AN EXTRAGALACTIC REFERENCE FRAME FROM DSN VLBI MEASUREMENTS – 1989

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ABSTRACT. Assessment of the impact of recent improvements in Deep Space Network (DSN) instrumentation, as well as of joint data analyses, provide a prognosis for the accuracy level to be expected in future realizations of an inertial radio reference frame. Intercontinental dual-frequency radio interferometric measurements during 68 sessions (including two recent sessions employing Mark III instrumentation) from 1978 to 1989 using NASA's DSN stations in California, Spain, and Australia give 8900 pairs of delay and delay rate observations. Analysis yields a catalog of positions of 200 extragalactic radio sources north of −45° declination. The resulting source position formal uncertainty distributions peak below 1 milliarcsecond, with three fourths being smaller than 2 mas. Comparison with independent measurements shows some evidence for systematic errors at the milliarcsecond level.

1. Introduction

During the past decade, the field of radio interferometric measurements on intercontinental baselines has matured, and is now on the threshold of yielding determinations of angular position that are accurate to a milliarcsecond over the entire sky. The extragalactic radio sources which are observed with Very Long Baseline Interferometry (VLBI) are thus the leading candidates for establishing a reference frame for angular positioning at the 1 mas level. This paper is a report of recent progress in VLBI astrometric measurements with Deep Space Network antennas. Recent instrumentation improvements promise a substantial increase in measurement precision in the 1990s. The source position catalogs resulting from two independent astrometric programs are compared, and the effects of errors in the standard models of precession and nutation are considered in an attempt to establish a confidence level for the accuracy of VLBI reference frames.

2. Observations and Analysis

A total of 68 day-long VLBI observing sessions were carried out during 1978-89 on the two DSN intercontinental baselines: California to Spain and California to Australia. Until late 1988, the experiments employed Mark II data acquisition systems and a bandwidth synthesis technique with channels of 2 MHz bandwidth, spanning about 40 MHz at both

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2.3 and 8.4 GHz. Recently, Mark III data acquisition systems were introduced, with spanned bandwidths of 100 to 400 MHz. 8578 pairs of Mark II delay (D) and delay rate (DR) observables were included in the analysis, along with 321 D+DR pairs from two Mark III sessions in 1989. All observations were dual-frequency, and employed H-maser frequency standards.

Modeling was performed in Solar System barycentric coordinates defined in terms of the mean equator of J2000.0, and used the Project MERIT standards (Melbourne et al., 1983) for astronomical constants and Earth models, with certain exceptions noted below. Tropospheric delay modeling employed the Lanyi (1984) mapping function, and included the effects of varying surface temperature. The usual reference source 3C 273 fixed the origin of right ascension. Universal time and polar motion values were taken from the uniform series BIH87C02, extended through 1989. A multiparameter diagonally weighted least-squares fit estimated session-specific clock and station location parameters, a troposphere zenith delay at each station for every 3-hour period, and the right ascension and declination of each source. Corrections to the present IAU model of nutation were estimated for each session in the form of daily nutation offsets in longitude and obliquity. This is imperative for the Mark III data, which show a 50% higher scatter without nutation corrections.

3. Results: 1989 DSN Source Catalogs

Several fits to DSN VLBI data during 1989 produced a number of source catalogs. Three of these are described in some detail in order to illustrate some points concerning effects of selection of data and alternative sets of estimated paramaters.

Two catalogs were generated in early 1989 for submittal to the International Earth Rotation Service (IERS). One, JPL 1989-3, was our standard analysis of all DSN data through 1988. This fit estimated a set of coordinates for each Spanish or Australian station, along with the position of the celestial pole, in each observing session. The latter results were expressed in terms of corrections to the 1980 IAU angles in longitude ($\Delta\psi$) and obliquity ($\Delta\varepsilon$). The data base for a second catalog, JPL 1989-2, also included all TEMPO (Time and Earth Motion Precision Observation) dual-frequency data collected at JPL from 1980 to 1988, an additional 5340 observations. The relatively short duration (<3 hr) of the TEMPO observing sessions prohibits estimation of station coordinates and celestial pole position for each session; hence the fit assumed the Minster-Jordan AM02 plate motion model, and estimated corrections to the 1980 IAU precession constant and nutation amplitudes. With the exception of a reference day, values of UT1 and the two components of polar motion were also estimated.

The third catalog, JPL 1989-5, is an exact analog of 1989-3, with the exception that 669 new observations were included. Half of the new observations were derived from analyses of the first two DSN VLBI sessions employing Mark III data acquisition systems. Table 1 summarizes the characteristics of the observations, modeling, and statistics of the resulting source position uncertainties for these three catalogs, while Figs. 1 and 2 show histograms of average observation epochs and uncertainties in arclengths in the RA and δ directions for JPL 1989-5.

