THE JPL 1986-3 EXTRAGALACTIC REFERENCE FRAME

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ABSTRACT. Intercontinental dual-frequency radio interferometric measurements were carried out during 1978 to 1985 between NASA's Deep Space Network stations in California, Spain, and Australia. Analysis of 6800 pairs of delay and delay rate observations made during 51 sessions produced a catalog of positions of 106 extragalactic radio sources, fairly uniformly distributed over the celestial sphere between $-45°$ and $+85°$ declination. Almost all of the resulting source positions have formal uncertainties between 0.5 and 3 milliarcseconds, with their distributions peaking somewhat below 1 mas. Root-mean-square uncertainties are 2.1 and 2.0 mas for RA and declination, respectively. Evidence is found for a long-term drift of the Earth's rotation axis in inertial space, relative to the 1984 IAU precession and nutation models. Tests for time variability of positions of 32 frequently observed sources place limits at the 1 mas/yr level. Comparisons with independently determined source catalogs of comparable quality show differences of positions of common sources that amount to a few mas, and may indicate the level of systematic errors in VLBI source position measurements.

1. INTRODUCTION

We present a summary of the astrometric results of analysis of Very Long Baseline Interferometry (VLBI) measurements on two intercontinental baselines (Goldstone, California to Madrid, Spain and to Tidbinbilla, Australia). Since publication of a paper describing VLBI with Deep Space Network (DSN) antennas from 1971 to 1980 (Fanselow et al., 1984), the volume of available data has nearly tripled. The present data base includes only dual-frequency measurements, and only observing sessions employing hydrogen maser frequency standards at all participating stations. A single multiparameter fit is made to a 7-year span of data to estimate geophysical and astrometric parameters, yielding substantial improvements in both the quality and quantity of source coordinates in the catalog of extragalactic radio sources, which serve as a reference frame for interplanetary navigation. Typical formal uncertainties are reduced to the level of approximately 1 millarcsecond (mas).

Analogous measurements by NASA's Crustal Dynamics Project (CDP) have been expanded to global scope (Ryan and Ma, 1985), and the International Radio Interferometric Surveying (IRIS) project of the National Geodetic Survey (NGS) has been reporting sub-milliarcsecond Earth orientation parameters at 5-day intervals since the beginning of 1984 (Robertson et al., 1986). All three data sets appear to be close to fulfilling the

S. Débarbat et al. (eds.), Mapping the Sky, 461–464.

https://doi.org/10.1017/S0074180900140021 Published online by Cambridge University Press

long-promised potential of VLBI for milliarcsecond accuracy. Concomitant advances have been made in refining existing tropospheric and Earth models and in identifying effects that are significant at the centimeter level. The most significant model change since our 1984 paper is the use of the Lanyi (1984) tropospheric mapping function.

2. OBSERVATIONS, DELAY MODEL, AND FITTING ALGORITHM

A total of 51 VLBI observing sessions were scheduled and carried out during 1978-85, mostly of 24-hr duration. Of these, 48 involved intercontinental baselines, equally divided between California-Spain (470 hr) and California-Australia (415 hr). Throughout the series of measurements, JPL Mark II data acquisition systems were employed. We used the bandwidth synthesis technique with channels of 2 MHz bandwidth, spanning about 40 MHz in a given radio frequency band. Simultaneous measurements were made at 2.3 and 8.4 GHz to permit calibration of ionospheric delays. The observational strategy was to schedule nearly concurrent pairs of sessions on the CS and CA baselines, to attempt to observe each source several times in a given session to cover the full range of mutual visibility, and, when possible, to observe each source on both baselines. Many different schedules were used on each intercontinental baseline. Each observing session included observations of 3C 273, the source used as a reference for right ascension.

Delays and delay rates were modeled in Solar System barycentric coordinates defined in terms of the mean equator of J2000.0. With minor exceptions, we adhered to the Project MERIT standards (Melbourne et al., 1983) for astronomical constants and Earth modeling. Tropospheric zenith delays were mapped to the desired elevations with the mapping function of Lanyi (1984). This function incorporates surface temperature measurements, which were available for approximately half of the observing sessions. The Goldstone station DSS 13 was adopted as a reference point, and the customary value, $12^h29^m6^s.6997$, at J2000.0 was taken for the right ascension of the reference source 3C 273.

A multiparameter diagonally weighted least-squares fit (the "standard fit") was performed which simultaneously fit all of the delay and delay rate data to determine approximately 1300 parameters. Weighting of each observable was in inverse proportion to the sum of squares of its experimental error and a session-specific adjustable error, which was chosen in order to make χ^2 per degree of freedom (χ^2_ν) close to 1 for each session. The fit included session-specific parameters describing clock behavior, a troposphere zenith delay at each station for every 3 hour period, and a set of station coordinates for each observing session. The only "global" parameters common to all sessions were the right ascension and declination of each source. Variants of the standard fit were performed which estimated independent positions of 32 sources in three subsets of the 1978-85 time span, and/or offsets from the 1984 IAU values for precession and nutations in longitude and obliquity.

3. RESULTS AND DISCUSSION

Positional coordinates of 106 sources from the standard fit form a source catalog named JPL 1986-3. An additional group of positions of 22 sources were estimated, but these sources had fewer than 10 intercontinental baseline observations per source, with consequently larger formal errors. Histograms of the (1σ) formal uncertainties in right ascension and declination (arc lengths) for JPL 1986-3 peak somewhat below 1 mas. Root-mean-square uncertainties are nearly equal for RA and declination: 2.1 and 2.0 mas, respectively. The catalog is not of uniform average observing epoch, with that for the entire catalog being 1982.9, and ranging from 1980.0 to 1984.4 for individual sources. The 13 sources with uncertainties $\geq$ 2.5 mas in declination have a limited number of observations. Some have been dropped from the observing schedules.

