VERY LONG BASELINE INTERFEROMETRY

EARTH ORIENTATION PARAMETERS FROM IRIS-S VLBI MEASUREMENTS

GIUB 94 R 01

A. Nothnagel, R. Haas, J. Campbell, A. Mueskens, Geodetic Institute of the University of Bonn, Federal Republic of Germany
G.D. Nicolson, Hartebeesthoek Radio Astronomy Observatory, South Africa

Since 1990 the VLBI group at the Geodetic Institute of the University of Bonn (GIUB) has regularly correlated and analysed VLBI experiments which are observed once per month under the acronym IRIS-S (International Radio Interferometric Surveying - South). Until now 71 experiments have been observed with a network of stations which is grouped around the Wettzell (Germany) - Westford (US East Coast) - HartRAO (Hartebeesthoek Radio Astronomy Observatory, South Africa) baseline triangle. Since early 1986 when HartRAO was first equipped with a hydrogen maser frequency standard and a Mark III data acquisition terminal the IRIS-S network has been scheduled to observe for two months each year in the beginning and regularly in monthly intervals from late 1989. The network first consisted of the stations Wettzell, HartRAO, Westford and Richmond with Onsala and Fort Davis participating in a few experiments (Carter *et al.*, 1988). In the meantime, several changes were necessary: Mojave replaced Fort Davis and was closed eventually, Santiago (Chile) was excluded again after 10 months of participation for financial reasons and Fortaleza (Brazil) started operation in July 1993. Today the network is formed by the stations of Wettzell, HartRAO, Westford and Fortaleza.

In recent months the field of data analysis activities at the Geodetic Institute has been extended to the data gathered with the new German station O'Higgins in Antarctica (Hase and Nothnagel, 1993). So far the station of O'Higgings has successfully observed two bursts of five experiments each with networks consisting of the stations of Santiago (Chile), Hobart (Tasmania, Australia), DSS45 (NASA Complex of Tidbinbilla, Australia) and HartRAO. The first burst was observed in January/February 1993 while the second burst took place in September 1993 with three experiments being available to date. These experiments contribute a number of precise source positions in the deep south.

The IRIS-S and the O'Higgins 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.

IERS(1994) Technical Note No 17.

The apriori EOP values for each observation are calculated by linearly interpolating the USNO Rapid Service Series and subsequently applying corrections for diurnal and semidiurnal tidal variations in polar motion and UT1. The corrections are modelled using the Wünsch and Busshoff (1992) amplitudes for UT1 and the Brosche and Wünsch (1994) amplitudes for polar motion (both scaled by 1.13 to subtract the equatorial moment of inertia of the core):

UT1 tidal terms

l	l'	F	D	Om	GST +π	Tide	A1 Amplitude [μs]	A2 Amplitude [μs]
0	0	0	0	0	-1	K1	14.64	11.48
0	0	2	-2	2	-1	P1	-6.09	-5.91
0	0	2	0	2	-1	O1	-12.90	-32.10
0	0	2	-2	2	-2	S2	-3.58	18.25
0	0	2	0	2	-2	M2	-23.34	27.14
1	0	2	0	2	-2	N2	-4.75	5.93

Polar motion tidal terms

l	l'	F	D	Om	GST +π	Tide	A1 Amplitude [μs]	A2 Amplitude [μs]
0	0	0	0	0	1	K1 p	160.18	-65.37
0	0	-2	2	-2	1	P1 p	-50.44	21.93
0	0	-2	0	-2	1	O1 p	-177.89	38.46
0	0	2	-2	2	-2	S2 r	-64.02	227.65
0	0	2	0	2	-2	M2 r	164.97	258.94
1	0	2	0	2	-2	N2 r	15.66	35.95
0	0	-2	2	-2	2	S2 p	-11.65	-29.45
0	0	-2	0	-2	2	M2 p	26.88	-103.40
-1	0	-2	0	-2	2	N2 p	12.32	-18.26

p = prograde, r = retrograde

The observations are individually calibrated for ionospheric refraction effects applying delay differences of 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 piecewise-linear function where surface meteorological data is available. Only if station logs indicate a rapidly changing climatic environment or surface meteorological data is not available shorter intervals are chosen. 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. A smaller number of clock parameters as compared to a stochastic treatment of the clocks is chosen in order not to weaken diurnal and sub-diurnal signals in the Earth orientation parameters. Only delay observables are used and no restrictions are applied to the data in terms of elevation limits which are set to 7 degrees during preparation of the observing schedules.

In a combined solution (GIUB 94 R 01) all IRIS-S measurements since January 19, 1987, and eight experiments of the O'Higgins bursts have been 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. The origin of the terrestrial reference frame is fixed through the Wettzell station coordinates which are kept at the ITRF 1992 (Boucher *et al.*, 1993) values applying drift effect corrections according to the NNR-NUVEL-1 model (Argus and Gordon, 1991). The station coordinates of all other stations are estimated. The experiment observed on December 21, 1989 is used as a reference for the determination of the Earth orientation parameters, i.e. pole components and UT1 are fixed at the USNO Rapid Service values (IERS Bulletin A) and the nutation angles are calculated according to the IAU 1980 nutation theory (Wahr, 1981). For each of all other experiments one set of Earth orientation parameters consisting of two pole components, UT1-UTC, and two offsets relative to the IAU nutation theory are estimated. The reference epochs for UT1-UTC and polar motion are the midnight epochs of each measurement period while the nutation offsets are estimated at the beginning of each experiment. The values quoted represent EOPs smoothed over 24 hours and thus do not include diurnal and subdiurnal contributions for the specific epochs.

In respect to the continental drift history the participating stations are divided into three groups. O'Higgins, Santiago, DSS45, Hobart and Fortaleza have contributed data to the two projects which span too short periods to detect any significant motion. Wettzell, Westford and Richmond have shown relative drifts which agree with the NNR-NUVEL-1 model to within 1 mm in the north and east components while HartRAO and Mojave disagree at a 6 to 8mm/year level (Ryan *et al.*, 1993). Taking these peculiarities into account the motions of the stations are parametrized as follows: In the absence of a truly global distribution of stations the motion of the Wettzell - Westford - Richmond triangle is modelled according to NNR-NUVEL-1 defining the long term orientation of the network. Horizontal drift components are estimated for HartRAO and Mojave. Vertical drifts for these stations are constrained to zero since the network and the duration of the series are not considered sufficient for a reliable estimation of height variations at these stations. All other stations with only a short history are also supposed to move according to NNR-NUVEL-1.

The origin of right ascension is fixed by the ICRF 1992 position of OJ287 (IERS, 1993). 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.

References

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

Boucher, C., Altamimi, Z., and Duhem, L., 1993: *IERS Technical Note 15*, Observatoire de Paris, Paris.

Brosche, P., and Wünsch J., 1994: *Astronomische Nachrichten* (in press).

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

Carter, W.E., Robertson, D.S., Nothnagel, A., Nicolson, G.D., Schuh, H., Campbell, J., 1988: *J. Geophys. Res.*, **93**, No. B12, 14947.

Hase, H., and Nothnagel, A., 1993: Proceedings of the Ninth Working Meeting on European VLBI for Geodesy and Astrometry, in *Mitteilungen aus den Geodätischen Instituten der Rheinischen Friedrich-Wilhelms-Universität Bonn*, Nr. **81**, p. 87.

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

Herring, T.A, 1992 : *Proceedings of the symposium on Refraction of Transatmospheric Signals in Geodesy, Netherlands Geodetic Commission*, Publ. in Geodesy No. **36**, p. 157.

IERS, 1993: *1992 IERS Annual Repport*, Observatoire de Paris, Paris.

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

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

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

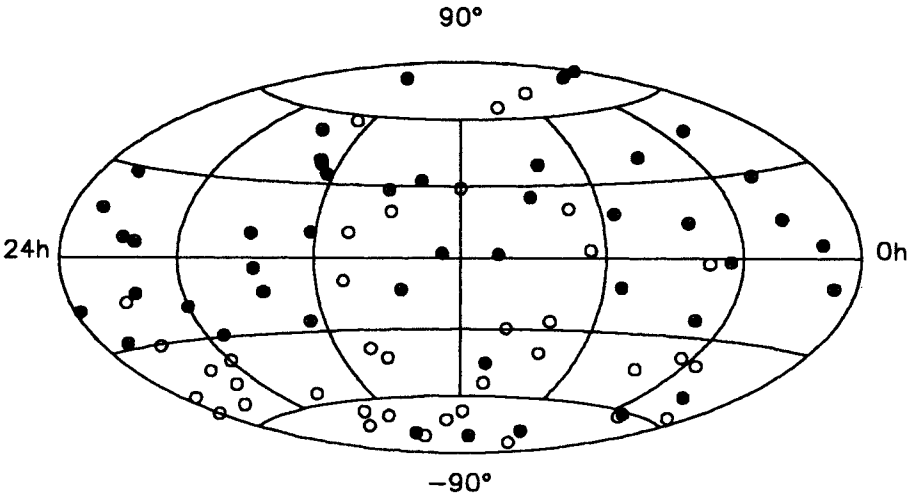
Scherneck, H.G., 1991: *Geophys. J. Int.*, **106**, 677.

Wahr, J.M., 1981: *Geophys. J. R. Astron. Society*, **64**, 705.

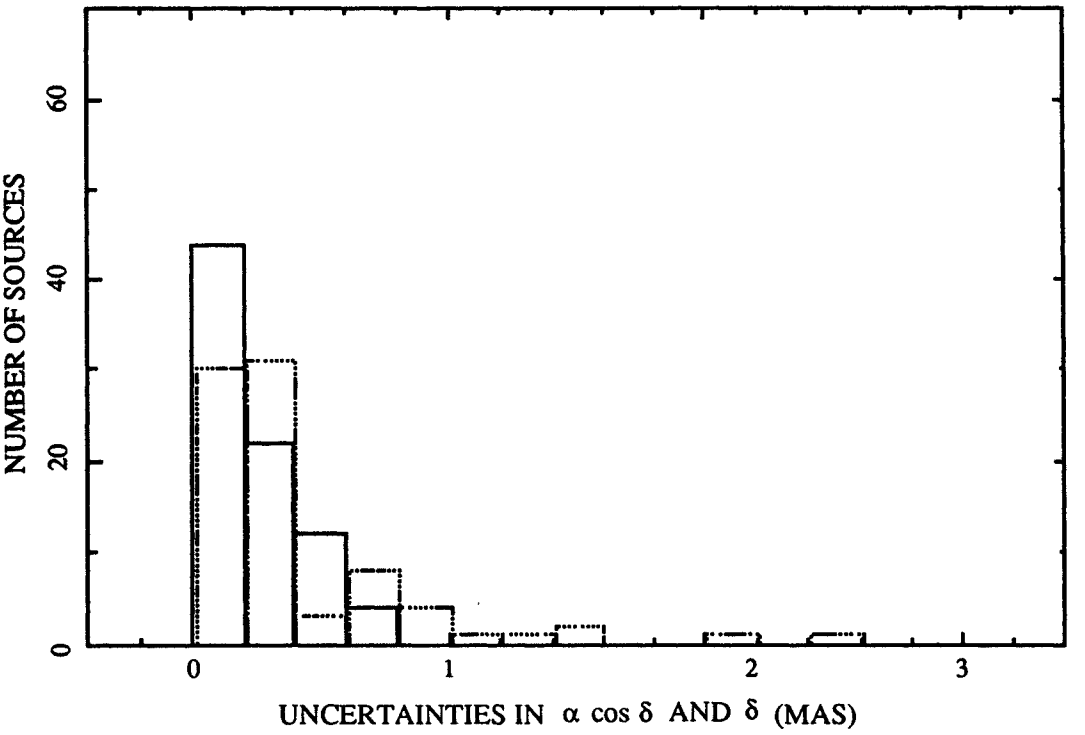
Wünsch, J., and Busshoff, J., 1992: *Astron. Astrophys.*, **266**, 588.

Summary description of solution GIUB 94 R 01

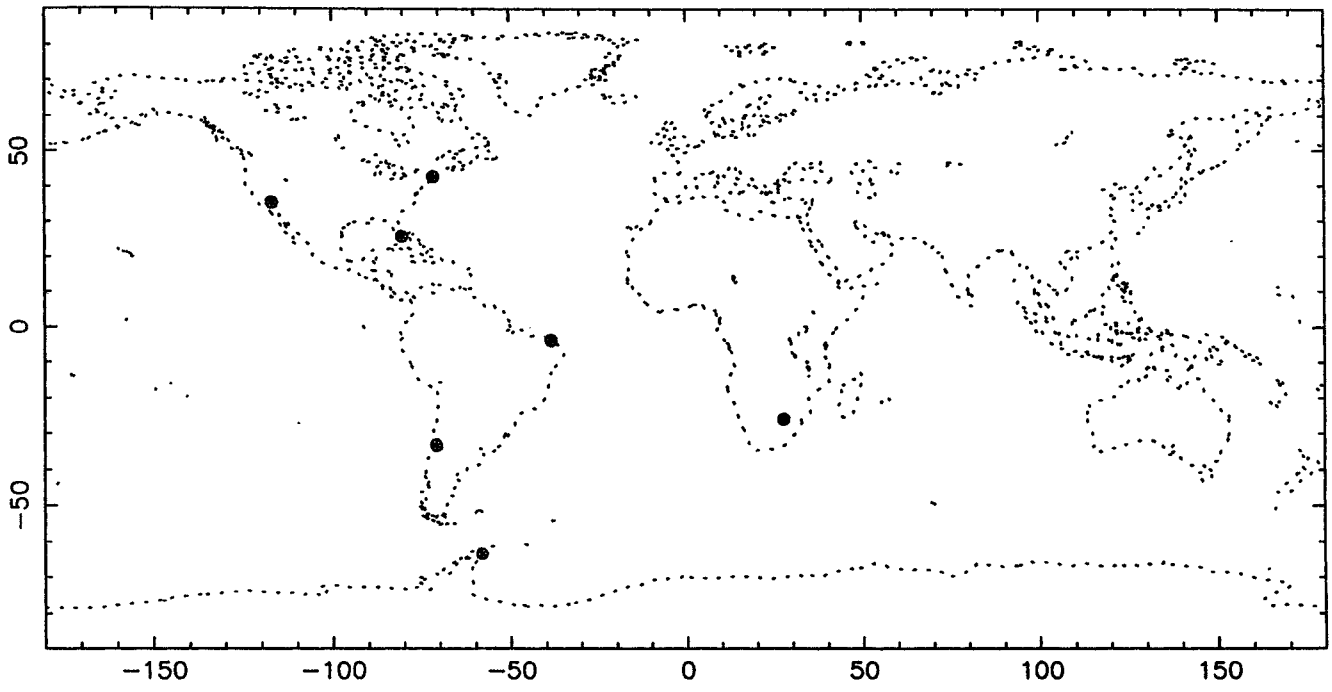
1 - Technique:		Mark III VLBI, Group delay observables
2 - Analysis Center:		Geodetic Institute of the University of Bonn, Nussallee 17, D-53115 Bonn, Germany
3 - Solution identifier:		GIUB 94 R 01
4 - Software used:		CALC 7.6, SOLVE/GLOBL
5 - Relativity scale:		Solar System Barycenter
6 - Permanent tidal correction on station:		Not applied
7 - Tectonic plate model:		NUVEL-1 NNR
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, horizontal velocities of HartRAO and Mojave, radio source positions
12 - Definition of origin:	Terrestrial:	Fixing Wettzell ITRF 1992 coordinates
	Celestial:	Fixing OJ287 ICRF 1992 right ascension
13 - Definition of orientation:		Fixing USNO concrete EOP series and IAU 1980 Nutation for 1989 Dec. 21
14 - Evolution in time:		Velocities estimated for Mojave and HartRAO, all other stations move according to NUVEL-1 NNR



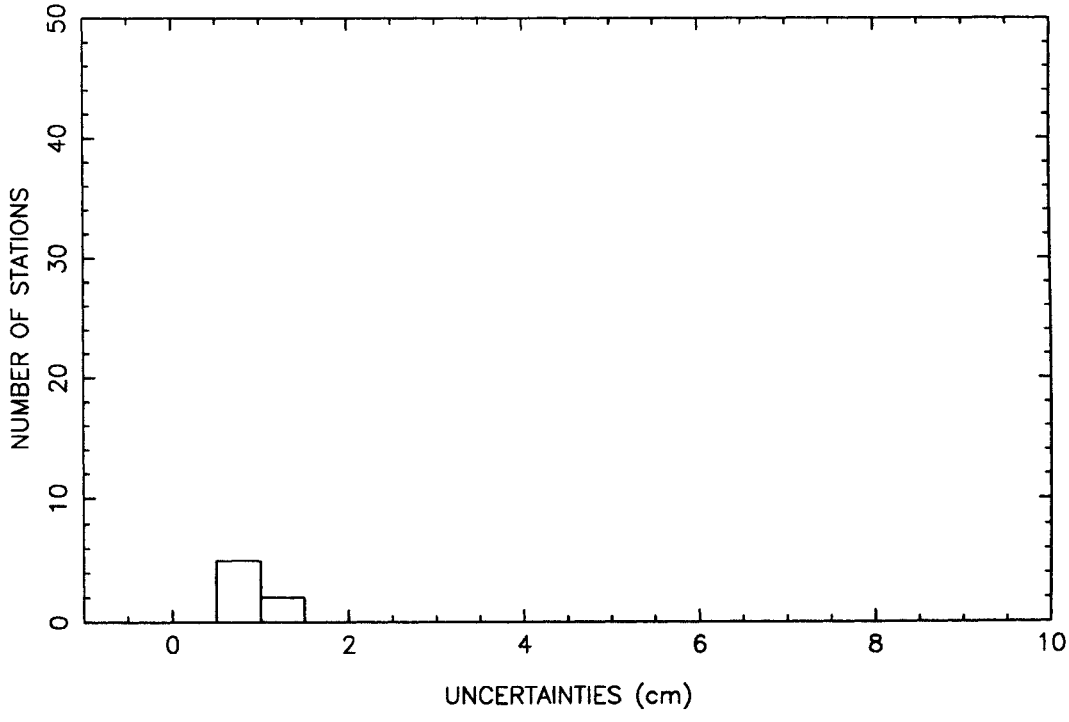
Distribution over the sky of the 83 extragalactic radio sources of the celestial frame RSC(GIUB) 94 R 01. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(GIUB) 94 R 01. 2 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 7 sites of the terrestrial frame SSC(GIUB) 94 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 7 stations of the terrestrial frame SSC(GIUB) 94 R 01.

EOP(GIUB) 94 R 01 From Jan 1987 to Dec 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
1987	8	0.47	8	0.33	8	0.36	8	0.52	8	0.23
1988	4	0.41	4	0.30	4	0.47	4	0.53	4	0.25
1989	6	0.45	6	0.32	6	0.27	6	0.61	6	0.30
1990	11	0.36	11	0.26	11	0.19	11	0.50	11	0.24
1991	12	0.34	12	0.26	12	0.18	12	0.47	12	0.23
1992	12	0.35	12	0.27	12	0.19	12	0.45	12	0.21
1993	20	0.40	20	0.31	20	0.21	20	0.49	20	0.22

SITE POSITIONS AND VELOCITIES, SOURCE POSITIONS, AND EARTH ORIENTATION PARAMETERS FROM THE NASA SPACE GEODESY PROGRAM-GSFC: SOLUTION GLB932

GSFC 94 R 01

C. Ma, Code 921, Goddard Space Flight Center, Greenbelt, MD 20771, USA
J. M. Gipson, NVI, Inc., 8150 Leesburg Pike, Vienna, VA 22182, USA
D. Gordon, Hughes STX, 4400 Forbes Blvd., Lanham, MD 20706, USA
D. S. Caprette, Hughes STX, 4400 Forbes Blvd., Lanham, MD 20706, USA
J. W. Ryan, Code 926, Goddard Space Flight Center, Greenbelt, MD 20771, USA

Mark III VLBI delay and delay rate data acquired since 1979 by the NASA Crustal Dynamics Project, POLARIS/IRIS, the Geographical Survey Institute (Japan), the Communications Research Laboratory (Japan), the Naval Research Laboratory Reference Frame Program, the USNO NAVNET/NAVEX, and the NASA Space Geodesy Program-GSFC have been analyzed for the terrestrial and celestial reference frames. The sessions used for GLB932 include all geodetic and astrometric VLBI sessions available to the NASA Space Geodesy Program-GSFC except for the data acquired by the NASA Deep Space Network for spacecraft navigation.

The combination of all data in a single solution and the constraints for the origin, translation, and rotation of the terrestrial reference frame (TRF) are the major changes from our previous submissions. A 10-cm correction to the vertical eccentricity measurement used for GORF7102 between 91/08 and 92/06 changes the position and velocity from the last submission.

