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

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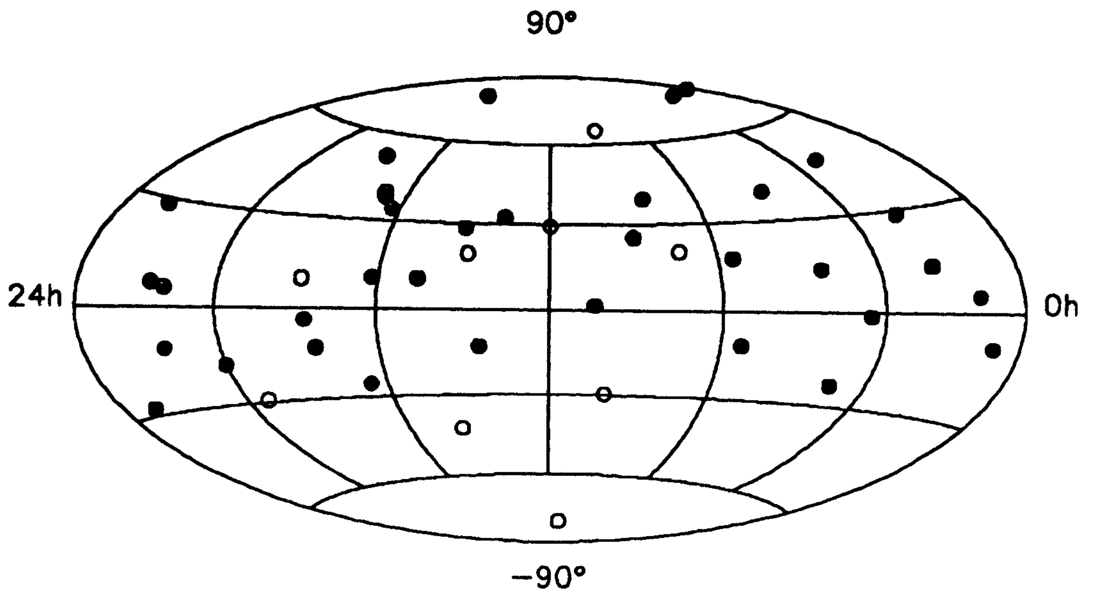
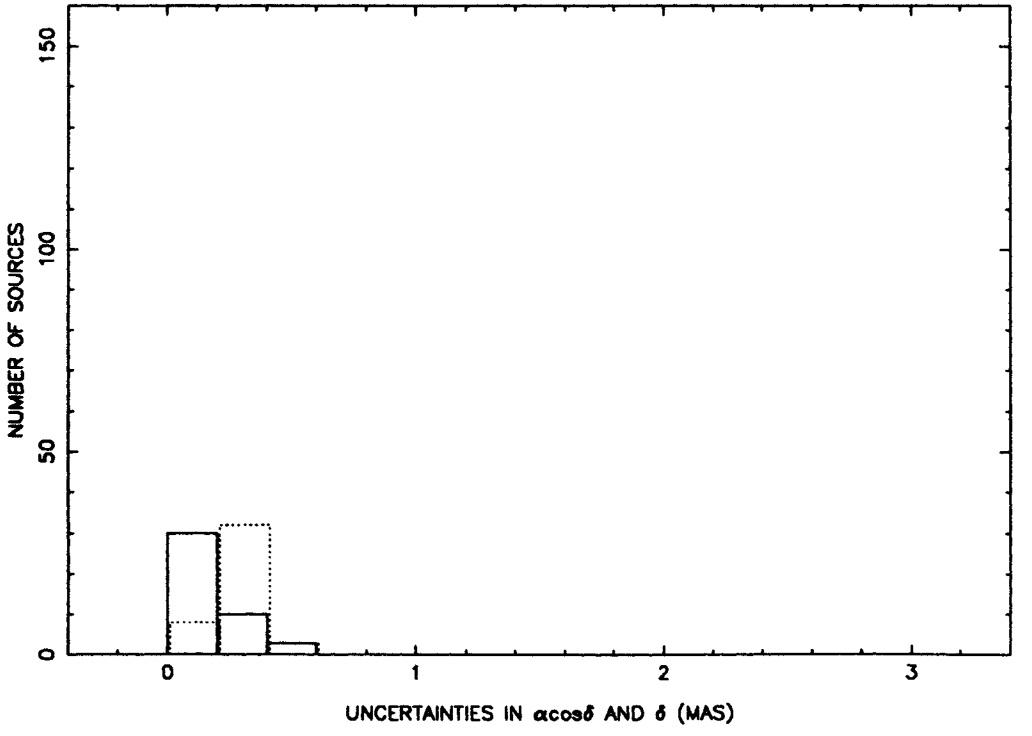
Summary description of the terrestrial system attached to the set of station coordinates GIUB 93 R 02

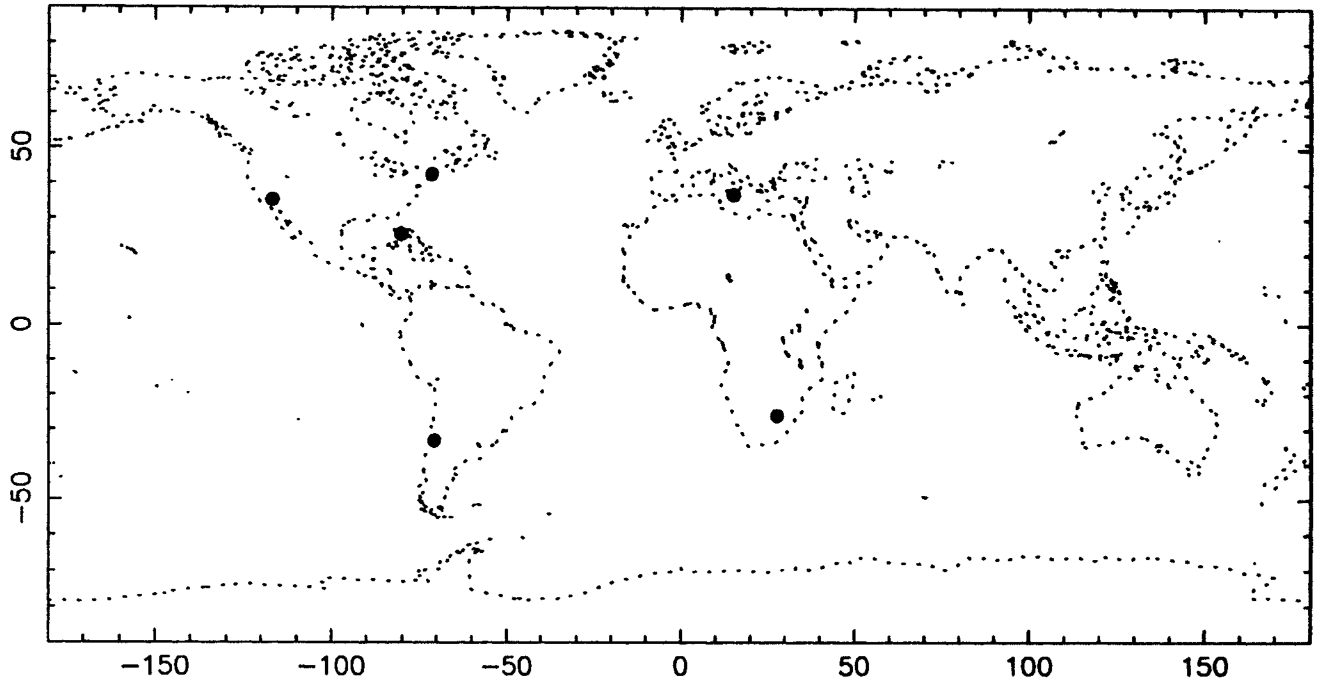
1 - Technique:	Mark III VLBI, Group delay observables
2 - Analysis Center:	GIUB
3 - Solution identifier:	SSC(GIUB) 93 R 02
4 - Software used:	CALC 7.6, SOLVE/GLOBL
5 -Relativity scale:	Solar System Barycenter
6 - Permanent tidal correction on station:	Not applied
7 - Tectonic plate model:	NNR-NUVEL1
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:	Fixing Wettzell ITRF 1991 coordinates
Celestial:	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