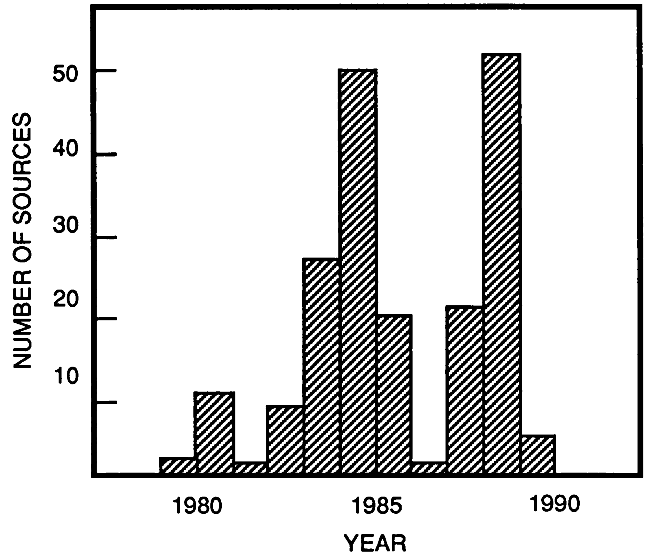

Figure 1. Average observation epochs for the 200 sources in the JPL 1989-5 catalog.

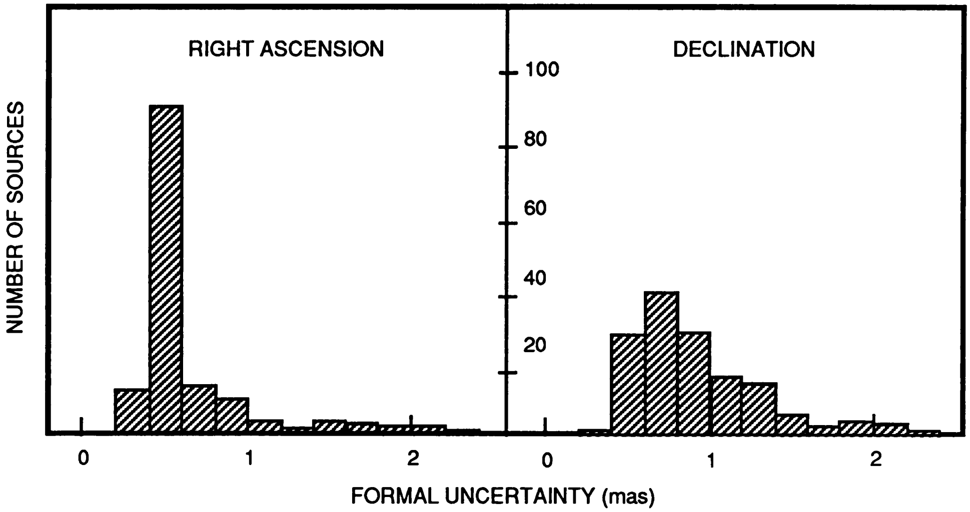

Figure 2. Histograms of formal uncertainties in RA (arclength) and δ for JPL 1989-5.

Table 1. Recent DSN Source Catalogs

Catalog Name	1989-2 TEMPO	1989-3 IERS	1989-5 Current
Obsvs.: Mk II	13570	8230	8578
Mk III	–	–	321
Modeling:			
Tectonics	AM0-2	Estimated	Estimated
UTPM	Estimated	Constant	Constant
Nutation	Amplitudes	Angles	Angles
Post-fit resids.:			
RMS D, ps	399	330	318
RMS DR, 10^{-13}	1.29	1.35	1.33
Number of sources	186	195	200
Declination σ			
<0.5 mas	13	1	5
<1.0 mas	76	46	95
<2.0 mas	123	112	149
>10 mas	42	45	21

Taking 1989-3 as a reference, it is seen that inclusion of the TEMPO data increases the delay (D) residuals substantially while decreasing the delay rate (DR) residuals somewhat. Modeling plate motion and celestial pole position as smooth functions produces substantial reductions in formal uncertainties of source positions, with nearly double the number of sources having $\sigma_\delta < 1$ mas compared to 1989-3.