The TRF origin is set close to that of ITRF92 by minimizing the station position adjustments at 1988.0 with respect to ITRF92 for nine stations (WESTFORD, RICHMOND, GILCREEK, KAUAI, HOBART26, DSS45, HARTRAO, WETTZELL, and ONSALA60). The translational and rotational defects of the TRF are removed by minimizing the horizontal velocity adjustments of eight stations with respect to NUVEL-1 NNR (Argus and Gordon, 1991) and by minimizing their vertical rate adjustment. The stations (WESTFORD, RICHMOND, GILCREEK, KAUAI, HOBART26, DSS45, WETTZELL, and ONSALA60) are chosen for their global distribution, strong data, location in relatively stable parts of their respective plates, and absence of large deviations from the NUVEL-1 model. While this type of constraint removes the singularity present in the WESTFORD-RICHMOND-KAUAI constraint used in previous GSFC submissions, it distributes the discrepancies in relative motion from NUVEL-1 into individual site velocities in a manner that may be more difficult to interpret. The orientation of the terrestrial and celestial reference frames is defined by EOP and nutation offset values from the one-day EOP(IERS) 90 C04 series modified to match ITRF92 (M. Feissel, personal communication) and the standard J2000.0 precession and IAU 1980 nutation models for the EOP reference date 1993 Sep. 30. The right ascension origin is defined by the ICRF92 value for 2145+067.

IERS(1994) Technical Note No 17.

In general, the three-dimensional velocities of sites with sufficient data were estimated. Those sites whose vertical rates had formal errors in excess of 3 mm/yr in an unconstrained solution were constrained to have zero vertical rate in this solution. The positions of seven sites (YAKATAGA, SOURDOGH, WHTHORSE, FORTORDS, PRESIDIO, MOJAVE12, and DSS15) each had one discontinuous change in position related to seismic events, and one site (NRAO85_3) had a discontinuous change for unknown causes. The velocities of some sites (FORT_ORD-FORTORDS, KASHIMA-KASHIM34, DSS65-ROBLED32, KAUAI-HALEAKAL-KOKEE-MK-VLBA, 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, YELLOWKN-YLOW7296, GORF7102-GGAO7108) 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.

About 180 sources used in the geodetic programs form the core of the celestial reference frame. These have ~100 to ~90000 observations each. About 390 sources have formal errors under 1 mas. The remaining sources include a number with weak data. Sources with uncertainties >10 mas are not reported.

Instantaneous EOP values and UT1 rates 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 modeled diurnal and semidiurnal tidal variations.

All uncertainties are 1-sigma formal standard errors from the sequential least-squares solution GLB932 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 input series. The UT1 value for each observation was derived from the one-day series by first removing the IERS standard UT1R tidal model, interpolating linearly to the epoch of observation, then restoring the standard tidal model. In addition, diurnal and semidiurnal EOP variations (derived from a subset of the Mark III geodetic data) were added to the interpolated pole and UT1 values. 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. 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 GLB932 solution was constructed in several steps using an incremental solution and arc-parameter elimination (Ma *et al.*, 1990). First the sessions comprising large networks and strong data as well as the single baseline POLARIS days (1903 sessions, 1112475 delays, 40256 delay rates) were combined to form a preliminary TRF using the modified one-day EOP(IERS) 90 C 04 values as a priori input. The adjusted parameters included site positions and velocities, source positions, EOP values, UT1 rates, nutation offsets, and clock and troposphere parameters. Weak EOP constraints (45 mas and 3 ms for X/Y pole and UT1, respectively) were applied so that all three EOP components could be estimated for single baseline sessions with reliable indication of uncertainty and correlation. The EOP values, UT1 rates, and their covariances from each day were then input to a simple Kalman filter to generate a one-day VLBI EOP series. The covariances and interpolated EOP values from this series were used as a priori information when the solution was incremented with the remaining data (291 sessions, 106101 delays, 2427 delay rates), largely mobile and small network sessions. Finally the reported EOP and nutation offset values were generated from a back solution, again using the modified EOP(IERS) 90 C 04 series as a priori values and weak EOP constraints. While EOP values are given for all sessions, a flag indicates which values are useful.

In total 1218576 dual-frequency Mark III delays and 42683 delay rates from 2194 sessions were included. Only delay rate data from astrometric and survey sessions were included. The least-squares solution had 1799 global parameters and 434611 arc parameters with 974918.3 degrees of freedom. The weighted rms post-fit delay residual of the solution was 38.4 ps in delay and 77.9 fs/s in delay rate. The reduced chi-square was 1.029 including the constraints for the wet troposphere, clocks, and EOP in the computation of the degrees of freedom (Theil, 1963).

The site coordinates and velocities at 1988.0 are designated SSC(GSFC) 94 R 01. Other results are the Earth orientation time series designated EOP(GSFC) 94 R 01 and source positions designated RSC(GSFC)94 R 01.

References

Argus, D. F., and Gordon, R.G., 1991: *Geophys. Res. Let.*, **18**, 2039.

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

Herring, T. A., 1992: *Proceedings of the Symposium on Refraction of Transatmospheric Signals in Geodesy, Publications on Geodesy*, No. **36**, ed. by De Munck, J.C. and T. A. Th. Spoelstra, Netherland Geodetic Commission, Delft, Netherlands, p. 247.

Ma, C., Sauber, J.M., Bell, L.J., Clark, T.A., Gordon, D., Himwich, W.E., and Ryan, J.W., 1990: *J. Geophys. Res.*, **95**, 21991.

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

Summary description of solution GSFC 94 R 01

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 geodetic VLBI 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 this solution.

UT1 tidal terms (microseconds)

l	l'	F	D	Om	GST +π	term	Cos	Sin
0	0	0	0	0	-1	K1	7.486602	16.707637
0	0	2	-2	2	-1	P1	-3.500205	-5.392255
0	0	2	0	2	-1	O1	-15.575852	-16.762598
1	0	2	0	2	-1	Q1	-3.394904	-3.902930
0	1	0	0	0	-1	S1	593333	1.932245
1	0	0	0	0	-1	M1	1.003345	1.299982
0	0	0	0	0	-2	K2	261715	3.896805
0	0	2	-2	2	-2	S2	-1.182862	8.706599
0	0	2	0	2	-2	M2	-8.517385	12.338927
1	0	2	0	2	-2	N2	-4.378455	1.168543

Polar motion tidal terms (microarcseconds)

l	l'	F	D	Om	GST +π	term	Cos	Sin
0	0	0	0	0	1	P K1	125.285183	-38.476327
0	0	-2	2	-2	1	P P1	-54.470359	26.152833
0	0	-2	0	-2	1	P O1	-136.319298	63.668538
-1	0	-2	0	-2	1	P Q1	-33.990240	18.096315
0	0	0	0	0	-2	R K2	-15.899321	15.676795
0	0	2	-2	2	-2	R S2	-76.296961	105.813157
0	0	2	0	2	-2	R M2	15.018756	285.140733
1	0	2	0	2	-2	R N2	-24.572257	58.610024
0	0	0	0	0	2	P K2	22.589310	-5.801947
0	0	-2	2	-2	2	P S2	-7.259654	-11.309321
0	0	-2	0	-2	2	P M2	30.337902	-72.186765
-1	0	-2	0	-2	2	P N2	-11.643736	-30.168262

P = Prograde, R = Retrograde

- Instantaneous EOP and UT1 rate 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 piecewise-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.

- Data to SHANGHAI (7226), VLA (7619), and USSURISK (7247) lack ionosphere calibration. The USSURISK vertical position is not considered reliable since the adjustment of the axis offset gives a value of several meters.

- Solution in several steps to apply VLBI EOP information to some sessions.

2) - Analysis Center:
GSFC - the VLBI group of the NASA Space Geodesy Program at the Goddard Space Flight Center.

3) - Solution Identifier:
GLB932

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:
1993 September 30 for both earth rotation and nutation, 1988 January 1 for site positions. Source coordinates are J2000.0.

11) - Adjusted parameters:
X/Y pole, UT1, dUT1/dt, daily nutation offsets, global station positions and velocities, global source positions except the right ascension of 2145+067, and session-dependent clock and atmosphere parameters.

12) - Definition of the origin:
The origin of the terrestrial reference frame is set by minimizing the Cartesian adjustments of nine stations (WESTFORD, RICHMOND, GILCREEK, KAUAI, HOBART26, DSS45, HARTRAO, WETTZELL, ONSALA60) with respect to ITRF92 at 1988.0.

13) - Definition of the orientation:
The orientation of the terrestrial reference frame is defined by the a priori EOP values on the reference day (1993 Sep 30) from the modified EOP(IERS) 90 C 04 series that is consistent with ITRF92 (M. Feissel, private communication). 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 corrected by the nutation offsets from the modified EOP(IERS) 90 C 04 series and by the ICRF92 right ascension of 2145+067.

14) - Evolution with time:
The horizontal rate residuals of eight stations (WESTFORD, RICHMOND, GILCREEK, KAUAI, HOBART26, DSS45, WETTZELL, ONSALA60) with respect to No-Net-Rotation NUVEL-1 are minimized. The adjusted vertical rates of the same stations are also minimized. The stations with insufficient data or time interval are constrained to move with NNR-NUVEL-1 with uncertainties in vertical, east and north rates of 0, 3, and 3 mm/yr, respectively. These stations are:

SEST	OCOTILLO	VICTORIA	FORTLEZA	OHIGGINS	BR-VLBA
TITIJIMA	MIYAZAKI	MIZNAO10	CHLBOLTN	USSURISK	HN-VLBA
VLA	MIZUSGSI	SAGARA	AUSTINTX	CARROLGA	BERMUDA
SINTOTU	USUDA64	MILESMON	BLOOMIND	LEONRDOK	SC-VLBA
BREST	CARNUSTY	METSHOVI	HOHENFRG	GRASSE	HOFN
KARLBURG	TOULOUSE	AZORES	HOHNBERG	KIRSBERG	

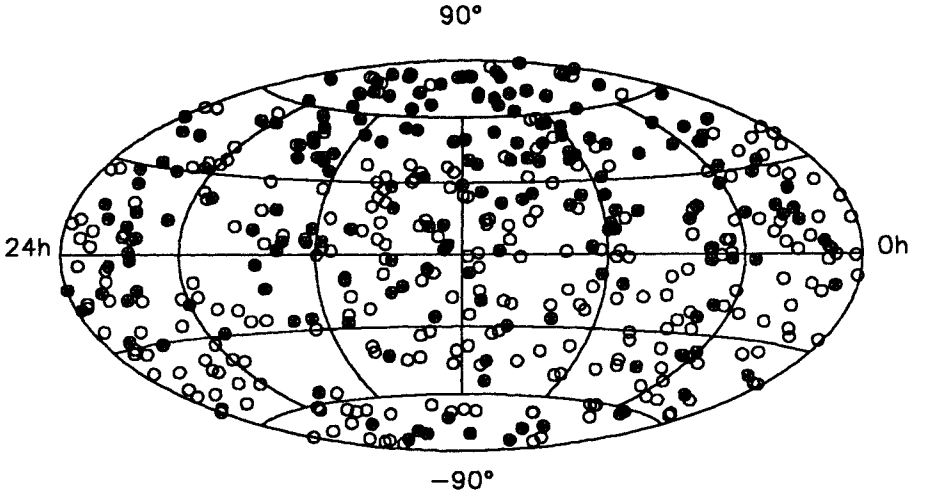
The vertical rates for stations that had uncertainties in their vertical rates in excess of 3mm/yr in an unconstrained solution are also constrained to zero with the exception of YELLOWKN/YLOW7296. These stations are:

MON_PEAK	PLATTVIL	QUINCY	TSUKUBA	PT_REYES	KWAJAL26
PINFLATS	PRESIDIO	JPL_MV1	NOME	GORF7102	GGAO7108
NL-VLBA	TROMSONO	YUMA	FORTORDS	FORT_ORD	ELY
SANTIA12	FLAGSTAF	MARCUS	KODIAK	DSS15	KP-VLBA
VERNAL	PBLOSSOM	SNDPOINT	SANPAULA	PVERDES	PENTICTN
BLKBUTTE	TRYSILNO	SOURDOGH	YAKATAGA	SEATTLE1	MAMMOTHL
WHTHORSE	DEADMANL	NOBEY_6M			

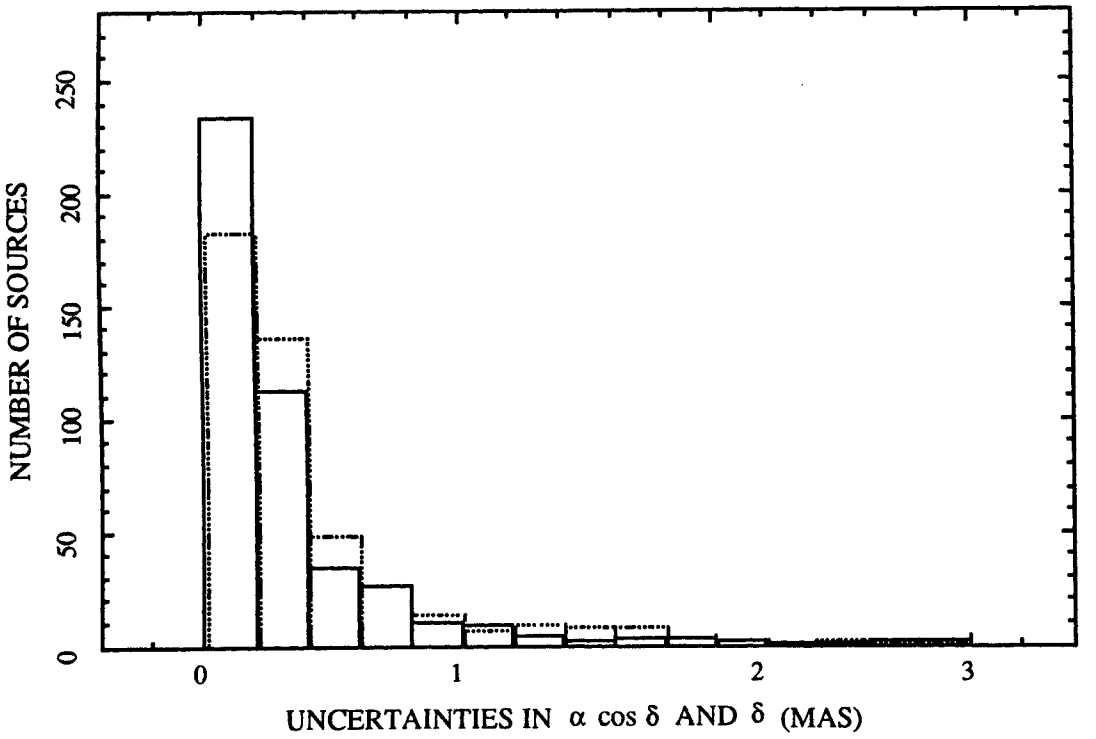
EOP(GSFC) 94 R 01 From Aug 1979 to Dec 1993

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

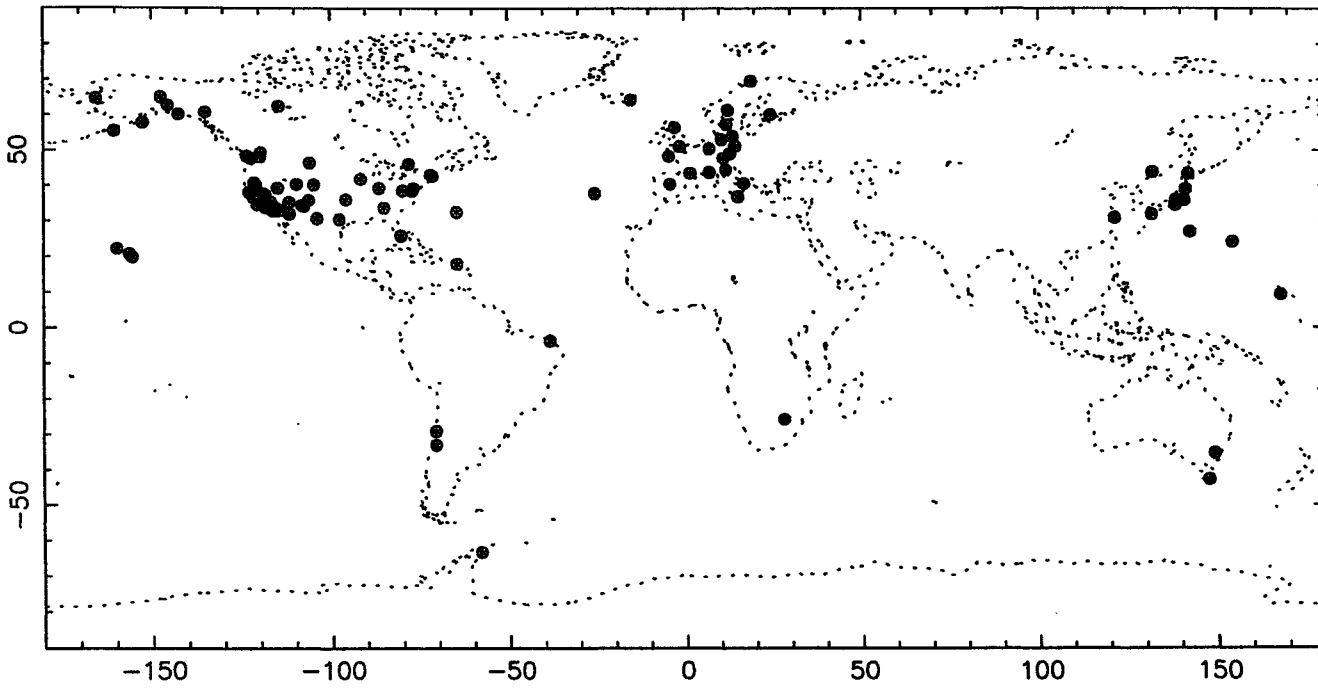
YEAR	X		Y		UT1		$\delta\psi$		$\delta\epsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1979	2	1.17	2	2.28	2	0.84	2	1.87	2	0.67
1980	20	0.61	20	0.62	20	0.30	20	0.98	20	0.43
1981	34	12.75	34	40.55	34	10.32	34	3.21	34	1.14
1982	62	12.74	62	40.55	62	10.32	62	2.89	62	1.11
1983	85	12.67	85	33.24	85	10.23	85	2.27	85	0.94
1984	119	0.76	119	0.69	119	0.37	119	1.10	119	0.43
1985	130	0.47	130	0.45	130	0.24	130	0.73	130	0.27
1986	152	0.47	152	0.42	152	0.24	152	0.71	152	0.25
1987	184	0.47	184	0.43	184	0.24	184	0.71	184	0.26
1988	208	0.46	208	0.45	208	0.26	208	0.64	208	0.25
1989	247	0.35	247	0.36	247	0.19	247	0.55	247	0.22
1990	268	0.26	268	0.27	268	0.14	266	0.44	266	0.18
1991	244	0.21	244	0.22	244	0.12	241	0.37	243	0.15
1992	254	0.20	254	0.20	254	0.09	253	0.34	253	0.15
1993	185	0.16	185	0.14	185	0.07	184	0.26	184	0.11



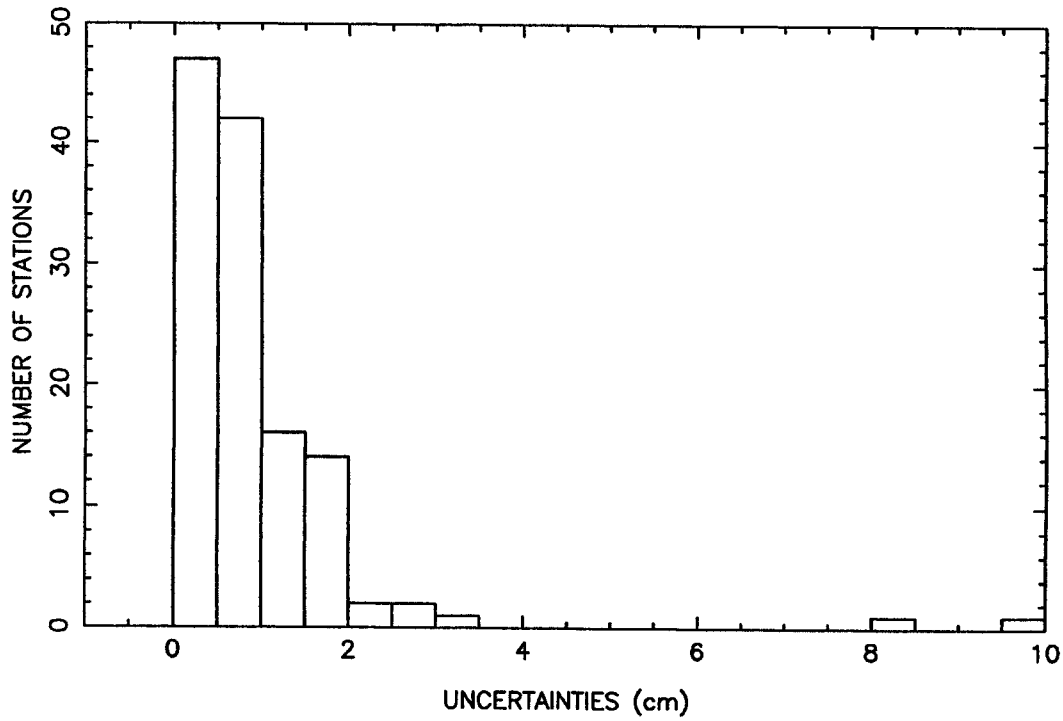
Distribution over the sky of the 469 extragalactic radio sources of the celestial frame RSC(GSFC) 94 R 01. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(GSFC) 94 R 01. 24 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 99 sites of the terrestrial frame SSC(GSFC) 94 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 127 stations of the terrestrial frame SSC(GSFC) 94 R 01. 1 station with uncertainly langer than 10 cm is not shown.