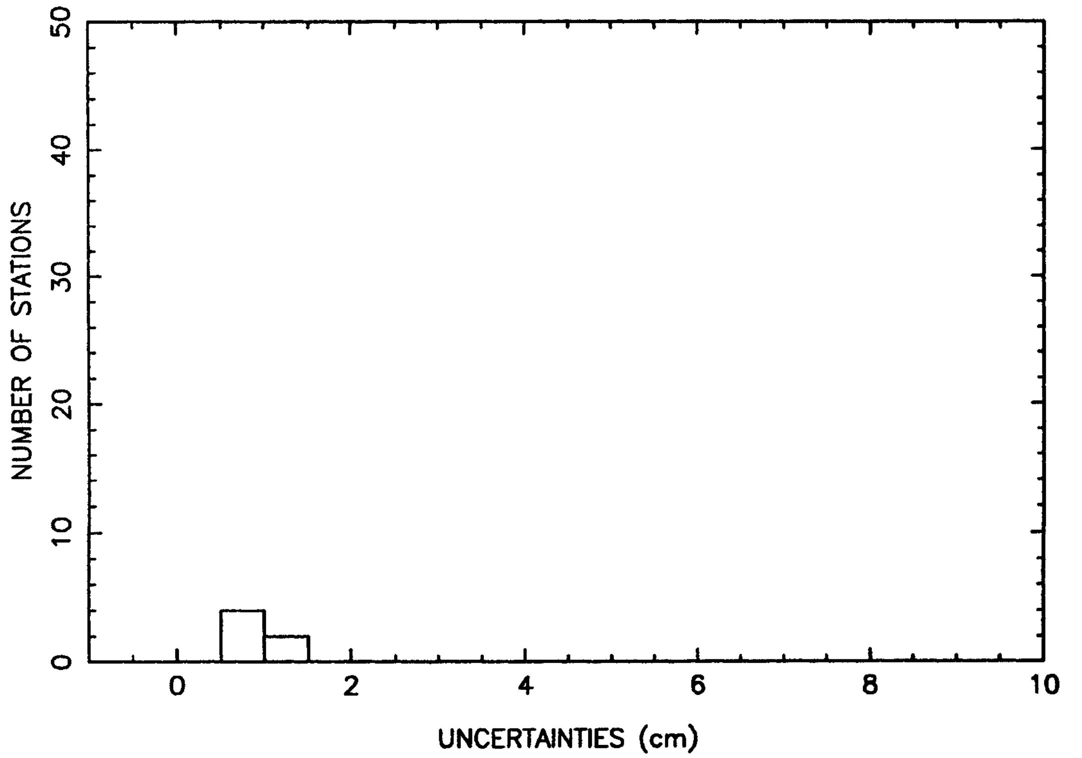
Distribution over the sky of the 44 extragalactic radio sources of the celestial frame RSC(GIUB) 93 R 01. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



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 $\sigma_x, \sigma_y, \sigma_z$) 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, $\delta\psi$, $\delta\epsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$\delta\psi$		$\delta\epsilon$	
	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, $\delta\psi$, $\delta\varepsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$\delta\psi$		$\delta\varepsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
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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J.W. Ryan, Code 926, Goddard Space Flight Center, Greenbelt, MD 20771, USA

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.

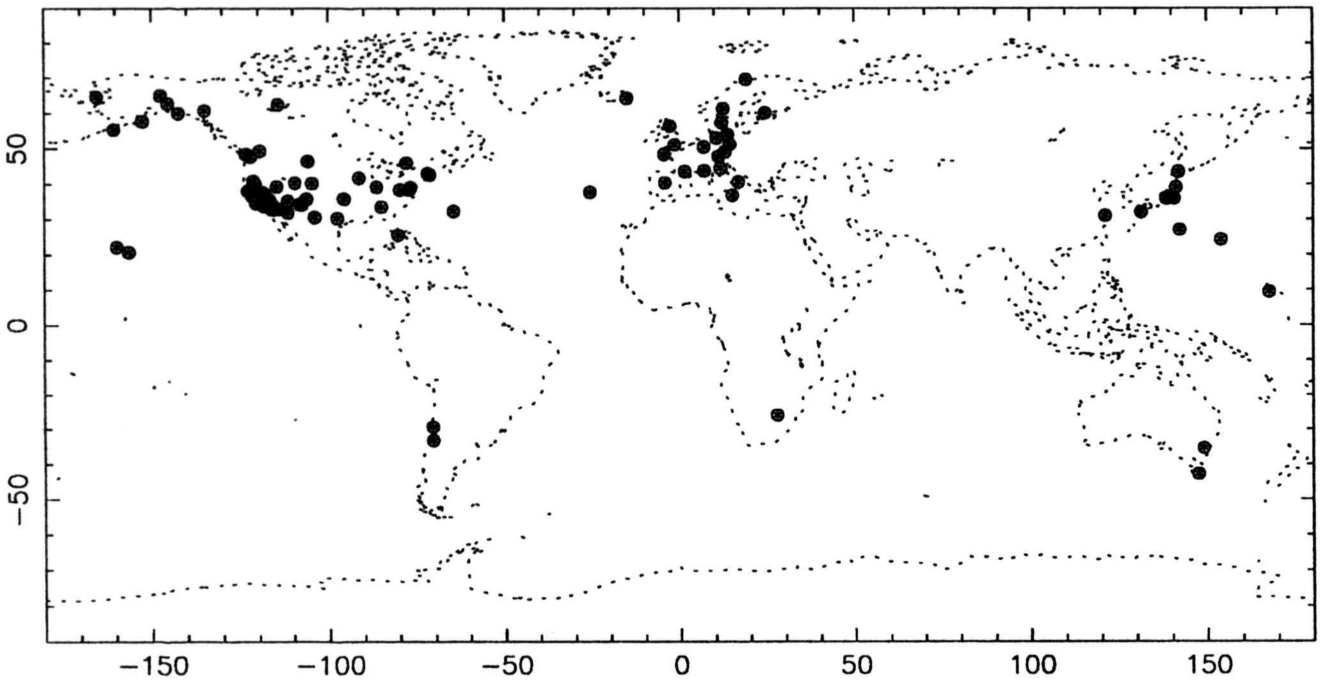
References

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

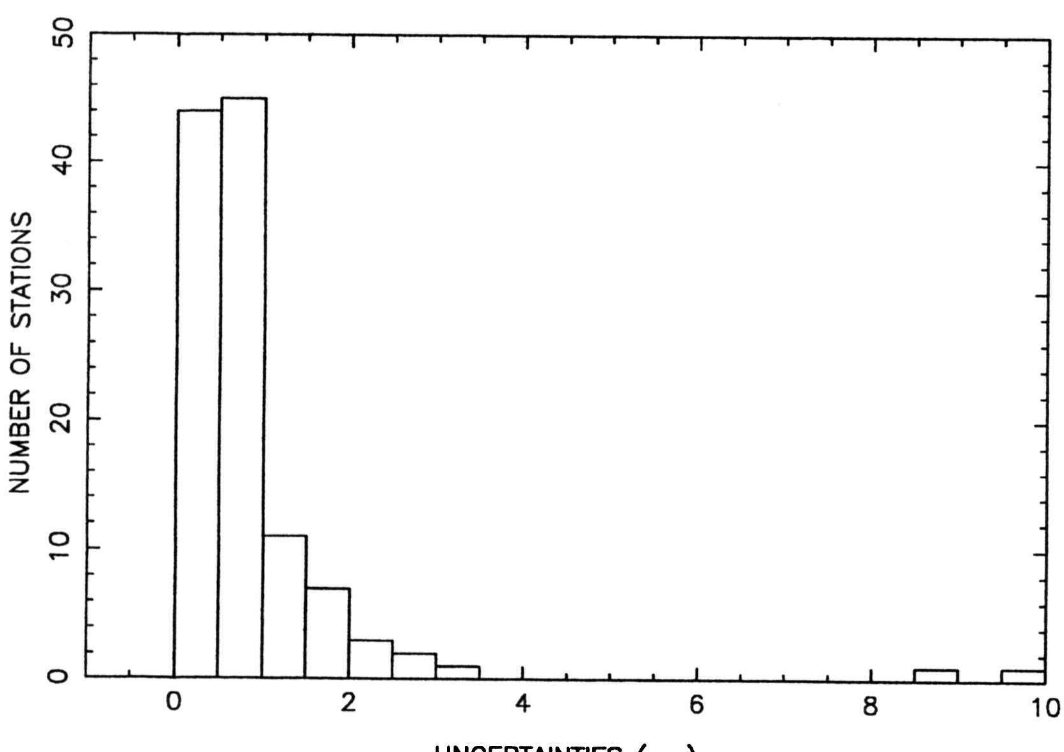
Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36,** 157.

