialized at these points (to allow for discontinuities of the forces at these times).

Problem if the sun is in the orbital plane:

The rules which are given by Fliegel (1992) to compute the orientation of the satellites (x-, y-, and z- axes) ask for very rapid rotations by the angle of 180 deg of the spacecraft around the z-axis at two points in the orbit in this case. This may cause numerical problems. The same problem of course occurs in reality. One should know how the GPS satellites actually behave under these circumstances. Experience shows that the orbit modelling is usually more delicate if these situations occur.

Solid Earth Tides :

Implemented according to the IERS standards (Mc Carthy, 1992).

General Relativity :

Taken into account according to IERS standards.

System of Orbit Integration :

J2000.0. The IAU 1980 models for precession and nutation are used. The corrections $d\psi$, $d\varepsilon$ distributed by the IERS bulletins were not used so far.

Our realization of the ITRF

Table 2 gives the list of tracking stations we keep fixed in our analysis. The corresponding site eccentricity information can be found in IGS Mail No 90. The used coordinates are VLBI and SLR coordinates in the ITRF system according to the IGSMAIL No 90.

In addition it is important to note that we apply the deformations due to the solid earth tides (Mc Carthy, Chapter 7, Eqn.6) before using a station position at a special time t.

Table 2: Fixed stations ,*): these stations are not any more fixed since the beginning of the IGS Pilot service

```
--------------------------------------------------------------------------------
 Fixed stations in the processing (Global set):
                               1.   KOSG 13504M002
                               2.   MADR 13407S010
                               3.   MATE 12734S001 *)
                               4.   TROM 10302M002
                               5.   WETT 14201S004
                               6.   ONSA 10402S002
                               7.   KOKB 40424S001 *)
                               8.   ALGO 40104S001
                               9.   FAIR 40408S002
                              10.   GOLD 40405M013
                              11.   YELL 40127M001
                              12.   RCM2 40499M002
                              13.   CANB 50103S010
                              14.   YAR1 50107M001
--------------------------------------------------------------------------------
```

Miscellaneous Modelling components

Orbits:

A pseudo-stochastic orbit modelling capability was introduced around January 1993. The principle is the following : At predetermined times (e.g. six times during the day (equidistant spacing)) impulse-changes may be solved for, where it is again possible to constrain those changes. The resulting orbital trajectory is, but its first derivative is not continuous. A series of 'stochastic' solutions over a time interval of months is available now. The results are interesting, the only real problem seems to be the long-term stability of the UT1-UTC estimates. Residual difficulties with cases where no or only few observations are available still exist. These solutions are not part yet of the official CODE results.

Troposphere:
Modelling tropospheric refraction is a crucial element. We use an a priori model based on the Saastamoinen theory. In addition we may introduce for each site a number n of troposphere parameters (zenith delays) per day. These parameters may be constrained in two different ways, (a) by imposing a priori weights (thus constraining their absolute variations), (b) by imposing a priori weights to the difference of subsequent troposphere parameters. This allows us to model the troposphere in many different ways, e.g. as a random walk with predetermined characteristics. (For more information see Rothacher (1992)).

Earth Rotation Parameters:
In the parameter estimation program the total time interval covered by observations may be divided into smaller time intervals, so called partial intervals. Within each partial interval the pole may be modeled as a polynomial in time, where the polynomial degree (separately for x, y, and UT1-UTC) has to be specified by the user. It is possible to ask for a continuous pole at the partial interval boundaries.

Ambiguity parameters:
Ambiguity parameters (at least one per day and satellite, in general it is necessary to introduce more (after breaks, losses of lock)).

Characteristics of the routine solutions

Table 3 : Solution Characteristics for NG SERIES and EU SERIES

(a) Global Solution

```
Agency               : CODE
Solution Identifier: "NG"

Orbit Arc Length     : 3 days, overlapping
Orbit Parameters     : Osculating Keplerian Elements (6 per arc & satellite)
                       direct radiation pressure p0 (on top of ROCK Models,
                       compare Table 1) and y-bias.

Troposphere           :4 zenith delays per day and station, at present virtually
unconstrained

Fixed Coordinates    : KOSG, MADR, MATE, TROM, WETT, ONSA, KOKB, ALGO,
                       FAIR, GOLD, YELL, RCM2, CANB, YAR1

Earth Rotation       : Each 3-day solution is divided into 3 one-day intervals.
Parameters             x, y, and UT1-UTC are modeled as polynomials of degree 0
                          (on top of the most recent pole distributed by the IERS
                        Rapid Service) within each one-day interval. No continuity
                        conditions were imposed. The UT1-UTC estimate of the first
                       day is fixed to the a priori value (from the RAPID service)
```

(b) European Solution

Agency:	CODE
Solution Identifier:	"EU"
Orbit Arc Length:	3 days, overlapping
Orbit Parameters:	Osculating Keplerian Elements (6 per arc & satellite) direct radiation pressure p0 (on top of ROCK Models, compare Table 1) and y-bias.
Troposphere:	4 zenith delays per day and station, at present virtually unconstrained
Fixed Coordinates:	a) during the 1992 IGS Campaign: NONE (only a priori constraints according Table 4) b) during the IGS Pilot Service: WETT is kept fix together with the other global sites of Table 2.
Earth Rotation:	Each 3-day solution is divided into 3 one-day intervals. Parameters x, y, and UT1-UTC are modeled as polynomials of degree 0 (on top of the most recent pole distributed by the IERS Rapid Service) within each one-day interval. No continuity conditions were imposed. The UT1-UTC estimate of the first day is fixed to the a priori value (from the RAPID service)

Table 4: A priori constraints on the European coordinates during the 1992 IGS Campaign

Constaint on	East and North-Coordinates	Up-Coordinate
WETTZELL:	0.02 m	0.05 m
all other Stations:	0.05 m	0.10 m

3. RESULTS

3.1 Earth Rotation Parameters: EOP(CODE) 92 P 04

Figures 2a, 2b, and 2c contain the differences of our NG pole with respect to the C04 pole as computed by the IERS Central Bureau in Paris. The straight solid line shows the correction that should be applied (IERS Annual Report, 1991, Table II-3) to the C04 pole to be comparable with GPS estimates. With the exception of a short time interval in January 1993 (reason to be found) the agreement is satisfactory in x and y, there are significant differences however in our integrated UT1-UTC values. This is not too surprising in view of the fact that GPS is only capable of measuring the derivative of the UT1-UTC curve.

3.2 Coordinates

During the 1992 Test Campaign we produced free-network solutions for Europe. Independently from the processing of the globally distributed stations we performed solutions only with European stations. The European coordinates got weak constraints (see Table 4). Let us point out that the introduced constaints (Wettzell) are really weak.

For 115 3-day solutions (overlapping) (Days 171-285) residuals to the ITRF coordinates are analysed (after 6 Parameter Helmert transformation (3 Rotations, 3 Translations)).

The mean coordinate set EU P 92 SSC(CODE) 92 P 01 has the following properties:

- The sum of the residuals (after 6-Parameter Helmert transformation of each 3-Day Solution to EU P 92) of each coordinate is zero.

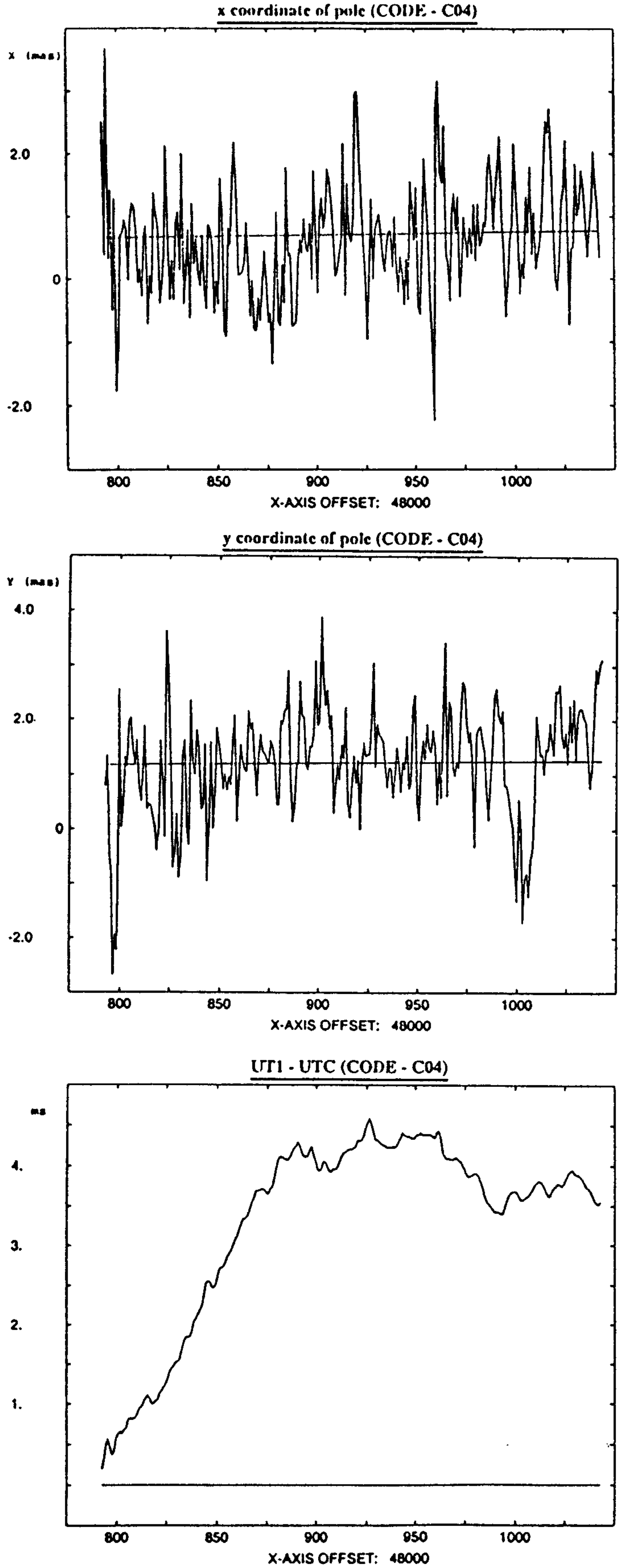
- Scale, translation and orientation of EU P 92 is the same as ITRF.

These results were handed over to the IERS.

To confirm these coordinates, a second coordinate set is estimated with data since the beginning of the IGS Pilot Service (WETT is kept fix together with other global distributed sites of Table 2, all European stations are free):

Combining 119 3-day Solutions (day 312 (1992)- day 063 (1993)) with the full variance covariance matrix to a mean coordinate set gives coordinate set EU P 92-2 SSC(CODE) 92 P 02. No helmert transformation is necessary for this proceeding.

The consistency of these different coordinate sets, due to the used data (only European data -- global supported data) and due to the computation (Residual analysis after Helmert transformation -- Least square adjustment with full variance covariance matrix) is proved with a helmert transformation of EU P 92 and EU P 92-2. With one exception (TROM North direction) all residuals are below the 1 cm level.



Figures. 2a, 2b, 2c

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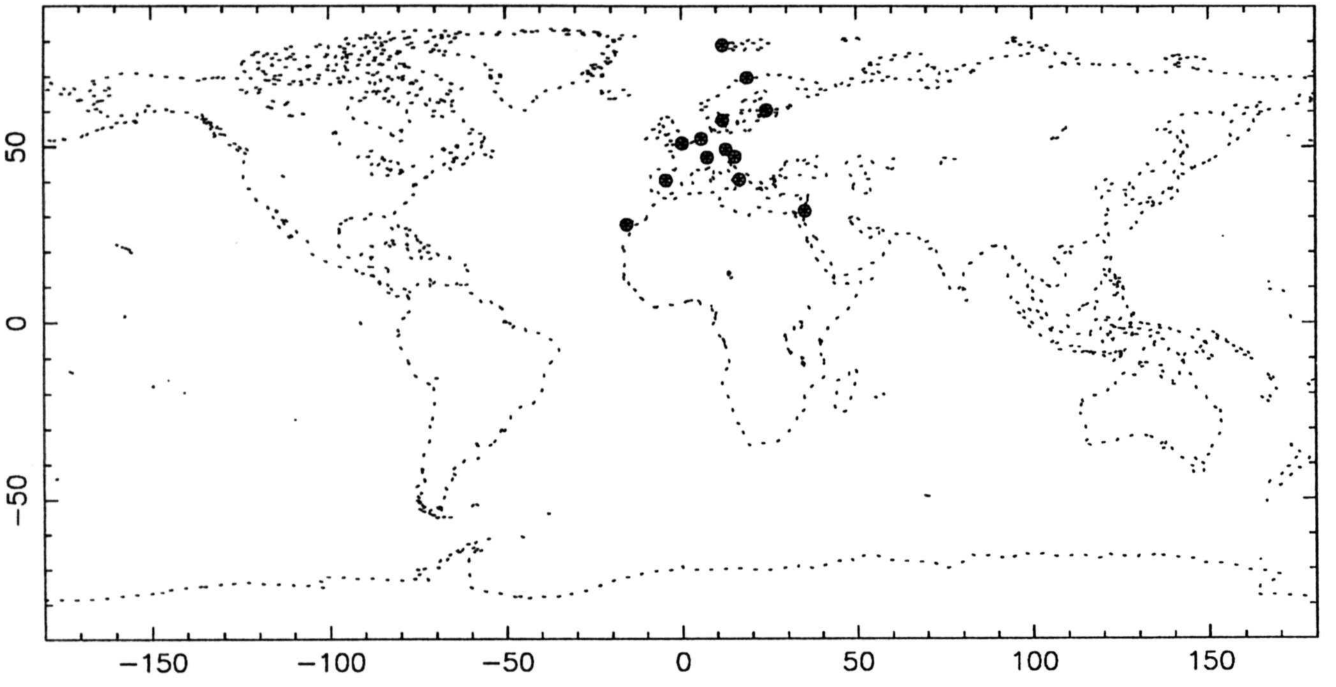

Distribution of the 13 sites of the terrestrial frame SSC(CODE) 92 P 01.

EOP(CODE) 92 P 04 From Jun 1992 to Jul 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
1992	196	0.10	196	0.10	196	0.07
1993	196	0.08	196	0.07	196	0.05

SITE COORDINATES FROM THE CENTER FOR SPACE RESEARCH SOLUTION CSR 92 P 03

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Mean positions for all sites processed at the University of Texas Center for Space Research were adjusted using a noncontiguous 54 day subset of the data span from the IGS campaign in Weeks 650 through 662. The solution is fiducial free, so no sites were held fixed. The resulting site positions were corrected for geocenter motion in order to coincide with the CSR92L01 (which defines ITRF91) geocenter and frame orientation.

The a priori polar motion and UT1 were derived from Lageos laser ranging (constrained by IRIS VLBI at periods > 60 days) produced operationally at UTCSR for inclusion into the IERS rapid service bulletins.

The force and measurement models used for this solution conform generally to the IERS/IGS Standards, with the following exceptions:

1) The mean gravity field was TEG-2, a state of the art gravity field computed at the University of Texas Center for Space Research.
2) The ocean tide model was an enhanced version of the Schwiderski model extrapolated to include 80 consituents complete through degree and order 20, assuming admittances which vary linearly with frequency.
3) The solid tide model has been expanded to include third degree and fourth degree terms.
4) The geogravitational constant, GM, was 398600.4415 km^3/s^2.

Notes concerning the interpretation of the coordinates:

(1) The corrected antenna heights of 5.203 m at Ny Allesund and of 9.754 m at Hartebeesthoek have been used.

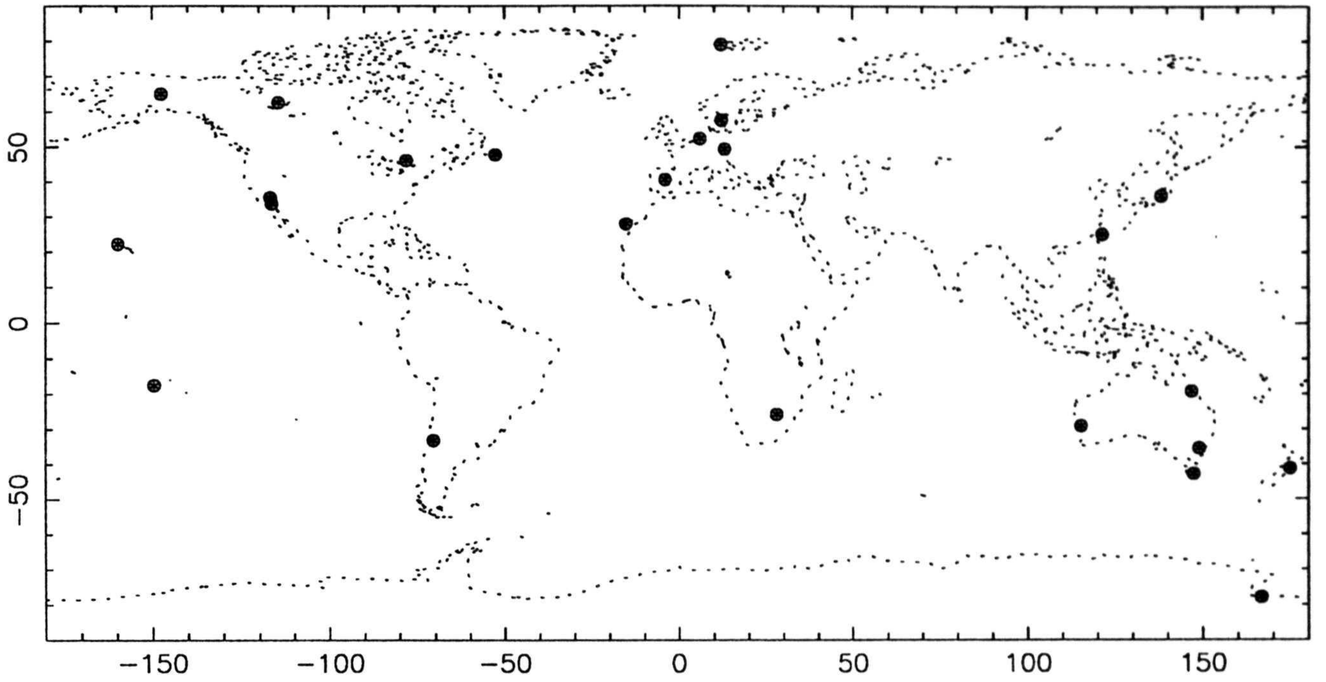
(2) The epoch of 1992.6 is reported because it is the (rounded) mean of the data used to adjust the sites, however, no tectonic velocities were modelled in the adjustment in order to achieve this exact epoch uniformly for each site.

(3) The position for Pinyon spans the Landers earthquake, but with 7 days before and 38 days after, so the position will agree more closely with postquake positions from other groups, but may be slightly in error because of this.

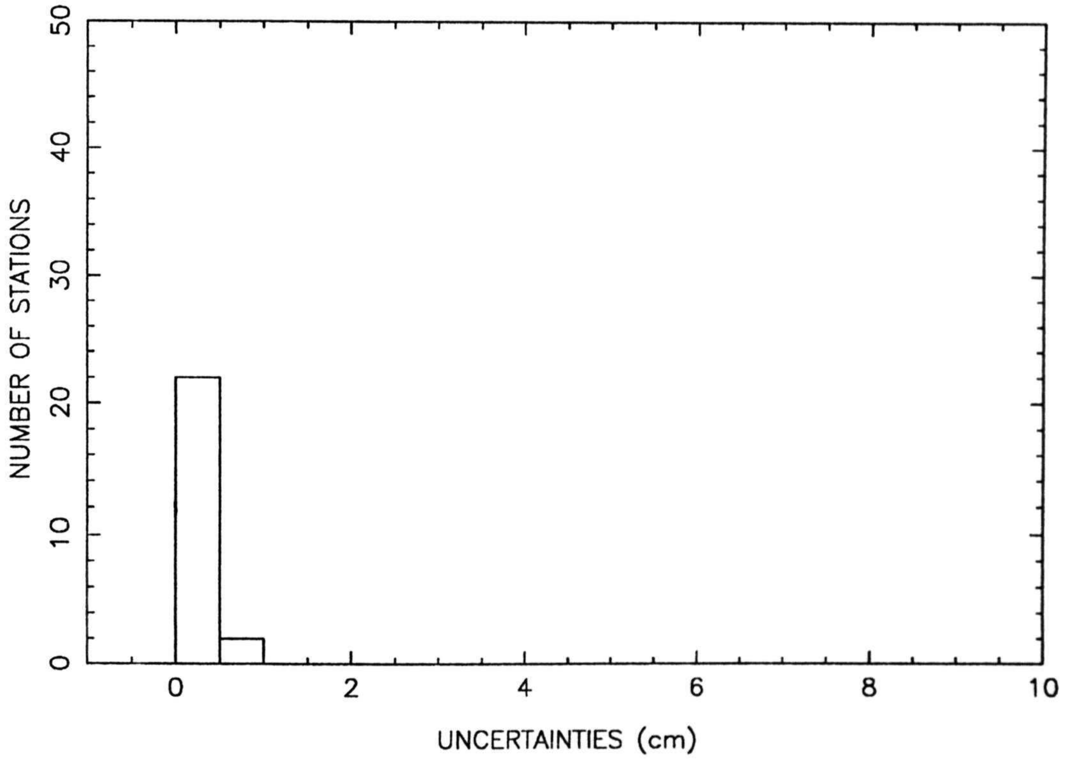
(4) Usuda data after day 222 was not included in the solution, so the position reflects the position over the period from days 173-222, and does include the anomalous position afterwards.