EARTH ROTATION PARAMETERS FROM DSN VLBI: 1994

JPL 94 R 01

J.A. Steppe, S.H. Oliveau, O.J. Sovers
Jet Propulsion Laboratory, California Institute of Technology Pasadena, California 91109, USA

The main changes in this year's report from last year's report are evolutionary, due to the acquisition of another year's data.

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. Most observing sessions use antennas in only 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 1994 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 1994 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 1994-1 (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.

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 for data 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 have had nearly-diurnal and nearly-semidiurnal tidal frequency variations removed according to the parametric model 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)94 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 1994-1 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 1042 observing sessions between October 28, 1978, and March 13, 1994.

During calendar year 1993, the TEMPO project produced earth rotation measurements from 93 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 1993 the median turnaround time for TEMPO measurements, from observation to availability of earth orientation parameters, was 49 hours.

The JPL 1994-1 Catalog

The JPL 1994-1 catalog was developed specifically for use in TEMPO operational ERP solutions during 1994. 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 1994-1 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 1994, and will presumably need revision in 1995. 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 1994-1 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 1994-1 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 19, 1993, and most of the TEMPO data through December 29, 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 SPACE93 series (Gross, 1994) 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 66 such pairs of TEMPO sessions; there were 7 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. This year there is one CAT M&E session (December 19, 1993) in which one station in each complex participated (DSS 15,45,65), with small groups of observations on the California-to-Spain and California-to-Australia baselines interleaved. Although the duration of this session was only 8 hours, it has significantly improved our knowledge of the rate of change of the length of the Australia-to-Spain vector. (A special thank you to Chris Jacobs for leading the effort to acquire this data, and for getting the results to us in time for this analysis).

5 - The terrestrial frame of the JPL 1994-1 system was tied to the International Earth Rotation Service Terrestrial Reference Frame ITRF-92

(IERS, 1993, 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 1994-1 and ITRF-92 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-92.

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-92 velocity field (IERS, 1993, 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 1994-1 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 1993 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)93 C 01 (IERS, 1993, 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)94 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 1994-1 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 parametric model for the nearly-diurnal and nearly-semidiurnal tidal frequency variations of UT1 and polar motion obtained as part of the JPL 1994-1 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 13 to 53 microarcseconds but realistic uncertainties are probably about 75 microarcseconds (one standard deviation).

Short Period Tidal ERP Variations

	Period	UT1 (microseconds)		Polar Motion			
				Amplitude		Phase	
Term	(hours)	Cosine	Sine	(microarcseconds)		(degrees)	
				prograde	retrograde	prograde	retrograde
K2	11.96724	3.0	4.0	43	54	59	246
S2	12.00000	1.3	9.9	40	143	58	314
M2	12.42060	- 8.4	18.0	64	242	119	274
N2	12.65835	0.1	2.8	20	32	106	188
K1	23.93447	13.1	26.2	191	0	163	*
P1	24.06589	- 4.5	- 4.3	59	0	342	*
O1	25.81934	-13.3	-13.5	145	0	314	*
Q1	26.86836	3.6	- 1.8	38	0	323	*

The model of the celestial motion of the CEP obtained as part of the JPL 1994-1 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. 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.

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	-3.21/yr	0.06/yr	0.14/yr
obliquity rate			Obliquity	-0.28/yr	0.05/yr	0.06/yr
Y-offset			L sin eps	-18.70	0.34	0.74
X-offset			Obliquity	+ 5.94	0.76	0.77
1	-6798.38	In	Longitude	- 0.98	0.31	0.73
			Obliquity	- 0.01	0.16	0.17
		Out	Longitude	+ 1.13	0.21	0.41
			Obliquity	- 0.15	0.29	0.29
2	-3399.19	In	Obliquity	- 0.23	0.08	0.08
		Out	Longitude	- 0.70	0.17	0.20
			Obliquity	+ 0.17	0.12	0.13
10	365.26	In	Longitude	- 0.50	0.08	0.10
			Obliquity	+ 0.03	0.03	0.03
		Out	Longitude	+ 0.64	0.08	0.09
			Obliquity	+ 0.00	0.03	0.04
9	182.62	In	Longitude	- 0.06	0.06	0.07
			Obliquity	- 0.04	0.02	0.03
		Out	Longitude	+ 0.18	0.06	0.07
			Obliquity	+ 0.01	0.02	0.03
31	13.66	In	Longitude	- 0.20	0.05	0.14
			Obliquity	+ 0.11	0.03	0.05
		Out	Longitude	+ 0.47	0.07	0.13
			Obliquity	+ 0.10	0.02	0.06
	-429.8	In	Longitude	- 0.04	0.08	0.09
			Obliquity	+ 0.02	0.04	0.04
		Out	Longitude	- 0.61	0.09	0.10
			Obliquity	- 0.12	0.03	0.03

For the 1994-1 catalog solution, the data set used has NOT been restricted to have only elevation angles above some arbitrary minimum value. Note however that low elevation observations are effectively down-weighted by the observable uncertainty adjustment procedure described above. Because the most frequently used stations in this data set (DSS 14,15,43,45,63,65) have antenna limits at 6.0 to 6.35 degrees elevation, almost all the data in this data set has elevation angles above 6 degrees. Because of the very long lengths of the DSN baselines, the DSN VLBI observing schedules have included low elevation observations since their inception. Since at least 1983, the TEMPO sessions have been designed to improve the determination of the troposphere zenith parameters and their separation from the geodetic parameters by deliberately including a few observations for this purpose, which have low elevation angles and are not near the cusps of the visibility sector. In the set of

elevation angles associated with the observations included in the 1994-1 catalog solution, the portion that fall in each 10 degree increment is as follows (in percent):

0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80	80 - 90	
8.8	23.8	21.5	17.5	13.9	9.0	3.0	1.9	0.7	degrees / percent

The average elevation angle is 30.70 degrees.

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 1994-1 catalog solution and reported here. Approximate values are:

Baseline	Latitude (degrees)	Longitude (degrees)
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.

References:

Eubanks, T. M., 1991: A consensus model for relativistic effects in geodetic VLBI, *Proceedings of the U. S. Naval Observatory Workshop on Relativistic Models for Use in Space Geodesy*, Washington, D. C.

Gross, R. S., 1994: A combination of earth orientation data: SPACE93, *IERS Technical Note 17*, Observatoire de Paris, Paris, pp. C-5.

Herring, T.A., 1991: The ZMOA-1990 nutation series, *Proceedings of the 127th Colloquium of the International Astronomical Union, Reference Systems*, U. S. Naval Observatory, Washington, D. C., pp. 157-166.

Herring, T. A., Buffett, B. A., Mathews, P. M., and Shapiro, I. I., 1991: Forced nutations of the earth: influence of inner core dynamics 3. very long baseline interferometry data analysis, *J. Geophys. Res.*, **96**, B5, 8259-8273.

IERS, 1993: *1992 IERS Annual Report*, Observatoire de Paris, Paris.

Lanyi, G.E., 1984: Tropospheric delay effects in radio interferometry, *Telecommunications and Data Acquisition Prog. Rept. 42-78*, Jet Propulsion Laboratory, Pasadena, California, pp. 152-159.

Scherneck, H.G., 1983: Crustal Loading Affecting VLBI Sites, University of Uppsala, Institute of Geophysics, Dept. of Geodesy, Report No. 20, Uppsala, Sweden.

Scherneck, H.G., 1991: A parameterised solid earth tide model and ocean tide loading effects for global geodetic baseline measurements, *Geophys. J. Int.*, **106**, 677-694.

Sovers, O.J., 1991: Observation Model and Parameter Partials for the JPL VLBI Parameter Estimation Software "MODEST"-1991, Publication 83-39, Rev. 4, Jet Propulsion Laboratory, Pasadena, California.

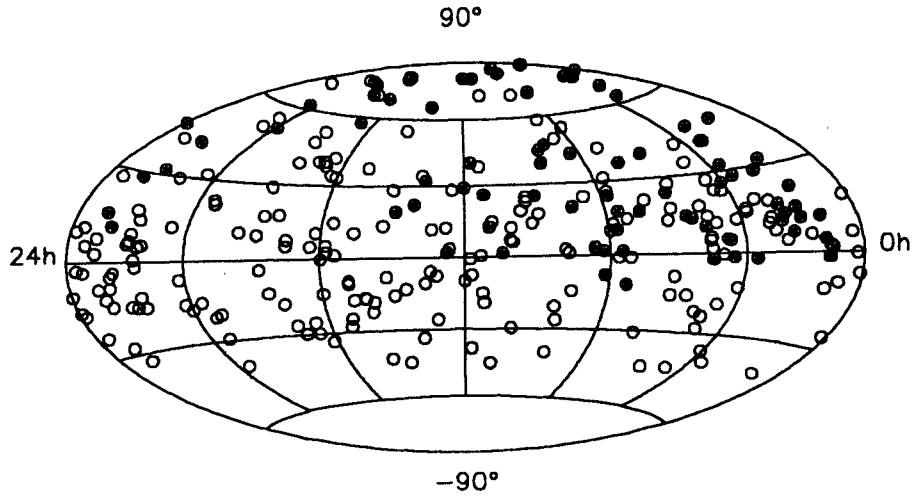
Sovers, O.J., Jacobs, C.S., and Gross, R.S. 1993: Measuring rapid ocean tidal earth orientation variations with very long baseline interferometry, *J. Geophys. Res.*, **98**, B11, 19959-19971.

Summary description of the terrestrial system attached to the set of station coordinates SSC (JPL) 94 R 01

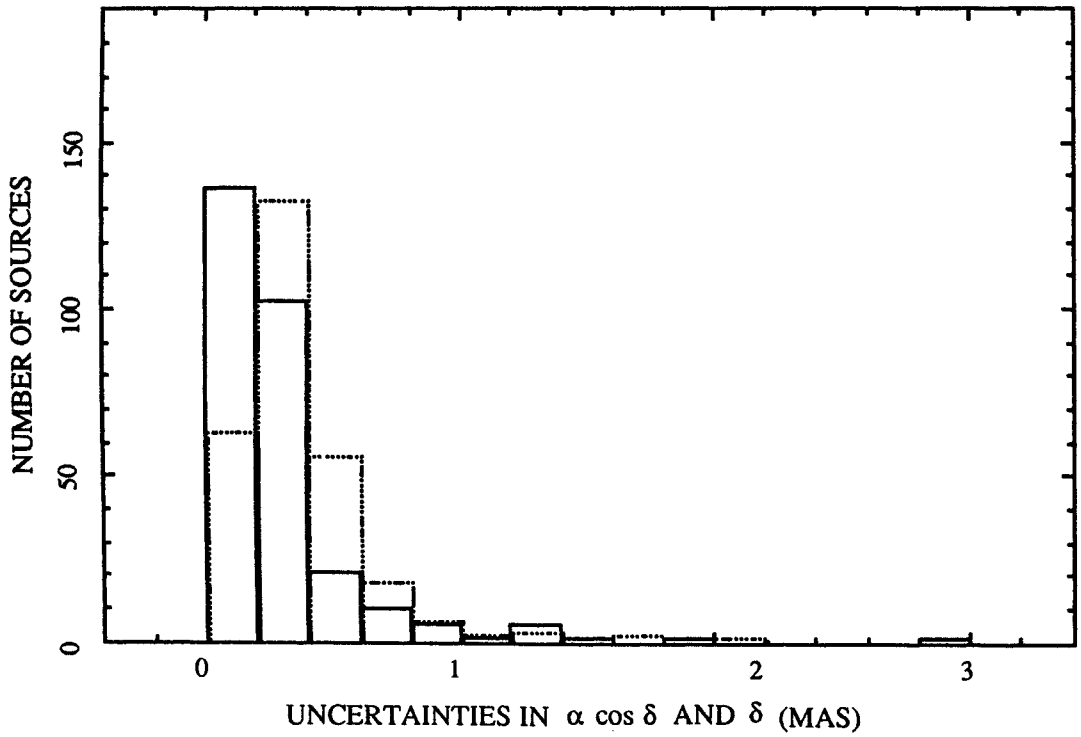
1 - Technique:	VLBI
2 - Analysis Center:	JPL
3 - Solution identifier:	1994-1
4 - Software used:	MODEST (nee Masterfit)
5 - Relativity scale:	LE (TDT = geocentric with IAT)
6 - Permanent tidal correction:	No
7 - Tectonic plate model:	ITRF-92 plus adjustments
8 - Velocity of light:	299 792 458 m/s
9 - 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 1994-1 and ITRF-92 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.

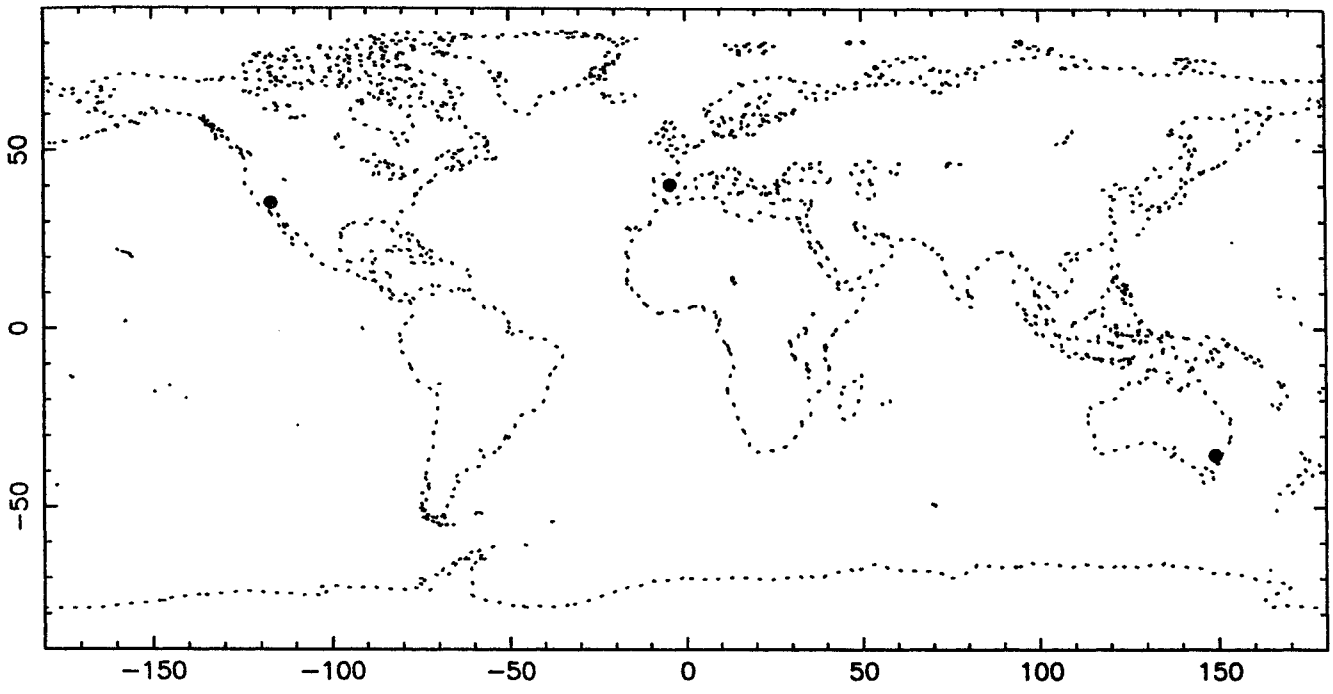
14 - Constraint for time evolution:
Six constraints were applied (with 1.0 mm/yr uncertainty) to the nine site-velocity parameters of the DSN network so as to yield no-net-translation-rate and no-net-rotation-rate with respect to the net motion of the three sites Madrid, Goldstone, and Canberra as specified by the ITRF-92 velocity field. See text for details.



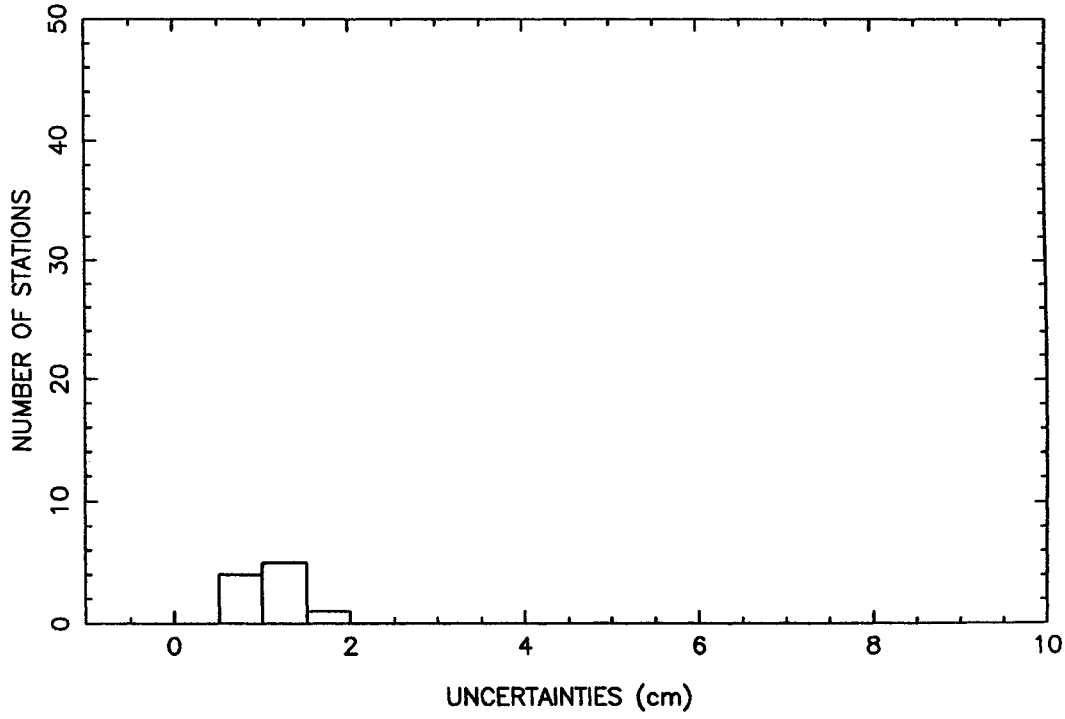
Distribution over the sky of the 285 extragalactic radio sources of the celestial frame RSC(JPL) 94 R 01. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(JPL) 94 R 01. 2 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 3 sites of the terrestrial frame SSC(JPL) 94 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) 94 R 01.

EOP(JPL) 94 R 01 From Oct 1978 to May 1994

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	0.62	93	1.71
1990	108	0.90	108	1.81
1991	111	0.44	111	1.02
1992	114	0.40	114	0.69
1993	101	0.62	101	0.95
1994	38	0.95	38	0.90

ANALYSIS OF VLBI OBSERVATIONS, 1984-1993

NAOMZ 94 R 01, 02

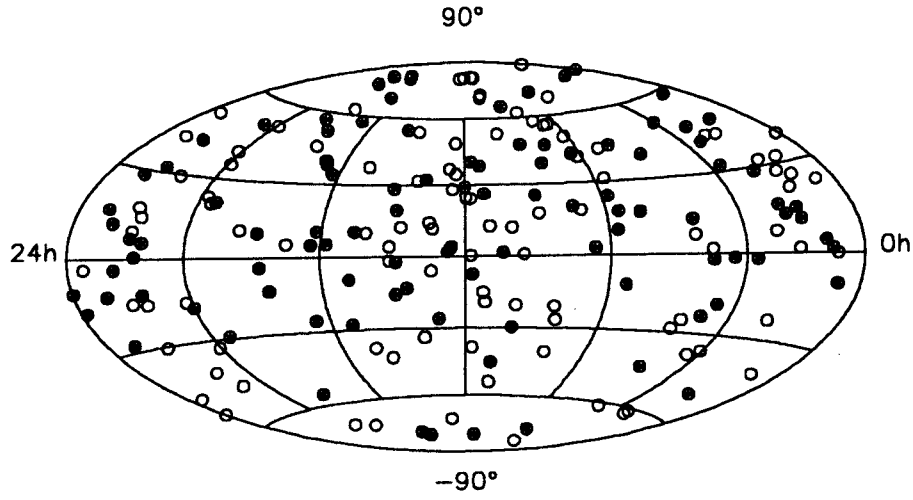
Seiji Manabe, Koichi Yokoyama
Mizusawa Astrogeodynamics Observatory, National Astronomical Observatory, Japan

The report contains the results of the analysis of the VLBI observations from 1984-1993 conducted under IRIS and CDP. The analysed material contains most of the IRIS-A and -P and part of the IRIS-S and CDP observations.