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.

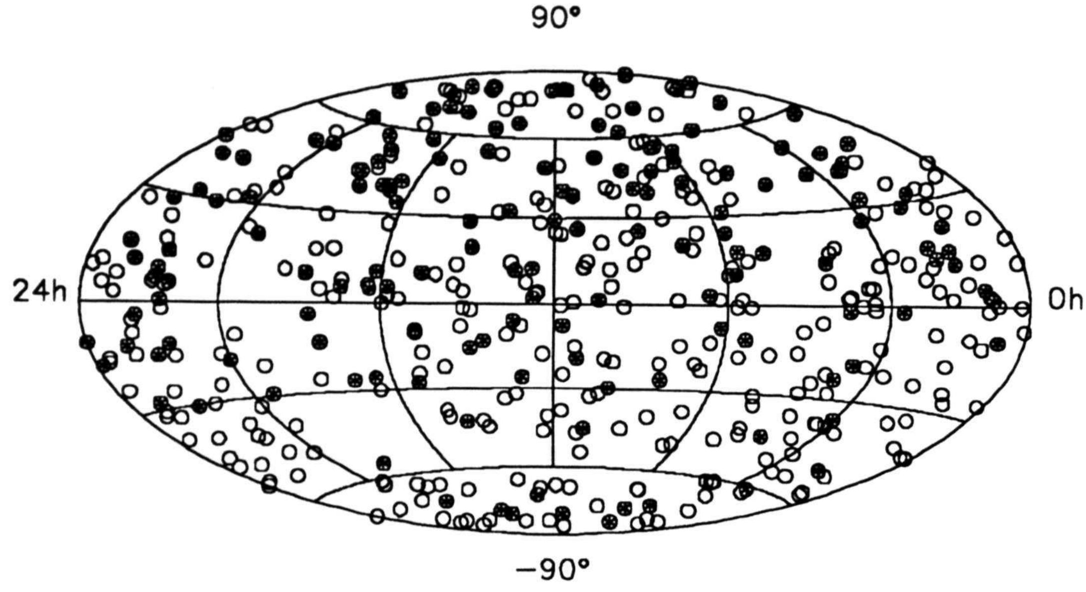
References

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

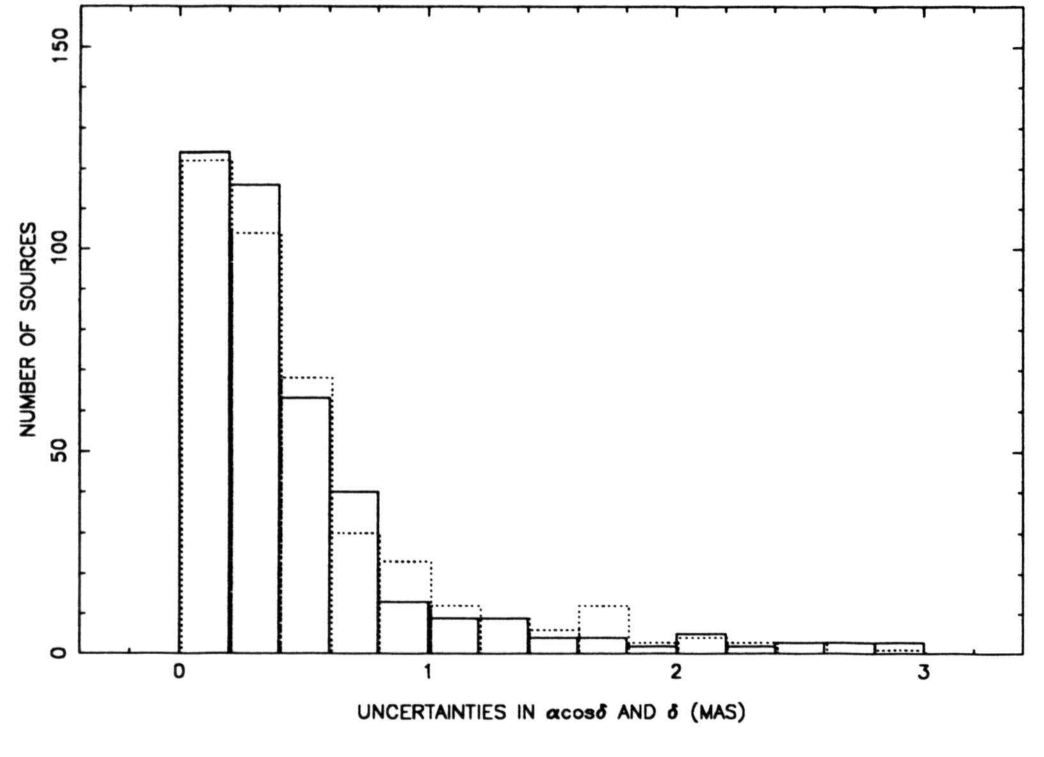
Herring, T.A., 1992: *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy*, ed. by J.C. De Munch and T.A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, *Publications on Geodesy* No **36**, 157.