Summary description of the terrestrial system attached to the set of station coordinates SSC(CSR) 92 P 03

1 - Technique:		GPS
2 - Analysis Center:		CSR
3 - Solution Identifier:		(CSR) 92 P 03
4 - Software Used:		MSODP1/LLISS
5 - Relativity Scale:		Geocentric (LE)
6 - Permanent Tidal Correction on station:		Tidal correction has nonzero mean. Positions do not reflect true mean.
7 - Tectonic Plate model:		Adjusted
8 - Velocity of light (C) :		299792458 m/sec
9 - Geogravitational constant (GM) :		398600.4415 km^3/s^2
10 - Reference Epoch :		1992.6
11 - Adjusted Parameters:		
	Coordinates:	Epoch 1992.6 position for sites in cartesian coordinates solved globally for entire data span.
	Phase Ambiguities:	Adjusted where necessary.
	Orbit:	Epoch position and velocities, Rock4 Scale parameter, Y bias adjusted daily.
	EOP:	Fixed to UTCSR operational series
12 - Definition of the origin:		Geocentric, C10 = C11 = S11 = 0.0
13 - Definition of the orientation:		System oriented to agree with ITRF91 in rotation and translation
14 - Constraint for time evolution:		None due to short time span



Distribution of the 24 sites of the terrestrial frame SSC(CSR) 92 P 03.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 24 stations of the terrestrial frame SSC(CSR) 92 P 03.

GPS DATA PROCESSING AT THE EMR ANALYSIS CENTRE

EMR 93 P 01

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Since August 1992 the GSD's Master Active Control System (MACS) Centre has been reducing GPS data from six Canadian ACS stations augmented by up to 12 stations of the International Geodynamics GPS Service (IGS) global core station network. The GIPSY II/ OASIS GPS software system developed by the Jet Propulsion Laboratory has been adopted for daily processing. The GIPSY II processing has been highly automated using UNIX script to consolidate and integrate procedures into a single run. Eleven stations were constrained at the IGS coordinates (Table 2) and adopted constants, gravity and radiation pressure models conform to the IGS/IERS standards (Boucher *et al.*, 1992; McCarthy, 1992) The global ocean loading model due to Pagiatakis (1982) has been adopted. The submitted EMR EOP series starts on July 27, 1992 and does not include days with Anti Spoofing (AS).

The EMR processing is based on undifferenced phase and smoothed pseudorange data at 5 minutes sampling intervals using 15 degree elevation angle cut off. Both phase and pseudorange observations are considered uncorrelated and weighted according to sigmas computed from the following exponential model:

$$\sigma(E) = \sigma_0 + \sigma_1 e^{-(E/E0)}$$

where E is the elevation angle in degrees and the constants are: $E_0 = 20$, $\sigma_0 = 4$ mm, $\sigma_1 = 15$ mm for phase measurements at all stations; $\sigma_0 = 180$ and 780 mm for pseudoranges at most stations. Some stations (e.g. PAMA, STJO, YELL) have higher pseudorange noise due to multipath and are being weighted accordingly. We have also enhanced the GIPSY II software to allow different weighting of satellites, data segment deletion and corrections of biases. This proved to be useful for data reduction when AS satellites can be down weighted, deleted or bias corrected.

We have adopted 24h arcs without any data overlap. For each 24h arc the initial a priori state vector is taken from the previous day solution and propagated to the beginning of the current day making the estimation process self contained. Broadcast orbits are used only when introducing a new satellite, or after a large gap such as those due to early hardware problems associated with AS tracking. Using the preceding arc solution is not only more accurate than the broadcast orbit initialization, but it also offers a self check on daily solutions and a quick indication of orbit errors and/or problems relating to a particular satellite. The differences between the state vector estimation for successive days are typically below 1m and values larger than 1.5m are usually reported in the weekly summary files. In most cases larger differences have been found for eclipsing satellites. This approach also facilitates another type of orbit modelling and estimation of DUT1. By assigning a priori orbit sigmas of 1m and 0.5 mm/s in fact approximates a random walk stochastic process with daily updates and sigmas of $1m/day^{0.5}$ and $(.5mm/s)/day^{0.5}$. This is due to the fact that the other sigmas are much smaller, typically below 10 cm and 0.03 mm/s. As a consequence of the colinearity between DUT1 and R. A. of the ascending orbit nodes, the estimated DUT1 contains both the DUT1 changes as well as the orbit node errors common to all satellites with sigmas and correlation characteristic of a random walk process, i.e. the covariance between day i and i+1 is

$$\sigma^2_{i,i+1} = \sigma^2_{i,i}$$

The variance $\sigma^2_{i,i}$ increases approximately with $i^{0.5}$, where i is the number of days since the DUT1 initialization. DUT1 is initialized the first non AS day of the GPS week using the most current USNO/IERS Bull. A values. The summary of estimated parameters, their a priori values and sigmas are listed in Table 1.

Table 1 : Summary of estimated parameters, a priori values and sigmas

Parameters	type	a priori values	a priori sigmas
StationX,Y,Z	constant	IGS/ITRF91 (1992.5)	50m (fixed .002-.02m)
Pole x,y	"	IERS/USNO Bull. A	3m
DUT1	"	" "	3m ; fixed/reset every week
Trop. Z. dely	"	2.0m	.2m
Satell. states	"	prev. day solution	1km, .005m/s or 1m, .0005m/s
Sol. rad. Gx,Gz	"	1.0	.1 (10%)
Sol. rad. Gy	"	0	1.0 10E-9 m/s^2
Init. phase amb.	"	0	300000km
Trop. bias	random w.	0	.01m/sqrt(1h)
Station clock	w. noise	0	1s (ALGO H-Maser fixed)
Satell. Clock	"	0	0.001/.0001s for Block I/II

The orientation and to a large extend the scale of the EMR orbit/EOP solutions are nominally those of ITRF91 (epoch 1992.5) as realized through the set of up to 11 stations (Table 2) constrained at the ITRF91 coordinates which are primarily based on VLBI solutions. Also the DUT1 prediction is derived from VLBI DUT1 solutions/ For this submission the DUT1 estimations has been reinitilized by using the final values (FV) of IERS/NOES Bull. A, to ensure agreement with the Bull. A.

The reported EOP sigmas are the formal sigmas as estimated by the adjustment. As experienced from the repeatability of position solutions the formal sigma may be too optimistic, and need to be multiplied by a factor of 2 or 3.

Table 2: IGS/IERS station coordinate set used in EMR GPS processing: (ITRF91 system epoch: 1992.5)

Station	IGS Code	DOMES	X (KM)	Y(km)	Z(km)	L1 m	L2-L1 m
Contrained Stations: 2mm - ALGO: 10mm - TROM, WETT, MADR; 20mm - all others							
Algonquin	ALGO	40104M002	918.129616	-4346.071224	4561.977800	0.1919	-0.0185
Fairbanks	FAIR	40408M001	-2281.621327	-1453.595775	5756.961976	0.1939	-0.0185
Goldstone	GOLD	40405S031	-2353.614083	-4641.385406	3676.976471	0.0779	-0.0185
Hartebee.	HART	30302M002	5084.625404	2670.366499	-2768.494039	9.8319	-0.0185
Madrid	MADR	13407S012	4849.202506	-360.329179	4114.913003	0.0779	-0.0185
Mcmurdo	MCMU	none	-1310.69525	310.468880	-6213.363449	5.0679	-0.0185
Santiago	SANT	41705M003	1769.693228	-5044.574103	-3468.321138	0.1709	-0.0185
Canberra	TIDB	50103S017	-4460.996091	2682.557181	-3674.444005	0.0779	-0.0185
Tromsoe	TROM	10302M003	2102.940451	721.569379	5958.192072	2.5510	-0.0185
Wettzell	WETT	14201S020	4075.578683	931.852634	4801.569980	0.0779	-0.0185
Yarragad.	YAR1	50107M004	-2389.025331	5043.316830	-3078.530926	0.1509	-0.0185
Yellowkn.	YELL	40127M003	-1224.452369	-2689.216048	5633.638286	0.1949	-0.0185
Unconstrained Stations							
A. Head	ALBH	40129M003	-2341.332759	-3539.049484	4745.791405	0.2079	-0.0185
Holberg	none	none	-2503.040302	-3188.233327	4908.701573	0.1979	-0.0185
Kokee Pk.	KOKB	40424M004	-5543.838080	-2054.587522	2387.809570	0.1709	-0.0185
Pamatai	PAMA	none	-5245.195148	-3080.472201	-1912.825643	8.4979	-0.0185
Penticton	DRAO	40105M002	-2059.164587	-3621.108390	4814.432423	0.1959	-0.0185
Prince Al.			-1050.708041	-3680.985753	5085.127839	0.0779	-0.0185
Calgary (Priddis)			-1659.60276	-3676.725778	4925.493699	0.1889	-0.0185
St. Johns	STJO	40101M001	2612.631359	-3426.807033	4686.757736	0.2399	-0.0185

References

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McCarthy, D.D. (ed), 1992: *IERS Tech. Note 13*, Observatoire de Paris, Paris.

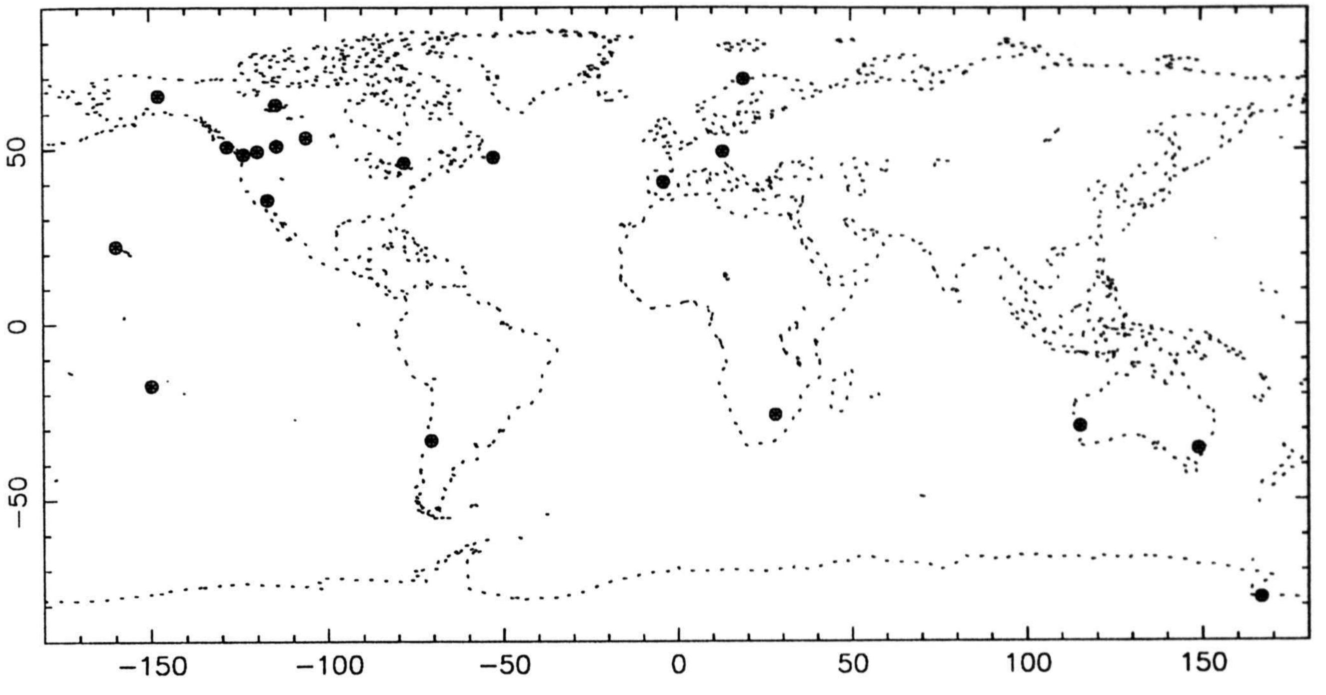
Pagiatakis, S.D., 1982: Ocean loading, body tides and polar motion effects on very long baseline interferometry, UNB Technical Rep. No. 2, Dept. of Surv. Engineering, Univ. of New Brunswick, Fredericton, N.B.

Summary description of the terrestrial system attached to the set of station coordinates SSC(EMR) 93 P 01

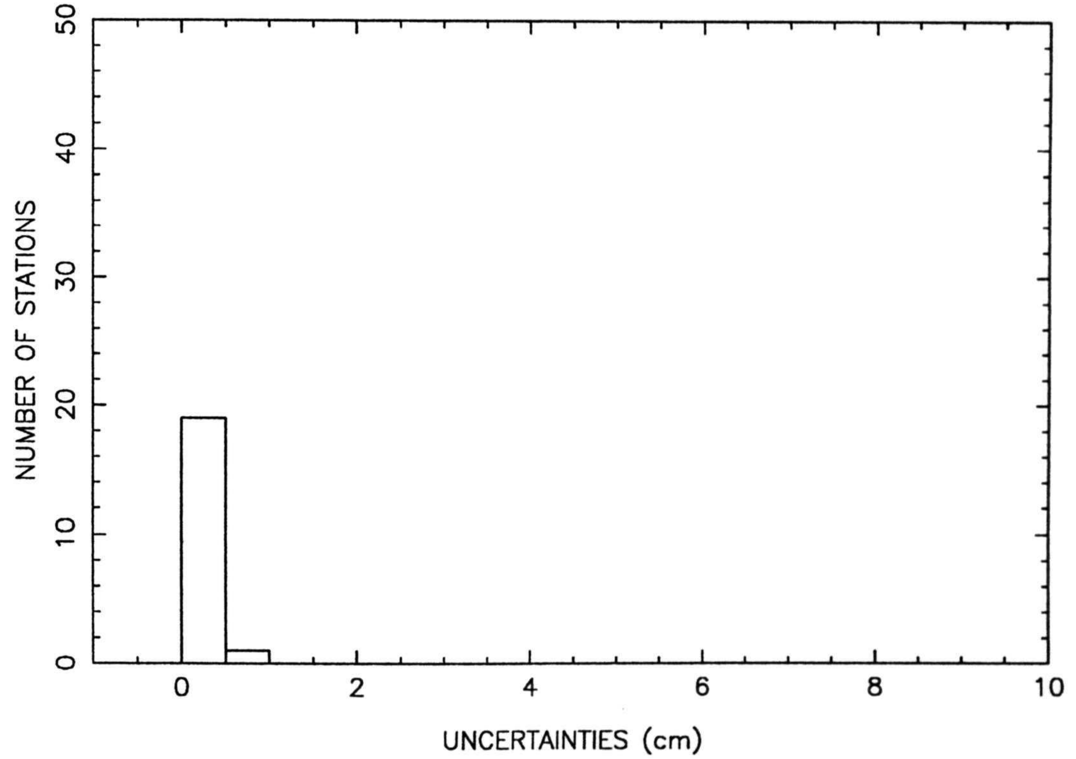
1 - Technique:	GPS
2 - Analysis centre:	Geodetic Survey Division (GSD), SMRSS, EMR
3 - Solution identifier:	EMR 93 P 01
4 - Software used:	GIPSY/OASIS II (UNIX)
5 - Relativity scale:	LE
6 - Permanent Tide correction:	none
7 - Tectonic plate model :	none, single epoch
8 - Velocity of light:	299792458 m/s
9 - GM:	389600.4414 km^3/s^5
gravity model:	GEMT3(8,8) +C21+S21
10 - Reference epoch:	1992.79

11 - Adjusted parameters:
- undifferenced phase and smoothed pseudorange data > 15 degrees @ 5 min
- single day (24h) arc with 6 IC and 3 rad. parameters per satellite (up to 21sat.)
- trop. zenith delay corr. parameter augmented with random walk stoch. process
- initial phase ambiguity parameters (1 for each satellite/station pass or initial phase)
- station positions X,Y,Z, up to 19 stations. ALGO, FAIR, GOLD, HART, TROM, WETT, YELL, MADR, MCMU, SANT, TIDB and YAR1 are constrained
- x, y pole position, once a day (DUT1 fixed/solved; DUT1, x, y apriori sigma=3m)
- station clock biases once per each epoch/station (except for ALGO h. maser which provides the time reference) with sigma 1 s
- satellite clock biases once per each epoch/satellite with 1 ms or 0.1ms sigma.

12 - Origin:	Nominally ITRF91
13 - Orientation:	" "
14 - Constraint for time evolution:	none



Distribution of the 20 sites of the terrestrial frame SSC(EMR) 93 P 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 20 stations of the terrestrial frame SSC(EMR) 93 P 01.

EOP(EMR) 93 P 01 From Jul 1992 to Dec 1992

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
1992	113	0.22	113	0.19	77	2.10

DAILY EARTH ORIENTATION PARAMETERS AND GROUND STATION POSITIONS FROM ROUTINE IGS92-CAMPAIGN PROCESSING EOP(ESOC) 92 P 02 SSC(ESOC) 93 P 01

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The GPS group at ESOC has been participating in the IGS service from June 21 1992. We are using double-differenced phase observables to estimate the IGS products (EOP's and precise orbits) and to obtain the observation equations for other geodetic parameters. For this processing we use BAHN, the standard ESOC orbit determination and geodetic parameter estimation program, also used for other precise orbit determinations (Lageos, ERS-1). We also have a program for multiarc processing that uses the observation equations generated by BAHN to produce estimates of geodetic parameters.

Description of the EOP-solution EOP(ESOC) 92 P 02

GPS data acquired since the beginning of the IGS'92 campaign at 21 June 1992 have been analyzed to obtain orbits, earth orientation parameters and positions of participating ground stations. The incoming IGS data is evaluated on a daily basis, EOPs are determined for 24-hour-intervals. The initial values are taken from IERS Bulletin A. For the period of 21 June 1992 to 14 November 1992, UT1 has been fixed to the IERS Bulletin A values. Since 15 November, the rate of change of the difference between UT1 and TAI has been included as additional unknown EOP parameter into the estimation process.

The terrestrial reference frame is defined by fixing a set of 11 ground stations, whose coordinates are provided in the ITRF91 (IERS Terrestrial Reference Frame, *IERS Tech. Note 13*) and are referred to epoch 1992.5. These coordinates have been provided in "IGS site information and coordinates", (Boucher and Altamimi, IGS Mail 33). These coordinates have been updated and distributed several times and in the meantime the coordinates of IGS Mail 90 are used (for a detailed history see Table 2). The names of the 11 fixed stations are listed in the under point 11.

NNR-NUVEL1 plate motion has been used for the station velocities, as recommended by IERS standards. No ocean loading has been applied to the ground stations and no relativity corrections to propagation or/and acceleration have been calculated (see point 15 in the summary).

The celestial frame is defined by standard J2000.0, and celestial pole offsets from IERS Bulletin A are included.

For a detailed desciption of the models used at the beginning of the ESOC-IGS evaluations at 21 June 1992 and the history of changes since then until today, see Tables 1 and 2. Results were obtained for all days, including those when anti-spoofing was applied.