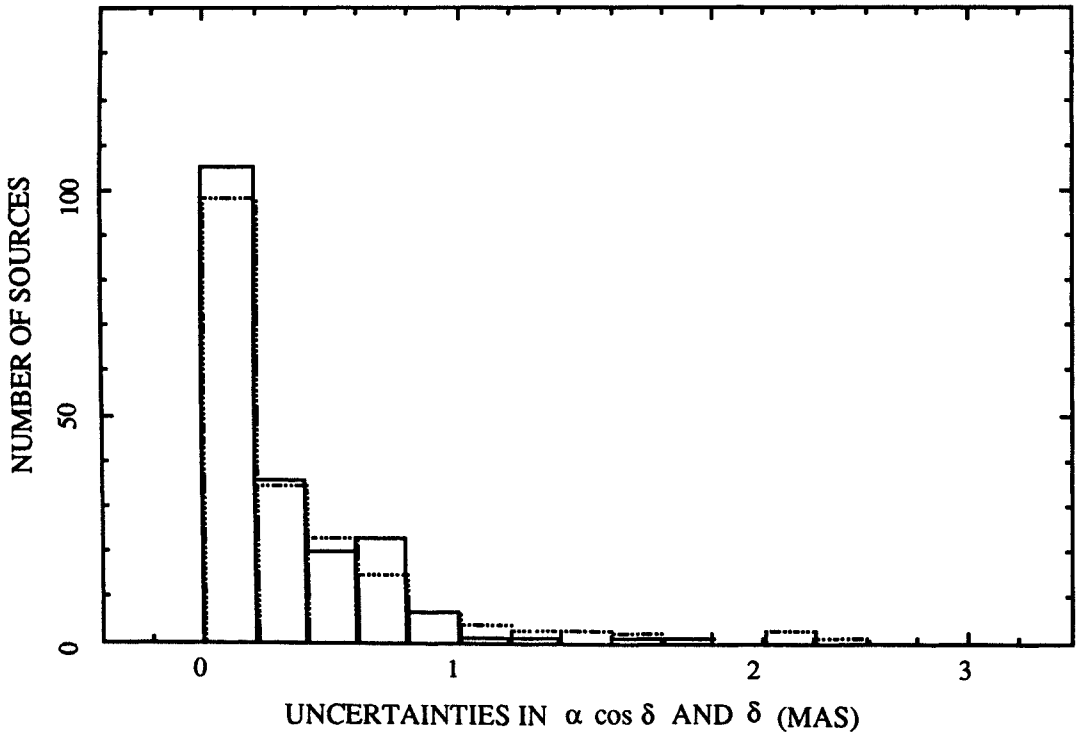
The basic system of the astronomical and geophysical constants are the IERS standards. However, there are some points differing from them. The vertical displacements of the station due to the atmospheric loading are corrected by adopting the method by Manabe (1991). Another difference is in the ocean loading effect on station positions. The displacements are computed with GOTIC by Sato and Hanada (1984) on the basis of Schwiderski's tidal map with the modification to conserve the mass of the oceans. Niell's (1993) NHMF2 is used as the mapping function of the atmospheric delay. The programs used in the analysis are the Mizusawa version of CALC, MSLV3 and GLK. MSLV3 and GLK correspond to SOLVE and GLOBL of Mark III.

Summary of the solutions NAOMZ 94 R 01 and R 02

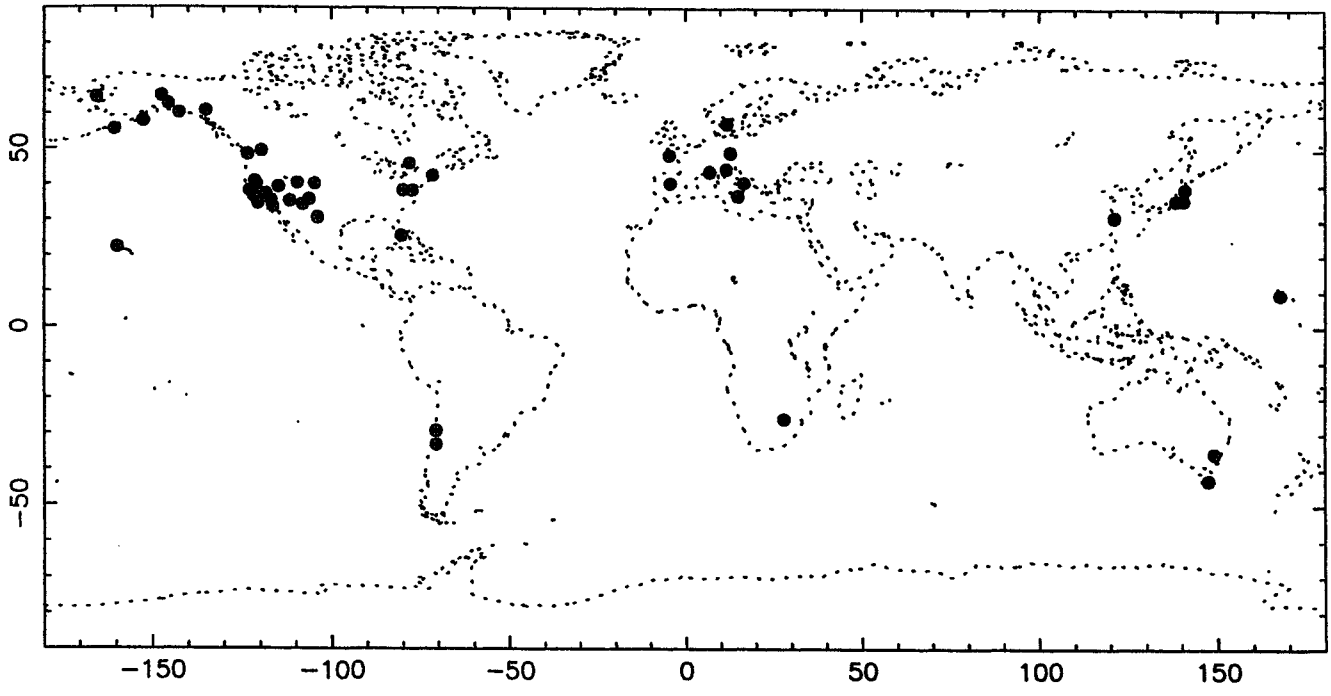
1 - Technique:	VLBI
2 - Analysis Center:	Mizusawa Astrogeodynamics Observatory, National Astronomical Observatory, Japan
3 - Solution identifier:	SG000084
4 - Software used:	CALC3, MSLV3 and GLK developed at Mizusawa
5 - Relativity Scale:	
6 - Permanent tidal correction on station:	yes
7 - Tectonic plate model:	NUVEL-NNR
8 - Velocity of light:	
9 - Gravitational constant:	
10 - Reference epoch:	1988.0
11 - Adjusted parameters:	EOP, station coordinates and velocities, radio source positions
12 - Definition of Origin:	Westford's coordinates(m) (1492206.755, -4458130.499, 4296015.503)
13 - Definition of Orientation:	Mean orientation of GILCREEK, ONSALA60, NRAO85 3, WETTZELL, RICHMOND, WESTFORD, KAUAI and mean of KASHIMA and KASHIM34 are adjusted to that of ITRF92.
14 - Constraint for time evolution:	linear in time



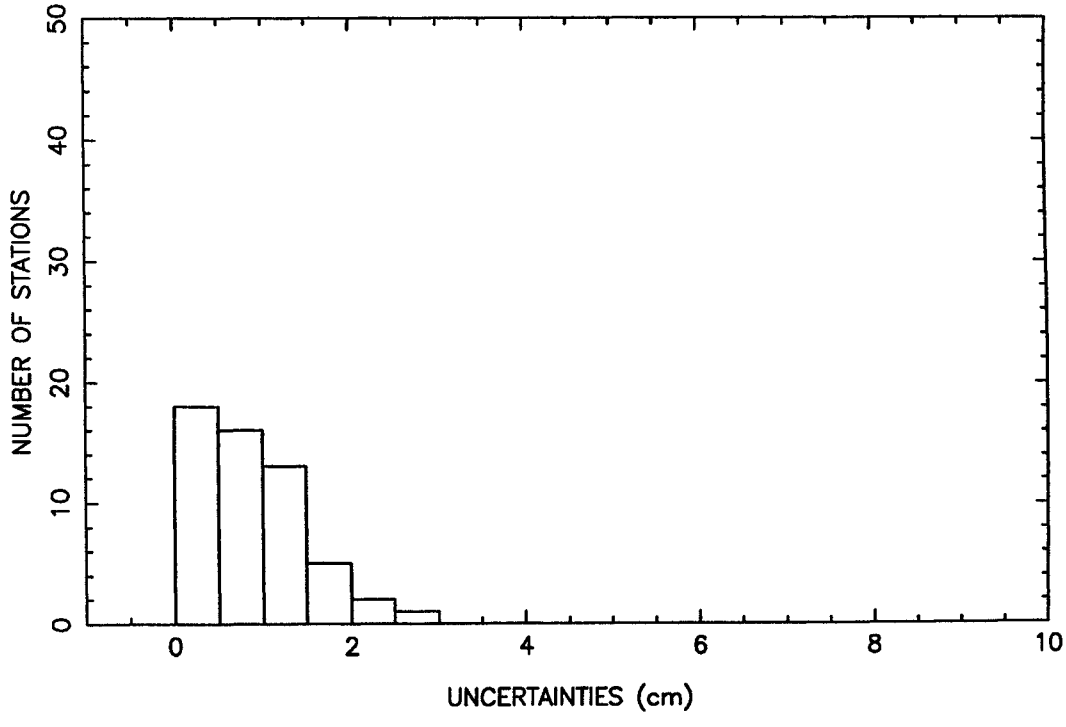
Distribution over the sky of the 206 extragalactic radio sources of the celestial frame RSC(NAOMZ) 94 R 01. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(NAOMZ) 94 R 01. 10 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 49 sites of the terrestrial frame SSC(NAOMZ) 94 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 55 stations of the terrestrial frame SSC(NAOMZ) 94 R 01.

EOP(NAOMZ)94 R 02 From Jan 1984 to Feb 1994

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1984	76	0.63	76	0.56	76	0.30	76	0.72	76	0.26
1985	77	0.60	77	0.54	77	0.28	77	0.65	77	0.24
1986	92	0.62	92	0.54	92	0.29	92	0.68	92	0.26
1987	101	0.61	102	0.56	102	0.30	102	0.71	102	0.26
1988	106	0.55	106	0.50	106	0.28	106	0.61	106	0.25
1989	165	0.50	165	0.48	165	0.25	165	0.61	165	0.24
1990	174	0.33	173	0.38	174	0.18	174	0.44	174	0.19
1991	143	0.24	143	0.26	143	0.12	143	0.36	143	0.14
1992	148	0.27	148	0.27	148	0.11	148	0.41	148	0.17
1993	72	0.20	72	0.17	72	0.07	72	0.32	2	0.13
1994	5	0.12	5	0.11	5	0.05	5	0.21	5	0.09

NOAA EARTH ORIENTATION AND REFERENCE FRAME RESULTS DERIVED FROM VLBI OBSERVATIONS: 1994 ANALYSIS PROCEDURES

NOAA 94 R 01, 02

J.R. Ray, M.D. Abell, W.E. Carter, W.H. Dillinger, M.L. Morrison, and D.S. Robertson, Geosciences Laboratory, NOAA N/OES13, SSMC 4, 1305 East-West Highway, Silver Spring, Maryland 20910-3281, USA. [e-mail: `jimr', `mikea', `bcarter', `billd', `mikem', and `doug', @ internet node `ray.grdl.noaa.gov']

1. Introduction

Estimated values for terrestrial site coordinates and velocities, radio source coordinates, and a time series of Earth orientation parameter (EOP) values have been determined from a composite set of Mark III Very Long Baseline Interferometry (VLBI) data. The data sets included were collected under the sponsorship of several national and international agencies and programs with a wide variety of objectives. A total of 1,009,298 bandwidth-synthesis group delay observables amassed during 1609 one-day observing sessions between 1980 September and 1994 March were combined in a single least-squares adjustment to obtain an EOP time series (EOP(NOAA) 94 R 01), coordinates for 176 radio sources (RSC(NOAA) 94 R 01), and geocentric coordinates and velocities for 106 VLBI reference points (SSC(NOAA) 94 R 01).Unlike past years, our EOP time series is not partitioned into two distinct files so as to emphasize the unitary nature of the VLBI analysis.

In addition, a separate series of quasi-daily UT1 values for the period 1984 April - June and 1985 April to 1994 March has been produced; EOP(NOAA) 94 R 02 contains results from 2224 sessions. These UT1 values were determined from a special series of 'Intensive' observing sessions using only a single east-west baseline for about one hour each day [Robertson *et al.*, 1985], sufficient to determine only UT1. Usually, the WESTFORD-WETTZELL baseline was used for Intensive observations, although a small number of sessions have used either NRAO85-3 or MATERA. The EOP(NOAA) 94 R 02 Intensive UT1 time series is produced separately but is otherwise fully consistent with the UT1 values in the EOP(NOAA) 94 R 01 series from the 24-hour observing sessions.

The most significant changes since our submission last year [Carter *et al.*, 1993] are summarized below. Detailed discussions of these items are presented in the following sections.

• The total number of VLBI observations analyzed has increased almost 45%, including data from 51 more sites and 69 new radio sources. Apart from including new observational data collected during 1993, the significant additional data source was the assimilation of 234 sessions involving 37 mobile VLBI sites throughout N. America. In addition, first data from the following new facilities were included: six of the 25-m VLBA antennas; the 14.2-m antenna at Fortaleza (Brazil); the 20-m Kokee antenna on Kauai (Hawaii, USA); the 9-m antenna at the O'Higgins Base (Antarctica); and the 10-m dish at Mizusawa (Japan).

• The modelling of the elevation angle dependence of the tropospheric path delay has been changed from the CfA-2.2 model [Davis *et al.*, 1985] for the "dry" delay plus the Chao [1972] model for the "wet" delay to the new NMF "dry" and "wet" models [Niell, 1993 and in preparation]. The main consequence of this change is a reduction in the scale of the NOAA terrestrial reference frame by nearly 3 parts per billion (ppb).

• The no-net-rotation (NNR) version of the NUVEL-1A global plate motion model [DeMets *et al.*, 1994] has been used instead of the previous NNR-NUVEL-1 model. The new model yields rates that are scaled by the factor 0.9562 compared with NUVEL-1 due to recent recalibration of the geomagnetic time scale. This change affects the net rotational and translational velocity constraints applied to the VLBI system and the projected geocentric coordinates for those sites with insufficient measurement histories to permit direct velocity determinations. The number of sites used to specify the net velocity constraints has been increased from 9 to 10.

• Seven pairs or triplets of adjacent sites have been constrained to have the same velocity estimates. Instances of nearby sites with independently robust velocity determinations have not been linked in this way.

• New fixed EOP values for the reference epoch 1991 August 12 19:49:50 (see below) have been computed based on the series EOP(IERS) 90 C 04 with appropriate consistency corrections applied for the latest realization of the ITRF and ICRF. The changes in our EOP reference values are -0.1058 mas, +0.2729 mas, +0.075 ms, - 0.4155mas, and +0.3053 mas for x, y, UT1, ψ, and ε, respectively. The combined effect of all changes in our new analysis procedures produces total shifts in our current EOP series of -0.2068 mas, +0.2741 mas, +0.076 ms, -0.3826 mas, and +0.2644 mas, respectively.

• The constraint defining the geocentric coordinate origin of the NOAA terrestrial reference frame has been updated to use ITRF-92 coordinates rather than ITRF-91 values; see Dillinger *et al.* [1993] for a description of the constraint algorithm. The set of constraining sites has been increased from 16 to 20. Compared to the previous realization, the origin of ITRF-92 is shifted by -1.1, -1.4, and 0.6 cm in X, Y, and Z, respectively, and the scale is smaller by 1.4 ppb [Boucher *et al.*, 1993].

• The constraint defining the right ascension (RA) origin of the NOAA celestial reference frame has been updated to use ICRF-92 coordinates rather than

ICRF-91 values. In addition, the constraint algorithm [Dillinger *et al.*, 1993] has been modified so that in forming the sum of adjusted RA values each contributor is weighted by the cosine of its declination in order to de-emphasize sources near the celestial poles. The set of constraining radio sources has been changed to include all common sources designated as "primary" in the ICRF-92 catalog thereby increasing the number of constraining sources from 36 last year to 71.

2. Summary of Analysis Procedures

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 and on changes from our previous submission:

• The right ascension (RA) origin of the NOAA celestial reference frame at epoch J2000.0 is specified by constraining the sum of the adjusted RA values for 71 radio sources, each weighted by the cosine of its declination, to be equal to the corresponding value obtained from the IERS Celestial Reference Frame ICRF-92. The constraint algorithm differs from that used last year and described by Dillinger *et al.* [1993] by the inclusion of the cosine(declination) weighting. The set of 71 constraining sources include all those designated as `primary' in the ICRF-92 catalog which are common to the two frames. Previously, 36 sources, preferentially but not necessarily primary, were used for the RA constraint.

• 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-92 for the set of 20 VLBI sites listed below:

Westford,	MA, USA *
Richmond,	FL, USA *
Algonquin Park,	Ont., Canada *
Gilmore Creek, Fairbanks,	AK, USA *
NRAO85-3, Green Bank,	WV, USA *
Platteville,	CO, USA *
Mojave,	CA, USA
Owens Valley,	CA, USA
Vandenberg,	CA, USA
Onsala,	Sweden *
Effelsberg,	Germany *
Wettzell,	Germany *
Kashima,	Japan
Shanghai,	China
DSS-65, Madrid,	Spain
Kauai,	HI, USA *
Kwajalein Atoll,	Marshall Islands
Hobart, Tasmania,	Australia
DSS-45, Tidbinbilla,	Australia
Hartebeesthoek,	South Africa

The Pie Town (NM, USA) VLBA station was dropped from the list of constraint sites used last year while EFLSBERG, MOJAVE12, OVRO_130, VNDNBERG, and KASHIMA were added. We note that the origin of ITRF-92 is shifted by -1.1, -1.4, and 0.6 cm in X, Y, and Z relative to ITRF-91, which was used for our origin constraint last year, and the scale of ITRF-92 is smaller by 1.4 ppb [Boucher *et al.*, 1993].

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 10 VLBI sites be equal to the corresponding vector sum obtained assuming station velocities as predicted by the NNR-NUVEL-1A global plate motion model [DeMets *et al.*, 1990; Argus and Gordon, 1991; DeMets *et al.*, 1994]. 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-NUVEL-1A model for the same set of 10 sites. See Dillinger *et al.* [1993] for details of the constraint equations. The 10 sites used for the velocity constraints are indicated in the list above with asterisks; with the addition of EFLSBERG, the list is otherwise the same as last year. 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 or regions of large-scale tectonic deformation. NNR-NUVEL-1A is the no-net-rotation version of the NUVEL-1A plate motion model, a recalibration of the previous NUVEL-1 model to account for revisions to the geomagnetic time scale; all angular velocities are 4.38% smaller in NUVEL-1A [DeMets *et al.*, 1994].

The velocity values used to project station coordinate values to arbitrary epochs for those sites with brief data spans, usually less than about two years, are adopted from the NNR-NUVEL-1A model. (However, velocity parameters are adjusted in the data analysis for all sites, including those with brief data spans.) There are 34 sites in SSC(NOAA) 94 R 01 with coordinate projection done using model velocities. They are denoted by having velocity formal errors equal to zero. In several cases, more than one reference point has been measured at a given site but only one point has an adequate history to permit a robust velocity determination. These include sites with collocated mobile occupations adjacent to permanent fixed VLBI antenna locations, shifts in VLBI operations from one permanent antenna to another nearby, and discontinuities due to episodic earthquake motions. We have distinguished post-earthquake sites by modifying their VLBI station names to change the last two characters to `pq'. In all such instances, the VLBI reference points are assumed to have identical long-term velocities and constraints to this effect have been applied in the analysis. For sites affected by earthquake motions, this assumption is consistent with the analysis of Argus and Lyzenga [1994]. Sites whose velocity parameters have been linked in this manner are:

MOJAVE12 - MOJ_7288 - MOJAVEpq
OVRO_130 - OVR_7853
KAUAI - KOKEE
GORF7102 - GGAO7108
FORT_ORD - FORTORDS - FORTORpq
YAKATAGA - YAKATApq
YELLOWKN - YLOW7296

Other cases of adjacent VLBI sites having independently robust histories for velocity determinations, such as WESTFORD and HAYSTACK, have not been specially constrained.

• In the transformation between the celestial and terrestrial systems, 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 described 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 for the reference epoch 1991 August 12 19:49:50. 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 EOP values for the reference epoch were computed in a two-step process somewhat changed from last year: first, linear interpolation was performed between tabulated values in the series EOP(IERS) 90 C 04 for 1991 August 12 and 13 (after correcting for the offsets and drift rates reported by the IERS to give consistency with the ITRF-92 and ICRF-92 frames [IERS, 1993]); then, contributions due to diurnal and semi-diurnal variations of polar motion x, y, and UT1 were added based on the model of Herring [1993]. The values so determined for the reference epoch (MJD 48480.8262731479) are given in Table 1. Also shown in Table 1 are the EOP reference values used in our analysis last year and the change for each component. These are compared with the changes in the IERS system itself due to different realizations of the terrestrial and celestial reference frames in 1991 and 1992; see the rightmost column.