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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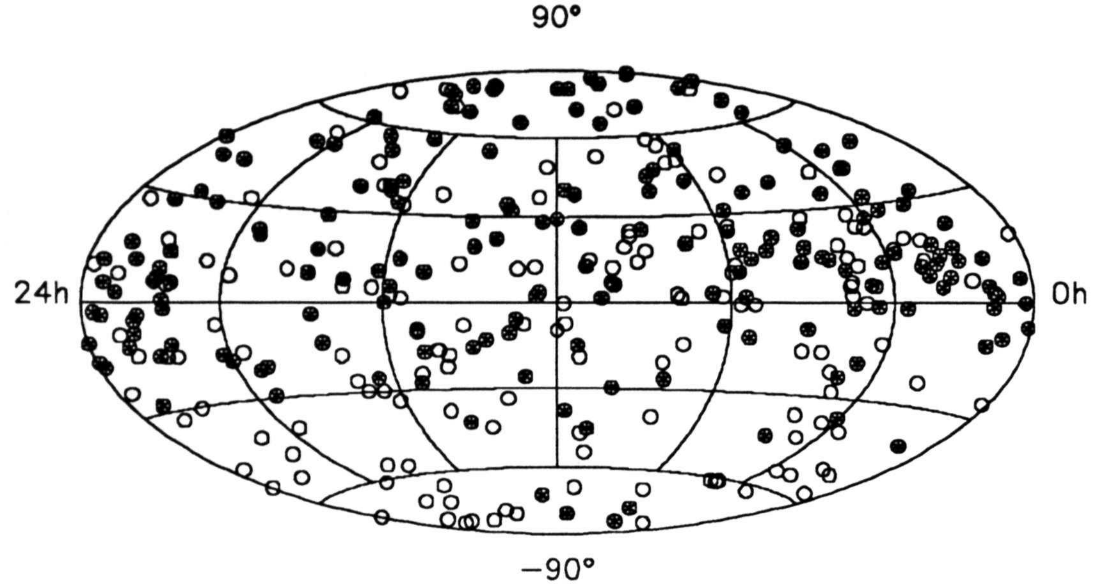
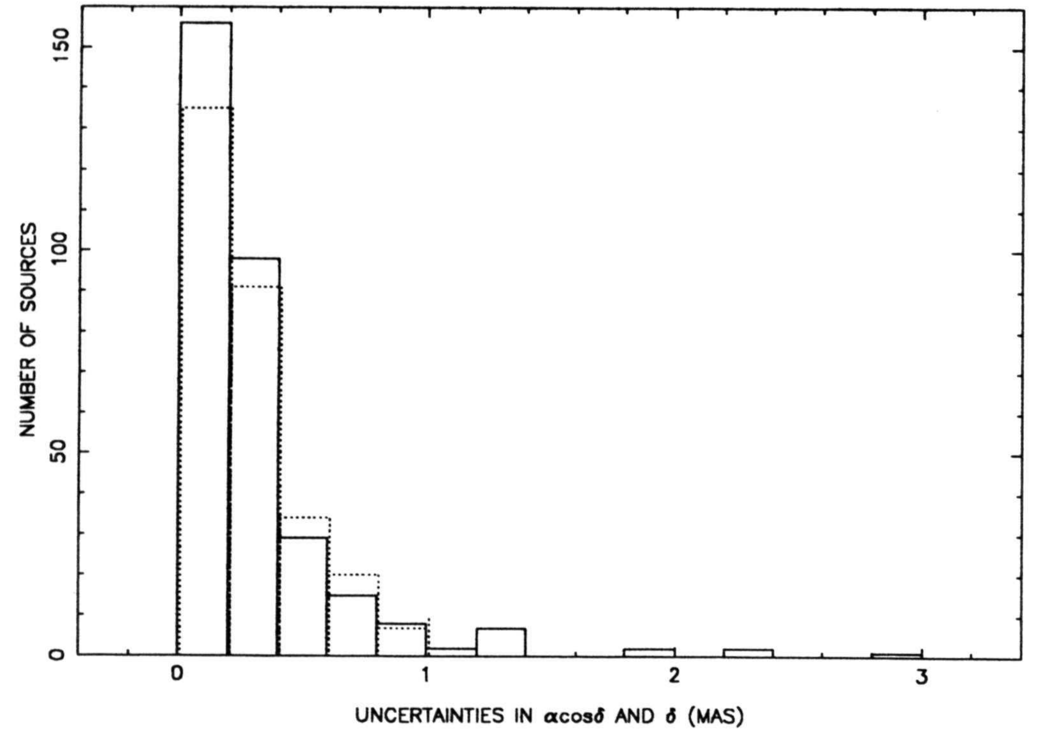
This set of radio source coordinates is based on a combination of all available VLBI data. It is the catalog that was generated in the analysis leading to the JPL model for short-period tidal UTPM variations (Sovers *et al.* 1993). Details of the fit can be found in that manuscript. The celestial frame 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 ($\alpha\cos\delta$) 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	Sine	Polar Motion Amplitude (microarcseconds) prograde	retrograde	Phase (degrees) prograde	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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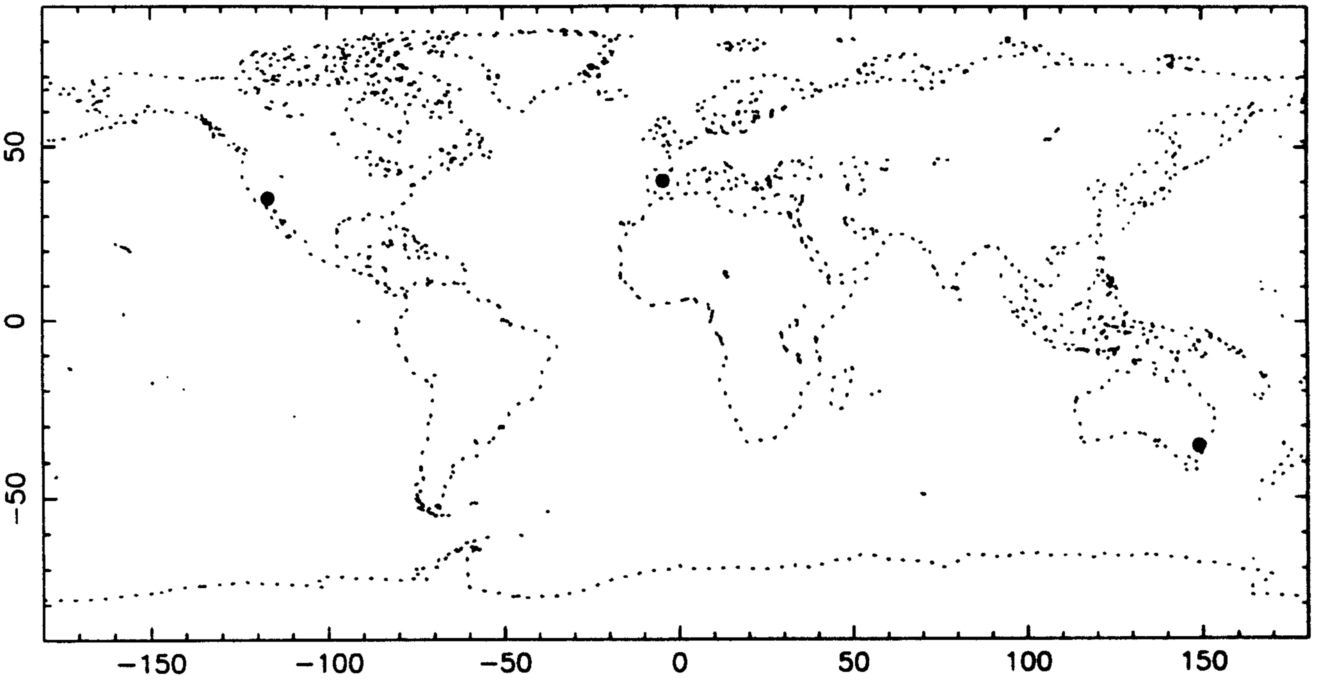
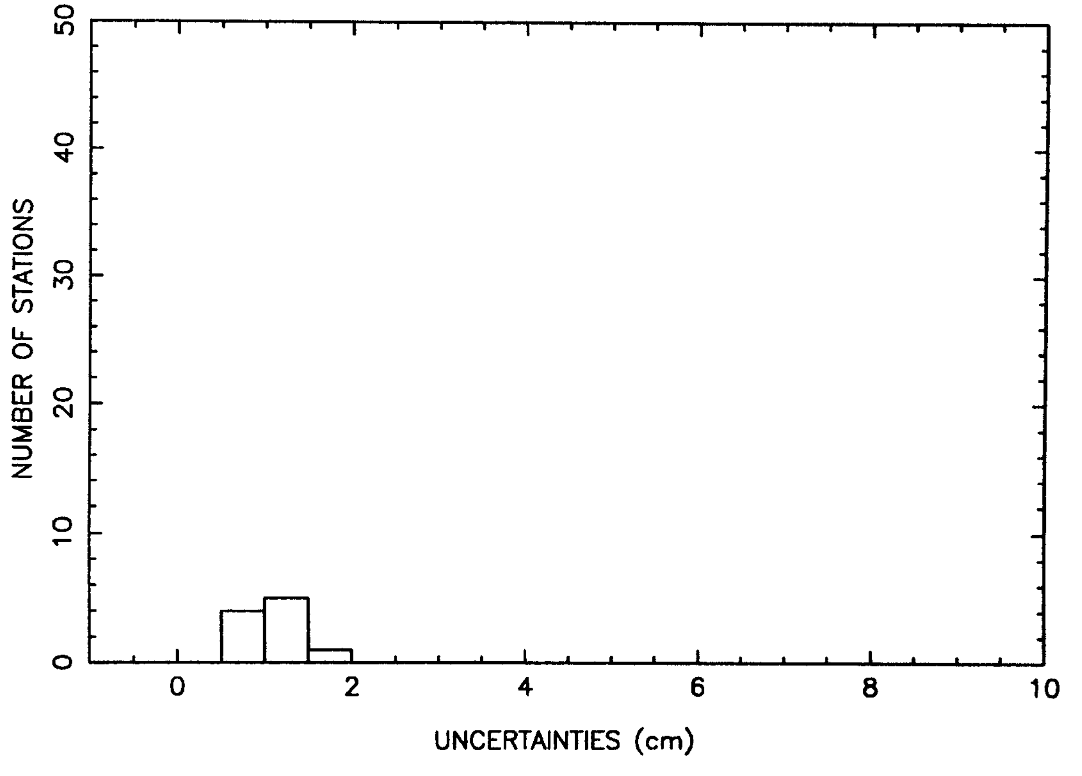
Summary description of the terrestrial system attached to the set of station coordinates SSC(JPL) 93 R 01