Table 1. Models and constants used

The routine of IGS evaluations started at 21 June 1992 (IGS Mail 51)

- Velocity of Light: c = 299792.458 km/s
- Earth Gravitational Constant: GM = 398600.4415 km^3/s^2
- Mean Equatorial Earth Radius: Ae = 6378.137 km
- Solid Earth Tidal Love number.: h = 0.6090
- Solid Earth Tidal Shida number.: l = 0.0852

GPS data handelling
- GPS double-differenced phases, ionosphere-free combination, sampling rate 6 min, 10 degrees elevation cutoff; IGS data evaluation on a daily basis, i.e. 24-hour-arcs

Satellite force model
- Geopotential, GEM-T3 (n = 8, m = 8 plus C21 = -0.17 10^{-9} and S21 = 1.19 10^{-9})
- Solar Third Body Attraction
- Lunar Third Body Attraction
- Solid Tides, k2 = 0.300, phi = 0, Wahr frequency dependent corrections
- Ocean Tides, Schwiderski; n = 6, m = 2, 11 tidal constituents
- Non-Gravitational: Solar Pressure + Thermal Emission: Fliegel *et al.* (1992),
  models T10 for BLOCK I and T20 for BLOCK II/II-A
  Y-bias acceleration
- All active GPS satellites are included

Ground stations
- Coordinates referred to ITRF91 at epoch 1992.5 (IGS Mail 33)
- station velocities are modelled with NNR-NUVEL1 model

Earth orientation parameters
- IERS Bulletin A, UT1 held fixed

Other parameters
- atmospheric modelling according to Willmann Model

Table 2. History of changes since beginning of the IGS evaluations at 21 June 1992
(only valid for EOP solution EOP(ESOC) 92 P 02)

9 August 1992 (IGS Mail 78): An updated set of ITRF91 ground station coordinates has been adopted from IGS Mail 65. The epoch remains at 1992.5.

18 August 1992 (IGS Mail 108): Data evaluation in 30-hour-arcs i.e. the arcs start 3 hours before - and end 3 hours after the central day. So overlaps of 6 hours between successive days are obtained.

3 September 1992 (IGS Mail 93): An updated set of ITRF91 ground station coordinates has been adopted from IGS Mail 90. The epoch remains at 1992.5.

20 September 1992 (IGS Mail 114): A priori constraints are given to the estimated parameters:

- Satellite	position:	± 100 m
	velocity :	± 10 cm/sec
	ROCK4(2) scaling factor :	± 5 % deviation from value 1
	Y-bias :	± 0.2 10^{-5} (Newton)
- EOPs	xp :	± 5 mas
	yp :	± 5 mas
- Station	position :	± 20 cm
	atm. zenith delay :	± 20 cm

11 October 1992 (IGS Mail 123): Elevation cutoff has been changed from 10 degrees to 20 degrees.

15 November 1992 (IGS Report 27): The data evaluation span was set back to 24-hour. As additional unknown, we started to evaluate rate of change of the difference between UT1 and TAI. The a priori constraint for this parameter was set to 0.5 ms/day.

Description of the station coordinate solution SSC(ESOC) 93 P 01

A total of 33 days have been used to produce a multiarc solution for the station coordinates. These days span the Epoch'92 period and another 23 additional days in November and December of 1992. Only non anti-spoofing days have been used for this solution.

Summary description of the terrestrial system attached to the solution EOP (ESOC) 92 P 02

1 - Technique: GPS
2 - Analysis Center: ESA/European Space Operations Centre (ESOC)
3 - Solution identifier: EOP(ESOC) 92 P 02
4 - Software used: GPSOBS/BAHN-Version 5
5 - Relativity Scale: Local Earth
6 - Permanent tidal correction on station: To be added to listed coordinates
7 - Tectonic plate model : NNR-NUVEL1 plate motion model
8 - Velocity of light (c) : 299792.458 km/s
9 - Geogravitational constant (GM) : 398600.4415 km^3/s^2
10 - Reference epoch : 48960.5 (mean between 3 Sep 1992 and 6 Mar 1993)
11 - Adjusted parameters : On daily basis (24-hour arc), for the a priori constraints see above.

Satellite parameters per Spacecraft:
- one orbital state X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$ at start epoch
- one scaling factor for solar pressure T10 or T20 model
- one Y-bias acceleration

Station related parameters per ground station:
- ground station positions (if not member of the fixed stations)
- every 3 hours an atmospheric zenith delay parameter (Willmann Model)
- Double-difference phase ambiguities as real-valued parameters

Earth orientation parameters (EOPs):
- one set of pole coordinates xp,yp and d(UT1R-TAI)/dt per day

Parameters to be kept fixed:

Satellite parameters per Spacecraft:
- solar pressure scaling factor GX and GZ in spacecraft body fixed x- and z-axis are kept fixed with value 1.0

Station related parameters per ground station:
- ground station position X,Y,Z of the following sites: Algonquin, Fairbanks, Goldstone, Hartebeesthoek, Madrid, Matera, Onsala, Santiago de Chile, Wettzell, Yaragadee and Yellowknife.

12 - Definition of the origin : Geocentre through gravity model (C10 = C11 = S11 = 0)
13 - Definition of the orientation : by fixing the ITRF91-coordinates of the above ground stations
14 - Constraint for time evolution : NNR-NUVEL1 plate motion model
15 - Deviations from IERS standards:
- The velocities of all ground stations are taken from NNR-NUVEL1 plate motion model
- no relativity corrections to propagation or/and acceleration
- no station ocean loading

EOP(ESOC) 92 P 02 From Jun 1992 to Mar 1993

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1992	194	0.28	194	0.28	47	0.45
1993	65	0.29	65	0.28	65	0.46

Summary description of the terrestrial system attached to the set of station coordinates SSC (ESOC) 93 P 01

1 - Technique:	GPS
2 - Analysis Center :	ESA/European Space Operations Centre (ESOC)
3 - Solution identifier :	SSC(ESOC) 93 P 01
4 - Software used :	GPSOBS/BAHN-Version 5/MULTIARC
5 - Relativity Scale :	Local Earth
6 - Permanent tidal correction on station :	To be added to listed coordinates
7 - Tectonic plate model :	NNR-NUVEL1 plate motion model
8 - Velocity of light (c) :	299792.458 km/s
9 - Geogravitational constant (GMo) :	398600.4415 km^3/s^2
10 - Reference epoch :	MJD 48805.0 1992.5

11 - Adjusted parameters :

On daily basis (24-hour arc):

Satellite parameters per Spacecraft:
- one orbital state $X, Y, Z, \dot{X}, \dot{Y}, \dot{Z}$ at start epoch
- one scaling factor for solar pressure T10 or T20 model
- one Y-bias acceleration

Station related parameters per ground station:
- every 3 hours an atmospheric zenith delay parameter (Willmann Model)
- Double-differced phase ambiguities as real-valued parameters

For the whole campaign:

Station related parameters per ground station:
- ground station positions

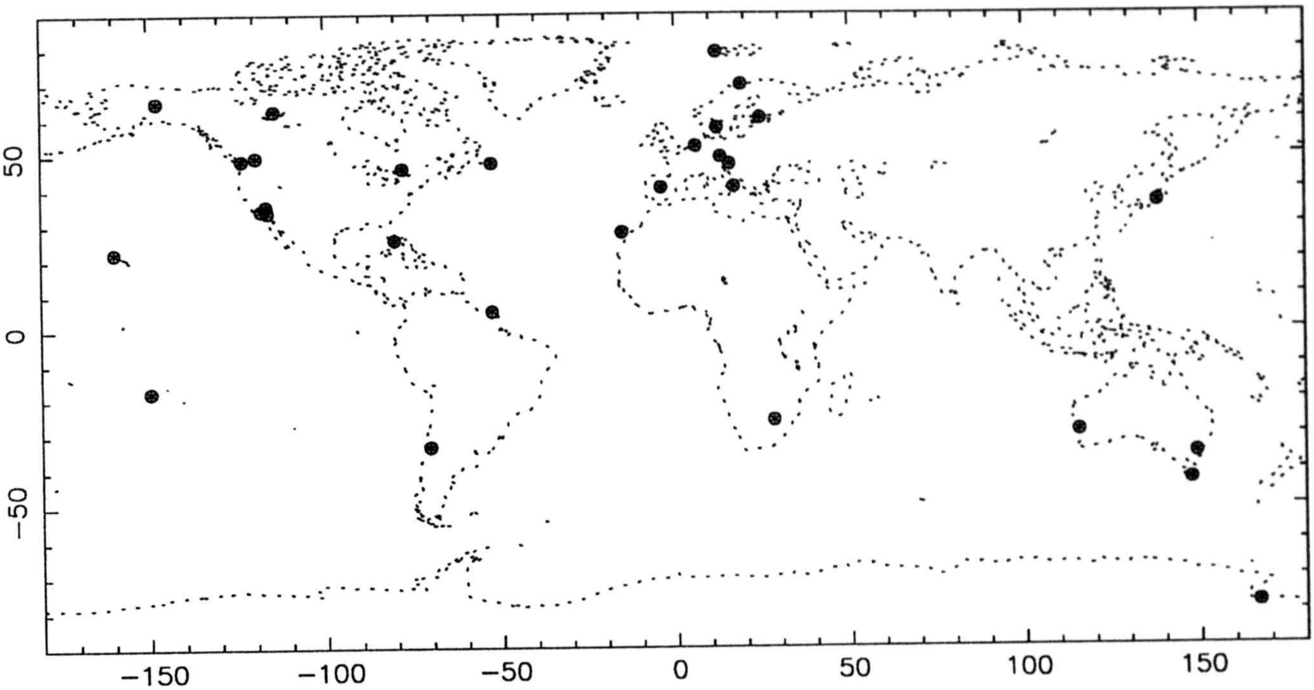
Parameters to be kept fixed:

Satellite parameters per Spacecraft:
- solar pressure scaling factor GX and GZ in spacecraft body fixed x- and z-axis are kept fixed with value 1.0

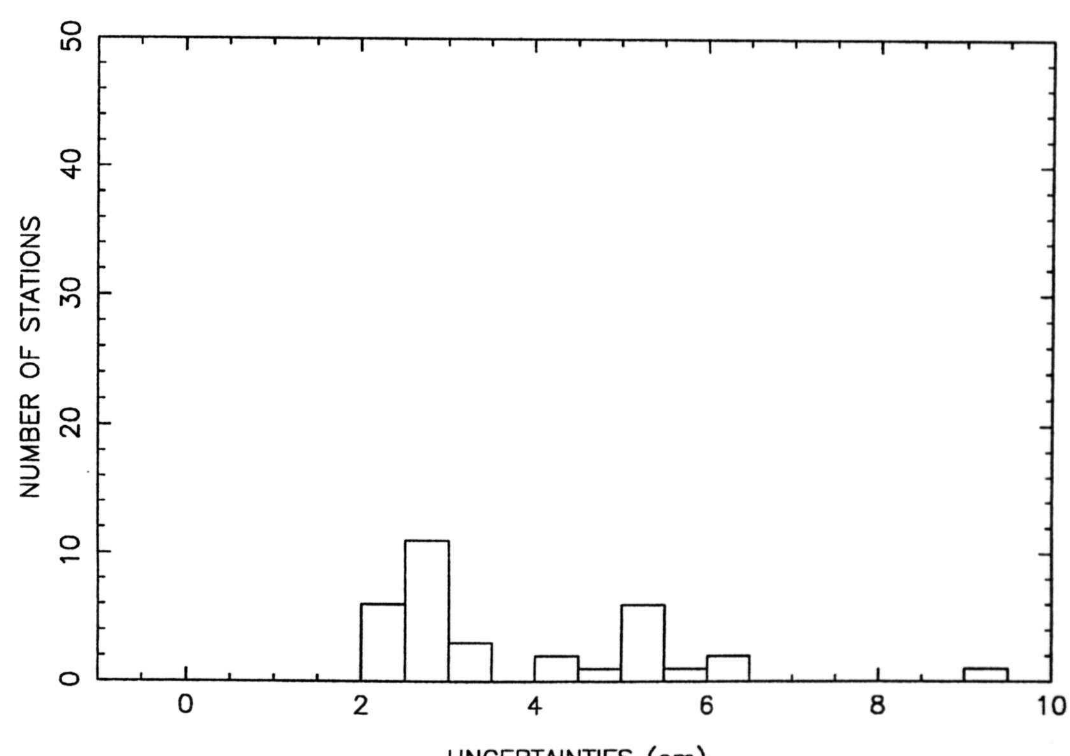
EOP values:
- from IERS Rapid Service.

12 - Definition of the origin :	Geocentre through gravity model (C10 = C11 = S11 = 0)
13 - Definition of the orientation :	the EOP's are fixed to IERS Bulletin A, 12 stations are constrained in longitude and latitude with a priori uncertainty of 5 cm. These stations are: Madrid, Kootwijk, Matera, Onsala, Metsahovi, Tromso, Wettzell, Algonquin, Yellowknife, Albert Head, Goldstone and Fairbanks. The initial coordinates used are those from IGS Mail 90.
14 - Constraint for time evolution :	NNR-NUVEL1 plate motion model

15 - Deviations from IERS standards:
- The velocities of all ground stations are taken from NNR-NUVEL1 plate motion model
- no relativity corrections to propagation or/and acceleration
- no station ocean loading



Distribution of the 30 sites of the terrestrial frame SSC(ESOC) 93 P 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 33 stations of the terrestrial frame SSC(ESOC) 93 P 01.

EARTH ORIENTATION PARAMETERS FROM THE JET PROPULSION LABORATORY USING GPS

EOP(JPL) 92 P 02

J.F. Zumberge, G. Blewitt, D. Jefferson, M. B. Heflin, and F.H. Webb
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA.

Since 1992 June 21, GPS data from a globally-distributed network of Rogue GPS receivers have been analyzed with GIPSY/OASIS-II software to give daily estimates of a variety of parameters, including those related to Earth orientation.

The measurements consist of undifferenced dual-frequency (1.2276 and 1.5742 GHz) carrier phase and P-code pseudorange. For both carrier phase and P-code, linear combinations of the individual frequencies provide the ionosphere-free phase and pseudorange. Data noise values for these are taken to be 1 cm and 1 m, respectively. Data below 15 degrees elevation are not used. The phase data are decimated to 6 minutes (5 min beginning 1992 Sep 05, and 10 min beginning 1993 Feb 04), and the P-code data are carrier-smoothed over the same interval.

Data corresponding to each GPS day are analyzed in 30-hour batches (24 hours prior to 1992 Sep 28) centered on GPS noon. GPS time is a constant offset from TAI time, and currently differs from UTC by 8 sec.

Estimated parameters are satellite state vectors, receiver coordinates, zenith wet troposphere delay at each receiver site, station and satellite clock offsets, carrier phase ambiguities, and earth orientation. Daily solutions contain 800-1200 solved-for parameters. The rms post-fit residulas for the phase measurements are typically a few mm. Those measurements with more than 5 cm post-fit residual for phase, or 5 m for pseudorange, are considered outliers and excluded.

The Williams solid Earth tide model is used. Pole tide and ocean loading are not modeled.

The Earth's gravity field is described by the GEM-T3 multipole expansion using terms up through degree and order 8. IERS-recommended values for C21 and S21 of $-0.17\ 10^{-9}$ and $1.19\ 10^{-9}$ are also used. The value of GM is taken as 398600.4415 km^3/s^2. Beginning with 1992 November 18 JGM1_8x8 gravity field is used.

Nominal values of the 9-component state vector for each GPS satellite [3 parameters each for position, velocity, and solar radiation pressure (srp)] are from the broadcast ephemeris (digital information included in the GPS signal which contains satellite almanacs whose accuracies vary from 10 to 1000 m). Weak a priori constraints of 1 km and 10 mm/s for position and velocity, respectively, are imposed. The ROCK4 model is used for srp. Beginning on 1992 Sep 06, in addition to the constant components, colored noise parameters are included for srp, with a 4-hour time constant.

Table 1 GPS Receiver Sites Used in EOP(JPL) 92 P 02

ALGO* Algonquin Park	Canada (Ontario)
ALBH Alberthead	Canada (British Columbia)
DRAO Penticton	Canada (British Columbia)
FAIR* Fairbanks	U.S. (Alaska)
GOLD Goldstone	U.S. (California)
HART* Hartebeesthoek	South Africa
HARV Harvest	U.S. (California)
HERS Herstmonceaux	U.K.
JPLM Jet Propulsion Lab	U.S. (California)
KOKB* Kokee Park	U.S. (Hawaii)
KOSG Kootwijk	Netherlands
KOUR Kourou	French Guiana
MADR* Madrid	Spain
MASP Maspalomas	Canary Islands
MATE Matera	Italy
METS Metsahovi	Finland
MCMU McMurdo	Antarctica
NYAL Ny Alesund	Norway
ONSA Onsala	Sweden
PAMA Pamatai	Tahiti
PGC1 Victoria	Canada (British Columbia)
PINY Pinyon Flat	U.S. (California)
RCM2 Richmond	U.S. (Florida)
SANT* Santiago	Chile
SCRI Scripps	U.S. (California)
STJO St. Johns	Canada (Newfoundland)
TAIS Taiwan	Taiwan
TIDB Canberra	Australia
TROM* Tromso	Norway
USUD Usuda	Japan
WETB Wettzell	Germany
YAR1* Yaragadee	Australia
YELL Yellowknife	Canada (NW Territories)

*Indicates fiducial site.

Table 1 contains a list of sites used in 1992. Receiver locations are modeled as constant over each analysis day. Locations of fiducial sites (ALGO, FAIR, MADR only through 1992 Jul 18, add HART, KOKB, SANT, TROM, and YAR1 for 1992 Jun 05, 08, 11, and from 1992 Jun 19 onwards) were assumed known. Prior to 1992 Jul 19, the epoch used was 1992 Jul 01. From Jul 19 through Nov 18, the epoch was 1992 Aug 01. From Nov 18 through Nov 30, the epoch was Nov 01. Changes in assumed locations of fiducial sites are based on corrections and/or updates to site-tie information as well as plate motion as described by Boucher & Altamimi in International GPS Geodynamics Service mail message #90. Beginning on 1992 Dec 01, we update fiducial locations at the beginning of each month.

Non-fiducial sites are solved for as constant parameters for each analysis day.

The wet troposphere zenith delays at each site are modeled as a random walk in time with a 1 cm^2/hour variance derivative, and are mapped to satellite elevations using the Lanyi mapping function. Their nominal values are 0.1 m at every site and are estimated with 500-m a priori constraints.

The zenith dry delays are assumed fixed for every site, and are also mapped to satellite elevations using the Lanyi mapping function. Prior to 1992 Nov 18, the zenith dry delay was assumed to be 2 m at every site. Beginning with 1992 Nov 18, this was changed to 2.3 m x exp (-H/Ho), where H is the height of the site and Ho = 8621 m. Because the wet and dry delays are nearly degenerate parameters, the estimated wet delay in fact represents the combined delay which deviates from the nominal wet+dry.

Clocks for all but one station and satellite are estimated as a white-noise process with updates at each new time datum. One maser-based clock is chosen as a reference. Prior to 1993 Jan 06, this was the clock at FAIR. Beginning 1993 Jan 06 and later, the reference clock site was changed to ALGO. These clocks are generally believed accurate to better than 1 μsec.

The carrier phase ambiguities are estimated as real-valued parameters.

Nominal values for X and Y polar motion and UT1R-UTC, as well as the rates for these quantities, are obtained for each analysis day from the IERS Bulletin B predicted values. Estimates of polar motion are weakly (5-m) constrained, while UT1R-UTC is tightly constrained (0.01 mm) to be the nominal.

The X- and Y- pole biases with respect to IERS Bulletin B Final change abruptly on Jul 19 when we began using 8 fiducials. We have therefore adjusted the estimates prior to and including 1992 Jul 18 by -0.000095" for X and -0.001643" for Y to account for this step.

Prior to and including Aug 29, the deviation from nominal of polar motion was modeled as piecewise constant, with new estimates every UTC day. So that we would be less sensitive to errors in the a priori rates, we estimated rate terms beginning 1992 Aug 30.

The UT1R-UTC values use GPS-measured LODR (our first series). LODR is integrated to form UT1R-UTC values. The series was initialized with the IERS Bulletin B value on 1992 Jun 01. The series is very weakly forward filtered using an IERS Bulletin B value every 60 days. This was unnecessary for this submission, but the intent is to produce a continuous time-series which will not, in principle, ever diverge from the IERS series more than a few milliseconds (worst case). The forward running filter has an exponential response with a 60-day time constant. This weak filtering changes LODR by an insignificant amount on any given day. We intend to use this filter for routine processing, starting with the last point of this submitted series, and submit weekly reports on UT1R. For missing days, LODR was interpolated before integration. These days have an error of 0.99999s assigned to the UT1R value. Errors for days for which we have a true LODR solution actually refer to LODR, and not UT1R.