In order to check and extend the limits on source position repeatability that were obtained for 19 sources for the older JPL 1983-3 catalog, we also performed a fit to the 1978-85 data in which separate positions were estimated in each of three time spans for sources with at least 10 intercontinental observations in each period. The observations are divided into three time periods : 1978-80 (average epoch 1980.0), 1981-83 (1983.2), and 1984-85 (1984.5). Along with three sets of coordinates of 32 sources, the estimated parameters included a single set of positions for all other sources, and the nutation angles for each intercontinental observing session. Differences of the three sets of source coordinates derived in this manner were calculated, with error estimates taking into account correlations between coordinates at different epochs. While there are four cases of $> 2\sigma$ differences, no source shows 2σ shifts between both pairs of epochs. Of these four sources, only for DA 55 and P 0202+14 are the directions of the shifts consistent between the two pairs of epochs. Root-mean-square differences are approximately 2 mas for both pairs of epochs, and χ^2_νs are close to 1 with the exception of that for 1984.5 minus 1983.2 right ascension differences, which is $\chi^2_\nu = 2.6$, but drops to $\chi^2_\nu = 1.0$ when one outlier (3C 371) is omitted. From these results, upper limits of the order of 1 mas/yr can be placed on the time variation of the 32 source coordinates.

To test the adequacy of the 1984 IAU models of precession and nutation, we modified the standard fit to solve for the precession constant and various nutation amplitudes. Estimates were made in turn of a) two nutation angles for each intercontinental session, b) precession, and c) precession plus the amplitudes of two sets of semiannual, annual, and 18.6-year terms, in and out of phase with those in the 1980 IAU nutation series. Table I gives the results of fits b) and c), plus a fit d) in which the annual and semiannual nutation amplitudes are fixed at the results of Herring et al. (1986), and the out-of-phase 18.6-year amplitudes are also fixed at the Herring et al. theoretical estimates (values in parentheses). The precession values are relative to the 1976 IAU precession constant (time rate of change of ψ), while nutation amplitudes are relative to the 1980 IAU series (Seidelmann, 1982), with term indices corresponding to Table I of that paper. The superscript "o" symbolizes terms 90° out of phase with the corresponding 1980 IAU terms. All errors are formal, statistical estimates.

Table I. Corrections to the 1984 IAU Precession and Nutation Amplitudes.

Term	Period, d	Fit b	Fit c	Fit d
Precession, mas/yr	...	-1.97±0.17	-1.56±0.28	-2.28±0.24
Nutation ψ_1, mas	6798.4	...	-26.37±8.05	4.12±1.73
ε_1	6798.4	...	5.32±0.63	0.13±0.23
ψ_1^o	6798.4	...	-7.62±2.87	(3.19)
ε_1^o	6798.4	...	-2.95±0.55	(1.61)
Nutation ψ_{10}, mas	365.3	...	4.26±0.48	(4.50)
ε_{10}	365.3	...	2.14±0.17	(1.81)
ψ_{10}^o	365.3	...	-0.76±0.53	(1.58)
ε_{10}^o	365.3	...	0.02±0.13	(-0.22)
Nutation ψ_9, mas	182.6	...	1.06±0.49	(1.48)
ε_9	182.6	...	-0.97±0.19	(-0.32)
ψ_9^o	182.6	...	0.93±0.50	(-0.83)
ε_9^o	182.6	...	0.40±0.20	(-0.29)

Estimates of the nutation amplitudes from the daily nutation offsets [fit a), not shown] are in good agreement with those solved for directly in fit c) of Table I. Values of χ^2_ν are approximately 2 and 3 for $\sin\varepsilon_0\Delta\psi$ and $\Delta\varepsilon$, respectively. As may be seen from Table I, with the possible exception of ε_9 and the out-of-phase terms, our corrections to the annual and semiannual amplitudes are in agreement with those of Herring et al. It is quite evident that no firm conclusions can be drawn concerning the magnitudes of corrections to precession and both the phase and amplitude of the 18.6-year nutation, given the time span and distribution of our measurements. This may be ascribed to the large correlations between the in- and out-of-phase 18.6-year nutation terms. These correlation coefficients are 0.97 for ψ and -0.91 for ε, while the largest correlation between precession and any 18.6-year nutation is only -0.51 (for ψ_1.) Our present precession revision of -1.6 ± 0.3 mas/yr differs by approximately 2σ from the value we obtained from the 1971-80 DSN data (-3.8 ± 0.9 mas/yr), and is slightly larger than the uncertainty of 1.5 mas/yr in the 1976 IAU value (Fricke, 1981).

Two recent extragalactic source catalogs [GSFC (Ma, 1986), and IRIS (Robertson et al., 1986)] have 55 (of 101) and 19 (of 26) sources in common with JPL 1986-3, respectively. Since these VLBI programs employ completely different hardware, baselines, observing schedules, and correlation and parameter estimation software, comparison of results is valuable in identifying residual systematic errors in the VLBI technique. For the sources that the catalogs have in common, the rms formal coordinate uncertainties are smaller than 2 mas for both GSFC-JPL and IRIS-JPL, indicating that the quality of the three catalogs is essentially comparable. Rms differences are of the order of 2 mas, except for GSFC-JPL declination (6 mas), and the χ^2_ν values (1.2 to 2.3) indicate that one or both sets of formal uncertainties may slightly underestimate the true errors.

4. ACKNOWLEDGMENTS

We thank C. Ma for kindly providing the GSFC 1986 catalog prior to publication. The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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