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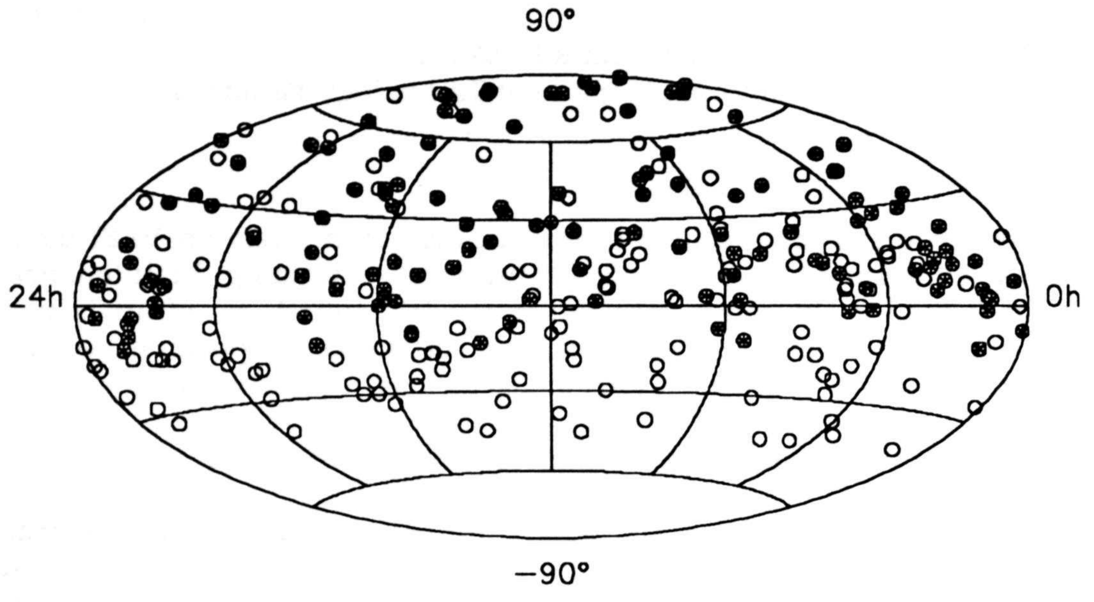
This collection of radio source coordinates is based solely on VLBI data from the JPL/DSN experiments performed in support of Catalog Maintenance and Enhancement (CM&E). In contrast to the frame JPL 1993-1, no effort is made to maintain continuity, for example by constraining certain source positions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

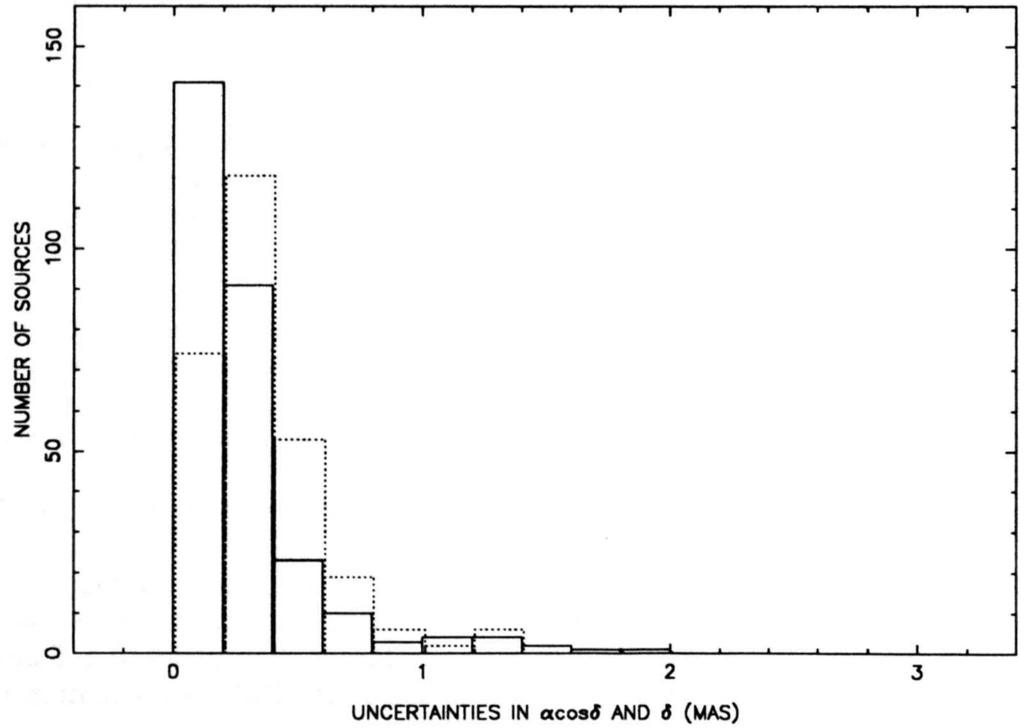
Some details of the analysis performed to generate JPL 1993-2 are:

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 ($\alpha\cos\delta$) 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 <u>NOAA celestial reference frame</u> at epoch J2000.0 is specified by constraining the sum of the adjusted RA values for <u>36 radio sources</u> 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

$$\sum \Delta\alpha_i = C_\alpha \quad (1)$$

where

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

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:

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

which means that the constraint in this case is equivalent to

$$\sum \alpha_i = \sum \alpha_{i,icrf} \quad (4)$$

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

$$\sum \Delta R_i = C_{xyz} \quad (5)$$

where

$$\Delta R_i = \text{vector position adjustment for site i} = R_i - R_{i,prior} \quad (6)$$

and for the choice

$$C_{xyz} = \sum (R_{i,itrf} - R_{i,prior}) \quad (7)$$

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 **V** times components of **R**. Using the relationship for the variance of a product to describe the elements of the variance of this equation gives

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

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

$$F = \begin{vmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t \\ & & \multicolumn{2}{c}{\Delta t = t_1 - t_0} & & \end{vmatrix} \tag{16}$$

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 $\text{ps/hr}^{1/2}$.

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

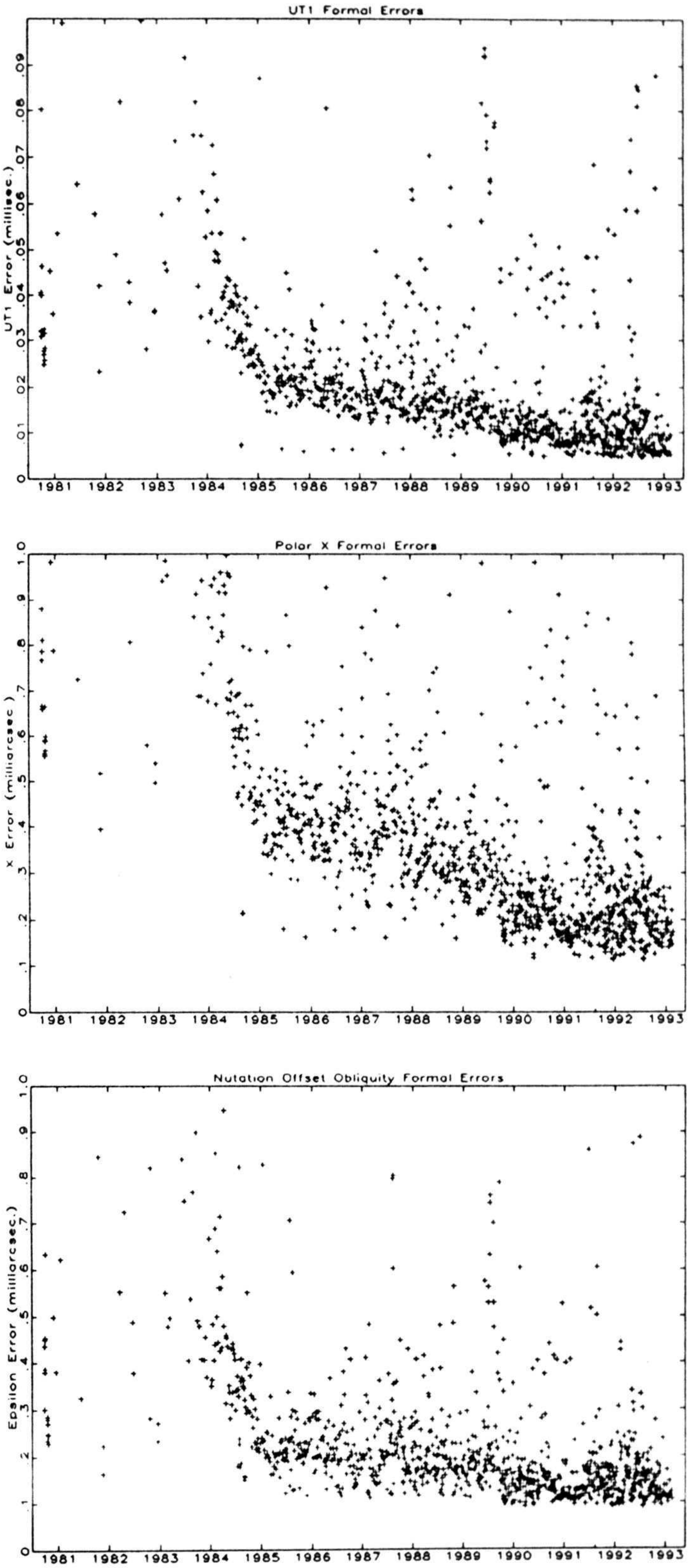

Fig. 1. EOP formal errors for UT1 (top), X (middle), and nutation obliquity (bottom).

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.

Intensive UT1 Results. 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.