1992 Sep 14, Sep 21, Oct 05, and Oct 19 were deleted because these were Mondays during which Anti-Spoofing (encryption of P-code) was implemented for the first ten hours of the day, and the formal errors for the daily estimates are several times larger than usual.

The values for 1992 Jul 26 through 1992 Aug 8 result from our re-processing of the IGS Epoch '92 period, and reflect the current, more-sophisticated analysis strategy.

Summary description of the terrestrial system attached to the solution EOP(JPL) 92 P 02

1- Technique :	GPS
2- Analysis Center :	JPL
3- Solution identifier :	EOP(JPL) 92 P 02
4- Software used :	GIPSY/OASIS-II
5- Relativity scale :	Local Earth
6- Permanent tide correction on station :	No
7- Tectonic Plate Model :	No model assumed. Station coordinates updated at discrete reference epochs given below using ITRF91 velocities given by SSC(IERS) 92 C 04.
8- Velocity of light :	299792458 m/s
9- GM :	3.986004415 10^{14} m^3/s^2
10- Reference epoch :	1992 Jul 01, Aug 01, Nov 01, and Dec 01 for fixed site positions.
11- Adjusted parameters : (all reset every UTC midnight)	Station X, Y, Z, except for fiducials (ALGO FAIR HART KOKB MADR TROM SANT YAR1). Daily pole X, Y at noon. Daily X and Y rates. Daily UT1R-UTC rate (LODR). GPS epoch states reset daily: X, Y, Z, Vx, Vy, Vz as constant; solar radiation pressure Gx, Gy, Gz estimated as constant plus colored process noise with 4-hr correlation time. Gx and Gz biases are lumped (100% correlated), but process noise not lumped.

	Zenith troposphere biases as random walk process noise of 1 cm per sqr. root hour. Station and satellite clocks as white process noise (one site chosen as reference) Carrier phase ambiguities as real valued (not bias-fixed)
12- Definition of origin:	ITRF91 (8 sites held fixed)
13- Definition of orientation:	ITRF91 (8 sites held fixed)
14- Constraint for time evolution:	Fixed coordinates reset at reference epochs given above according to SSC(IERS) 92 C 04 (IGS mail message #90).

EOP(JPL) 92 P 02 From Jun 1992 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
1992	176	0.17	176	0.18	164	0.60
1993	30	0.14	30	0.16	30	0.50

GEOCENTRIC SITE COORDINATES FROM THE JET PROPULSION LABORATORY USING GPS SSC(JPL) 93 P 01

G. Blewitt, M. B. Heflin, Y.Vigue, F.H. Webb, J.F. Zumberge, and D. Jefferson
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA.

GPS data spanning 1992 June 01 to 1993 Feb 17 from a globally-distributed network of Rogue receivers have been specially analyzed with GIPSY/OASIS-II software in order to estimate geocentric site coordinates. SSC(JPL) 93 P 01 is a more refined, self consistent analysis than the Earth orientation solution, EOP(JPL) 92 P 02, which was produced as part of a rapid service. Unlike the fiducial approach that was taken for EOP(JPL) 92 P 02, all station coordinates were free to adjust in SSC(JPL) 93 P 01. In addition, note that SSC(JPL) 93 P 01 includes a reanalysis of earlier data in order to apply improved estimation strategies developed later in the year. The reanalysis is still in progress, hence this solution contains a data gap from 1992 September 01 to 1993 January 01, which will be filled in future submissions.

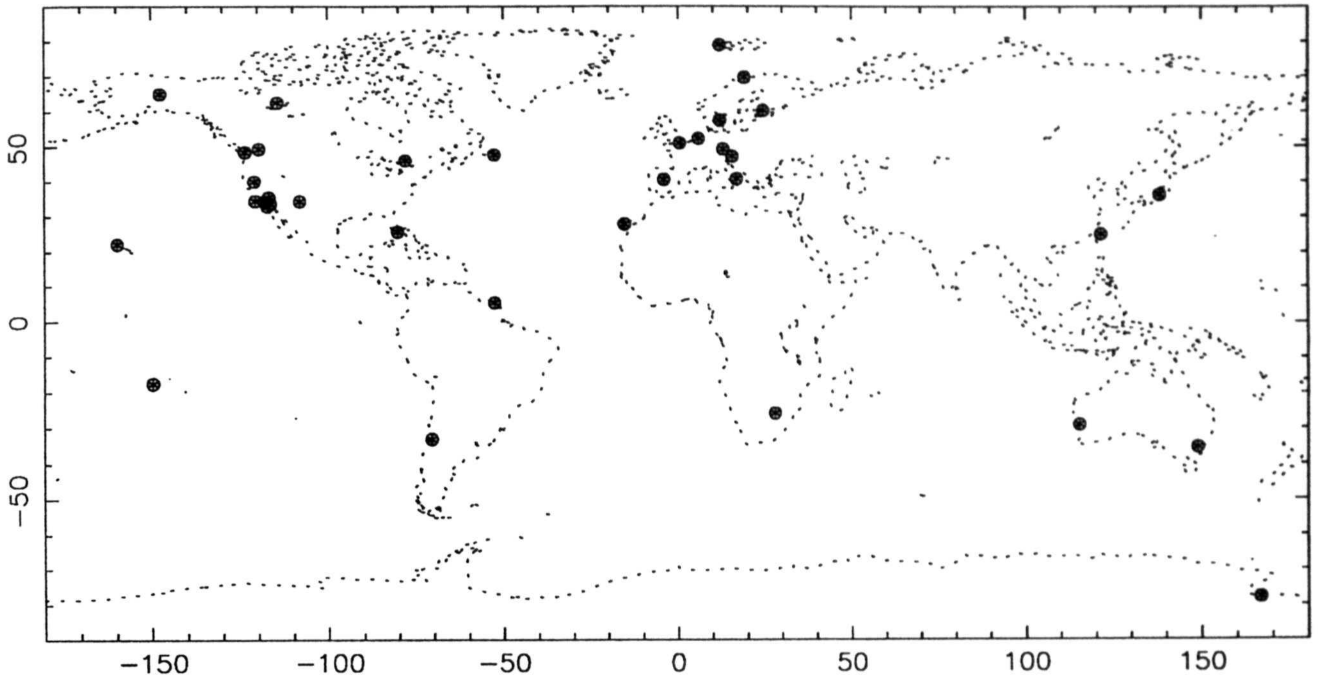
Details of the models are given in the description of EOP(JPL) 92 P 02. Data from 1992 June 01 to 1992 Aug 30 were reanalyzed, a very important change being the introduction of stochastic solar radiation parameters to absorb systematic force model errors on the GPS satellites. While degrading the computed uncertainty in locating the geocenter, this strategy effectively reduces systematic bias in the geocenter location, leaving a statistical error which tends to average down in time. Our studies show a net translation between SSC(JPL) 93 P 01 and ITRF91 at the subcentimeter level, indicating the level of accuracy for locating the geocenter.

The orientation of SSC(JPL) 93 P 01 was fixed by applying the estimated rotation angles into SSC(IERS) 92 C 04. Since the Earth orientation solution EOP(JPL) 92 P 02 used 8 sites fixed to the coordinates in SSC(IERS) 92 C 04, the pole series ought to be consistent with SSC(JPL) 93 P 01 coordinates. Small inconsistencies may be present due to station coordinate errors in ITRF91 for those stations (and their local ties) held fixed in EOP(JPL) 92 P 02. As an indication of the level of this inconsistency, the RMS difference between coordinates in ITRF91 and SSC(JPL) 93 P 01 is approximately 1.4 cm. Given that there were 8 fiducial sites in EOP(JPL) 92 P 02, we might therefore expect the orientation inconsistency to be at the level of 0.2 mas. Although the same Earth orientation parameters were also freely estimated in SSC(JPL) 93 P 01, a current software limitation prevents us from back substituting the final coordinate solution to derive daily polar motion estimates in the same reference frame. This will be corrected for future submissions, thus eliminating the current need for a separate Earth orientation and station coordinate solution.

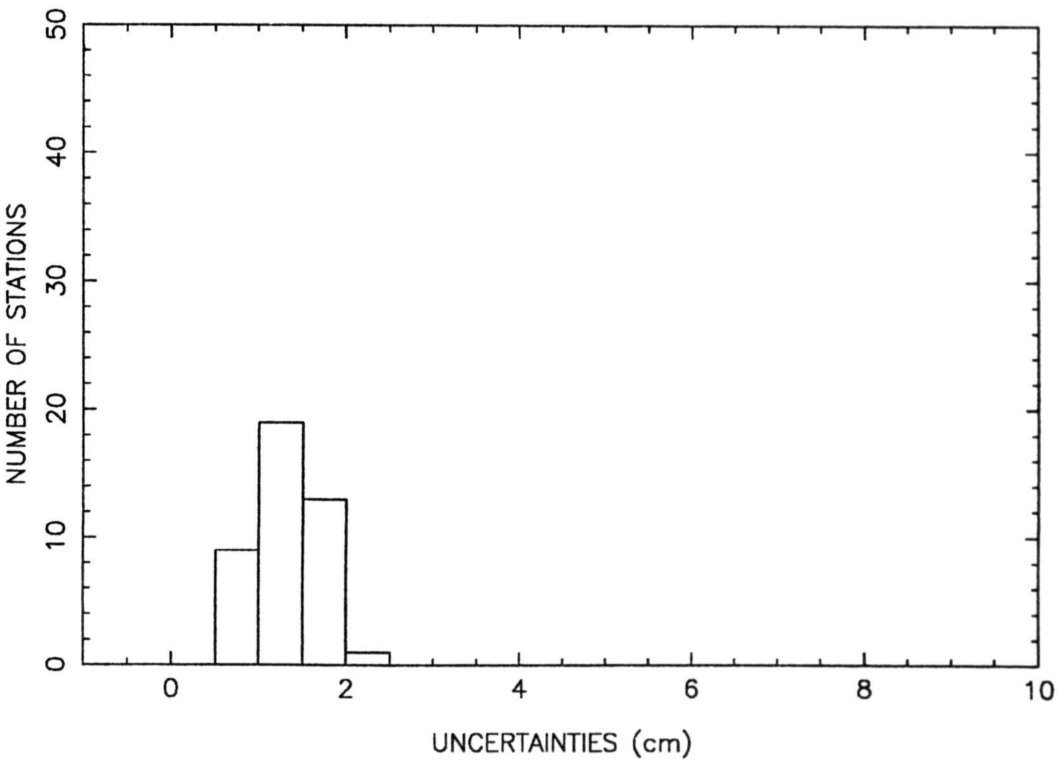
Time evolution is such that stations move with ITRF91 velocities as reported in SSC(IERS) 92 C 04 (IGS mail message number 90). For some sites in California, station coordinates are estimated independently for pre -and post- earthquake positions (1992 June 28 Landers earthquake). The receiver at Usuda, Japan, is estimated independently 3 different times because the antenna was moved twice during this time period. Moreover, its starting location (USU2) is different than the location during the GIG'91 experiment of January-February 1991 (as in ITRF91).

Summary description of the terrestrial system attached to the set of station coordinates SSC(JPL) 93 P 01

1- Technique :	GPS
2- Analysis Center :	JPL
3- Solution identifier :	SSC(JPL) 93 P 01(JPL identifier: JGC9302)
4- Software used :	GIPSY/OASIS-II
5- Relativity scale :	Local Earth
6- Permanent tide correction on station :	No
7- Tectonic Plate Model :	ITRF91 site velocities.
8- Velocity of light :	299792458 m/s
9- GM :	3.986004415 10^{14} m^3/s^2
10- Reference epoch :	1992.5
11- Adjusted parameters :	All station X, Y, Z with loose a priori standard deviation of 10 m (ITRF91 is nominal). Multiple estimates for sites which moved suddenly either due to earthquakes or antenna relocation. Daily pole X, Y at noon. Daily X and Y rates. Daily UT1R-UTC rate (LODR). GPS epoch states reset daily: X, Y, Z, Vx, Vy, Vz as constant; solar radiation pressure Gx, Gy, Gz estimated as constant plus colored process noise with 4-hr correlation time.Gx and Gz biases are lumped (100% correlated), but process noise not lumped. Zenith troposphere biases as random walk process noise of 1 $cm/hr^{1/2}$. Station and satellite clocks as white process noise (one site chosen as reference) Carrier phase ambiguities as real valued (not bias-fixed)
12- Definition of origin:	Geocenter: C10=C11=S11=0. (All sites free to adjust).
13- Definition of orientation:	Applied 3 rotation angles to align solution with ITRF91 at the reference epoch, using SSC(IERS) 92 C 04 coordinates for 22 sites.
14- Constraint for time evolution:	Stations velocities fixed to according to ITRF91 as given by SSC(IERS) 92 C 04.



Distribution of the 35 sites of the terrestrial frame SSC(JPL) 93 P 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 42 stations of the terrestrial frame SSC(JPL) 93 P 01.

1991-1993 SIO POLAR MOTION SERIES SIO 93 P 01

Yehuda Bock, Peng Fang, Keith Stark, Scripps Institution of Oceanography.

Definition of Terrestrial Reference Frame:
(described in detail in IGSMAIL #168)

Origin: Nominally ITRF91
Orientation: Nominally ITRF91
Reference epoch: 1992.836
Station coordinates: Given on IGS mail #168
Station Velocities: IERS ITRF91 values given in IGS mail #90.
Relativity Scale: Terrestrial
Velocity of light: 299792458.0 m/s
Permanent tidal correction: None

Analysis Strategy:

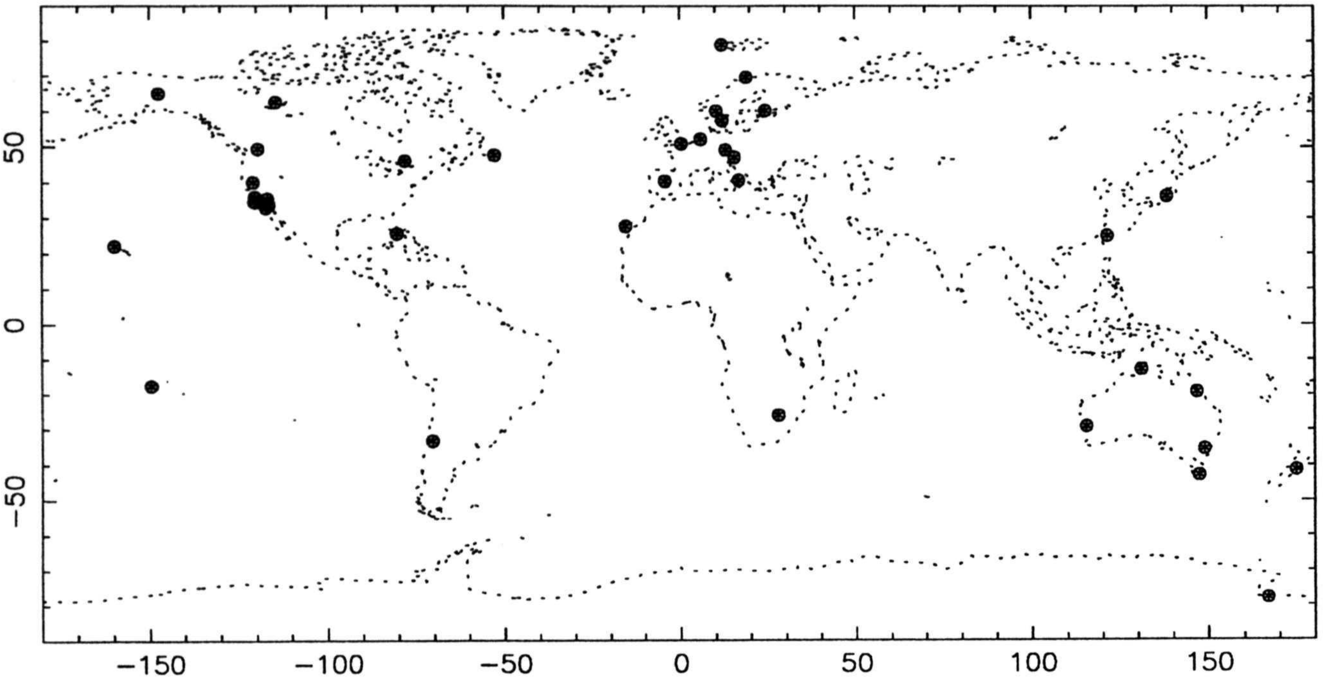
(1) GAMIT weighted least squares analysis

(a) Double-difference phase data
(b) Single day orbit arcs, 6 ICs and 2 radiation parameters per satellite-per-day
(c) One-per-day-per-station zenith tropospheric parameter,
(d) Bias parameters, one for each independent double difference combination.
(e) All parameters are given loose constraints in the daily GAMIT adjustment and the adjusted parameters and corresponding variance-covariance matrix for station and orbital parameters is recorded on auxiliary file for GLOBK processing.

(2) GLOBK Kalman Filter analysis

(a) Input auxiliary files from daily GAMIT solutions.
(b) Station positions with ± 10 m constraints at stations other than: ALGO, FAIR, KOKB, KOSG, MADR, MASP, MATE, MCMU, METS, ONSA, PAMA, DRAO, TIDB, TROM, WTZ1, YAR1, YELL. For these stations constraints of ± 0.001 m for horizontal components, and ± 0.005 m for height.
(c) In forward filter estimate station coordinates for all sites using constraints described in (b), to realize reference frame
(d) In back filter estimate daily orbital parameters and X and Y pole positions that are consistent with positions determined in forward filter. (No estimate is made of UT1-AT since these deviations are absorbed into the orbital parameters).

References: Dong, D., and Bock, Y., 1989: *J. Geophys. Res.*, **94**, 3949-3966.
Herring, T.A., Davis J.L., and Shapiro, I.I., 1990: *J. Geophys. Res.*, **95**, 12561-12583.



Distribution of the 38 sites of the terrestrial frame SSC(SIO) 93 P 01.

EOP(SIO) 93 P 01 From Aug 1991 to Jul 1993

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

YEAR	X		Y	
	Nb	Sigma	Nb	Sigma
1991	140	0.39	140	0.43
1992	325	0.19	325	0.20
1993	205	0.09	205	0.10

SATELLITE LASER RANGING

EARTH ORIENTATION PARAMETERS AND STATION COORDINATES FROM CENTRAL LABORATORY FOR GEODESY CLG 92 L 01, L 02, L 03, L 04

Ivan Georgiev and Valentin Kotzev, Central Laboratory for Geodesy,
Bulgarian Academy of Sciences , Sofia

CLG 92 L 01, 02, 03 and 04 are four years LAGEOS solutions derived by the SLRP-2 (Satellite Laser Ranging data Processor) computer program system from laser tracking data, acquired by the international laser tracking network during the period from January 1984 to December 1987.

1. MODELS

The models and constants underlying the CLG 92 solutions follow the IERS Standards:

Reference frame

CIS:	Mean equator and equinox of J2000.0
Precession:	IAU 1976
Nutation:	IAU 1980 + Herring 1987 correction
Planetary ephemeris:	JPL DE200/LE200
Initial Earth orientation:	BIH, Circular D
Initial station coordinates:	ITRF 89
Time evolution:	AM0-2 plate motion model
Equatorial radius of the Earth:	6378136 m
Eccentricity 1/f :	298.257

Dynamical model

Gravity model:	NASA/GSFC GEM-T1, truncated at 20 x 20, with GM =398600.436 km^3/s^2 and a =6378137m as scale parameters with the geopotential coefficients and GM =398600.440 km^3/s^2 with the two-body term.
C(2,1), S(2,1):	Applied according to IERS Standards.
Third body:	Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn.
Direct solar radiation pressure :	Occultation by Earth and Moon
Ocean tides:	Wahr model (IERS Standards)
Solid tides:	Schwiderski model (IERS Standards)
Empirical drag acceleration:	CT nominal value -3.1

Relativistic motion equation correction:	Applied according to IERS Standards
Air drag:	Not applied
Albedo:	Not applied

Measurement model

Marini-Murray Refraction Model:	IERS Standards
Solid Earth tidal displacement:	IERS Standards
Ocean loading site displacement:	Applied for stations 1181, 7086, 7090, 7105, 7109, 7110, 7112, 7121, 7122, 7210, 7400, 7401, 7805, 7810, 7833, 7834, 7835, 7837, 7838, 7839, 7840, 7886, 7907, 7939, 8833
Pole tide:	Applied
Relativistic propagation correction:	Applied

2. DATA

LAGEOS normal points used, were received from GAOUA. The entire 4.0 years period contains about 200 000 normal points. All the data is equally weighted.