Table 1. Fixed EOP values for reference epoch 1991 August 12 19:49:50

EOP	value this year	value last year	change	IERS change
x =	136.4637 [IERS]			
	-.0616 [d/sd]			
=	136.4021 mas	136.5079 mas	-0.1058 mas	-0.3252 mas
y =	554.4026 [IERS]			
	-.4195 [d/sd]			
=	553.9831 mas	553.7102 mas	+0.2729 mas	+0.2000 mas
UT1 =	171.218 [IERS]			
-UTC	+.021 [d/sd]			
=	171.239 ms	171.164 ms	+0.075 ms	+0.0534 ms
psi =	-17.1806 mas	-16.7651 mas	-0.4155 mas	-0.4000 mas
eps =	-4.4022 mas	-4.7075 mas	+0.3053 mas	+0.3000 mas

Note: [IERS] refers to values interpolated linearly from EOP(IERS) 90 C 04 after correcting for annual offsets and drift rates needed to achieve consistency with the ITRF-92 and ICRF-92 frames; [d/sd] refers to the diurnal and semi-diurnal corrections from the model of Herring [1993].

• 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 h2 and Shida number l2 are 0.60967 and 0.0850, respectively, rather than the IERS Standards (1992) values of 0.6090 and 0.0852. 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 unchanged from last year and consists of the following steps: 1) tabulated EOP values are taken from a previous NOAA solution for the set of all IRIS-A, NAVNET, and NEOS-A 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 between 5.64 days and 18.6 years with corrections due to oceanic tides (see IERS Standards, McCarthy, 1992); 2) diurnal and semi-diurnal variations of x,y, and UT1 derived by Herring [1993] 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.

• Tropospheric refraction in the local zenith direction caused by the "dry" (hydrostatic) and "wet" (water vapor) 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 NMF dry and wet models [Niell, 1993 and in preparation]. Residual atmospheric delay, presumably due to the wet troposphere, is treated by adjusted parameters (see below) using the NMF wet elevation mapping function. The new NMF mapping functions perform comparably to the MTT mapping functions of Herring [1992]. However, the bias in the hydrostatic mapping is significantly smaller [Niell, private communication] which should minimize potential scale errors in the terrestrial and celestial reference systems. In addition, because the NMF functions do not rely on surface met data, those VLBI sessions which lack met data can be combined with other sessions with less risk of biases due to inhomogeneties. This year's change in tropospheric mapping functions, by itself, causes a reduction in the NOAA terrestrial reference frame of about 2.7 ppb. 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 Silver Spring (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; Dillinger *et al.*, 1993]. Delay rate observations are not included, nor any observations with an elevation angle lower than 5 degrees. The solution was done with a forward pass to reduce and combine all the data to determine values for the "global" parameters (those values are affected by all observing sessions) followed by a separate step to determine the "arc" parameters (those affected only by data from an 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-NUVEL-1A 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 Space Geodesy Program) 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. Some 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 in a regional observing program. For these cases (totalling 183 sessions of which 143 are from the newly added N. America mobile VLBI campaigns), 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 determinations of EOP values became routine.

The full solution included 1,009,298 group delay observations and 166,225 constraint equations to adjust a total of 221,488 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. Comparison of VLBI station coordinates with independent determinations using satellite laser ranging (SLR) 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 east-west baseline, generally 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. For brief periods, the Matera (Italy) station has substituted for Wettzell and the NRAO85-3 antenna (at Green Bank, WV, USA) for Westford. Beginning 1994 February 24, Intensives operations were moved from Westford to NRAO85-3 permanently. 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.

3. Discussion of Results

3.1 Celestial Reference Frame:

The current NOAA celestial reference frame consists of 176 radio sources, an increase of 69 sources over last year. Of these sources, 71 are designated "primary" in the IERS Celestial Reference Frame ICRF-92. The right ascension origin of the NOAA frame is defined by a constraint to match ICRF-92 for the subset of 71 primary sources (see discussion above). 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. It is expected that any non-rotational deformations in our frame [IERS, 1993], to the extent that they may be caused by biases in the modelling of tropospheric refraction, will be reduced in this year's submission due to the implementation of the NMF mapping function (see previous discussion).

The mean (or weighted mean) and root-mean-squared (rms or weighted rms) differences between our RSC(NOAA) 94 R 01 celestial frame and the ICRF-92 are shown in Table 2 for the set of 71 primary sources in common, for all sources in common, and for all sources in common except three. For the latter two sets, the reported formal uncertainties for both catalogs have been used to compute weighted mean and weighted rms (about the mean) values. In all cases the mean differences are quite small. The scatters are also small and consistent with the quoted formal uncertainties except for the RA scatter of the full source set. This discrepancy is caused by a very poor RA value for 0733-174, which was recently corrected by nearly 800 mas [Eubanks, private communication]. Excluding this source, 0316+413 (3C84), and 1947+079 from the statistics gives scatter results roughly consistent with the reported formal uncertainties; reduced chi-squared values are 1.15 and 1.37 for the RA and declination differences, respectively.

There are 11 sources being submitted in RSC(NOAA)94R01 which are not contained in the ICRF-92 catalog: 0010+405, 0108+388, 1053+704, 1128-047, 1307+121, 1409+218, 1417+273, 1420+326, 1424+240, 1432+200, and 1433+304. Data for all these are sparse, in one case relying on only four observations.

Table 2. Differences between RSC(NOAA) 94 R 01 and ICRF-92

	RA (mas)	RA * cos(dec) (mas)	dec (mas)
71 "primary" sources in common:			
mean	-0.018	= 0.000	-0.007
rms	0.351	0.241	0.299
all 165 sources in common:			
weighted mean	-0.011	-0.018	-0.016
weighted rms	2.538	2.038	0.341
162 sources in common: *			
weighted mean	-0.023	-0.026	-0.010
weighted rms	0.205	0.163	0.229

* Excluding 0316+413 (3C84), 0733-174, and 1947+079; see text. The mean difference in RA*cos(dec) is constrained to be zero for the 71 primary sources.

3.2 Terrestrial Reference Frame:

The motivation and procedure for defining the coordinate origin of the NOAA terrestrial reference frame were discussed in last year's report by Carter *et al.* [1993]. The NOAA site positions are adjusted so that the origin matches the IERS Terrestrial Reference Frame, ITRF-92, for a subset of 20 out of the full set of 106 VLBI sites. Connection of each VLBI station's position to the origin constraint is improved by distributing the constraint over as large a network as possible. Unlike the celestial RA 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. With these considerations in mind we have added five sites to the origin constraint this year: EFLSBERG, MOJAVE12, OVRO_130, VNDNBERG, and KASHIMA. Even though EFLSBERG is included in only six observing sessions, its history spans more than 13 years which yields very precise position and velocity determinations. The other new origin constraint sites lie in deformation zones near plate boundaries and were excluded for this reason last year. However, because ITRF-92 combines position determinations wherein non-plate motions are accounted for, this restriction does not appear necessary. Meanwhile, the PIETOWN VLBA site has been dropped from our origin constraint because its anomalous measured motion last year (-22.4 mm per year in the local vertical direction) cast doubt on the reliability of coordinate projection to epoch 1988.0.

Table 3 presents the coordinate transformation parameter values relating the NOAA terrestrial reference frame to ITRF-92 for the 20 sites used in the origin constraint. The largest value is the rotation about the X-axis which corresponds to a shift of about 17.7 mm at the Earth's surface. The largest contribution to the rms

residual comes from Hobart with differences of -29.1, 13.9, and -2.6 mm in X, Y, and Z, respectively. The next largest residuals are due to DSS65 (Madrid) and DSS45 (Tidbinbilla) at less than half that level. It appears likely that the Hobart discrepancy is caused by a significant change in its measured velocity since last year (see below) coupled with a relatively large time offset of 4.1 years between the 1988.0 coordinate reference epoch and the mean epoch of Hobart data.

Table 3. Coordinate transformation from ITRF-92 to SSC(NOAA)94R01 *

Transformation parameter	value	error
Rot. about X	0.573 mas	0.069 mas
Rot. about Y	0.054 mas	0.068 mas
Rot. about Z	0.078 mas	0.064 mas
X translation	-1.0 mm	1.7 mm
Y translation	8.3 mm	1.8 mm
Z translation	2.1 mm	1.7 mm
scale difference	0.3 ppb	0.3 ppb
3-D rms residual	10.6 mm	

* For the 20 VLBI sites defining the origin of the coordinate system, equally weighted.

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 10 VLBI sites are used in the velocity constraints and the defining motions are adopted from the NNR-NUVEL-1A global plate motion model. 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-NUVEL-1A model for rigid plate motions [DeMets *et al.*, 1990; Argus and Gordon, 1991; DeMets *et al.*, 1994] -- is an idealized representation of relative terrestrial motions that is totally independent of VLBI results. On the other hand, the ICRF-92 and ITRF-92 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 0.100-0.200 mas/yr). While the specification of these rates is arbitrary, some choices are preferred for practical reasons. For one, the NOAA frames are intended 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-NUVEL-1A 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 caution, 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 10 velocity constraint sites with six in N. America, three in Europe, and one in Hawaii. EFLSBERG was added to the set of nine velocity constraint sites used last year. The rms velocity residuals for the 10 constraint sites relative to NNR-NUVEL-1A motions are 1.7 mm/yr in the horizontal plane and 2.1 mm/yr in the vertical direction.

Table 4 shows the measured topocentric velocities for 40 VLBI sites having sufficiently long data spans, relative to the velocities predicted by the NNR-NUVEL-1A plate motion model. (For those sites with linked velocity estimates, only one site name is listed in Table 4.) There are, in addition, 23 mobile sites in western N. America whose motions are not shown in Table 4. Results for these sites, which lie mostly in tectonically deforming regions and which are generally not as well determined, especially in the vertical, have recently been reviewed by Gordon *et al.* [1993]. Also indicated in Table 4 are the sites used for the coordinate origin constraint and for the frame velocity constraints.

In the five cases in Table 4 of two or more independent sites located within a few kilometers of one another, indentation of the site names is used to denote the groupings. These results can be used as a gauge of the level of systematic velocity error that may be present. The most robust pair is HAYSTACK/WESTFORD, each of which has observed longer than a decade although WESTFORD has accumulated about 18 times as much data. Their velocities differ by -0.3, 0.3, and 0.9 mm/yr in N, E, U, respectively, only about one standard deviation or less in all three components. The Green Bank (NRAO_140 and NRAO85_3), Ft. Davis (HRAS_085 and FD-VLBA), Goldstone (MOJAVE12, GOLDVENU, and DSS15), and Kashima (KASHIMA and KASHIM34) groupings show poorer agreement with velocity differences up to 6 sigma in E at Green Bank and Ft. Davis and in U at Kashima. The 16.4 mm/yr downward motion of KASHIM34 seems possibly spurious.

Another measure of systematic error is the change in our velocity estimates this year compared to last year. Focussing on the vertical velocity (Vu) changes, 17 out of the 35 sites available for comparison show changes of one sigma or less. The eight sites which change by more than 3 sigma are listed in Table 5.

Table 4. Differences between NOAA site velocities and NNR-NUVEL-1A (all units mm/yr)

VLBI Site Name	Vn	Ve	Vu	Vn err	Ve err	Vu err	Constraint *
Eurasia:							
TROMSONO	-1.5	11.2	-3.2	1.0	1.0	5.7	
ONSALA60	0.1	-0.8	2.2	0.1	0.2	0.3	CV
TRYSILNO	0.7	-4.7	19.9	1.2	1.1	9.9	
EFLSBERG	0.9	1.4	-1.7	0.2	0.2	0.7	CV
WETTZELL	0.5	0.4	-3.1	0.1	0.2	0.3	CV
DSS65	0.2	0.9	4.3	0.3	0.3	1.1	C
MEDICINA	2.4	2.6	-4.3	0.2	0.3	0.7	
MATERA	5.0	3.5	-6.6	0.3	0.4	1.3	
SESHAN25	-3.7	9.3	-6.0	0.8	1.0	2.6	C
Africa:							
NOTO	-0.8	2.1	-5.6	0.3	0.4	1.4	
HARTRAO	-6.1	-6.1	-1.8	1.1	1.0	1.3	C
N. America, stable:							
HAYSTACK	-0.4	1.2	1.8	0.2	0.2	0.6	
WESTFORD	-0.1	0.9	0.9	0.1	0.2	0.5	CV
ALGOPARK	-0.9	0.9	1.9	0.2	0.2	0.7	CV
MARPOINT	1.0	-1.4	2.3	0.9	0.6	4.5	
GORF7102	2.7	4.1	-10.5	1.0	0.8	5.6	
NRAO_140	-0.1	0.7	0.2	0.2	0.2	0.8	
NRAO85_3	0.3	-0.7	1.7	0.3	0.2	0.8	CV
RICHMOND	0.6	1.3	2.2	0.3	0.2	0.6	CV
HRAS_085	0.8	0.6	1.9	0.3	0.2	0.9	
FD-VLBA	2.6	-2.1	-1.7	0.5	0.4	1.5	
PIETOWN	-1.0	-0.6	-4.5	0.3	0.2	0.9	
LA-VLBA	1.5	0.5	-2.9	0.3	0.3	1.0	
PLATTVIL	-1.5	0.4	-3.9	0.6	0.4	3.5	CV
YLOW7296	-1.6	3.0	19.1	0.7	0.7	2.9	
GILCREEK	-1.3	0.5	-0.8	0.1	0.2	0.4	CV
N. America, California:							
MOJAVE12	7.6	-3.4	-1.7	0.2	0.2	0.7	C
GOLDVENU	6.2	-2.7	-5.8	0.5	0.4	2.1	
DSS15	6.4	-5.1	-4.1	0.7	0.5	2.1	
OVRO_130	8.2	-5.2	-0.6	0.3	0.2	1.1	C
HATCREEK	4.6	-6.1	-1.1	0.3	0.3	1.2	
S. America:							
SANTIA12	17.4	16.7	-5.1	2.4	2.1	6.3	
Pacific:							
VNDNBERG	-1.4	-0.6	4.6	0.3	0.2	1.1	C
KAUAI	1.7	-3.5	0.2	0.3	0.5	0.6	CV
MARCUS	1.8	-0.7	-1.6	2.3	2.0	8.1	
KWAJAL26	-2.4	-2.1	-4.7	1.7	1.4	6.0	C
Australia:							
DSS45	0.6	1.3	8.8	1.1	1.5	1.6	C
HOBART26	2.0	1.4	4.5	1.2	1.6	1.7	C
Japan (N. America):							
KASHIMA	2.7	-10.1	-4.5	0.4	0.6	0.7	C
KASHIM34	2.0	-8.9	-16.4	0.7	0.9	2.0	

* `C' indicates site used in coordinate origin constraint; `V' indicates inclusion in frame velocity constraint. Adjacent sites are indicated by indentation of second and third site names of each group.

Table 5. NOAA Vu changes > 3 sigma

VLBI Site Name	Vu change (1994-1993) (mm/yr)	(sigmas)	Vu change due to NMF (mm/yr)
PIETOWN	+17.9	12.8	+7.1
LA-VLBA	+11.6	5.5	+2.8
HATCREEK	+9.5	4.5	+0.8
VNDNBERG	+7.1	3.6	+1.0
MATERA	+7.8	3.5	+2.1
DSS45	-8.6	3.4	-0.1
KASHIMA	-3.3	3.3	-1.6
MOJAVE12	+3.1	3.1	+0.8

Some of these changes can probably be attributed to the addition of significant new data sets. HATCREEK, VNDNBERG, and MOJAVE12 were involved in many of the 234 western U.S. mobile sessions which were added to our solution for the first time this year. The increase in number of observations for these three stations was 303%, 246%, and 39%, respectively. While the volume of new data for MOJAVE12 is not as great, most of the new sessions occurred during the early history of the station. MATERA and LA-VLBA also have substantially more data than last year, by 122% and 88%, respectively. Significantly, many of the new sessions involving these stations, and KASHIMA as well, used very large networks especially well suited for determining three-dimensional velocity components. Some of the change in the vertical velocity estimates can be attributed to the use this year of the NMF tropospheric refraction model, which does not rely on real-time surface met data collected at the sites. The effect of this change is listed in the rightmost column of Table 5. It is most significant for PIETOWN, for which some early sessions do not have met data. The NMF model also accounts for part of the Vu changes at LA-VLBA, MATERA, and KASHIMA.

Based on these considerations, we expect the velocity values reported here to be reasonably accurate measures of the actual long-term motions of most of the VLBI sites relative to one another. The uncertainty in the net systematic motion of the terrestrial frame itself is probably much larger, as much as 2-4 mm/yr. The formal velocity uncertainties reported here do not include a component to account for such systematic effects. The uncertainties are likely to be somewhat optimistic although probably by a factor less than two in most cases, based on the distribution of Vu changes from last year to this year. Recently, Watkins *et al.* [1994] showed that VLBI and SLR horizontal velocities for a set of 10 sites agree within 2-3 mm/yr with a reduced chi-squared of 1.7. On the other hand, Herring and Dong [1991] and others have noted apparently non-linear length changes for several baselines. In any event, there are a few sites listed in Table 4 whose estimated motions do not appear reliable even allowing for overly optimistic formal errors. Tromso, Norway (TROMSONO) is the most obvious example with a eastward motion 11 mm/yr greater than predicted by NNR-NUVEL-1A. However, this velocity result is based entirely upon two mobile VLBI occupations of the site separated in time by three years with four sessions per

occupation. Unfortunately, only one of the four sessions in the first occupation (in summer 1989) used a geometrically robust network, while the remaining three sessions involved only two other sites. There is, therefore, effectively no redundancy in the TROMSONO velocity determination. Any systematic error associated with the single strong session of the first occupation, such as an error in the eccentricity vector measurement, will be absorbed entirely and undetectably into the velocity estimate. On the other hand, a large displacement of the local site or monument cannot be excluded. The possibilities cannot be distinguished without additional observational data. The inferred horizontal motions for GORF7102 (GSFC, MD, USA) and YLOW7296 (Yellowknife, NWT, Canada) of a few mm/yr level are also suspect. Both of these sites rely on the combination of data from two different monuments with non-overlapping observing histories. The GSFC site has data from 1989.4-1992.5 at monument 7102 and 1993.3-present at 7108; Yellowknife was observed from 1984.7-1985.7 at monument 7285 before operations were shifted to a new installation (monument 7296) in 1991.5. In addition, the FD-VLBA site at Ft. Davis (TX, USA) shows motions greater than 2 mm/yr in both horizontal components, significant at the 5-sigma level. This may simply be an instance of an immature determination: while there is a substantial amount of data for FD-VLBA (40 sessions, most of which involve geometrically robust networks) its history began in 1992.5 providing a span of only about 1.5 years.

Apart from the specific exceptions discussed above, the results presented in Table 4 are generally in excellent agreement with the NNR-NUVEL-1A global plate motion model or indicate tectonic deformations. In Europe, the horizontal motions among ONSALA, EFLSBERG, WETTZELL, and DSS65 suggest the rigidity over that part of the Eurasian plate to be better than 2 mm/yr. SESHAN25 (Shanghai, China), near the far eastern egde of the plate, appears to be moving with respect to the plate by about 10.0 mm/yr at azimuth 112 degrees. While this magnitude agrees with that of Robaudo and Harrison [1993], who interpret Shanghai motion to be an effect of Philippine plate subduction, the direction of our velocity residual is nearly opposite to theirs (azimuth 314 degrees). Their analysis included both VLBI and SLR data but we can offer no explanation for this large discrepancy. Both Italian penisula sites show significant non-plate motions, especially MATERA which is observed to move at a rate of 6.1 mm/yr at azimuth 55 degrees relative to the model. Deformation is expected in this region due to collision of Africa with Eurasia. The Sicilian site of NOTO, assigned to the African plate, is consistent with the model except for a moderate residual motion of 2.1 mm/yr eastward. On the other hand, HARTRAO in South Africa displays a SW residual of 8.6 mm/yr. This site does lie within a broad region of suspected deformation.

There are 10 sites in N. America outside the western deformation zone with horizontal motion determinations having formal uncertainties of 0.3 mm/yr or less. Among these, the velocity residuals fall within -1.3 to +1.5 mm/yr in the north direction (weighted rms is 0.9 mm/yr) and within -0.7 to +1.3 mm/yr in the east (weighted rms is 0.8 mm/yr), suggesting a plate rigidity of about 3 mm/yr or better over distances exceeding 6000 km. Interestingly, the motion of HRAS_085 (at Ft. Davis, TX, USA) is among the closest of all the VLBI sites in agreeing with the plate model. (Note that it not be used in any of the frame constraints.) Numerous investigators have remarked on the apparent non-linear motion of this site [e.g.,

Herring and Dong,1991]. As is already well established, the sites in California east of the plate boundary all move northwestwardly due to interaction with the adjacent Pacific plate. The results for SANTIA12 (Santiago, Chile), with just over two years of data now available, strongly indicate deformation, presumably associated with the offshore subduction of the Nazca plate beneath S. America. The magnitude of this northeastward motion, about 24.1 mm/yr, compares with a residual velocity of 19mm/yr at azimuth 77 degrees for Arequipa (Peru) reported by Robaudo and Harrison [1993].