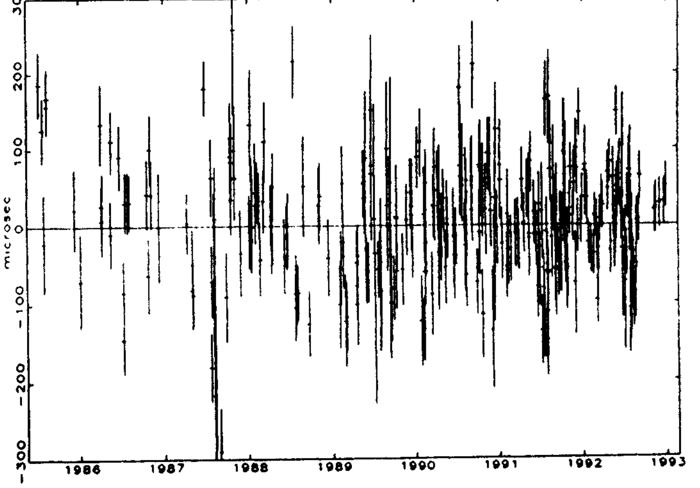

Fig. 2. Differences in UT1 from IRIS Intensives and coincident multi-baseline VLBI sessions.

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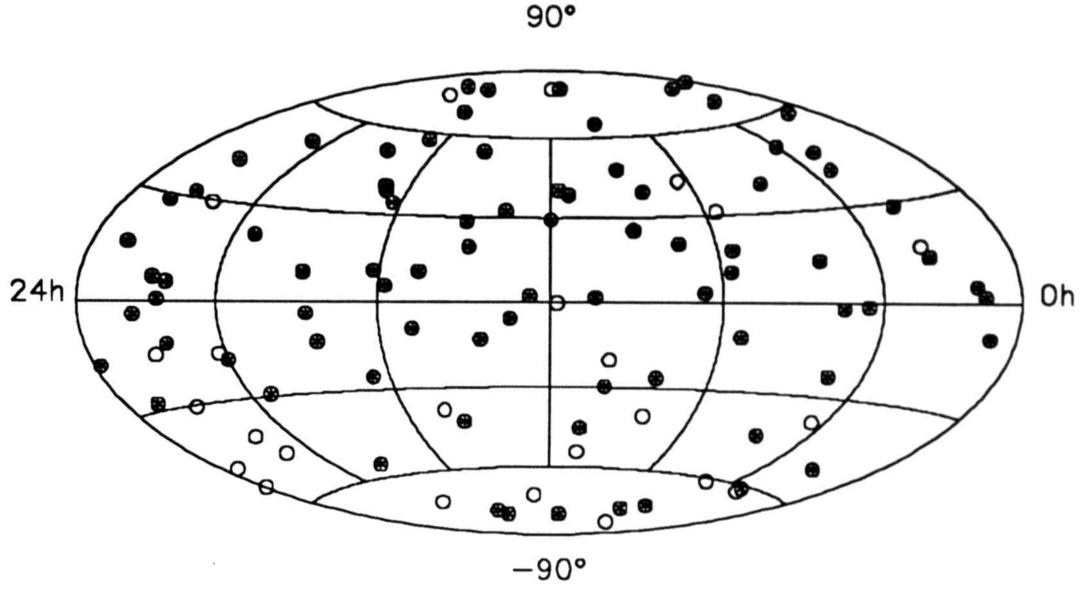
Summary description of the terrestrial system attached to the set of station coordinates SSC(NOAA) 93 R 02

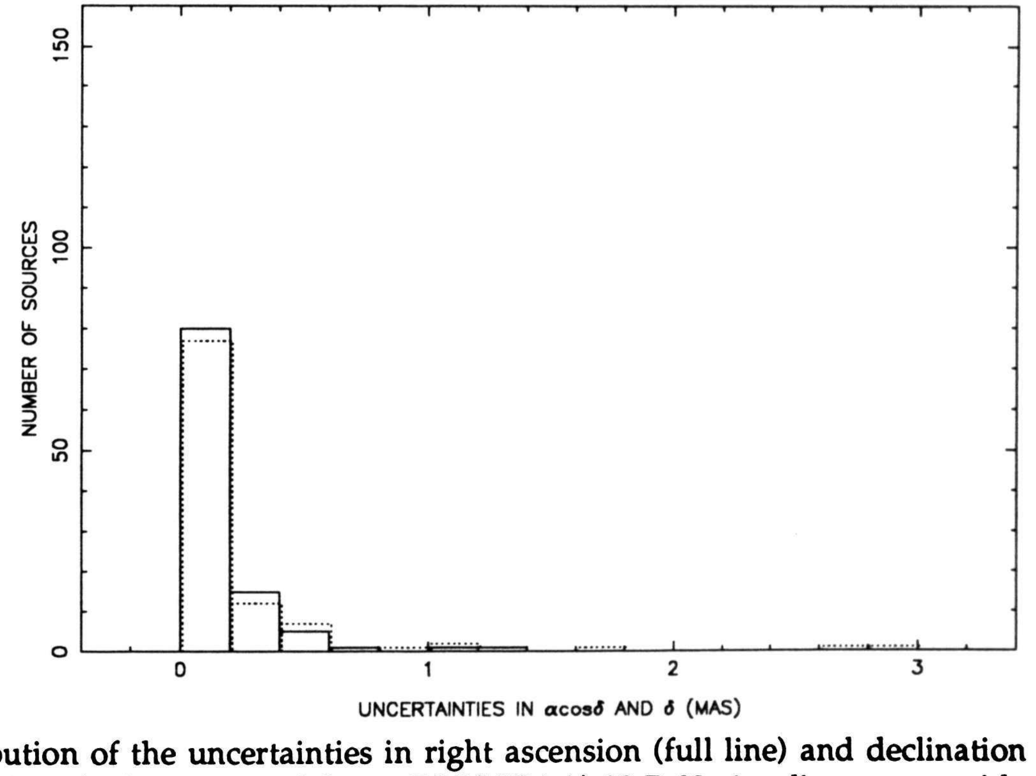
1 - Technique:	Bandwidth-synthesis Mark III VLBI
2 - Analysis Center:	NOAA VLBI Analysis Center, N/OES13 11400 Rockville Pike Rockville, MD, USA 20852
3 - Solution Identifier:	solution rundate = 09/03/93 17:23:57
4 - Software Used:	COREL and FRNGE for the Mark III data correlation; DE200 ephemerides, 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

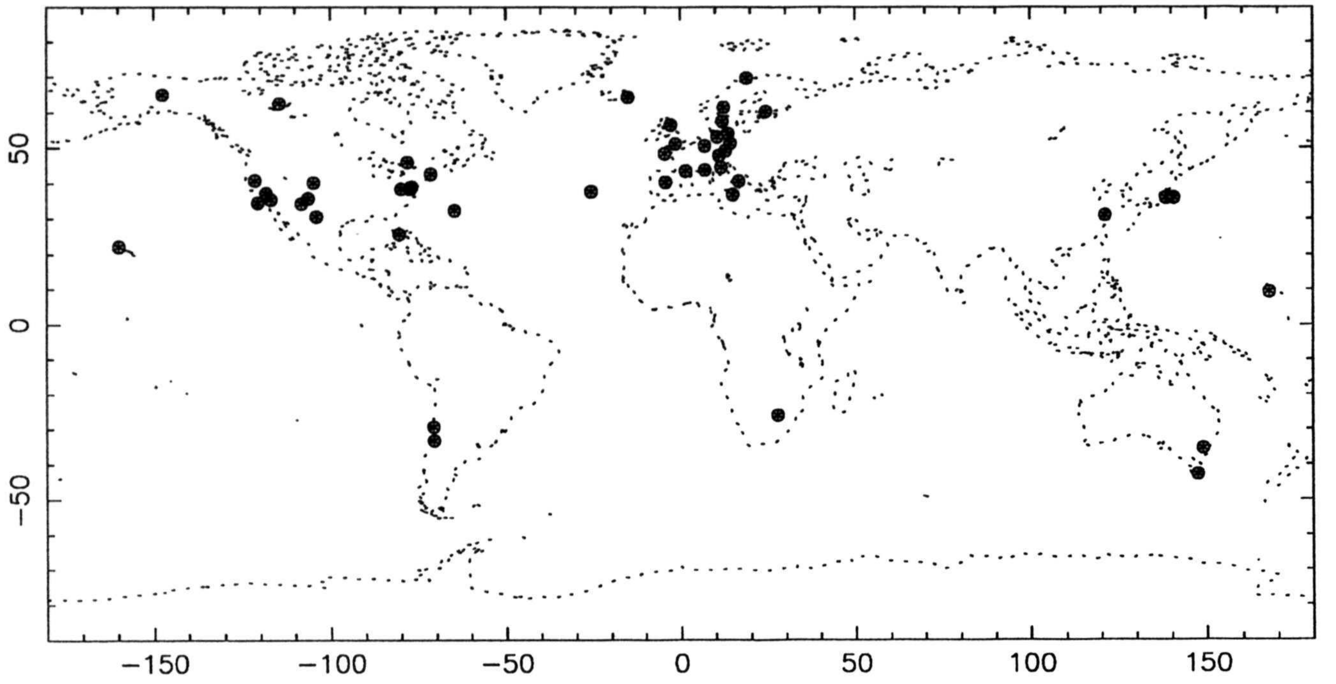
11 - Adjusted Parameters:	XYZ geocentric station coordinates and linear station velocities adjusted globally for all sites at their mean observation epochs; radio source coordinates adjusted globally for all sources; pole X and Y coordinates, UT1, nutation longitude and obliquity offsets adjusted for 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.