3. ANALYSIS PROCESS

The analysis was performed by the SLRP-2 computer program system. It consists of two main modules: the orbit computation module and the parameter estimation module. The processing sequence is schematically shown in the figure below.

All other parameters undergo unconstrained free adjustment.

Archived NP
|
Orbital computation
|
Monthly Observational Equations
|
Monthly Normal Equations ——→ Monthly solutions
|
Accumulation Solution Updating
|
Multi-year solution

4. SOLUTION CONSTRAINTS

There were two a priori constraints: (1) the first 5 days value of UT1-UTC in each arc was fixed to its BIH, Circular D value and (2) the orientation of the terrestrial reference frame was constrained by fixing the latitude of 7210 (Hawaii) and the latitude and longitude of 7907 (Arequipa) stations.

5. ADJUSTED PARAMETERS

The differences between the four solutions, outlined in Table 1, are in the intervals of validity of the following parameters: solar radiation pressure coefficient CR; along track acceleration CT; pole coordinates xp and yp and LODR.

Table 1.

Solution	Interval in days		
	CR	CT	xp, yp and LODR
L 01	30	30	5
L 02	15	15	5
L 03	15	15	3
L 04	30	30	3

The adjusted parameters are:

Geogravitational parameter:	GM
A selected set of geopotential coefficients:	C(2,0), C(3,0), C(4,0), C(2,1), S(2,1), C(3,1), S(3,1), C(4,1), S(4,1), C(2,2), S(2,2), S(3,2), S(3,2), C(4,2), S(4,2)
Direct solar radiation pressure coefficient:	CR
Along track acceleration coefficient:	CT
Orbital state vector:	6 parameters per monthly arc
EOP:	xp, yp and LODR
Station coordinates:	Geodetic coordinates

Arc-dependent parameters have been reduced in the monthly normal equations before combining the normal equations for a multi-year solution.

6. RESULTS

The SSC, geocentric x, y an z coordinates, and EOP results obtained in each solution have been provided to the IERS Central Bureau. All coordinates are referred to the optical axis of the ranging systems. The time span of each station is calculating by summing up all days in which it is tracked (one or more passes). The correlation matrices of the estimated station coordinates are also available.

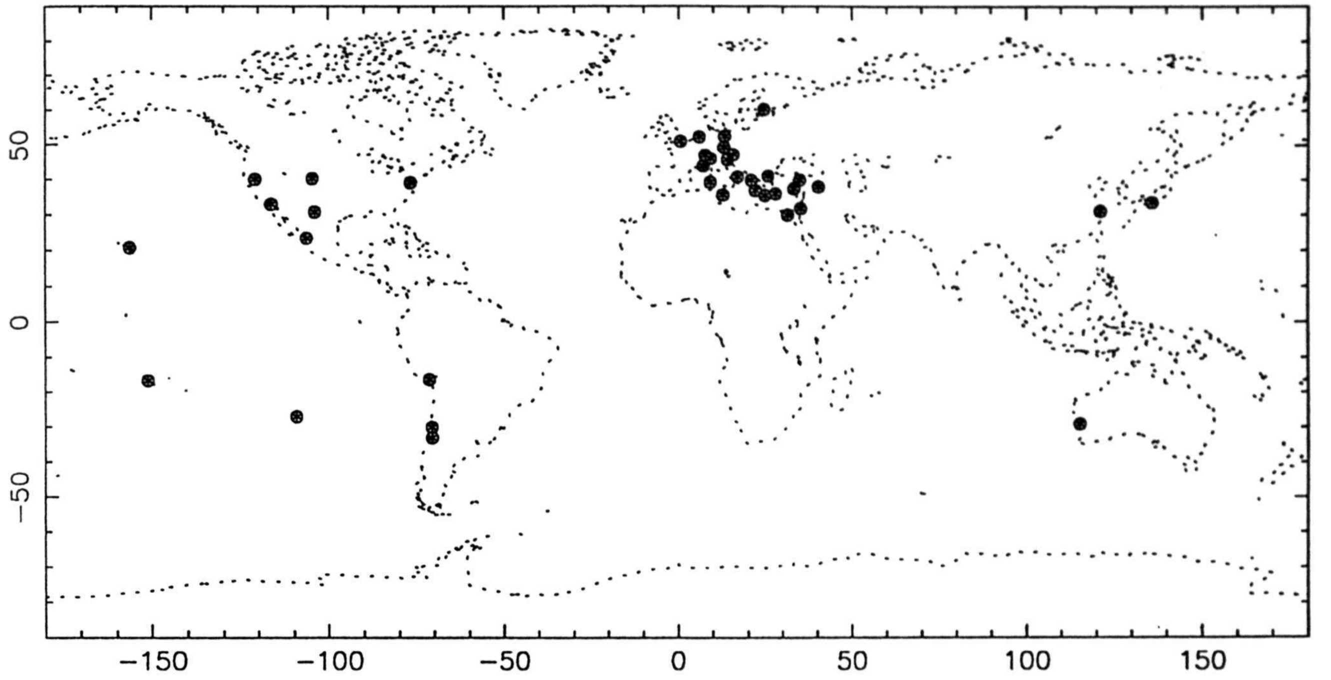
For LODR the reported epoch have to be decreased by the half of the tabulating interval since the LODR values were formed as forward differences of the estimated UT1-UTC series.

References

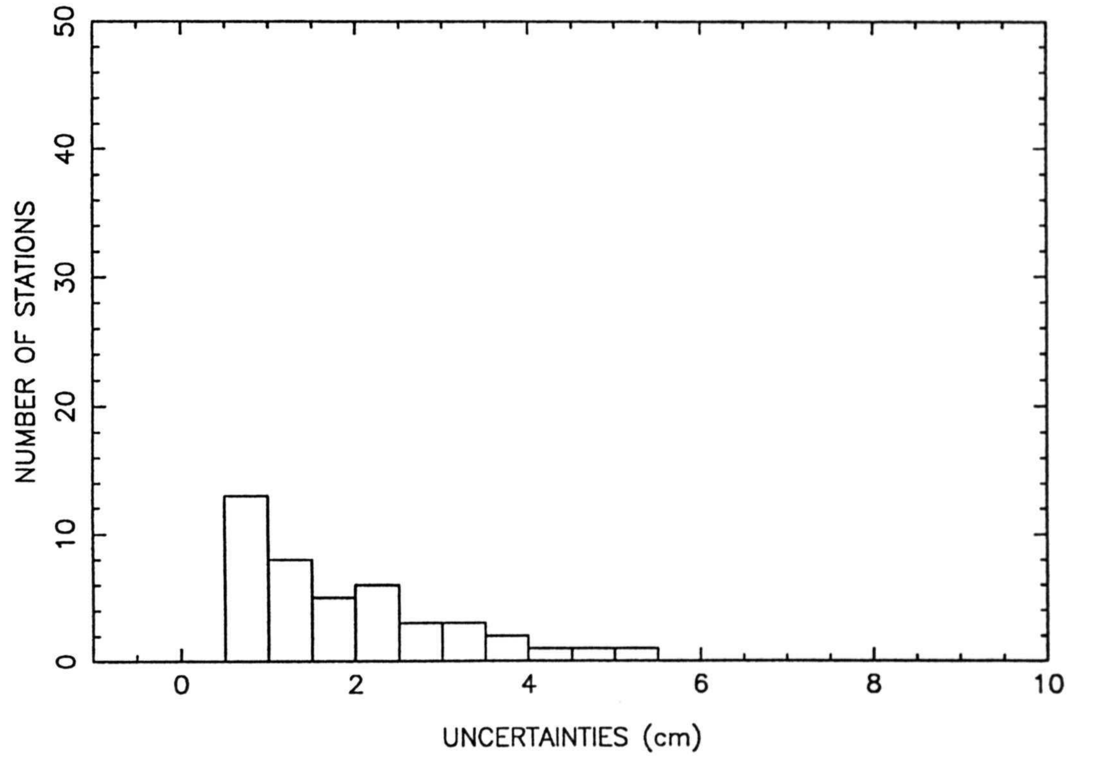
McCarthy (ed.), D.D., 1989: IERS Standards 1989, *IERS Tech. Note 3*, Observatoire de Paris, Paris.

Summary description of the terrestrial system attached to the set of station coordinates SSC(CLG) 93 L 01, 02, 03, 04.

1 - Technique:		SLR
2 - Analysis Center:		Central Laboratory for Geodesy (CLG)
3 - Solution identifier:		CLG 92 L 01, 02, 03, 04
4 - Software used:		SLRP-2
5 - Relativity Scale:		Geocentric (LE)
6 - Permanent tidal correction on station:		YES
7 - Tectonic plate motion model:		AM0-2
8 - Velocity of light (c):		299792458 m/s
9 - Geogravitational constant (GM):		398600.440 m^3/s^2 (solved for parameter)
10 - Reference epoch:		1984.0
11 - Adjusted parameters	Coordinates:	Epoch 1984.0 geodetic station position coordinates. All positions are for the optical axis of the laser ranging system.
	Orbit:	Cartesian coordinates and velocities solved for every 30 or 31 days
	EOP:	xp, yp and LODR (see Table 1)
	CR and CT:	see Table 1
	Geogravitational constant:	GM
	Geopotential coefficients:	A selected number of the low degree and order geopotential coefficients.
12 - Definition of the origin:		Geocentric, C(1,0), C(1,1), S(1,1)
13 - Definition of the orientation:		Fixed latitude for 7210. Fixed longitude and latitude for 7907.
14 - Constraint for time evaluation:		Fixed AM0-2 plate motion model



Distribution of the 38 sites of the terrestrial frame SSC(CLG) 93 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 45 stations of the terrestrial frame SSC(CLG) 93 R 01. 2 stations with uncertainties larger than 10 cm are not shown.

EOP(CLG) 93 L 01 From Jan 1984 to Dec 1987

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	72	0.69	72	0.66	52	0.25
1985	81	0.60	81	0.57	52	0.23
1986	77	0.68	77	0.59	53	0.23
1987	78	0.58	78	0.56	56	0.21

EOP(CLG) 93 L 03 From Jan 1984 to Dec 1987

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	107	0.86	107	0.76	87	0.44
1985	119	0.74	119	0.68	87	0.40
1986	115	0.85	115	0.71	91	0.42
1987	117	0.72	117	0.71	95	0.42

EARTH ORIENTATION AND SITE COORDINATES FROM THE CENTER FOR SPACE RESEARCH CSR 93 L 01

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Earth orientation parameters were derived from a combination of Lageos full rate and quick look data. Full rate data was used from 1976 until the end of June, 1991, and quicklook data was used for July 1991 through February 1993.

Mean positions for all sites were adjusted and horizontal site velocities were adjusted for 47 sites with good observing histories. For all other sites, velocities were held fixed to those predicted by the NNR-NUVEL1 model.

The force and measurement models used for this solution conform generally to the IERS Standards, with the following exceptions:

1) The apriori gravity field was JGM-1, a state of the art gravity field derived as a joint effort by the Goddard Space Flight Center and the Center for Space Research. Selected coefficients of this field were adjusted simultaneously with the stations positions.

2) The ocean tide model was an enhanced version of the Schwiderski model extrapolated to include 80 consituents complete through degree and order 20, assuming admittances which vary linearly with frequency. Some ocean tide coefficients were adjusted using Lageos-1 tracking data.

3) The solid tide model has been expanded to include third degree and fourth degree terms.

4) The geogravitational constant, GM, was 398600.4415 km^3/s^2.

5) The nominal plate motion model was NNR-NUVEL1.

6) The free core nutation period has been changed from 460 to 430 days.

The data was weighted in a piecewise continuous, linearly interpolated model to reflect the improvement in laser hardware over the data span. The weights are larger than the true random component of the laser ranges in order to reflect unmodelled systematic errors, and are thus scaled so that the formal uncertainties on the Earth orientation parameters are consistent with their internal precision.

The solutions for orbit elements and Earth orientation parameters were computed using residuals from a long arc fit spanning the period from 7 May 1976 through 06 February 1993, a period of 16.8 years. The short arc adjustments were made at 3 day intervals subject to the constraint that the posteriori uncertainties were less than specified values, to allow for the change in data quantity over time. If the solution for a given 3 day interval yielded unacceptably large uncertainties on the adjusted parameters, the interval was extended by 3 days and the solution repeated. Thus, each final interval is a multiple of 3 days. For each interval, regardless of length, 6 Keplerian mean elements and xp and yp were solved. The UT1 estimates are obtained from the Lageos node residuals, with the constraint that they follow the JPL SPACE92 series at periods longer than about 60 days [Gross, 1993].

References

Gross, R.S. 1993: A Combination of Earth Orientation Data: SPACE92, *IERS Tech. Note 14*, Observatoire de Paris, Paris, p. C-1.

Summary description of the terrestrial system attached to the set of station coordinates SSC(CSR) 93 L 01

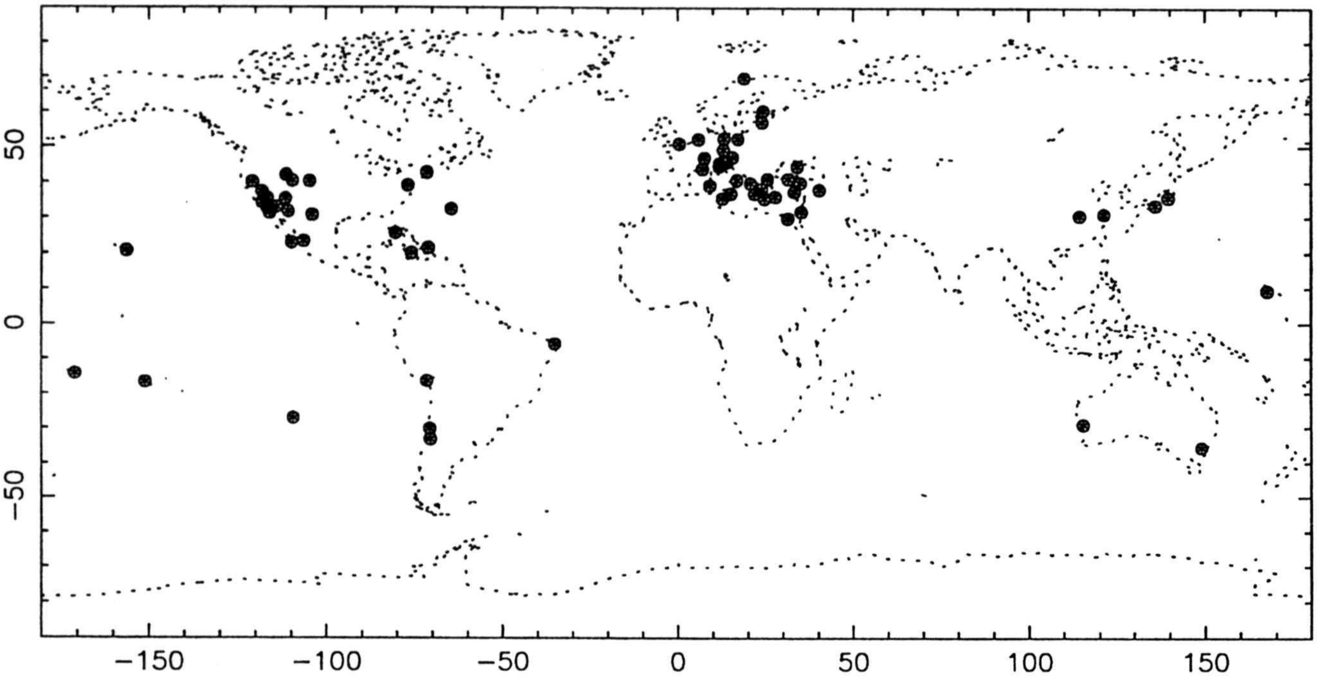
1 - Technique:	SLR
2 - Analysis Center:	CSR
3 - Solution Identifier:	SSC(CSR) 93 L 01
4 - Software Used:	UTOPIA
5 - Relativity Scale:	Geocentric (LE)
6 - Permananent Tidal Correction on Station:	Tidal correction has nonzero mean. Positions do not reflect true mean.
7 - Tectonic Plate model:	NNR-NUVEL1
8 - Velocity of light (C) :	299792458 m/sec
9 - Geogravitational constant (GM) :	398600.4415 km^3/s^2
10 - Reference Epoch :	1988.0
11 - Adjusted Parameters:	
Coordinates:	Epoch 1988.0 position for all sites in cartesian coordinates solved one time for entire data span. Horizontal velocities adjusted for 47 selected sites.

Site dependent biases:	Adjusted where necessary.
Geopotential coefficients:	Selected coefficients were adjusted.
Orbit:	6 Keplerian mean element corrections to long arc orbit solved every 3 days throughout span subject to constraint that posteriori uncertainties were less than specified values. If not satisfied, interval was extended in multiples of 3 days until solution was acceptable.
EOP:	x, y and UT1 (UT1 constrained by JPL SPACE92) were solved at the same intervals as the orbit.

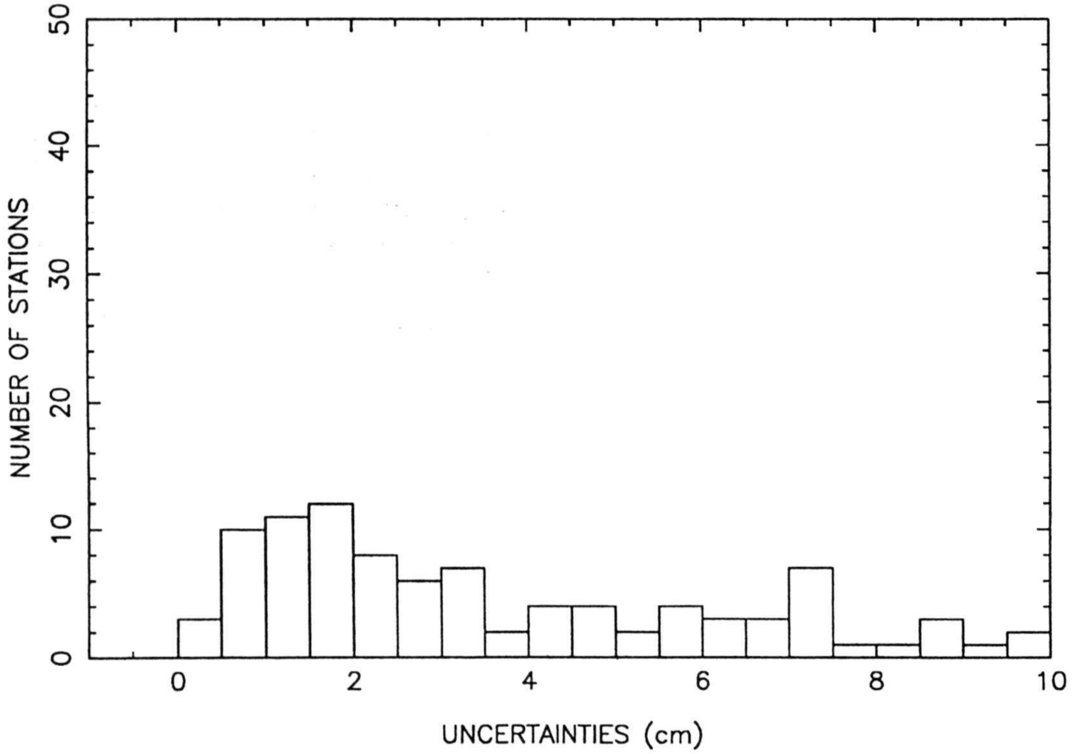
12 - Definition of the origin: Geocentric, C10 = C11 = S11 = 0.0

13 - Definition of the orientation: System oriented to agree with SPACE92 in a mean sense over period 1981-1992, maintained through fixing the latitude and longitude of site 7210 (HOLLAS) and the latitude of site 7105 (GRF105). This definition was enforced by applying offsets to the adjusted polar motion. This adjustment could create a closure error between the origins implied by the EOP and the SSC.

14 - Constraint for time evolution: Latitude and longitude rate of site 7210 (HOLLAS) and latitude rate of site 7105 (GRF105) fixed to NNR-NUVEL1 velocities. Horizontal site velocities adjusted with a priori sigma of 100 mm/yr for the other sites with sufficient data. Because of weak SLR data from Mojave (7288) and Owens Valley (7853) their velocity adjustment was constrained using a priori sigma of 5 mm/yr.



Distribution of the 68 sites of the terrestrial frame SSC(CSR) 93 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 111 stations of the terrestrial frame SSC(CSR) 93 L 01. 17 stations with uncertainties larger than 10 cm are not shown.