Two of the Pacific sites have robust velocity determinations, VNDNBERG on the California coast and KAUAI in the Hawaiian Islands. The magnitude of the non-plate motion at KAUAI -- 3.9 mm/yr at azimuth 296 degrees -- approaches a level of concern because this site is used in our constraint for the motion of the terrestrial frame and its isolated location gives it considerable leverage in the constraint. Closer study of this result is warranted. The velocities for the two Australian sites are in much better agreement with the plate model this year than in our previous report. We attribute this primarily to the adoption of the recalibrated NNR-NUVEL-1A plate model as our reference velocity frame. Nonetheless, the estimated vertical motions, especially for DSS45, remain large enough to be a concern. To some extent, this could be caused by net translational motion of the reference frame, relative to the Earth's center of mass, contributed by the set of velocity constraint sites, which are roughly antipodal to Australia. The westward motions of the two Japanese sites listed in Table 4 show the effect of Pacific plate subduction, as many investigators have discussed.

As we noted in our report last year [Ray *et al.*, 1993], the VLBI vertical rates of motion for very well determined sites in N. America and Europe differ significantly from the rates expected due to post-glacial rebound. Examples are shown in Table 6. In general, the observed differential rates in N. America are smaller than the rates predicted by the ICE-3G model of Tushingham and Peltier [1991] whereas the observed difference between ONSALA and WETTZELL is much larger than predicted. The best agreement is for sites along the east coast of the U.S., where both the measured and predicted differential motions are small. To some extent, the discrepancies could again be due to the inherent ambiguity in the net motion of the terrestrial frame but that is unlikely to account fully for the differences. Mitrovica *et al.* [1993] considered also the horizontal motions expected due to post-glacial rebound and found significant differences compared with VLBI measurements.

Table 6. Observed versus predicted differential uplift rates due to post-glacial rebound (all units mm/yr)

VLBI Sites Name		VLBI uplift difference value	sigma	ICE-3G uplift difference* value
N. Europe:				
ONSALA	- WETTZELL	+5.3	0.4	+1.0
N. America:				
ALGOPARK	- WESTFORD	+1.0	0.9	+4.4
"	- HAYSTACK	+0.1	0.9	+4.4
"	- NRAO85_3	+0.2	1.1	+4.4
"	- NRAO_140	+1.7	1.1	+4.4
"	- RICHMOND	-0.3	0.9	+3.1
"	- GILCREEK	+2.7	0.8	+4.0
WESTFORD	- NRAO85_3	-0.8	0.9	0.0
"	- RICHMOND	-1.3	0.8	-1.3
"	- GILCREEK	+1.7	0.6	-0.4
RICHMOND	- GILCREEK	+3.0	0.7	+0.9

* Post-glacial rebound rates are from the ICE-3G model by Tushingham and Peltier [1991]. Note that the observed VLBI uplift rates are inherently ambiguous due to the net motion of the terrestrial frame.

3.3 Earth Orientation Results:

We reiterate the important change made in our analysis procedures last year, which continues to apply this year: Herring's [1993] model for diurnal and semi-diurnal variations in the polar x and y coordinates and in UT1 is used in our interpolation of a priori EOP values (see description of procedures in section 2). In that sense, 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, our time series should fully preserve tidally coherent components with periods down to about 12 hours.

Table 7 gives the mean EOP offset values for our series EOP(NOAA) 94 R 01 compared with a solution using last year's analysis procedures and the identical set of 1374 VLBI observing sessions (the 1609 sessions being submitted less the 234 newly added mobile VLBI sesssions less the reference epoch session). The weighted rms scatters about the mean differences are also shown in Table 7 as are the EOP offset values due solely to new values for the reference epoch (from Table 1). It can be seen that the overall offset changes are nearly entirely due to the new reference epoch values, which in turn are predominantly caused by realignment of the IERS system itself as a result of the newest realizations of the terrestrial and celestial reference frames. The total polar motion offset in the x coordinate, however, is about twice the size of the offset in x for the reference epoch (and is about two-thirds the magnitude of the IERS system change in x; see Table 1). These varied x offset values are probably related to the comparatively large rotational difference about the X-axis between the NOAA terrestrial frame and ITRF-92 (see Table 3).

Table 7. Offset changes in NOAA EOP values (1994 - 1993)

	x (mas)	y (mas)	UT1 (ms)	ψ (mas)	ε (mas)
Offsets due to new reference values (from Table 1):	-0.1058	+0.2729	+0.075	-0.4155	+0.3053
Total offsets due to all changes:					
wtd. mean	-0.2068	+0.2741	+0.0762	-0.3826	+0.2644
wtd. rms	0.1071	0.1154	0.0055	0.0814	0.0333

3.4 Intensive UT1 Results:

We have previously shown that the accuracy of UT1 determinations from the 1-hour single-baseline IRIS Intensive sessions is about 0.055 ms based on comparison with results from 24-hour VLBI sessions [Ray *et al.*, 1993]. The largest contributor is likely to be error in the a priori calibration of the tropospheric delay, including problems in the collection of meteorological data from the stations. The character of this error source should be random if changes in local weather dominate the variation and systematic if there are discrete biases in the met data or in the tropospheric refraction models. The IERS Central Bureau [IERS,1993] has reported applying systematic corrections to the Intensive UT1 to remove effects associated with quarterly changes in the observing program. (The Intensive schedule is held fixed in local sidereal time for three-month periods.) The corrections range from -0.120 to +0.080 ms. Our own analysis confirms the existence of such quarterly biases, however, the magnitudes are generally much smaller -- typically +/- 0.020 ms or smaller with a few excursions up to about 0.040 ms; the third quarter of 1987 was exceptional with a bias of about -0.090 ms. These biases are probably caused by non-pointlike brightness structures in many of the radio sources that have been used for the Intensive observations. For example, 3C273B was used until late 1987. Even since the shift to less complex sources beginning in 1988, the magnitude of known source structure effects could easily account for UT1 biases at the level of 0.020 ms. Other possible sources of bias, such as offsets in the station met data, are more difficult to estimate without assessments of reasonable magnitudes for such offsets.

4. Electronic Access

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 outside users. The data files described here, as well as the operational EOP data files updated weekly and others, are available through Internet using the `ftp' file transfer protocols. The Internet node where the files can be retrieved is `ray.grdl.noaa.gov' at IP address `140.90.159.197'. The user should login as `anonymous' and reply with the user's name when asked for a password. After logging into the system, the user should change to the appropriate subdirectory by issuing the command `cd dist/vlbi' and use the ftp `get' command to transfer the appropriate files. A README file in that directory provides explanatory information.

Acknowledgements. We thank Arthur Niell of Haystack Observatory for providing code to implement the NMF troposphere mapping function.

References

Argus, D.F., and Gordon, R.G., 1991: No-Net Rotation Model of Current Plate Velocities Incorporating Plate Motion Model NUVEL-1, *Geophys. Res. Lett.*, **18**, 2039-2042.

Argus, D.F., and Lyzenga, G.A., 1994: Site Velocities Before and After the Loma Prieta and Gulf of Alaska Earthquakes Determined from VLBI, *Geophys. Res. Lett.*, **21**, 333-336.

Boucher, C., Altamimi, Z., and Duhem, L., 1993: ITRF 92 and its Associated Velocity Field, *IERS Tech. Note 15*, Observatoire de Paris, Paris.

Caprette, D.S., Ma, C., and Ryan, J.W., 1990: Crustal Dynamics Project Data Analysis - 1990, NASA Technical Memo. No. 100765, pp. A-1 - A-6.

Carter, W.E., Abell, M.D., Dillinger, W.H., Morrison, M.L., Ray, J.R., and Robertson, D.S., 1993: NOAA Earth Orientation Time Series and Reference Frames from VLBI Observations: 1. Description of Analysis Procedures, in *IERS Tech. Note 14*, Observatoire de Paris, Paris, R-47 - R-52.

Chao, C.C., 1972: A Model for Tropospheric Calibration from Daily Surface and Radiosonde Balloon Measurements, California Inst. Tech., Jet Propulsion Lab. Technical Memo. No. 391-350.

Davis, J.L., Herring, T.A., Shapiro, I.I., Rogers, A.E.E., and Elgered, G., 1985: Geodesy by Radio Interferometry: Effects of Atmospheric Modeling Errors on Estimates of Baseline Length, *Radio Science*, **20**, 1593-1607.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990: Current Plate Velocities, *Geophys. J. Int.*, **101**, 425-478.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994: Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions, *Geophys. Res. Lett.* (submitted).

Dillinger, W.H., and Robertson, D.S., 1986: A Program for the Combined Adjustment of VLBI Observing Sessions, *Manuscripta Geodaetica*, **11**, 278-281.

Dillinger, W.H., Robertson, D.S., and Ray, J.R., 1993: NOAA Earth Orientation Time Series and Reference Frames from VLBI Observations: 2. Constraint Algorithms, in *IERS Tech. Note 14*, Observatoire de Paris, Paris, R-53 - R-57.

Fallon, F.W., and Dillinger, W.H., 1992: Crustal Velocities from Geodetic VLBI, *J. Geophys. Res.*, **97**, 7129-7136.

Gordon, D., Ma, C., and Ryan, J.W., 1993: Results from the CDP Mobile VLBI Program in the Western United States, in Contrib. of Space Geodesy to Geodynamics: Crustal Dynamics, *AGU Geodynamics Series*, **23**, pp. 131-138.

Herring, T.A., 1991: The ZMOA-1990 Nutation Series, in *Proc. IAU Coll. 127, Reference Systems* (J.A. Hughes, C.A. Smith, and G.H. Kaplan, eds.), U.S. Naval Observatory, Washington, pp. 157-166.

Herring, T.A., 1992: Modeling Atmospheric Delays in the Analysis of Space Geodetic Data, in *Symposium on Refraction of Transatmospheric Signals in Geodesy* (J.C. DeMunk and T.A. Spoelstra, eds.), Netherlands Geod. Comm., Delft, pp. 157-164.

Herring, T.A., 1993: Diurnal and Semidiurnal Variations in Earth Rotation, *Proceedings of the COSPAR World Space Congress, Adv. Space Res.*, **13**, 11281-11290.

Herring, T.A., and Dong, D., 1991: Current and Future Accuracy of Earth Rotation Measurements, in *Proc. AGU Chapman Conf. on Geodetic VLBI: Monitoring Global Change*, NOAA Tech. Rep. NOS 137 NGS 49, pp. 306-324.

IERS, 1993: *1992 IERS Annual Report*, Observatoire de Paris, Paris.

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

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

Mitrovica, J.X., Davis, J.L., and Shapiro, I.I., 1993: Constraining Proposed Combinations of Ice History and Earth Rheology using VLBI Determined Baseline Length Rates in North America, *Geophys. Res. Lett.*, **21**, 2387-2390.

Niell, A.E., 1993: A New Approach for the Hydrostatic Mapping Function, in *Proc. Intern. Workshop for Reference Frame Establishment and Technical Development in Space Geodesy*, Communications Research Laboratory, Tokyo, pp. 61-68.

Ray, J.R., Ma, C., Ryan, J.W., Clark, T.A., Eanes, R.J., Watkins, M.M., Schutz, B.E., and Tapley, B.D., 1991: Comparison of VLBI and SLR geocentric site coordinates, *Geophys. Res. Lett.*, **18**, 231-234.

Ray J.R., Dillinger, W.H., and Robertson, D.S., 1993: NOAA Earth Orientation Time Series and Reference Frames from VLBI Observations: 3. Discussion of Results, in *IERS Tech. Note 14* , Observatoire de Paris, Paris, R-59 - R-70.

Robaudo, S., and Harrison, C.G.A., 1993: Plate Tectonics from SLR and VLBI Global Data, in Contrib. of Space Geodesy to Geodynamics: Crustal Dynamics, *AGU Geodynamics Series*, **23**, pp. 51-71.

Robertson, D.S., Carter, W.E., Campbell, J.A., and Schuh, H., 1985: Daily UT1 Determinations from IRIS Very Long Baseline Interferometry, *Nature*, **316**, 424-427.

Saastamoinen, J., 1972: Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites, in The Use of Artificial Satellites for Geodesy, *Geophys. Monogr. Ser. 15* (S.W. Henriksen *et al.*, eds.), AGU, Washington, D.C., pp. 247-251.

Tushingham, A.M., and Peltier, W.R., 1991: ICE-3G: A New Global Model of Late Pleistocene Deglaciation Based upon Geophysical Predictions of Post-Glacial Relative Sea Level Change, *J. Geophys. Res.*, **96(B3)**, 4497-4523.

Watkins, M.M., Eanes, R.J., and Ma, C, 1994: Comparison of Terrestrial Reference Frame Velocities Determined from SLR and VLBI, *Geophys. Res. Lett.*, **21**, 169-172.

Summary description of the solutions NOAA 94 R 01 and 94 R 02

1 - Technique:
Bandwidth-synthesis Mark III VLBI

2 - Analysis Center:
NOAA VLBI Analysis Center, Geosciences Laboratory, N/OES13, SSMC 4, 1305 East-West Highway, Silver Spring, MD, USA 20910-3281

3 - Solution ID:
solution rundate = 9/ 3/94 20:39:59

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-NUVEL-1A is used to specify the large-scale motion of the entire terrestrial reference frame in both translational and rotational senses for 10 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:
299 792 458. 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:

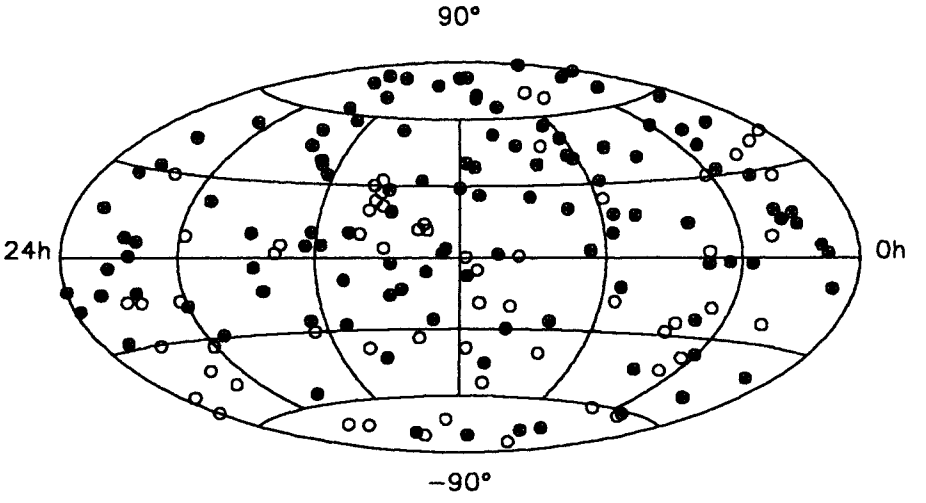
The coordinate origin of the terrestrial reference frame is specified by setting the vector sum of the adjusted coordinates for 20 VLBI sites equal to the corresponding vector sum for ITRF-92 (see text); the right ascension origin of the celestial reference frame is specified by setting the sum of the adjusted right ascensions for 71 radio sources, each weighted by the cosine of its declination, equal to the corresponding sum for ICRF-92 (see text)

13 - Definition of the Orientation:

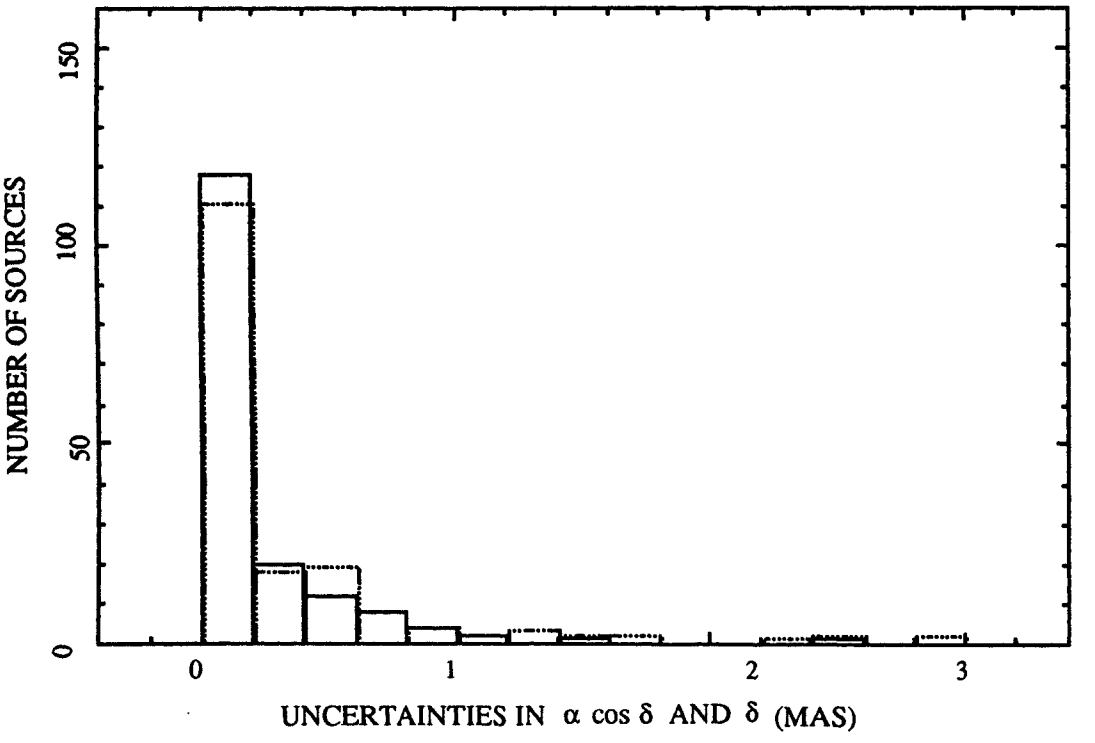
The relative orientation of the terrestrial and celestial reference frames is specified by fixing the EOP values to those interpolated from the EOP(IERS)90C04 series (corrected for the offsets and drift rates reported by the IERS to give consistency with the ITRF-92 and ICRF-92 frames) plus the diurnal and semi-diurnal contribution for x, y, and UT1 computed by the model of Herring [1993] for the reference epoch 1991 August 12 19:49:50.

14 - Constraint for Time Evolution:

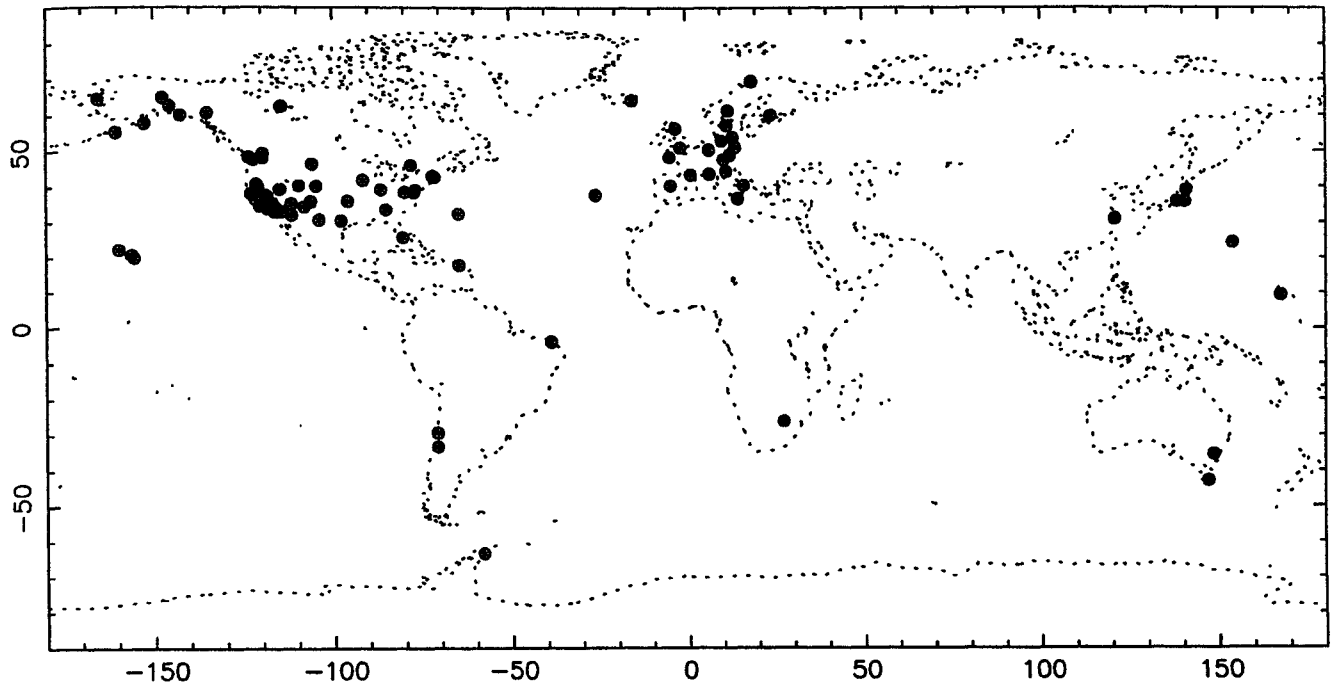
The secular translational velocity and rotational velocity of the terrestrial reference frame are specified through constraints; see item 7 above and text.