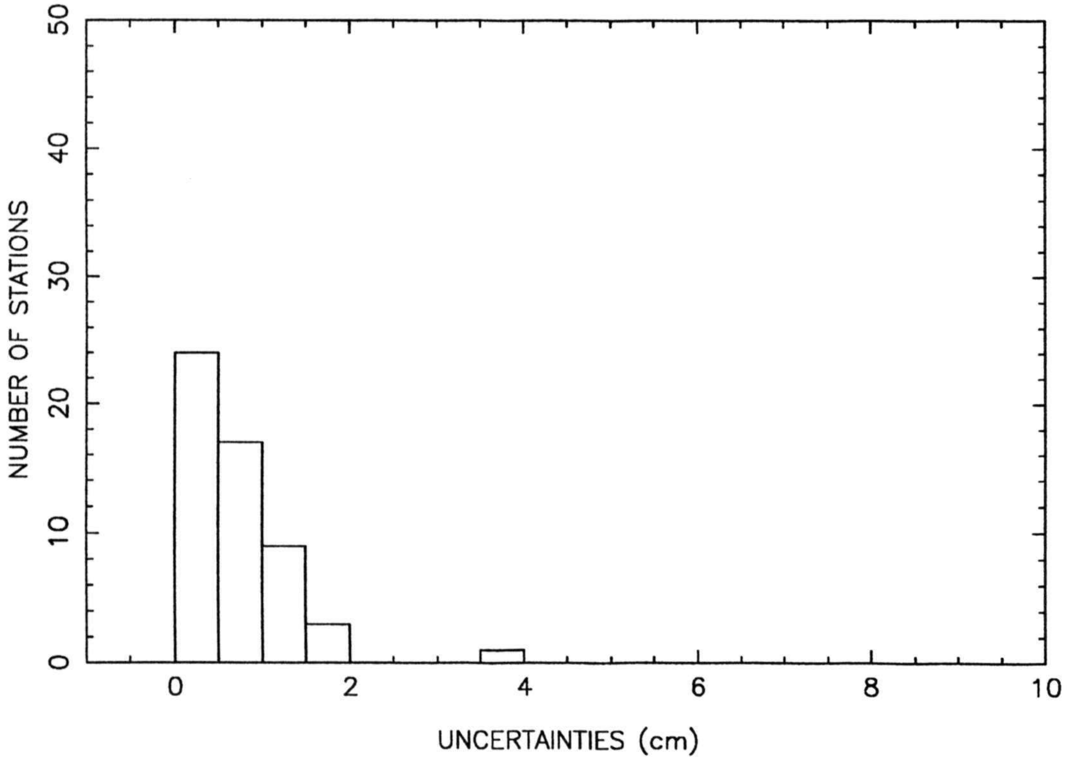
Distribution over the sky of the 107 extragalactic radio sources of the celestial frame RSC(NOAA) 93 R 02. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



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, $\delta\psi$, $\delta\epsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$\delta\psi$		$\delta\epsilon$	
	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, $\delta\psi$, $\delta\epsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$\delta\psi$		$\delta\epsilon$	
	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.

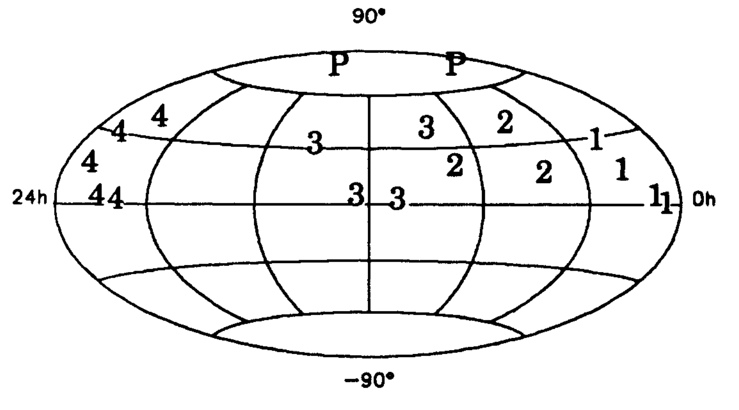

Figure 1. Program sources in the IRIS intensive observations. P : permanently observed, 1, 2, 3, 4 : observed during the corresponding trimester.

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.

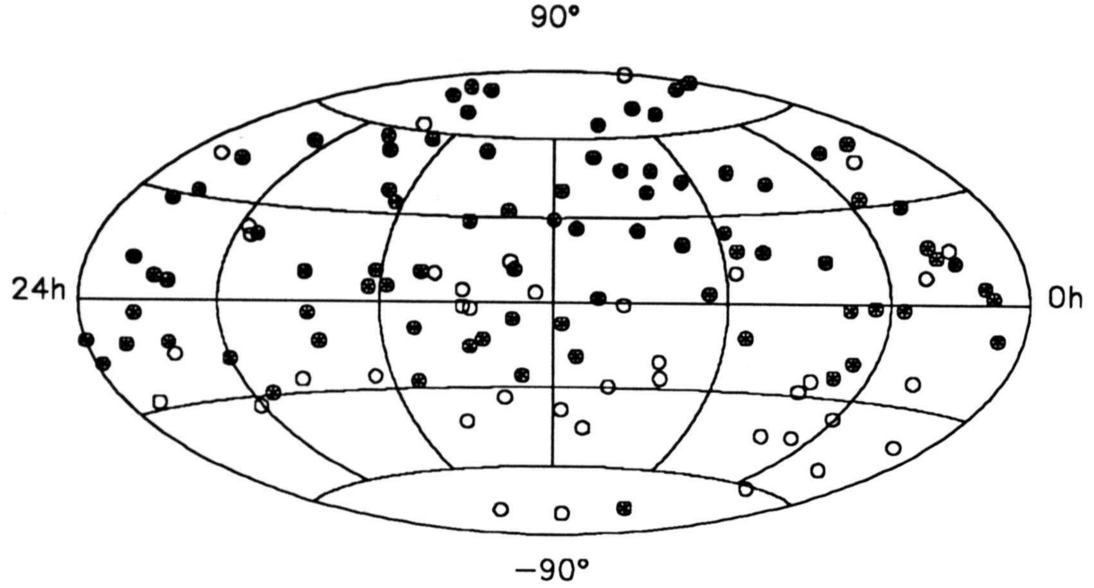
The errors presented in this report are formal errors obtained from the covariance matrix of the least squares adjustment. The post fit residual scatter is always larger than would be expected given the formal error estimates for the delay and delay rate observables provided by the correlator. The total 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.