EOP(CSR) 93 L 01 From May 1976 to Feb 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	32	12.54	32	14.29	32	7.29
1977	72	12.83	72	12.04	72	6.77
1978	72	12.04	72	10.21	72	6.49
1979	76	9.28	76	9.58	76	5.95
1980	117	5.46	117	3.48	117	3.04
1981	112	5.40	112	3.20	112	2.65
1982	113	3.60	113	2.76	113	2.30
1983	118	3.07	118	2.67	118	1.75
1984	121	1.22	121	1.08	121	0.94
1985	121	1.05	121	0.89	121	0.73
1986	122	0.87	122	0.80	122	0.68
1987	122	0.60	122	0.55	122	0.46
1988	122	0.48	122	0.52	122	0.39
1989	121	0.52	121	0.51	121	0.43
1990	122	0.49	122	0.52	122	0.40
1991	122	0.62	122	0.62	122	0.46
1992	122	0.61	122	0.58	122	0.47
1993	12	0.79	12	0.77	12	0.88

EARTH ROTATION AND STATION COORDINATES COMPUTED FROM SLR OBSERVATIONS ON LAGEOS-1 DUT 93 L 02

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The solution ERP/SSC(DUT) 93 L 02 consists of a coherent set of Earth Rotation Parameters (ERPs), determined at 5-day intervals, and coordinates of a global laser station network. The original solution was computed from laser range observations on the geodetic satellite LAGEOS-1, taken during the periods September 1983 through May 1985 and January 1986 through December 1992. Only ERP solutions for epochs since January 1986 are included in this contribution.

For the analysis, the 9.3-year data interval was divided into a total of 38 sub-periods, with a length of 13 weeks on average. The actual analysis was performed in a 2-step approach.

First, a continuous but mutually independent series of 38 global network and ERP solutions was computed by analyzing each batch of observations. The parameter estimation was based on a least-squares fit of the satellite orbit to the SLR observations. To limit the effect of potential dynamic model errors, the analysis programs GEODYN-2 and SOLVE-2 were executed in a so-called multi-arc mode, where each sub-period was further divided into a series of 7-day data arcs and satellite parameters (state-vector at epoch, a constant along-track acceleration and a 1-cpr radial acceleration) were estimated for each data arc. To prevent computational singularities, the parameters were constrained in a Bayesian way. The a priori standard deviation of the pole position and UT1 were assigned values of 0.1 arcsec and 0.01 s, respectively, with a priori values taken from the monthly IERS Bulletins B. The initial station coordinates, computed during a preliminary data screening run, were given an a priori uncertainty of 1 m. The ascending nodes of the satellite state-vectors were kept fixed at the values determined in the data screening.

The computation model is summarized in Table 1. The model closely follows the IERS Standards, with few exceptions: (i) the JGM-1 solution, both for the gravity field and for the ocean tides, was used instead of the advised GEM-T1 and Schwiderski models; (ii) the effect of ocean loading and atmospheric pressure loading on station positions was not applied; (iii) no plate motion was applied during each "13-week" sub-period; and (iv) new values for GM, ae and the flattening of the Earth were used.

The second step was primarly aimed at bringing coherency into the series of parameter solutions. This was done by fitting a model for tectonic deformations to the series of individual station coordinates, while eliminating systematic differences. This model consist of initial station coordinates at a reference epoch and the time-derivatives of these coordinates. A priori values for these time-derivatives were taken from the NUVEL-1 No Net Rotation model, and either kept fixed for a sub-set of 12 SLR stations, which are known to follow the motions described by this model, or estimated for the remainder of the stations. Next, the resulting model for instantaneous station positions was back-substituted into the GEODYN/SOLVE data reduction programs. Finally, new solutions for the ERPs were computed without application of any constraint, and keeping the station positions (and the ascending nodes) fixed. The computation model is identical to the one for step 1, already listed in Table 1.

The resulting series of ERP solutions and the station coordinates have been provided to the IERS Central Bureau. The effect of short-term perturbations in UT1, caused by zonal tides, has been removed. The solution for each station consists of the cartesian monument coordinates at epoch, the corresponding standard deviations (both in m), the apparent motions and the standard deviations of the latter (in m/yr). The reference epoch of the solution is January 1, 1988.

Table 1: Models and constants.

DYNAMIC MODEL:	
Gravity field:	NASA/GSFC JGM-1 model, truncated at 20x20
GM:	398600.4415 km^3/s^2
c :	299792.458 km/s
ae :	6378.1363 km
1/f :	298.2564
Solar and lunar attraction :	JPL DE-200 ephemeris
Solid earth tides:	Wahr model
Ocean tides:	NASA/GSFC JGM-1 model
Solar radiation:	CR fixed at 1.13; occultation by Earth and Moon; umbra and penumbra
Along-track acceleration:	constant value; adjusted
Radial acceleration:	sine and cosine term; adjusted
Third body attraction:	Sun, Moon, Venus, Mars, Jupiter, Saturn; positions from JPL DE200/LE200 ephemeris
Pole tide (dynamic part) :	applied
REFERENCE FRAME:	
Station coordinates:	adjusted (step 1); modelled with NNR-NUVEL1 (step 2)
Earth rotation:	adjusted at 5-day intervals; a priori values from IERS EOP 90 C 04
CIS:	mean equator and equinox of J2000.0
Precession :	IAU 1976 (Lieske model)
Nutation:	IAU 1980 (Wahr model)
Plate motion:	not applied
Tidal uplift :	h2 = 0.609, l2 = 0.0852
Pole tide (geometric part) :	applied

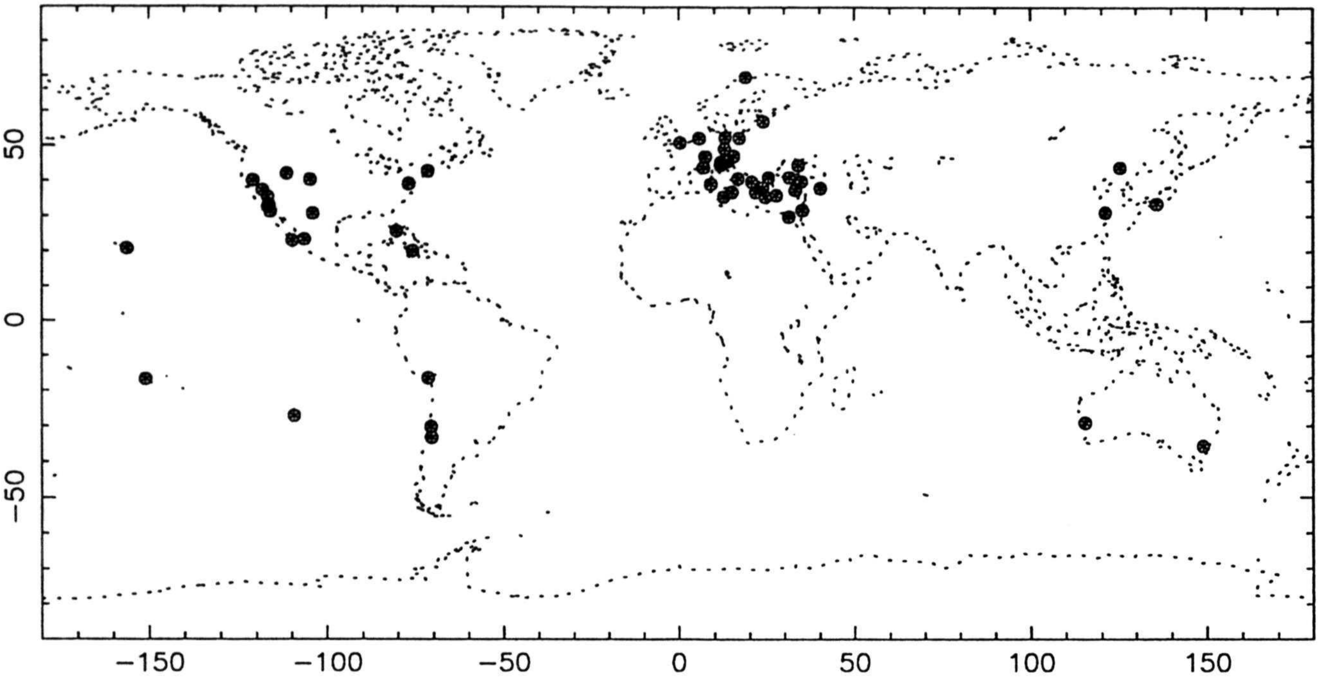
Ocean loading : not applied
Atmospheric pressure loading: not applied

MEASUREMENT MODEL:

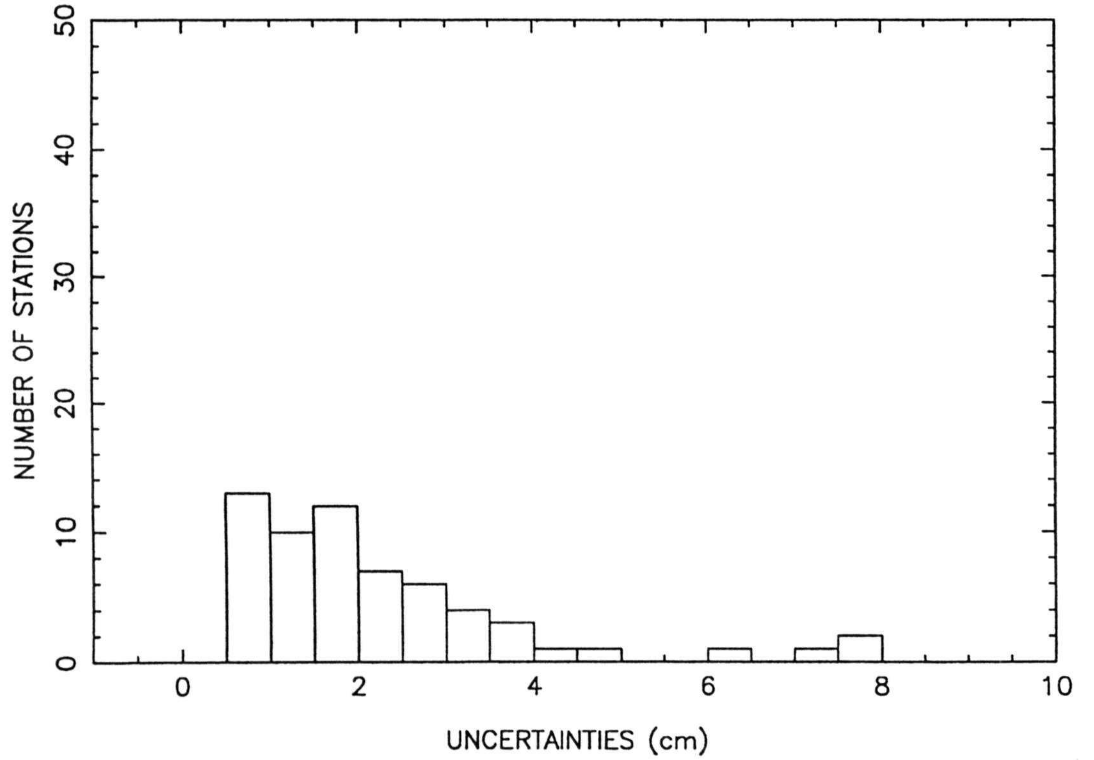
Observations :	Release B normal points, computed at NASA (September 1983 - May 1985), DGFII (January - October 1986, 1987), DUT (November, December 1986) and Bendix (1988 - March 1992); Release A normal points, computed at Bendix (April 1992 - June 1992); quick-look normal points (July 1992 - December 1992)
Data weighting :	Determined from overall model accuracy and system characteristics
Tropospheric refraction :	Marini-Murray model

Summary description of the terrestrial system attached to the set of station coordinates SSC(DUT) 93 L 02

1 - Technique :	SLR
2 - Analysis center :	DUT
3 - Solution identifier:	SSC(DUT) 93 L 02
4 - Software used :	GEODYN-2/SOLVE-2
5 - Relativity scale :	local Earth
6 - Tidal uplift :	yes
7 - Tectonic plate model :	NNR-NUVEL1 for selected sites (Yarragadee, Easter Island, Greenbelt, Platteville, Huahine, Mazatlan, Maui, Wettzell, Graz, RGO, Orroral Valley, Kootwijk); DUT solutions derived for the remainder of the stations, determined w.r.t. a reference frame moving according to NNR-NUVEL1
8 - Velocity of light :	299792.458 km/s
9 - Gravitational constant :	398600.4415 km^3/s^2
10 - Reference epoch :	January 1, 1988
11- Adjusted parameters :	X0, Y0, Z0 (for selected stations); X0, Y0, Z0, $\dot{X}$, $\dot{Y}$, $\dot{Z}$ (remainder)
12- Origin definition :	C(1,0) = C(1,1) = S(1,1) = 0
13- Orientation definition :	Initial coordinates at reference epoch
14- Evolution constraint :	NNR-NUVEL1 (for selected stations); DUT apparent motions (remainder)



Distribution of the 56 sites of the terrestrial frame SSC(DUT) 93 L 02.



Distribution of the uncertainties (quadratic mean of $\sigma_x, \sigma_y, \sigma_z$) for the 68 stations of the terrestrial frame SSC(DUT) 93 L 02. 7 stations with uncertainties larger than 10 cm are not shown.

EOP(DUT) 93 L 02 From Jan 1986 to Dec 1992

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
1986	72	0.23	72	0.19	72	0.17
1987	72	0.19	72	0.17	72	0.16
1988	73	0.20	73	0.19	73	0.17
1989	73	0.18	73	0.17	73	0.15
1990	73	0.16	73	0.16	73	0.14
1991	73	0.19	73	0.18	73	0.15
1992	72	0.19	72	0.18	72	0.15

EARTH ORIENTATION AND STATION COORDINATES FROM LAGEOS SLR OBSERVATIONS GAOUA 93 L 01

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Dept. of Space Geodynamics

Solution GAOUA 93 L 01 consists of the sets of 73 station cartesian coordinates, 45 station velocities having a good observing history, and Earth Orientation Parameters. Kiev-Geodynamics - 4 software package has been used for the analysis and Lageos SLR normal points, spanning the period from September 1983 through April 1993 have been taken as input data.

The models and constants used for this solution are those recommended by the IERS Standards with the following exceptions:

1. The GEM-T1 ocean tide model was used instead of Schwiderski model.
2. Tidal variations in UT1 due to zonal tides with periods exceeding 35 days were not applied.
3. Nutation corrections were taken according to McCarthy *et al.* (1991)
4. Only variations of radial components of site positions were taken into account when modelling ocean loading effect.

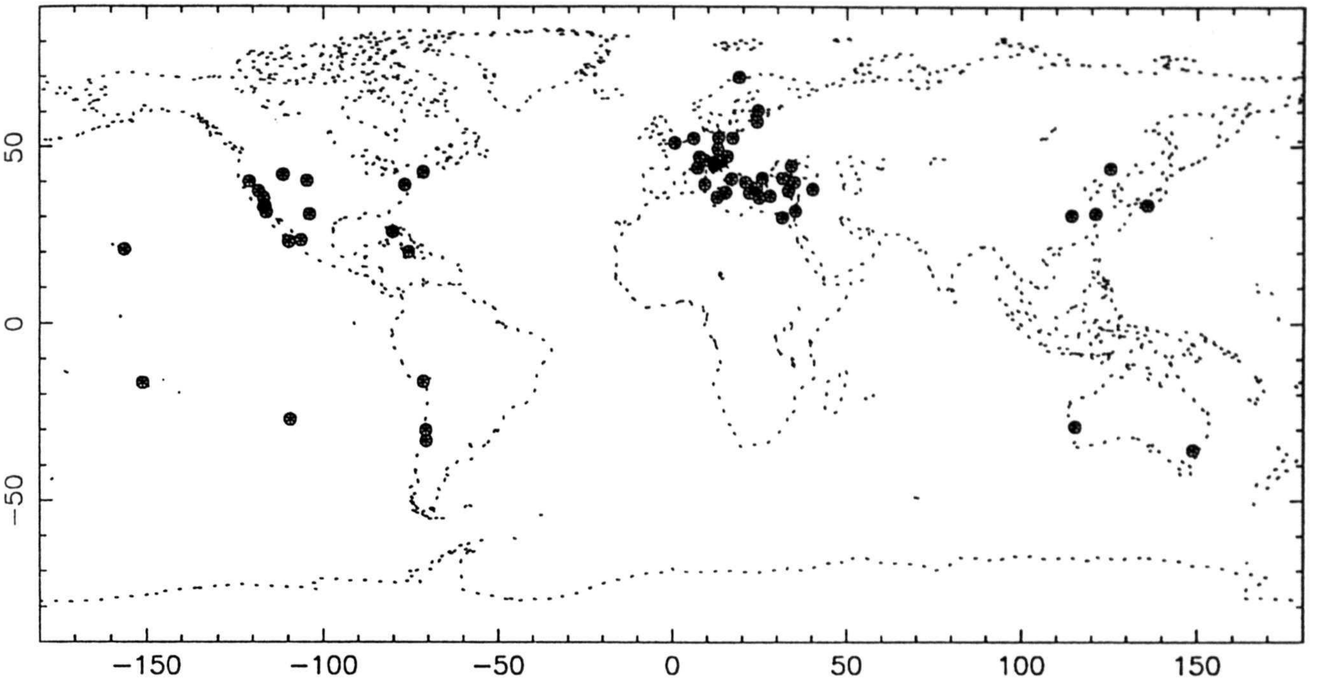
The solution was obtained in two steps. First, the whole data interval was divided in 15 day sub-intervals and 6 Keplerian mean elements were estimated on each of them. Next, the combination of all sub-intervals yielded the estimation of global and local parameters listed in summary sheet.

Rather simple weighting procedure was applied during the analysis. All the third generation laser station data were given the weights 3 with respect to those of the second generation.

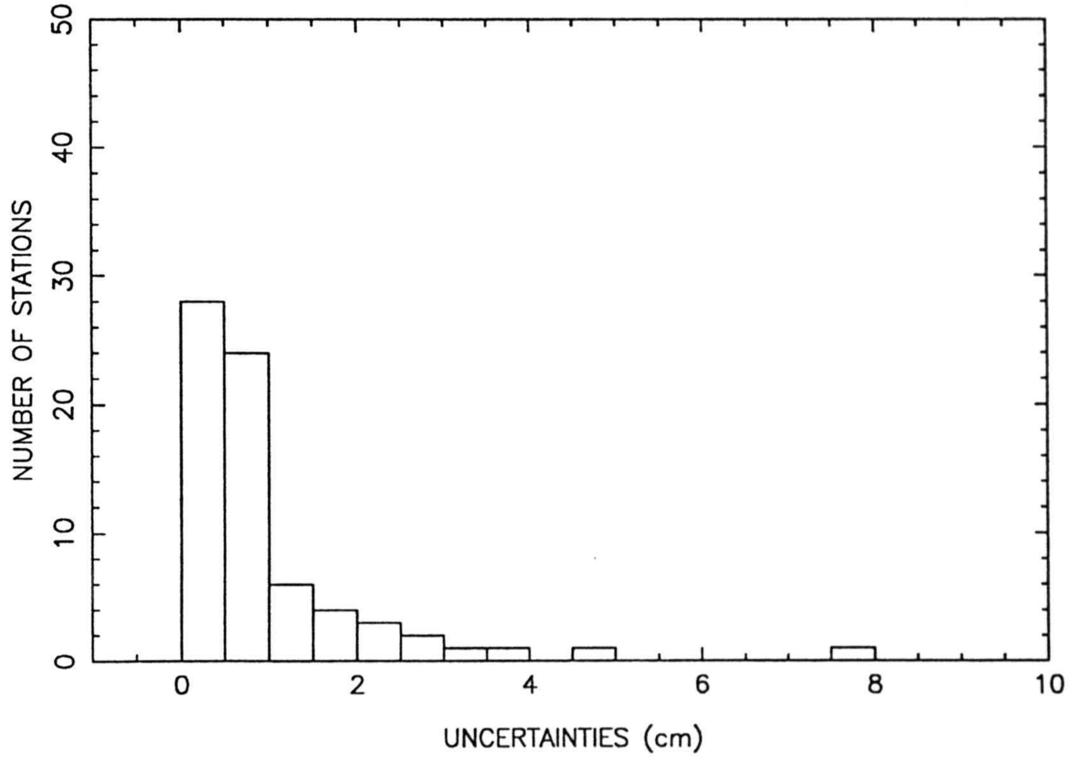
The reference system is attached to ITRF91 by fixing the latitude of station 7105 and the longitude and latitude of station 7210. Time evolution of the system is modelled by NNR-NUVEL1 for sites with either poor data distribution or short-term activity periods. The velocities of the other sites have been estimated and linked to NNR-NUVEL1 through fixing the latitude change rate of station 7210 and the longitude and latitude change rates of station 7105.