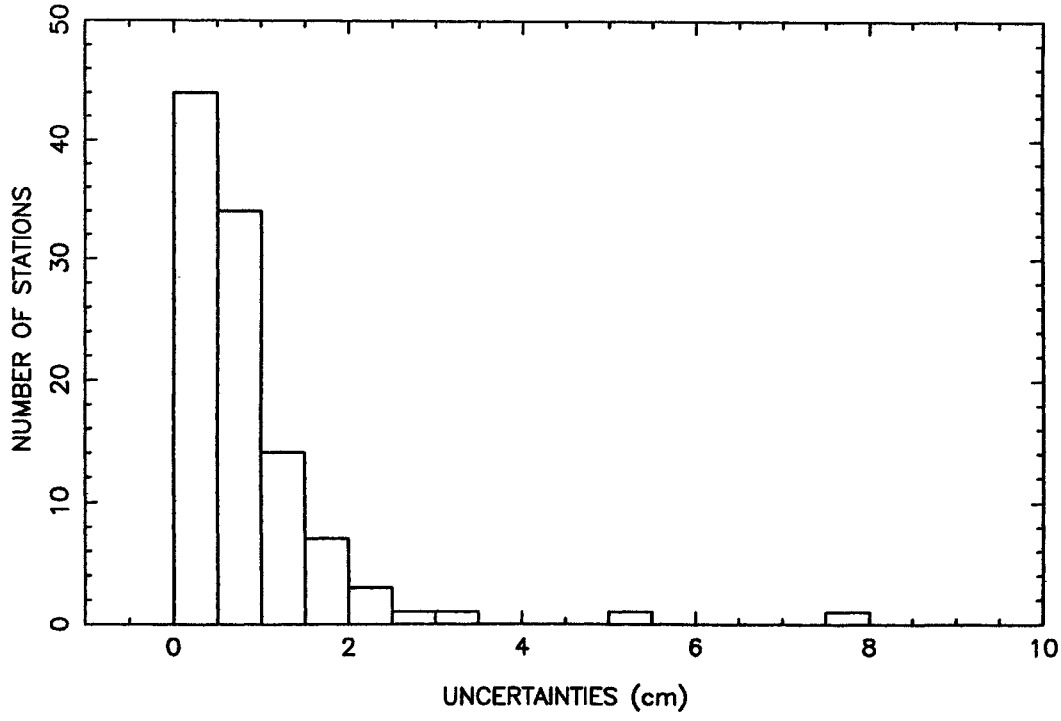
Distribution over the sky of the 176 extragalactic radio sources of the celestial frame RSC(NOAA) 94 R 01. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(NOAA) 94 R 01. 10 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 91 sites of the terrestrial frame SSC(NOAA) 94 R 01.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 106 stations of the terrestrial frame SSC(NOAA) 93 R 01.

EOP(NOAA) 94 R 01 From Sep 1980 to May 1994

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

YEAR	X		Y		UT1		$\delta\psi$		$\delta\varepsilon$	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1980	16	0.63	16	0.67	16	0.31	16	0.98	16	0.33
1981	6	1.00	6	1.14	6	0.57	6	1.33	6	0.46
1982	10	1.10	10	0.98	10	0.45	10	1.76	10	0.51
1983	17	0.96	17	1.74	17	0.72	17	1.58	17	0.49
1984	82	0.66	82	0.70	82	0.36	82	0.99	82	0.35
1985	108	0.43	108	0.44	108	0.22	108	0.62	108	0.23
1986	120	0.41	120	0.39	120	0.20	120	0.59	120	0.22
1987	141	0.43	141	0.42	141	0.20	141	0.61	141	0.23
1988	158	0.39	158	0.39	158	0.20	158	0.53	158	0.21
1989	186	0.33	186	0.32	186	0.16	186	0.46	186	0.19
1990	194	0.24	194	0.24	194	0.12	194	0.37	194	0.15
1991	173	0.20	173	0.21	173	0.09	173	0.33	173	0.13
1992	218	0.21	218	0.22	218	0.09	218	0.35	218	0.14
1993	165	0.16	165	0.15	165	0.07	165	0.28	165	0.12
1994	21	0.14	21	0.13	21	0.05	21	0.25	21	0.10

EOP(NOAA) 94 R 02 From Apr 1984 to May 1994

Number of measurements per year and median uncertainties
Units : 0.0001s for UT1

YEAR	UT1	
	Nb	Sigma
1984	64	0.74
1985	159	0.42
1986	237	0.43
1987	245	0.42
1988	255	0.42
1989	234	0.43
1990	261	0.43
1991	247	0.41
1992	223	0.30
1993	260	0.29
1994	82	0.30

ANALYSIS OF THE IRIS VLBI INTENSIVE SESSIONS

EOP(OPA) 93 R 02

A.-M. Gontier, E. Eisop, M. Feissel
Observatoire de Paris - 61 Avenue de l'Observatoire
75014 Paris, France

The series is based on the analysis of VLBI observations obtained on the Wettzell-Westford baseline in the frame work of the IRIS program. The analysis is similar to that described by Gontier *et al.* (1993).

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 were adopted from homogeneous IERS results: SSC(IERS) 93 C 03 and the NNR-NUVEL1 model for the terrestrial frame, RSC(IERS) 93 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 1992 IERS Annual Report, p. II-17).

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 is 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).

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.

References

Bretagnon, P., 1982: *Astron. Astrophys.*, **114**, 278.

Bougeard, M., 1992: *Contributions à l'optimisation non différentiable et de type proximale et à la modélisation mathématique d'observations astromé-triques,* Thèse d'Etat, Université Paris 6, Paris.

Capitaine, N., and Gontier, A.-M., 1993: *Astron. Astrophys.* , **275**, 645.

Chapront-Touzé, M., Chapront, J., 1983: *Astron. Astrophys.*, **124**, 50.

Gontier, A.-M., 1991: Notice for users of the Fortran procedure MATRIX P (March 1991), Observatoire de Paris, Paris.

Gontier, A.-M., 1992: *Orientation de la Terre par mesure VLBI. Contribution à la chaîne d'analyse de VLBI GLORIA.* Thèse de doctorat de l'Observatoire de Paris, Paris.

Gontier, A.-M., Eisop, E., Feissel, M.,1993: *IERS Tech. Note 14*, Observatoire de Paris, Paris, p. R-77.

Guinot, B., 1979: *Time and the Earth's rotation*, D.D. McCarthy and J.D. Pilkington (eds.), Reidel, 7.

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

EOP(OPA) 93 R 02 From Jan 1992 to May 1994

Number of measurements per year and median uncertainties
Units : 0.0001s for UT1

YEAR	UT1	
	Nb	Sigma
1992	211	0.20
1993	259	0.16
1994	83	0.17

EARTH ORIENTATION RESULTS FROM U.S. NAVAL OBSERVATORY VLBI PROGRAM

USNO 94 R 03

T.M. Eubanks, B.A. Archinal, M.S. Carter, F.J. Josties, D.N. Matsakis, D. D. McCarthy, U.S. Naval Observatory, Washington, D.C., 20392-5100

Abstract. 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) data acquisition and analysis to monitor changes in the orientation of the Earth on a regular basis. Starting with this annual report the operational USNO VLBI solution will include all available multiple baseline dual frequency VLBI data. The changes in the USNO VLBI data analysis system required to use the expanded data set will be described in this report, along with the resulting Navy 1994-3 reference frame and USNO/NEOS VLBI observing program during the past year.

1. Introduction

The Navy VLBI Network (NAVNET) measures the orientation of the Earth in space from Mark III VLBI observations. In the past the operational USNO VLBI reference frame and data reduction were based only on data acquired by the NAVNET and NEOS programs. In 1993, a large fraction of the world-wide collection of VLBI data from other observing programs was imported into the USNO VLBI analysis system from the Goddard Space Flight Center and, beginning in May 1994, the operational solution includes data from all sources. This large data set, with data back to 1979, requires considerable changes in the way operational VLBI solutions are performed and, in particular, the adoption of an empirically determined station velocity model, replacing the previously used NUVEL model based on geological information.

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 multiple baseline VLBI data are provided in this report in a uniform reduction using the Navy 1994-3 reference frame.

Section 2 of this report describes the USNO VLBI observing program for Earth orientation. Section 3 provides information about the USNO VLBI data analysis procedures and the Navy 1994-3 reference frame used in the operational VLBI data reduction process, while section 4 describes the VLBI data products available from the USNO Earth orientation program.

2. Data Acquisition by the USNO VLBI Earth Orientation Program

The NEOS is a joint cooperative effort of the USNO and the National Oceanic and Atmospheric Administration (NOAA), and the NAVNET VLBI program was initiated to complement the observations coordinated by the NOAA as part of the International Radio Interferometric Surveying (IRIS) subcommission. 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 antennas in Maryland, Alaska, Hawaii and Florida. One 24-hour GNUT was observed in September, 1988; monthly 24-hour NAVNETs commenced in April, 1989, and all of the weekly NAVNETs were nominally 24 hours in duration starting June 27, 1989. After the successful establishment of routine NAVNET operations, NAVNET and IRIS-A operations were coordinated starting in May, 1991, with there being one IRIS-A session on Monday/Tuesday, and one NAVNET session on Thursday/Friday, of every week. With the loss of the Richmond station in Hurricane Andrew on August 24, 1992, the NAVNET was reduced to only three stations (Alaska, Hawaii and Green Bank), and it was decided to combine IRIS-A and NAVNET operations into a weekly NEOS-A observing session, with the last NAVNET being NAVNET-226 on April 29/30th, 1993. The addition of the European IRIS-A station to the NEOS-A network provided the redundancy missing from the NAVNET since the loss of Richmond, together with an improvement in performance over previous NAVNET observations. In order to continue the "just in time" system of scheduling and processing observing sessions as quickly as possible to meet the weekly Thursday morning deadline for Earth orientation data, the start of the weekly runs were moved from 1800 UTC on Thursday to 1800 UTC on Tuesday. This change in start times makes it possible for the VLBI tapes from Germany and Brazil to be at the Washington Correlator on Monday morning at the latest, and thus for correlation and processing to be completed by Wednesday evening in time for the Thursday deadline.

Current NEOS operations, starting May 5th, 1993, consist of one weekly 24-hour duration NEOS-A observing session per week for Earth orientation. The operational NEOS-A network currently includes the VLBI stations at Gilmore Creek, Alaska, Kokee Park, Hawaii, Wettzell, Germany, Fortaleza, Brazil, and Green Bank, West Virginia. In addition, a monthly NEOS-B session is performed to improve the terrestrial reference frame, and special NAVNET EXperimental (or NAVEX) sessions continue to be observed on an irregular basis. The complete list of stations that have participated in the operational and experimental USNO Earth orientation VLBI program are given in Table 1.

The NEOS-A network was extended in the summer of 1993 to include 2 new VLBI stations, in Hawaii and Brazil. The new 20 meter VLBI antenna (site name KOKEE) constructed by the USNO at the Kokee Park Geophysical Observatory (KPGO), saw first light on May 28th, 1993, and conducted its first VLBI observations (three sources for a fringe test) on June 3rd, 1993. Strong fringes were detected immediately upon receipt of the tapes at the Washington Correlator at the USNO on June 4th, 1993. The first geodetic observations conducted by this antenna were during the NEOS-A-6 observing session (June 8/9), and the KOKEE antenna began routine VLBI observations as the

primary KPGO antenna with NEOS-A-9 (June 29/30). In general, good results have been obtained from the new KOKEE antenna, with the new system being about a factor of 2.4 times as sensitive as the old, so that Signal to Noise Ratios (SNRs) for a similar length scan are larger by about that factor (or the same SNR can be obtained with about 1/5th the integration time), and this improvement in sensitivity is reflected in lower postfit residual scatters for the new system compared to the old. Continued system tests and special experiments were conducted using the KOKEE antenna (together with the older 9 meter KAUAI antenna at the site) through the summer of 1993, after which the KAUAI system was placed on reserve status. The 9 meter KAUAI antenna was reactivated for the CONT'94 period, and was used for another set of joint observations with the KOKEE antenna between 12 January and 14 March, 1994.

Another addition to the NEOS-A network came with the development of a new VLBI site in Fortaleza, Brazil (site name FORTLEZA). This 14.2 meter antenna, originally part of the connected element interferometer operated by the USNO at Green Bank, West Virginia, was moved to a site outside Eusebio, a suburb near Fortaleza, Brazil, through the combined efforts of INPE (the Brazilian Space Agency) and NOAA, and is operated by INPE. The first use of this antenna in the NEOS-A network was in NEOS-A-10 (July 6 and 7th, 1993), and it continues to participate on a weekly basis.

Table 1 : Stations Participating in the U.S. Navy VLBI Program to date

Station	Location	Station ID Code
GILCREEK	Fairbanks, Alaska	AL
KAUAI	Kokee Park, Kauai, Hawaii (9 meter)	KU
KOKEE	Kokee Park, Kauai, Hawaii (20 meter)	KK
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
HOBART26	Hobart, Tasmania	HO
ONSALA60	Onsala, Sweden	O6
FORTLEZA	Fortaleza, Brazel	FT
MIZNAO10	Mizusawa, Japan	MN

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, Hobart, Tasmania, and Kashima, Japan, have also participated in NAVEX observations. The major goals of these experiments are to study sources of systematic error in VLBI Earth orientation measurements and to investigate high-frequency (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 a set of 4 NAVEX-Global sessions using Green Bank, Matera, Algonquin Park, Hartebeesthoek, Santiago and Kashima. NAVEX observations using this network, without Santiago, but plus the Gilmore Creek, Kokee and Hobart antennas, continued on a once every other month basis in 1993. These large (8 to 10 station) global NAVEX experiments, which are in general not simultaneous with other VLBI sessions, are intended to study the benefits obtained from the operation of large global networks, in addition to continuing the study of systematic errors and sub-diurnal variations in the VLBI data. Two northern hemisphere NAVEX sessions were conducted during 1993 simultaneously with independent NOAA VLBI observing sessions to continue the simultaneous observing program at a reduced level.

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 spread across 85 MHz at S band and 350 MHz at X band, using the "NARROW" channel frequencies shown in Table 2. In 1991 the potential spanned bandwidth was nearly doubled and operational use of the "WIDE" spanned bandwidth shown in Table 2 began on February 1, 1992. Not all antenna feed systems can adequately handle the complete WIDE bandwidth shown in Table 2, and the "NEOS WIDE" channel frequencies shown in Table 2 were developed to use the wider bandwidth subject to these feed limitations. At present, the operational NEOS-A observing sessions nominally use the NEOS WIDE bandwidth setup, and the NAVEX sessions, the NARROW bandwidth setup. In order to investigate possible systematic differences between the narrow and wide frequency assignments, the NEOS-A schedules started alternating between three sessions with NARROW channel assignments, and three with NEOS WIDE channel assignments, starting with NEOS-A-31 (30th November, 1993), which was a NEOS WIDE schedule. This alternation of schedules is intended to continue for one year.

A series of Mark III Mode-A double speed experiments on June 2nd, August 25th and September 16th of 1993 were used to observe the Supernova SN1993J and other weak radio sources that need the increased sensitivity available with Mode-A observations. It is expected that Mode-A double speed experiments (which use both

the upper and lower side bands of each VLBI channel for a total channel bandwidth of 8 MegaHz) will continue on an occasional basis in 1994.

Table 2 : NEOS Channel Frequencies

Channel Number	Band	NARROW Band Frequency Setup, MHz	WIDE Band Frequency Setup, MHz	New NEOS WIDE Frequency Setup, MHz
1	S	2217.99	2220.99	2212.99
2	S	2222.99	2230.99	2222.99
3	S	2237.99	2250.99	2257.99
4	S	2267.99	2305.99	2297.99
5	S	2292.99	2340.99	2317.99
6	S	2302.99	2345.99	2322.99
1	X	8210.99	8212.99	8182.99
2	X	8220.99	8252.99	8222.99
3	X	8250.99	8352.99	8422.99
4	X	8310.99	8512.99	8562.99
5	X	8420.99	8732.99	8682.99
6	X	8500.99	8852.99	8782.99
7	X	8550.99	8912.99	8842.99
8	X	8570.99	8932.99	8862.99

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.

3. Data Analysis by the USNO VLBI Earth Orientation Program

After correlation, fringe fitting, and the removal of any remaining bandwidth synthesis delay ambiguities, data from all available mutiple baseline VLBI 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. This is a considerable change from previous years, when only USNO acquired VLBI data were used in the USNO VLBI Annual Report, and a empirical station velocity model had to be adopted in order to adequately model the tectonic motion of the stations over the 14 years of available data.

The USNO Earth orientation program data reduction depends on a reference frame, which is derived from VLBI data and is intended to align the resulting Earth orientation determinations as closely as possible with both the terrestrial and celestial reference frames maintained by the IERS. Due to software limitations, the USNO VLBI celestial reference frame is obtained from the available 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 79 radio sources given in Table 3 is held fixed at the value given in the IERS combined celestial reference frame from the 1992 Annual Report (RSC(IERS) 93 C 01), and all other source coordinate parameters 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, 0229+131 and OJ287, are then fixed in a second solution to the values obtained in the first solution. This second solution globally adjusts all other source coordinates (subject to the same Right Ascension constraint as before). The IERS Rapid Service estimates of the UT1 and polar motion are treated as a priori measurements in this solution, and the nutation offsets are adjusted freely. Seven radio sources (3C273B 3C345 3C454.3 3C84 1117+146 1031+567 1947+079) were judged to have too much source structure to be usable for geodetic work to have repeatable positions. The coordinates of these "removed" sources are treated as "arc" parameters in the 1994-3 solution, and in the operational Earth orientation solutions, in that a separate position is estimated for each observing session in which they appear. Six other sources (CL4 0218+35A 0218+35B 1830-21A 1830-21B 0218+357) were judged to have such structure that they could not be used at all; these sources were deleted entirely from all reference frame and operational Earth orientation solutions.

Table 3 : Sources used to constrain Right Ascension in the Navy 94-3 reference frame :

0016+731	0048-097	0119+041	0133+476	0149+218	0201+113	0202+149
0202+319	0212+735	0229+131	0234+285	0300+470	0308-611	NRAO140
0420-014	0420+417	0434-188	0454-234	0458-020	0528+134	0552+398
0637-752	0642+449	0657+172	0727-115	0735+178	0742+103	0745+241
0804+499	0820+560	0823+033	OJ287	0859+470	4C39.25	OK290
0955+476	0954+658	1039+811	1044+719	1055+018	1123+264	1124-186
1144+402	1156+295	1252+119	1308+326	1334-127	1342+663	1354+195
1354-152	OQ208	1502+106	1510-089	1606+106	1611+343	1614+051
1633+38	1656+053	1738+476	1739+522	1741-038	1749+096	1823+568
1954+513	2007+777	2021+614	2021+317	2121+053	2128-123	2136+141
2144+092	2145+067	2201+315	2216-038	CTA102	2234+282	2243-123
2255-282	2355-106					

An empirical station velocity model was adopted for the Navy 1994-3 terrestrial reference frame. The translation degeneracy in station positions was removed by fixing the mean value for the positions of 15 stations (Table 4) to the values provided by the ITRF-92. The translation degeneracy in station velocities was removed by fixing the mean value for the velocities of the same 15 stations to those predicted by the Nuvel tectonic motion model.

A number of stations did not have enough data to meaningfully estimate tectonic motion rates, but were close to another VLBI station which did have sufficient data. The velocity estimates for these stations were constrained to be the same; the list of constrained stations is given in Table 5. Other sets of nearby stations with sufficient data to provide independent station motion estimates were not constrained in this fashion. A few other stations were allowed to have episodic motion due to nearby earthquakes causing seismic motions. These "episodic" stations have two position

estimates, one from before and one after the earthquake, and are given in Table 6, together with the date of the earthquake. The seismic motion was assumed to be instantaneous, and the same tectonic rate was assumed to apply before and after the step function change at the time of the earthquake.

Table 4 : Stations used to constrain the station position and velocity origin in the 1994-3 reference frame.

```
ALGOPARK DSS65    GILCREEK HARTRAO  HOBART26 KAUAI
KWAJAL26 MEDICINA NOTO     ONSALA60 PIETOWN  RICHMOND
VNDNBERG WESTFORD WETTZELL
```

Table 5 : Stations with velocity ties in the 1994-3 reference frame. Stations within each pair of parenthesis were constrained to share the same station velocity adjustments in the 1994-3 solution.

```
( MOJAVE12 GOLDVENU DSS15 )
( KASHIMA  KASHIM34 )
( NRAO85_1 NRAO85_3 )
( KOKEE    KAUAI    )
( DSS65    ROBLED32 )
( OV_VLBA  OVRO_130 )
( GGAO7108 GORF7102 )
( YELLOWKN YLOW7296 )
```

Table 6 : Stations with episodic motions (step function changes at a specified time) in the 1994-3 reference frame.