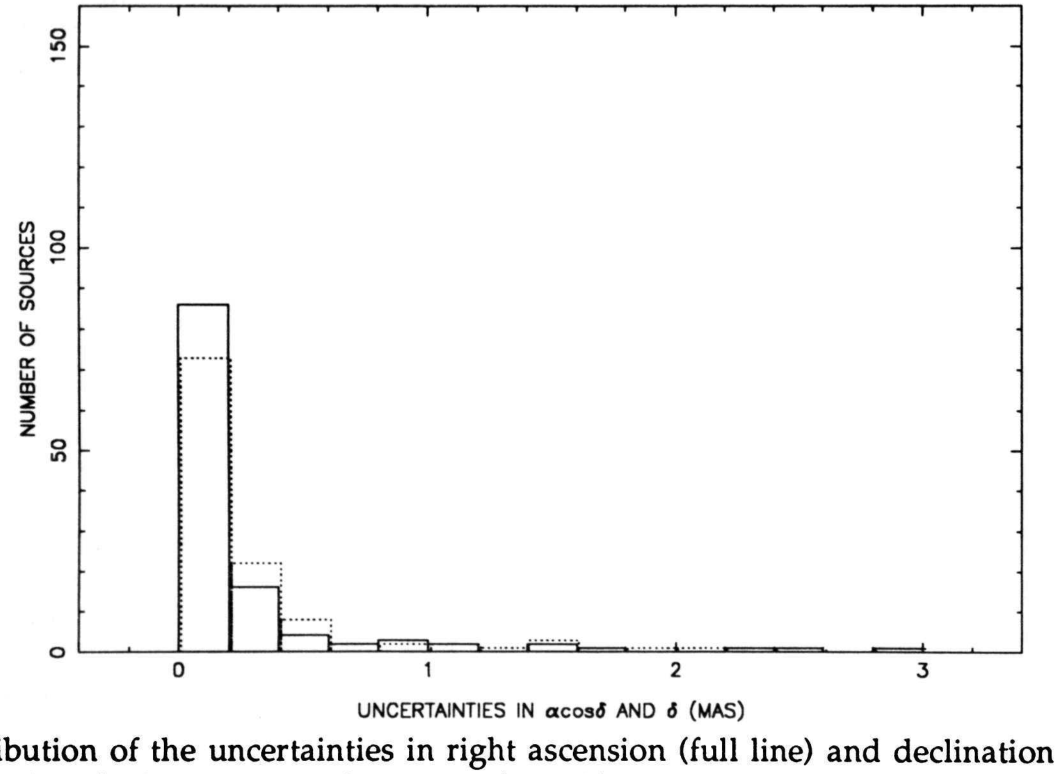
Questions, comments or requests to be placed on the NAVNET distribution list should be directed to T.M. Eubanks, Code TSEO, U.S. Naval Observatory, Washington D.C. 20392-5100, by phone at (202) 653-1501, on SPAN at CDDIS::USNO or USNO01::TME, and on Internet at tme@casa.usno.navy.mil or tme@usno01.usno.navy.mil.

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

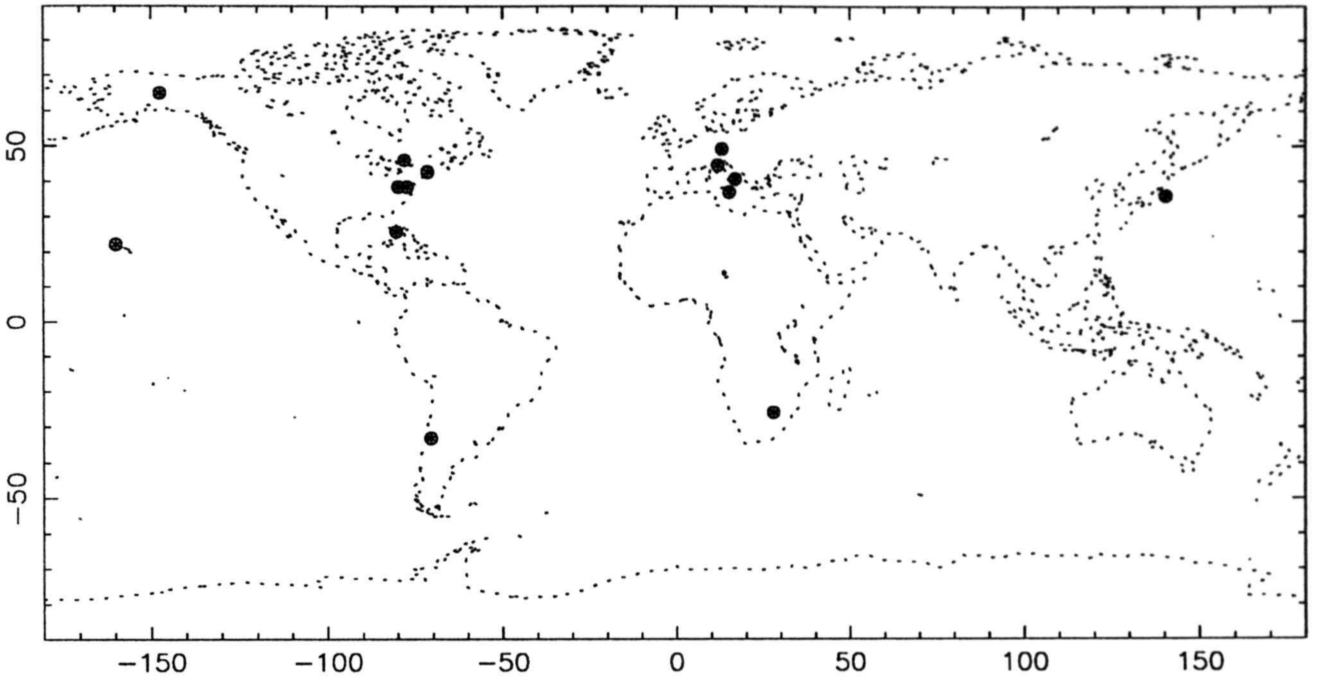
1 - Technique:	VLBI
2 - Analysis Center:	USNO
3 - Solution identifier:	1993-9
4 - Software used:	Calc 7.6
5 - Relativity scale:	Geocentric
6 - Permanent tidal correction:	No
7 - Tectonic plate model:	Nuvell
8 - Velocity of light:	299 792 458 m/s
10 - Reference epoch:	17 October 1980
11 - Adjusted parameters:	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



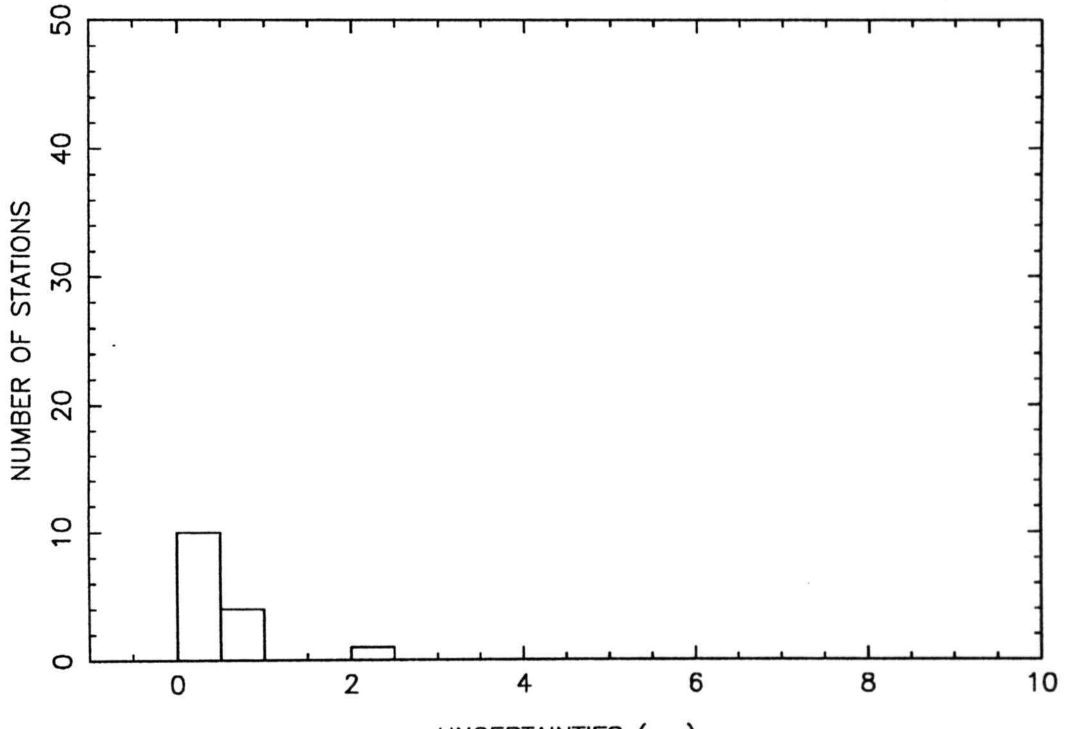
Distribution over the sky of the 123 extragalactic radio sources of the celestial frame RSC(USNO) 93 R 01. Filled circles indicate radio sources with uncertainties in right ascension (αcosδ) and declination smaller than 0.0003".



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, $\delta\psi$, $\delta\epsilon$; 0.0001s for UT1

YEAR	X		Y		UT1		$\delta\psi$		$\delta\epsilon$	
	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