Summary description of the terrestrial system attached to the set of station coordinates SSC(GAOUA) 93 L 01

1 - Technique :	SLR
2 - Analysis Center :	GAOUA
3 - Solution identifier :	SSC(GAOUA) 93 L 01
4 - Software used :	KIEV-GEODYNAMICS - 4
5 - Relativity scale :	LE
6 - Permanent tidal correction on station :	NO
7 - Tectonic plate model :	NNR-NUVEL1
8 - Velocity of light (C) :	299 792 458
9 - Geogravitational constant (GM) :	3.9860 04418 10^{14}
10 - Reference epoch :	MJD 47161 (1988.0)
11 - Adjusted parameters :	
Coordinates:	X, Y ,Z for 73 stations $\dot{X}$, $\dot{Y}$, $\dot{Z}$ for 45 stations
Orbit :	5 keplerian mean elements estimated every 5 days, Ct and Cr every 15 days
EOP :	Xp, Yp, UT1R every 5 days
12 - Definition of the origin :	C10 = C11 = S11 = 0
13 - Definition of the orientation :	ERP values from BIH Annual reports and IERS Bulletin B. Longitude and latitude of station 7105 and latitude of station 7210 fixed.
14 - Constraint for time evolution :	Fixed plate motion model for selected stations. Latitude and longitude change rates of station 7105 and latitude change rate of station 7210 fixed to NNR-NUVEL1 velocities.



Distribution of the 59 sites of the terrestrial frame SSC(GAOUA) 93 L 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 73 stations of the terrestrial frame SSC(GAOUA) 93 L 01. 2 stations with uncertainties larger than 10 cm are not shown.

EOP(GAOUA)93 L 01 From Sep 1983 to Apr 1992

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
1983	24	1.15	24	0.80	24	0.80
1984	73	0.80	73	0.60	73	0.70
1985	73	0.60	73	0.40	73	0.50
1986	73	0.40	73	0.30	73	0.30
1987	73	0.40	73	0.20	73	0.30
1988	73	0.30	73	0.20	73	0.30
1989	73	0.60	73	0.40	73	0.50
1990	73	0.50	73	0.40	73	0.50
1991	73	0.70	73	0.50	73	0.50
1992	24	0.65	24	0.40	24	0.60

EARTH ROTATION PARAMETERS AND STATION COORDINATES BY LAGEOS LASER RANGING DATA UPDATED TILL MID-SEPTEMBER, 1992

GFZ 93 L 01, L 02, 03, 04, 05

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SUMMARY

In continuation of the former years solutions two new Sets of Station Coordinates (SSC) were determined, the SSC(GFZ) 93 L 01 which includes the estimation of the site motions and the SSC(GFZ) 93 L 02 which fixed the site motions to the NUVEL-1 model. Comparing with the last year solutions, the series of Earth Rotation Parameters (ERP) were expanded by a 1-day resolution series (L 04). The others have a time resolution of 5 days (L 01 and L 05), 3 days (L 02) and 2 days (L 03).

DATA AND MODEL PARAMETERS

Using the further improved software package and the Satellite Laser Ranging (SLR) data to Lageos, two Sets of Station Coordinates (SSC) and 5 Sets of Earth Rotation Parameters (ERP) were determined. The data used concern SLR normal points of the global station net from the beginning of 1980 (MJD 44238) until September 14, 1992 (MJD 48879), in all 44208 passes from 101 stations. A statistical summary (r.m.s. station fits for 5-day orbit adjustments together with the number of passes and observations) for the time interval from March, 1991 to September, 1992 is given in Table 1.

The constants and model parameters used for these solutions conform to the IERS Standards (McCarthy, 1992) with the following exceptions:

- tidal variations in UT1 caused by zonal tides with periods larger than 35 days not considered
- nutation corrections derived by VLBI model.

In a multistage-multiarc procedure different parameters were solved for as given in the summary sheet. Here also details on the adopted model for the terrestrial system are stated.

STATION COORDINATES AND VELOCITIES

For the main solution SSC(GFZ) 93 L 01 the coordinates of all sites were adjusted simultaneously with site velocities using data from the whole time interval. For 45 stations (69 markers; colocated markers at one station were constrained to have the same velocity) the data distribution was good enough to determine site velocities, whereas the velocities of the other stations were held fixed to those of the NUVEL-1 model (De Mets *et al.*, 1990). In a second variant (additional solution SSC(GFZ) 93 L 02) all site velocities were fixed to that predicted by NUVEL-1 rigid plate model.

The site positions were refered to epoch 1988.0. The origin of the reference system was defined by C10 = C11 = S11 = 0. The orientation was constrained by fixing the latitude and longtitude of the station 7840 and the latitude of the station 7105. Additionally, no common net rotation were permitted in relation to the reference coordinate set SSC(GFZ) 92 L 01 (ITRF89). Corrections due to the permanent tidal deformation of the Earth were applied.

The station coordinates and the adjusted velocities for the 69 sites mentioned above have been provided to the IERS Central Bureau. The given errors have been scaled with a factor 5, because the calculated errors seem to be too optimistic.

EARTH ROTATION PARAMETERS

For the ERP (pole coordinates and length of day - LOD) two sets with 5-day time resolution were computed. The main solution ERP(GFZ) 93 L 01 refers to the SSC(GFZ) 93 L 01 with adjusted site velocities and the ERP(GFZ) 93 L 05 is based on SSC(GFZ) 93 L 02 with motions fixed to NUVEL-1. The two series with a time resolution of 3 days (ERP(GFZ) 93 L 02) and 2 days (ERP(GFZ) 93 L 03) were continued. Because of a new data release, several months in 1991 (March to September) were re-analysed. The series beginning in 1980 are now updated till mid-September 1992. Additionally, a series with a time resolution of 1 day (ERP(GFZ) 93 L 04) was produced starting in June 1983 and extending up to September 1992.

Whereas in the 5-day solutions the LOD values were estimated directly, in the L02, L03 and L04 solutions UT1 values were solved for instead of LOD. These UT1 results were converted into LOD. That means that the time scales for the ERP(GFZ) 93 L 02, L 03 and L 04 have to be transferred for the LOD values by -1.5 d, -1.0 d and -0.5 d, respectively.

Generally, the SLR data were weighted according to their estimated accuracy. In addition, several non-permanent stations were given smaller weights in order to reduce the influence of the change of the station distribution. No post-adjustment smoothing or filtering procedure was applied to the ERP series.

The standard deviations of the pole coordinates are about 0.1 mas for the series with a time resolution of 5 days and 3 days, 0.15 mas for the 2-day time resolution series, and 0.3 mas for the 1-day time resolution series. The accuracy was estimated to be about 1 mas to 2 mas. For the directly derived LOD results (5-day resolution) an extremely optimistic estimation was obtained for the formal standard deviations; therefore they were scaled by a factor of 4. Then the standard deviations are about 0.008 ms for the 5-day and 3-day time resolution series, 0.01 ms for the 2-day time resolution series and 0.02 ms to 0.03 ms for the 1-day time resolution series. The accuracy is in the order of 0.1 ms to 0.2 ms. All the accuracy is influenced by the data density and distribution. Mainly because of this data effect, the accuracy was significantly increased in the course of the last ten years.

In cases of poor data distribution the errors can be several times larger. Then also the correlation between the estimated ERP becomes very high. Therefore the correlation was used as an automatical elimination criterion (where higher than 0.9). This way about 3% of the results with a resolution of 2 days and about 15% of the results with a resolution of 1-day were eliminated; due to the station distribution the number of eliminated results for yp is twice as large as for xp.

The results show a good agreement with the previously reported series and with IERS results in the overlapping zones. The differences between the ERP results obtained on the basis of adjusted site velocities and on those obtained with NUVEL-1 site velocities are not significant.

References

DeMets, C., Gordon., R.G., Argus, D.F. and Stein, S., 1990: Current plate motions, *Geophys. J. Int.*, **101**, 425.

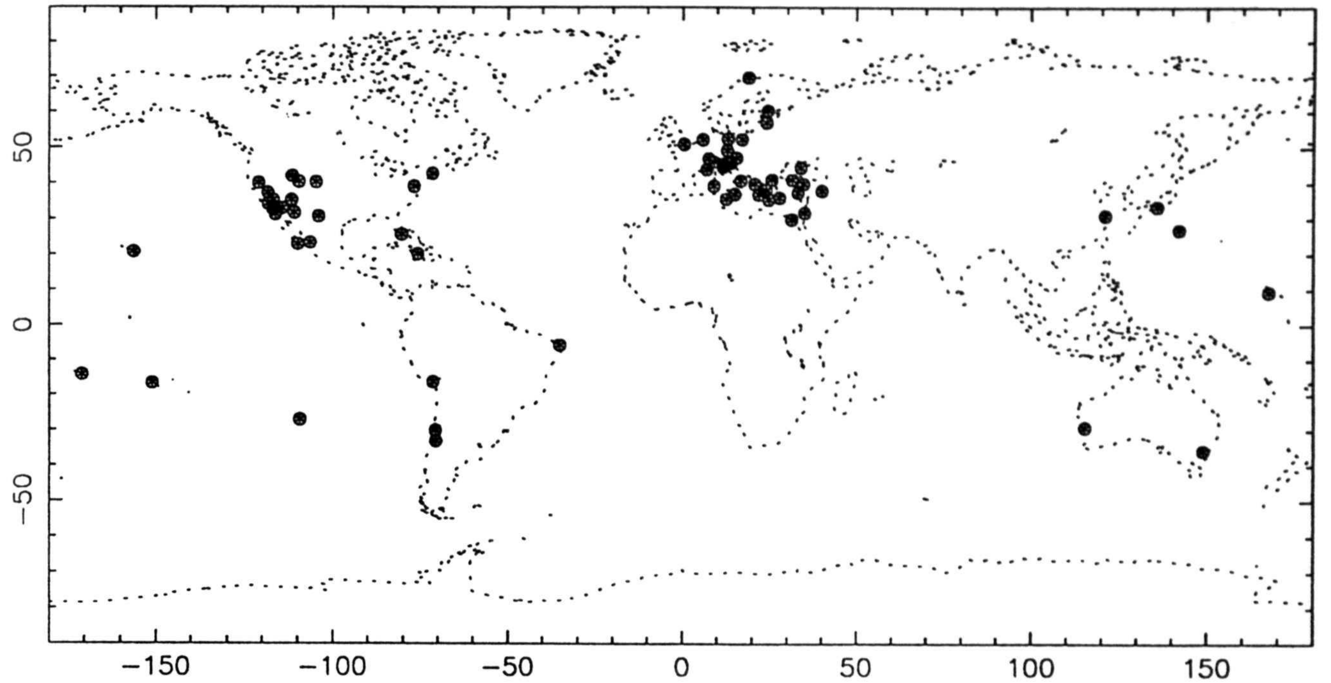
McCarthy, D.D. (ed.), 1992: IERS Standards. *IERS Tech. Note 13*, Observatoire de Paris, Paris.

TABLE 1. Summary of statistical information for 3/1991 to 9/1992

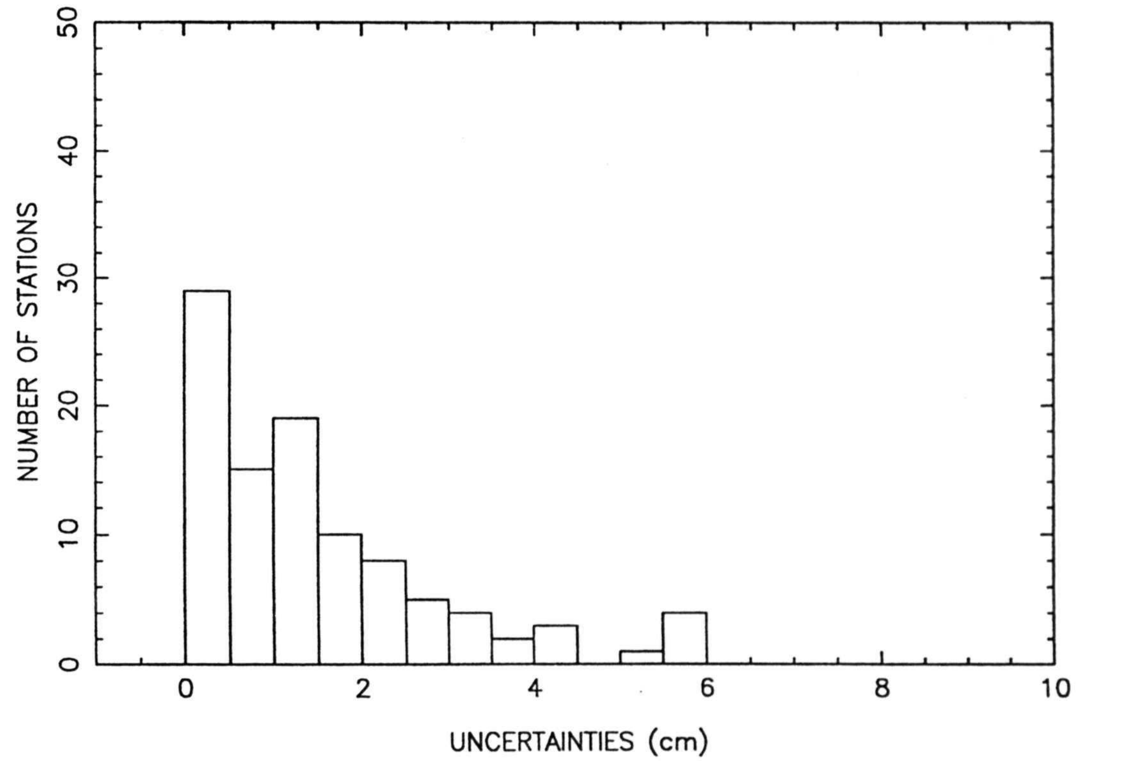
station	Number of passes	Number of obs.	mean rms (m)	station	Number of passes	Number of obs.	mean rms (m)
118101	20	100	0.165	7542	16	137	0.029
187301	57	427	0.146	7560	8	51	0.032
188401	92	1222	0.115	7561	50	648	0.044
189301	31	310	0.140	7587	8	67	0.034
195301	9	29	0.250	7810	294	3306	0.043
7046	60	858	0.026	781102	18	138	0.093
7080	234	2405	0.032	7831	205	1757	0.050
7090	364	5314	0.031	7835	509	6548	0.039
7097	45	539	0.039	7837	169	1512	0.078
7105	269	3774	0.028	7838	136	1720	0.054
7109	289	3697	0.021	7839	311	4708	0.033
7110	442	6255	0.027	7840	691	7683	0.033
7112	48	615	0.046	7843	15	141	0.109
7122	21	294	0.025	7882	41	592	0.026
7123	63	691	0.049	7883	50	645	0.036
7210	432	6160	0.029	7907	96	1010	0.101
7295	18	198	0.034	7918	15	207	0.029
7403	152	1888	0.041	7939	253	2729	0.071
7510	4	19	0.251	883401	565	5814	0.056
7512	58	615	0.041				
7517	44	533	0.035				
7525	43	471	0.028				

Summary description of the terrestrial systems attached to the sets of station coordinates SSC(GFZ) 93 L 01 and 92 L 02

1 - Technique:	SLR
2 - Analysis Center:	GFZ
3 - Solution Identifier:	SSC(GFZ) 93 L 01 and SSC(GFZ) 93 L 02
4 - Software Used:	EPOS.P.V1
5 - Relativity Scale:	Geocentric (LE)
6 - Permanent Tidal Correction on station:	Yes
7 - Tectonic Plate model:	Adjusted (L 01), resp. NUVEL-1 (L 02)
8 - Velocity of light (C):	299792458 m/sec
9 - Geogravitational constant (GM) :	Adjusted to 398600.4420 km^3/s^2
10 - Reference Epoch:	1988.0 (MJD 47160.)
11 - Adjusted Parameters:	
Coordinates :	Radius, longitude and latitude for all sites plus velocities in each of the coordinates, all solved one time for the whole data span (L 02: velocities are fixed to NUVEL-1)
Orbit:	6 Keplerian mean elements for intervals of 5 days
EOP:	x, y and LOD, solved at 5-day intervals (the same as orbit) x, y and UT1, solved at 1-, 2- and 3-day intervals.
12 - Definition of the origin:	Geocentric, C10 = C11 = S11 = 0
13 - Definition of the orientation:	System oriented by fixing: - the latitude of 7105 ,7840 - the longitude of 7840
14 - Constraint for time evolution:	L 01 - no net rotation by fixing the velocities of: - the latitude of 7105, 7840 - the longitude of 7840



Distribution of the 66 sites of the terrestrial frame SSC(GFZ) 93 L 01.



Distribution of the uncertainties (quadratic mean of $\sigma_x, \sigma_y, \sigma_z$) for the 101 stations of the terrestrial frame SSC(GFZ) 93 L 01. 1 station with uncertainty larger than 10 cm is not shown.

EOP(GFZ) 93 L 01 From Jan 1980 to Sep 1992

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1980	66	0.46	66	0.25	66	0.15
1981	65	0.40	65	0.22	65	0.13
1982	70	0.34	70	0.19	70	0.12
1983	70	0.23	70	0.20	70	0.09
1984	73	0.14	73	0.11	73	0.06
1985	73	0.10	73	0.08	73	0.04
1986	73	0.11	73	0.09	73	0.04
1987	73	0.10	73	0.08	73	0.04
1988	73	0.10	73	0.09	73	0.04
1989	73	0.10	73	0.09	73	0.04
1990	73	0.08	73	0.09	73	0.04
1991	73	0.10	73	0.09	73	0.04
1992	51	0.10	51	0.10	51	0.04

EOP(GFZ) 93 L 02 From Jul 1983 to Sep 1992

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1983	56	0.24	56	0.22	56	0.08
1984	121	0.19	121	0.16	121	0.07
1985	122	0.14	122	0.11	122	0.05
1986	121	0.14	121	0.12	121	0.05
1987	122	0.13	122	0.12	122	0.05
1988	121	0.13	121	0.12	121	0.05
1989	122	0.14	122	0.13	122	0.05
1990	120	0.11	120	0.12	120	0.05
1991	122	0.13	122	0.13	122	0.05
1992	86	0.15	86	0.13	86	0.06

EOP(GFZ) 93 L 03 From Jul 1983 to Sep 1992

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1983	78	0.30	78	0.26	78	0.15
1984	178	0.23	178	0.19	178	0.12
1985	176	0.17	176	0.14	177	0.09
1986	177	0.17	177	0.14	176	0.09
1987	180	0.16	180	0.15	180	0.10
1988	175	0.16	175	0.14	175	0.09
1989	177	0.17	177	0.16	177	0.10
1990	180	0.13	180	0.15	181	0.09
1991	172	0.15	172	0.15	171	0.08
1992	124	0.18	124	0.16	124	0.10

EOP(GFZ) 93 L 04 From Jul 1983 to Sep 1992

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

YEAR	X		Y		D	
	Nb	Sigma	Nb	Sigma	Nb	Sigma
1983	124	0.36	124	0.32	124	0.31
1984	303	0.28	303	0.23	303	0.28
1985	314	0.21	314	0.16	314	0.20
1986	309	0.21	309	0.17	309	0.20
1987	295	0.20	295	0.17	295	0.21
1988	287	0.19	287	0.17	287	0.20
1989	305	0.21	305	0.19	305	0.22
1990	328	0.17	328	0.17	329	0.20
1991	294	0.18	294	0.17	293	0.18
1992	225	0.22	225	0.20	225	0.23

EARTH ORIENTATION PARAMETERS FROM GSFC SOLUTION SL8.2 GSFC 93 L 01

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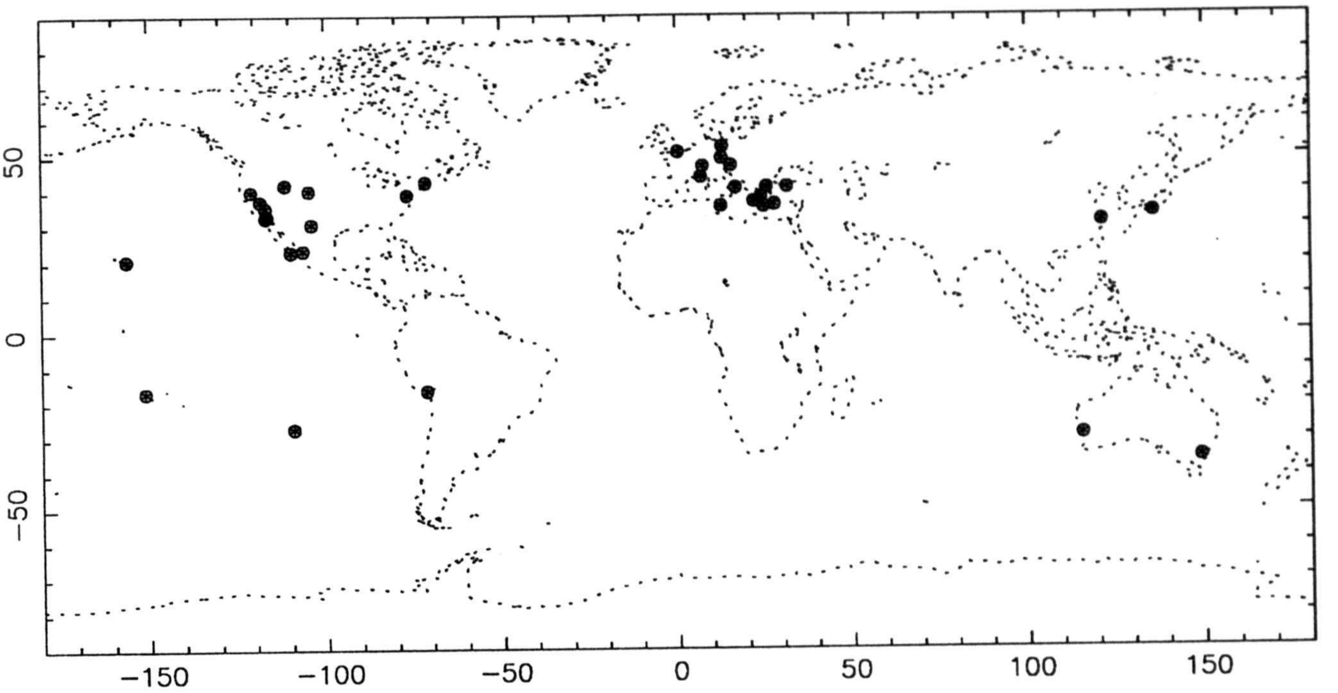
The SL8 solution was obtained by fitting the orbit of LAGEOS in 30 day (and once per year, 35 day) arcs using normal points from the global SLR tracking network between January 1980 and December 1992. The monthly arcs were combined to form a solution for a set of station positions at epoch 910101, and station velocities. Orbit and force model parameters were adjusted at the intervals listed below. Earth Orientation Parameters were estimated as independent values of time and polar motion at daily intervals since January 1983, and at 5 day intervals up to December 1982. The IERS standards were followed with the exception that the GEM-T3 gravity field with expanded ocean tidal terms was adopted and the value of the geogravitational constant was employed as listed below.