Station Name	Date of Motion
YAKATAGA	871201
SOURDOGH	871201
KODIAK	871201
WHTHORSE	871201
FORTORDS	891001
PRESIDIO	891001
DSS15	920627
GOLDVENU	920627
MOJAVE12	920627

The data used in the report are processed with IERS standard models to the maximum extent possible (see summary description at the end of this report), with the GSFC CALC 7.6 software being used throughout in the data reduction process. The CFA 2.2 tropospheric mapping function is used to relate line of sight tropospheric propagation delays to the tropospheric zenith delay, and an elevation angle lower limit of 7 degrees is used in all solutions. The IERS standard model for both horizontal and vertical deformations due to ocean tidal loading is applied, although ground

deformations due to atmospheric loading are currently not modeled. The reference time adopted was January 1, 1988.

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.

The new USNO Navy reference frame, Navy 1994-3, was prepared using 991,841 delay and delay rate observation pairs from 1578 observing sessions (complete through March 15, 1994), with a weighted rms residual scatter of 36.6 picoseconds for the delay observations and 90.0 femtoseconds per second for the delay rate data. The NAVNET station coordinates (at epoch 1988 January 1) and velocities from the reference frame solution have been submitted to the IERS Central Bureau as well as the corresponding source positions. Some stations did not have enough data to meaningfully estimate station velocities. For these stations the Nuvel model was used without adjustment; the velocity error entries in the station velocity table are blank for these stations.

The Navy 1994-3 reference frame is the operational reference frame used in the operational USNO Earth orientation solutions. The intention is to provide an a priori reference frame good at the level of 0.25 millisecond of arc. In order to do this, sources with position uncertainties in the 1994-3 frame less than 0.25 milliarcseconds (mas), and stations with position formal errors of 5 millimeters or less are fixed to the 1994-3 values without adjustment. These stations and sources are provided in Tables 7 and 8, respectively. The positions of the other sources, and the positions and velocities of any other stations, are estimated in the operational solutions.

Table 7 : Stations used without adjustment in the Operational Earth orientation solutions

ALGOPARK	DSS45	DSS65	EFLSBERG	FD-VLBA	GILCREEK
HARTRAO	HATCREEK	HAYSTACK	HOBART26	HRAS_085	KASHIM34
KASHIMA	KAUAI	KOKEE	LA-VLBA	MARPOINT	MATERA
MEDICINA	NOTO	NRAO_140	NRAO85_3	NRAO85_1	ONSALA60
OVRO_130	PIETOWN	PLATTVIL	RICHMOND	SESHAN25	TRYSILNO
VNDNBERG	WESTFORD	WETTZELL			

Table 8 : Sources used without adjustment in the Operational Earth orientation solutions

0014+813	0016+731	0048-097	0059+581	0104-408	0106+013
0119+041	0133+476	0201+113	0202+149	0208-512	0212+735
4C67.05	0229+131	0234+285	0235+164	0256+075	0300+470
0308-611	NRAO140	CTA26	NRAO150	0402-362	0420-014
0434-188	0438-436	0454-810	0454-234	0458-020	0528+134
0537-441	0552+398	0637-752	0642+449	0657+172	0716+714
0727-115	0735+178	0738+313	0742+103	0745+241	0804+499
0805+410	0814+425	0820+560	0823+033	OJ287	0859+470
0919-260	0917+624	4C39.25	OK290	0955+476	0954+658
1034-293	1038+52A	1039+811	1044+719	1053+704	1053+815
1055+018	1057-797	1104-445	1123+264	1124-186	1128+385
1144+402	1145-071	1150+812	1156+295	1219+044	1244-255
1251-713	3C279	1308+326	1334-127	1351-018	1354+195
1354-152	1357+769	1402+044	OQ208	1418+546	1424-418
1502+106	1510-089	1519-273	1548+056	1549-790	1606+106
1611+343	1614+051	1610-771	1622-253	1633+38	1637+574
NRAO512	1642+690	1705+018	1726+455	NRAO530	1739+522
1741-038	1745+624	1749+096	1803+784	1815-553	1823+568
1831-771	1921-293	1923+210	1928+738	1954+513	1958-179
2007+777	3C418	2113+293	2121+053	2128-123	2134+00
2136+141	2144+092	2145+067	2155-152	VR422201	2201+315
2216-038	CTA102	2234+282	2243-123	2255-282	2345-167
2355-106					

The NAVNET/NEOS Earth orientation results submitted to the IERS Central Bureau 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 NEOS data, as experiments are frequently processed using UT1 predictions. The operational USNO solutions now estimate the rate of change of the UT1 averaged over the entire observing session; the UT1 rate estimates from that solution are converted into estimates of the variation in the Length of Day (LOD). The reporting epoch for each observing session is the mid-point of the session, defined as the mean of the time of the first and the last observations in the session. The station coordinates and source positions for the stations and sources in Tables 7 and 8 are fixed at the a priori values given by the Navy 1994-3 reference frame; the positions of the other sources and stations are estimated in the Earth orientation solution. The tie to the 1994-3 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. The solution provided to the IERS Central Bureau used a total of 1,028,262 observation pairs (delay and delay rate) from 1606 sessions and produced weighted rms residual scatters of 36.4 picoseconds for the delay observations and 90.3 femtoseconds per second for the delay rate data. (This solution included experiments from 1994 which were not used in the reference frame solution.)

The USNO has conducted a series of 2 and 3 hour duration observing sessions, known as NAVNET INTensives, or NAVINTs, to investigate the determination of UT1 and Polar Motion from short duration experiments. These observing sessions nominally involve 3 stations, GILCREEK and KAUAI (or KOKEE) together with either RICHMOND or NRAO85_3, although a few 4 station sessions have been observed. The UT1 and Polar Motion estimates from the multiple baseline NAVINTs were also provided to the IERS Central Bureau. A total of 4161 observation pairs (delay and delay rate) from 120 observing sessions were used in this solution, with the total weighted rms residual scatter being ± 33.5 picoseconds for the delay data and 70.6 femtoseconds per second for the rate data. One difference between the NAVINT solutions and the 24-hour experiment solutions lies in the treatment of nutation. The nutation is not estimated in the NAVINT solutions, but is instead held fixed to the values given in the IERS Bulletin A, linearly interpolated to the epoch of the experiment. As in the long duration solutions, the station coordinates and source positions are fixed at the a priori values given by the Navy 1994-3 reference frame, and the reporting epoch for each observing session is the mid-point of the session.

The current accuracy of VLBI Earth orientation results is sufficient to clearly detect tidally coherent diurnal and semi-diurnal variations in UT1 and polar motion, mostly due to the non-linear response of the oceans to the luni-solar gravitational tides. These tidally forced variations can be a significant source of systematic error, and so have been removed from the 1994-3 reference frame solutions and Earth orientation solutions using the empirical model of T.A. Herring [*Proceedings of the COSPAR World Space Congress, Adv. Space Res.*, **13**, 281-290, 1993]. The model values were not added back into the UT1 and polar motion estimates, so that the orientation results provided in the long-duration solutions (and in the operational Earth orientation solutions) are close to the 24-hour average values for the Earth orientation centered on the epoch of observation. The model values are also not added back into the NAVINT results; these short duration estimates thus do not reflect the true orientation at the reporting epoch, but are instead closer to the 24-hour average for the reporting epoch.

4. Data Available from the USNO VLBI Earth Orientation Program

Earth orientation results from the USNO VLBI solutions are distributed in the form of three tables. The first table contains the Earth orientation data in the format requested by the IERS Central Bureau, and 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 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 second table presents 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. 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. A list of the stations participating in the experiments is also included in that table.

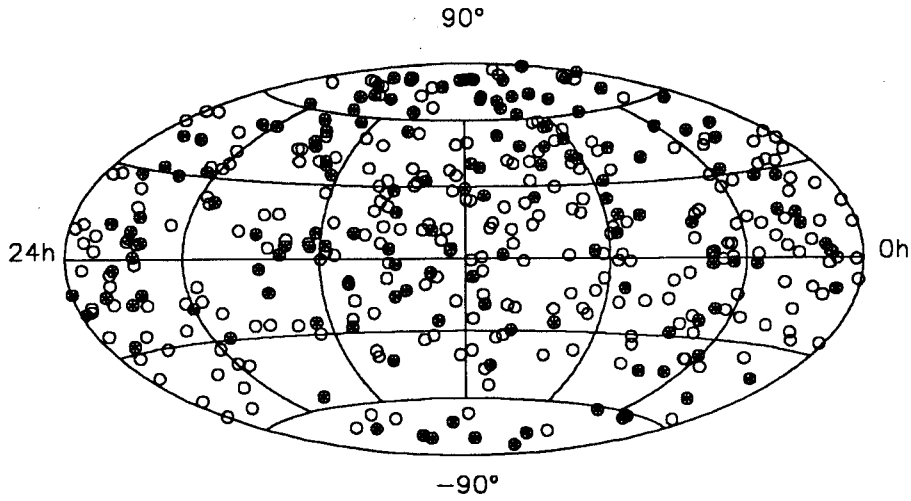
The operational NAVNET solutions now estimate the rate of change of the UT1 during each experiment. These UT1 rate estimates are comparable in accuracy to those obtainable through differencing of successive UT1 offset estimates, and thus make an interesting data product in themselves. The third EOP table contains 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).

USNO VLBI data are available by anonymous ftp from casa.usno.navy.mil, or by mosaic from http: //maia.usno.navy.mil. The operational Earth orientation solutions are updated weekly; please contact the USNO to be placed on the list for automatic notification of future updates.

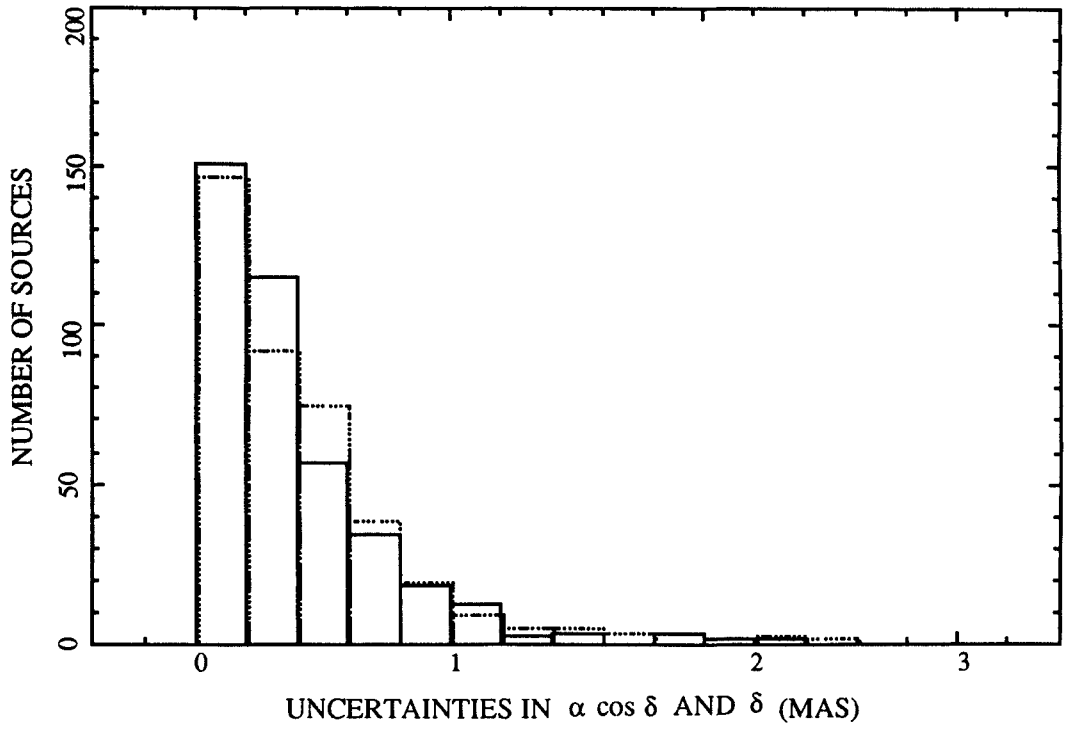
Questions, comments or requests to be placed on the NAVNET distribution list should be directed to T.M. Eubanks, Code TSEO, U.S. Naval Observatory, Washington D.C. 20392-5100, by phone at (202) 653-1501, on SPAN at USNO01::TME, and on Internet at tme@usno01.usno.navy.mil or tme@casa.usno.navy.mil.

Summary description of solution USNO 94 R 03 (USNO 1994-3)

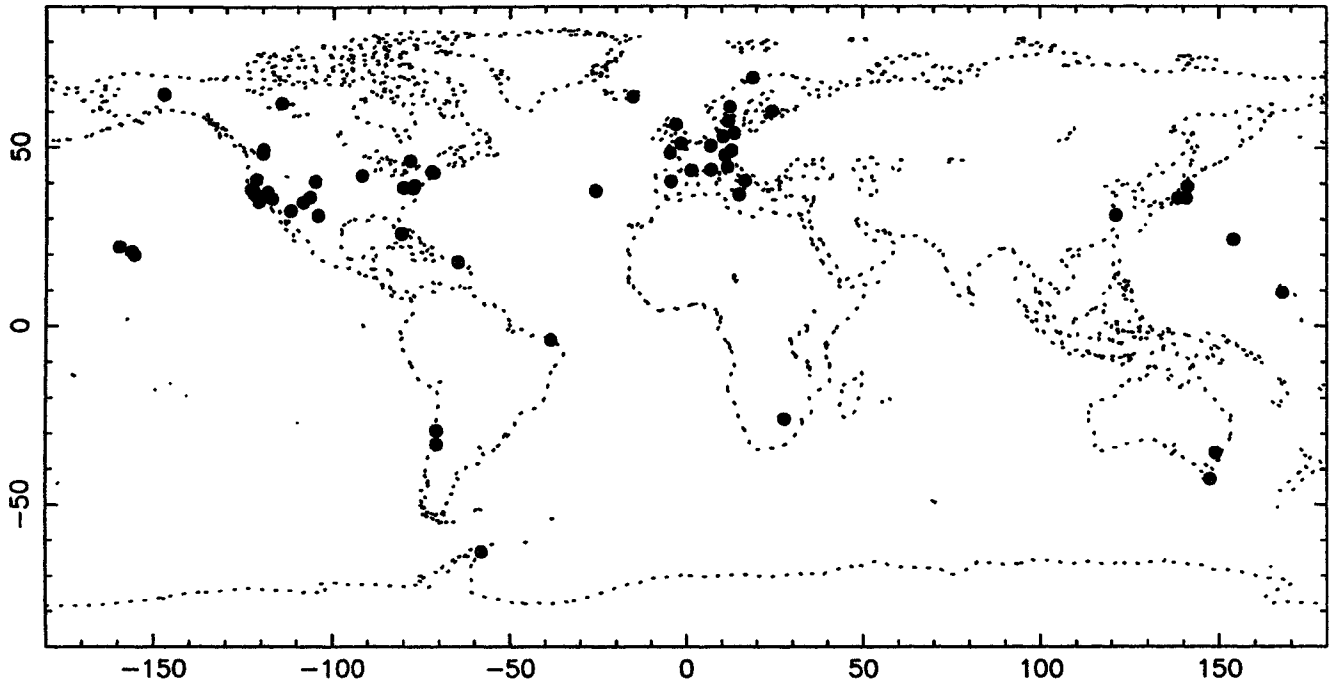
1 - Technique	VLBI
2 - Analysis Center	USNO
3 - Solution identifier	1994-3
4 - Software used	Calc 7.6
5 - Relativity scale	Geocentric
6 - Permanent tidal correction	No
7 - Tectonic plate model	1994-3 empirical model
8 - Velocity of light	299 792 458 m/s
10 - Reference epoch	1 January 1988
11 - Adjusted parameters	see text
12 - Definition of the origin	Mean of 15 station positions in ITRF-92
13 - Definition of the orientation	Mean 79 sources in Right Ascension, Mean IERS Bull. A values for UT1, Polar Motion and (indirectly) Nutation
14 - Constraint for time evolution	Mean of 15 station velocities with the Nuvel model as a priori



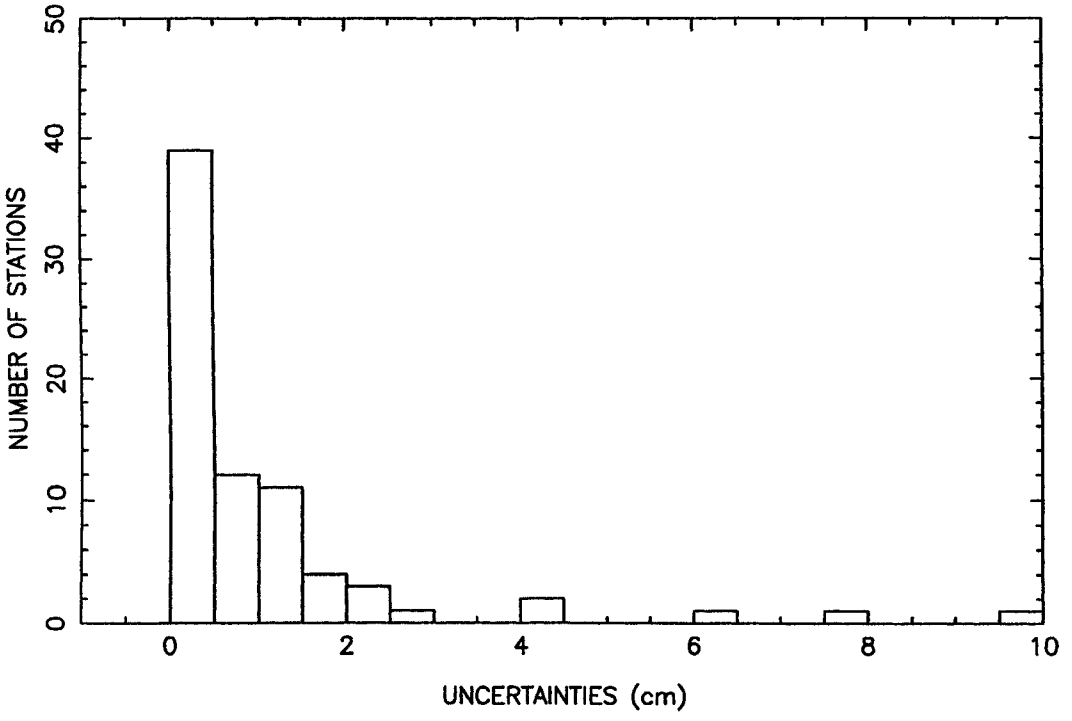
Distribution over the sky of the 411 extragalactic radio sources of the celestial frame RSC(USNO) 94 R 03. Filled circles indicate radio sources with uncertainties in right ascension ($\alpha \cos \delta$) and declination smaller than 0.0003".



Distribution of the uncertainties in right ascension (full line) and declination (dashed line) of the celestial frame RSC(USNO) 94 R 01. 13 radio sources with uncertainties larger than 0.003" are not shown.



Distribution of the 61 sites of the terrestrial frame SSC(USNO) 94 R 03.



Distribution of the uncertainties (quadratic mean of σ_x, σ_y, σ_z) for the 76 stations of the terrestrial frame SSC(USNO) 94 R 03. 1 station with uncertainty larger than 10 cm is not shown.

EOP(USNO) 94 R 03 From Aug 1979 to May 1994

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

YEAR	X		Y		UT1		δψ		δε	
	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma	Nb	Sigma
1979	2	1.04	2	1.82	2	0.69	2	1.63	2	0.72
1980	19	0.51	19	0.52	19	0.25	19	0.84	19	0.41
1981	7	0.73	7	1.23	7	0.50	7	0.95	7	0.52
1982	16	0.75	16	0.74	16	0.34	16	1.34	16	0.55
1983	17	1.05	17	1.95	17	0.72	17	1.99	17	0.71
1984	87	0.53	87	0.54	87	0.29	87	0.88	87	0.38
1985	92	0.34	92	0.34	92	0.19	92	0.57	92	0.25
1986	107	0.34	107	0.31	107	0.18	107	0.53	107	0.23
1987	136	0.33	136	0.30	136	0.17	136	0.49	136	0.22
1988	134	0.26	134	0.26	134	0.14	134	0.42	134	0.17
1989	166	0.22	166	0.21	166	0.11	166	0.38	166	0.15
1990	203	0.20	203	0.20	203	0.10	203	0.34	203	0.14
1991	200	0.17	200	0.16	200	0.08	200	0.31	200	0.12
1992	224	0.15	224	0.16	224	0.07	224	0.27	224	0.12
1993	152	0.12	152	0.11	152	0.05	152	0.22	152	0.09
1994	41	0.10	41	0.08	41	0.04	41	0.18	41	0.07