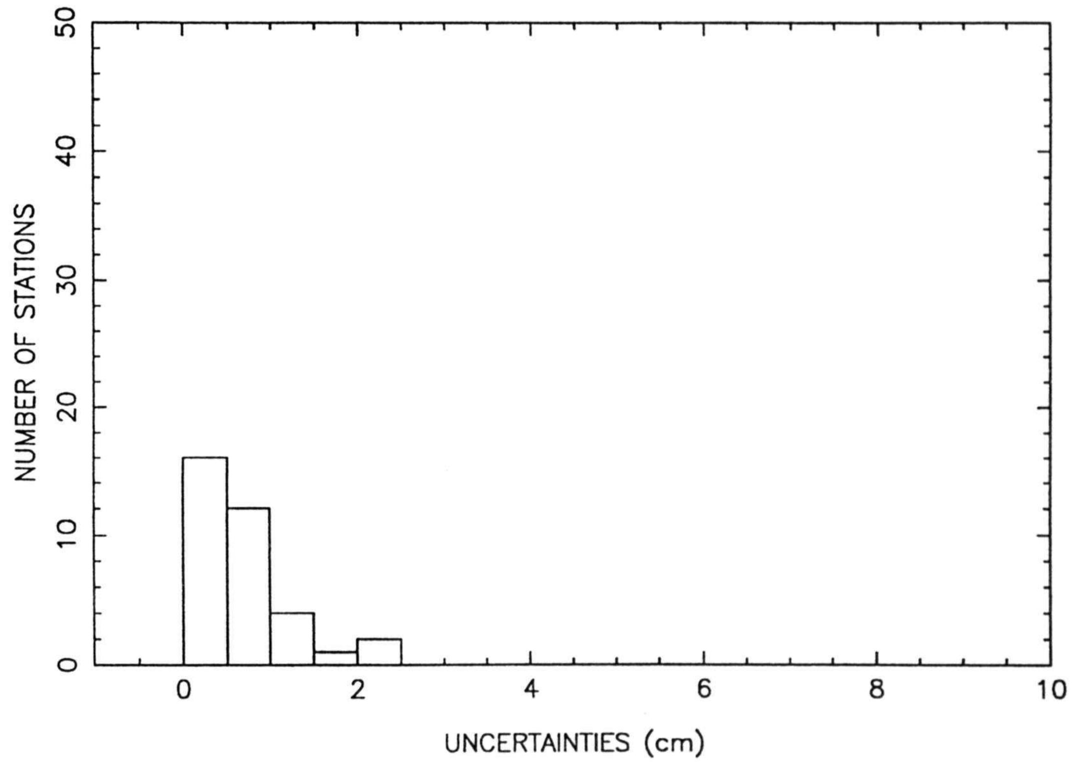
The EOP series that are attached to this submission were "Vondrak"-smoothed using an epsilon value of 0.05. The reason for the smoothing was the elimination of some spurious values due to lack of observations during the averaging interval. This only occured at a few instances, about 4% of the data have been edited in this fashion. The smoothing replaces these aberrant values with interpolated values based on those before and after the spurious point. The LODR series were obtained from the forward differencing of the UT1R series with IERS-nodes at arc-length intervals. The differencing was performed on the weakly smoothed UT1R series to minimize the noise amplification. Examination of the rms differences between the raw and the smoothed series indicates that given the accuracy of the series, the smoothing has not compromised its signal content.

Summary description of the terrestrial system attached to the set of station coordinates SSC(GSFC) 93 L 01

1 - Technique:		SLR to LAGEOS 1
2 - Analysis Center:		NASA/GSFC
3 - Solution Identifier:		GSFC SL8.2
4 - Software Used		GEODYN II and SOLVE II
5 - Relativity Scale:		Local Earth
6 - Station Tidal Correction:		Earth tides and Ocean loading (Scherneck)
7 - Tectonic plate model:		GSFC SL8.2
8 - Velocity of light:		299792458 m/s
9 - GM:		398600.4415 km^3/s^2
10 - Reference epoch:		88 01 01
11 - Adjusted Parameters	Orbit:	6 elements every 30(35) days along track accel. every 15 days once per rev. accel. every 15 days
	Stations:	position and velocity estimated except lat, lon of 7105 and lat of 7210 and lat, lon rate of 7105 and lat rate of 7210
	EOP:	X, Y, UT1 every 5 days from 80 01 01 to 82 12 28 every day from 82 12 29 to 91 12 31 one UT1 value fixed at IERS each month
12 - Definition of Origin:		Geocentric
13 - Definition of Orientation:		a priori ERP from IERS 90 C 04 and fixed station components
14 - Constraint for time evolution:		latitude and longitude rates of 7105 and latitude rate of 7210.



Distribution of the 34 sites of the terrestrial frame SSC(GSFC) 93 L 01.



Distribution of the uncertainties (quadratic mean of $\sigma_x, \sigma_y, \sigma_z$) for the 35 stations of the terrestrial frame SSC(GSFC) 93 L 01.

EOP(GSFC) 93 L 01 From Jan 1980 to Dec 1992

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
1980	74	1.31	74	0.52	61	0.90
1981	73	0.61	73	0.35	62	0.40
1982	76	0.74	75	0.63	64	0.70
1983	365	0.92	365	0.91	347	0.70
1984	366	0.56	366	0.49	354	0.50
1985	365	0.52	365	0.45	350	0.40
1986	365	0.50	365	0.44	349	0.50
1987	365	0.42	365	0.39	352	0.40
1988	366	0.44	366	0.43	354	0.40
1989	364	0.45	364	0.42	350	0.40
1990	365	0.39	365	0.41	351	0.40
1991	365	0.55	365	0.52	347	0.50
1992	365	0.52	365	0.50	353	0.80

COMBINATION

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
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)			
....									
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

COMBINATION OF PRECISE OBSERVATIONS OF THE ORIENTATION OF THE EARTH NEOS 93 C 01

[The procedure for obtaining this series is described in the IERS Annual Report for 1992, part. III].

EOP(NEOS) 93 C 01 From Sep 1980 to Jan 1993

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

YEAR	X		Y		UT1		$\delta\psi$		$\delta\varepsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1980	96	1.45	96	0.74	96	1.69	96	3.64	96	0.96
1981	365	1.96	365	1.47	365	2.70	365	3.64	365	0.96
1982	365	1.72	365	1.65	365	2.28	365	3.64	365	0.96
1983	365	1.75	365	1.27	365	2.29	365	3.64	365	0.96
1984	366	0.88	366	0.71	366	1.39	366	0.74	366	0.33
1985	365	0.70	365	0.56	365	0.93	365	0.74	365	0.28
1986	365	0.53	365	0.54	365	0.69	365	0.61	365	0.27
1987	365	0.78	365	0.64	365	0.83	365	0.66	365	0.34
1988	366	0.91	366	0.70	366	0.69	366	0.69	366	0.25
1989	365	0.92	365	0.56	365	0.57	365	0.64	365	0.31
1990	365	0.71	365	0.52	365	0.62	365	0.57	365	0.24
1991	365	0.62	365	0.51	365	0.52	365	0.64	365	0.29
1992	366	0.36	366	0.39	366	0.46	366	0.51	366	0.23
1993	19	0.46	19	0.37	19	0.54	19	0.40	19	0.33

ATMOSPHERIC ANGULAR MOMENTUM

EFFECTIVE ATMOSPHERIC ANGULAR MOMENTUM FUNCTIONS AND RELATED PARAMETERS COMPUTED AT THE U.S. NATIONAL METEOROLOGICAL CENTER

AAM(NMC) 87 * 01

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I. Introduction

As described in the *IERS Technical Note 2*, twice daily analysis values of effective atmospheric angular momentum (EAAM) functions (Barnes *et al.*, 1983) have been calculated from NMC global analyses throughout 1992. These include variables which relate to Earth rotation and polar motion. Starting 1 October 1989, the operational start date of the SBAAM, a more complete set of analysis and forecast values of EAAM functions and related analysis parameters have been produced.

II. SBAAM Data

Following Sub-Bureau specifications, two files have been produced by NMC beginning 1 October 1989. The first, an analysis file, contains hemispheric values of the EAAM functions χ_1, χ_2, and χ_3, each of which is further partitioned into wind, pressure, and pressure + inverted barometer components. The Sub-Bureau also requested that wind terms be calculated to 100 mb, as well as to the top of the model; however, this is done only for the χ_3 term. As a result of an earlier formulation, all NMC χ_3 values calculated before October 1989 were multiplied by a minus sign. This was stopped on 1 October 1989. This file also contains analyses of zonal mean zonal wind, zonal mean temperatures, mean surface pressure and low order spectral coefficients of surface pressure. With the exception of the surface pressure fields, all analysis parameters and EAAM functions are derived from an initialized global analysis. The complete analysis file is produced twice daily, at 00 and 12 UTC. The second file contains 21 sets of forecast values (00-h to 240-h) of the EAAM functions at 12-hour intervals starting at 00 UTC. These values are globally integrated. A more complete description of both files is found in Table 1.

These data are archived monthly, and are also available from a dial-up service at NMC. The analysis file and forecast file are transferred once daily are maintained on a 10-day rotating file. An additional file is produced for the dial-up service only and contains hemispheric values of the EAAM functions and forecast values of zonal mean zonal winds. Complete information on the NMC files and dial-up system is found in a NMC User's Guide, available from the Sub-Bureau.

III. NMC Global Analysis and Forecast System

The NMC global data assimilation and forecast system is described in detail by Kanamitsu (1989). The global analyses are produced every 6 hours with an intermittent assimilation of data that uses a 6-h forecast as an initial guess. A diabatic nonlinear normal mode initialization procedure is performed on the analyses and is necessary for dynamic balance. The initialization procedure was changed on 14 December 1989 to a procedure which initializes only the analysis increments. This new procedure reduces the effect of the initialization on the analyses.

The NMC global forecast model has 18 vertical sigma layers and a horizontal resolution of 80 waves with triangular truncation. The EAAM functions are calculated after a vertical interpolation from the sigma coordinates to constant pressure levels (1000 mb to 50 mb) and a grid with horizontal resolution of 2.5 lat/lon. Therefore, wind integrals are calculated to 50 mb. Pressure terms are calculated on the model surface, where the orography is an enhancement of silhouette orography (Mesinger *et al.*, 1988). On 14 December 1989 changes were implemented in the surface physics package which were designed to result in a more realistic cycle and pattern of evaporation. It is felt that this change will result in minor changes in the forecasted surface pressure.

Results of some of the NMC calculations are shown in the 1991 IERS Annual Report.

Table 1. Content of SBAAM Files

Variable	Analysis File Specification	Array size
$\chi_2, \chi_2, \chi_2,$	hemispheric values of wind to 100mb, wind to top of model (50mb), pressure, pressure + inverted barometer	(8,3)
zonal mean zonal wind (m/s)	5 degree latitude bands, 12 mandatory pressure levels (1000 - 50mb)	(37,12)
zonal mean temperature (K)	5 degree latitude bands, 12 mandatory pressure levels (1000 - 50 mb)	(37,12)
mean global surface pressure (mb)		(1)
low-order spherical harmonics of surface pressure	4 wave, triangular truncation 20 wave, zonals only with and without inverted barometer	(30) (21) (30) (21)
	Forecast File	
$\chi_2, \chi_2, \chi_2,$	global values of wind to 100 mb, wind to top of model, pressure, pressure + inverted barometer; forecast lead times every 12 hours (00-h to 240-h)	21 arrays of (4,3)

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Barnes, R.T.H., Hide, R., White, A.A,.and Wilson, G.A., 1983: Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *Proc. Roy. Soc. Lond.* **A, 387,** 31-73.

Kanamitsu, M., 1989: Description of the NMC Global Data Assimilation and Forecast System, *Wea. Forecasting,* **4**, 335-342.

Mesinger, F., Janjic, Z.I., Nickovic, S., Gavrilov D., and Deaven, D.G., 1988: The step-mountain coordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment, *Mon. Wea. Rev.*, **116**, 1493-1518.

AAM(NMC) 87 * 01 From 1976 to 1992

Year	Number of meas.	Year	Number of meas.
1976	182	1984	679
1977	358	1985	686
1978	352	1986	696
1979	333	1987	722
1980	326	1988	679
1981	630	1989	711
1982	630	1990	720
1983	656	1991	718
		1992	717

EFFECTIVE ATMOSPHERIC ANGULAR MOMENTUM FUNCTIONS COMPUTED AT THE EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

AAM(ECMWF) 87 * 01

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As reported in the *IERS Technical Note 2,* effective atmospheric angular momentum (EAAM) functions have continued to be calculated at ECMWF throughout 1991. The EAAM functions are calculated for the analyses every 6 hours and for forecasts from 12 UTC each day to 10 days (see Sakellarides, 1989). The inverted barometer terms are not calculated. The data are archived at ECMWF but are not supplied to the Sub-Bureau.

In May of 1989, ECMWF implemented changes in the cumulus convection and radiation schemes of its global model. The effect, if any, of these changes on the EAAM series is not known.

References

Sakellarides, G., 1989: Atmospheric effective angular momentum functions for 1986-1987, *ECMWF Research Department Technical Report No. 62.*

AAM(ECMWF) 87 * 01 From 1986 to 1991

Year	Number of Measurements
1986	365
1987	365
1988	732
1989	730
1990	730
1991	62

EFFECTIVE ATMOSPHERIC ANGULAR MOMENTUM FUNCTIONS COMPUTED FROM THE JAPAN METEOROLOGICAL AGENCY DATA AAM(JMA) 87 * 01

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The effective atmospheric angular momentum (EAAM) functions proposed by Barnes *et al.* (1983) have been computed from the global analysis data provided by the Japan Meteorological Agency (JMA) since September 28, 1983. In general, the operational numerical weather prediction produces the three data sets called the analysis-phase analysis data, the initialized phase analysis data and the predicted values. The JMA global analysis data are the analysis-phase analysis data. For the use of this file, it should be noticed that the results during 1983/12/1 - 1986/6/30 are once-a-day values computed from daily mean global data of the JMA global analysis data averaged at each grid and each level, otherwise twice-a-day (00 UT and 12 UT) values computed without averaging.

The JMA global analysis data have been made on 1.875-degree (2.5-degree before 1988/3/1) latitude-longitude grid system at sixteen levels (fifteen levels before 1988/3/1) up to ten millibars by the following analysis and forecast models. The analysis model is based on a multi-variate optimum interpolation method in troposphere and on a sinusoidal fitting method in stratosphere, with the initial guess of six hour forecast and the cut-off time of six hours after map time. The forecast model is based on a 1.875-degree (2.5-degree before 1988/3/1) and sixteen-level (twelve-level before 1988/3/1) global spectral model after a non-linear normal mode initialization with physics. The model has a horizontal resolution of triangular truncation at wavenumber 63 (42 before 1988/3/1) and incorpolates full physical processes. The details for the analysis and forecast models after 1988/3/1 can be found in Kitade(1988), Kashiwagi (1987) and Kanamitsu *et al.* (1983) for those before 1988/3/1.

For computing the EAAM functions, the sea level pressure, the geopotential height and the wind velocities at each level are used. In addition, mountain heights of the same grid system are used for estimating surface pressures on land and for computing sea level pressures on ocean with the Inverted Barometer (IB) hypothesis. The surface pressures on mountains are computed from the geopotential heights by using a cubic spline interpolation technique with estimating the thickness temperatures by the same techniques. Vertical integrations of the wind terms of the EAAM functions are done from surface pressure on land (or the sea level pressure on ocean) to ten millibars. The integral formula to evaluate the EAAM functions are basically due to the equations (5.1), (5.2) and (5.3) of Barnes *et al* (1983), but the axial component of the EAAM functions is due to the equation (5.3) multiplied by -1 for convenience. No smoothing have been done after evaluation. Details of the evaluation can be found in Naito *et al.* (1987).

Acknowledgements

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Naito, I., Kikuchi N., and Yokoyama, K., 1987: Results of estimating the effective atmospheric angular momentum functions based on the JMA global analysis data, *Publ. Int. Latit. Obs. Mizusawa,* **20**, 1-11.

AAM(JMA) 87 * 01 From 1983 to 1991

Year	Number of Measurements
1983	150
1984	357
1985	365
1986	549
1987	730
1988	732
1989	730
1990	730
1991	730

EFFECTIVE ATMOSPHERIC ANGULAR MOMENTUM FUNCTIONS CALCULATED AT THE U.K. METEOROLOGICAL OFFICE AAM(UKMO) 83 * 01

Throughout 1991, 00-hour and forecast values of effective atmospheric angular momentum (EAAM) functions as described by Barnes *et al.* (1983) have been calculated twice daily, from 00 and 12 UTC. The functions are archived at 24 hour intervals to 6 days, the limit of the UKMO global model. The matter terms are calculated without applying the inverted barometer correction. The UKMO global model and data assimilation have been described in the *IERS Technical Note 2*. Changes are routinely documented in each "Quarterly report on numerical products from Bracknell."

The UKMO forecast file is sent to the Sub-Bureau every three months. Starting in mid-1990, twice daily transmissions of these data will be completed using the GTS data link.

References

Barnes, R.T.H., Hide, R., White A.A. and Wilson, C.A., 1983: Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *Proc. R. Soc. Lond.* **A 387**, 31-73.

Quarterly report on numerical products from Bracknell - U.K. Meteorological Office, London.

AAM(UKMO) 83 * 01 From 1983 to 1992

Year	Number of meas.	Year	Number of meas.
1983	241	1988	725
1984	366	1989	727
1985	365	1990	721
1986	306	1991	679
1987	721	1992	713

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