For the 200 sources in the 1989-5 catalog, root-mean-square formal uncertainties are approximately equal for RA and declination: 1.6 mas. The sky distribution is fairly uniform above $-30°$ declination (20 ± 10 sources/sterad), and a factor of 5 sparser for $-30° > \delta > -45°$. Recent emphasis in our observing program has been on sources near the ecliptic plane, for potential use in navigating interplanetary spacecraft. This is reflected in some of the non-uniformity between $\delta = \pm 23°$. Approximately 10% of the sources have $\sigma_\delta > 10$ mas as a consequence of being recent additions to the observing program. Mean source observation epochs have a wide range, with peaks of $\approx$50 each in 1984.0–1985.0 and 1988.0–1989.0.

3a. Impact of Mark III Data

The impact of improved data quality is seen by examining the residuals in the fit producing the JPL 1989-5 catalog (Table 2). Mark III residuals are nearly a factor of 8 smaller than Mark II residuals, with a less dramatic improvement in delay rates. The instrumentation is so stable that data from one of the two Mark III observing sessions are adequately fit with a single (two-parameter) linear clock model over the entire 24 hours. At this level of tens of picoseconds, source structure effects are also becoming obvious. Comparing 1989-5 with 1989-3 shows that adding 321 Mark III and 348 Mark II observations has doubled the number of sources with $\sigma_\delta < 1$ mas, and increased the number with $\sigma_\delta < 2$ mas by 1/3. Expectations for JPL source catalogs in the near future are thus ≈200 sources with formal declination uncertainties below a milliarcsecond.

Table 2. 1978-89 Fit Residuals: Impact of Mark III Data

Data	Number of observations	RMS delay (ps)	RMS rate (fs/s)
All	8899	318	133
Mk II	8578	324	134
Mk III	321	43	112

3b. Nutation and Precession Corrections

To summarize the corrections to the 1980 IAU models of precession and nutation implied by DSN VLBI measurements, Table 3 reports the results of one such fit. The data base and parametrization were identical to those used to generate the 1989-5 catalog, with the exception that the precession constant, as well as the amplitudes of both in- and out-of-phase semiannual, annual, and 18.6-year nutation terms were estimated. These results are essentially in agreement with post-fit analyses of $\Delta\psi$, $\Delta\varepsilon$ values from the 1989-5 fit. Here the annual and semiannual nutations are terms #10 and #9, respectively, in the 1980 IAU series (Seidelmann, 1982). With the exception of the 18.6-year nutation in obliquity, the out-of-phase corrections are not significant. In contrast, all corrections to in-phase terms exceed 2σ, and the precession correction is also highly significant. These results further underline the necessity of correctly modeling the motion of the celestial pole in analyses of VLBI observations.

Table 3. Precession and Nutation Amplitudes from 1978-89 DSN VLBI Data

Term	In phase	Out of phase
Precession, mas/yr	-1.96±0.13	...
18-year ψ, mas	-3.45±2.12	0.07±1.00
ε	0.44 0.17	0.59 0.22
Annual ψ, mas	3.98±0.35	0.03±0.37
ε	1.57 0.13	0.10 0.11
Semiannual ψ, mas	1.27±0.28	0.38±0.36
ε	-0.51 0.12	0.17 0.13

It must be emphasized that the 12-year extent of data is not sufficient to separate precession from the 18-year nutation. Magnitudes of correlation coefficients between precession and any 18-year term do not exceed 0.79, however. The dominant problem is the high (0.93) correlation between in- and out-of-phase 18-yr nutation terms.

4. Accuracy Assessment: Source Coordinate Comparisons

One traditional way of assessing accuracy has been to perform comparisons of independently determined source coordinates. This was done for the 98 sources common to JPL 1989-5 and a recent catalog (GSFC 1989) based on CDP and IRIS data (Ma et al., 1989). After removal of a rotation (−2.1, 0.6, 5.1 mas about the x, y, z axes respectively), three sources (P 0420−01, P 1055+01, 3C 279) are noted as outliers ($> 4\sigma$ differences in RA). The comparison is summarized in Table 4, where it may be seen that the only effect of omission of the three outliers is to reduce the normalized χ^2 for RA differences. Figure 3 shows differences in RA and δ (arclengths), as well as the differences normalized by the root-sum-squared errors (note that the unmodified formal uncertainties are used for both catalogs, and the three outliers are included). With the exception of the RA outliers noted above, the normalized differences appear to be normally distributed. Examination of the position dependence of JPL-GSFC differences reveals no apparent systematic differences.

Root-mean-square differences in RA (arclength) and δ are 2.0 and 1.3 mas, respectively. If the outliers are omitted, both are nearly normally distributed ($\chi^2_\nu \approx 1$). The RMS arclength difference for 4465 common arcs between sources is 2.5 mas, with no discernible trend *vs.* arc length over the range of 0° to 180°. The normalized χ^2 for arclength differences, however, is 1.5 (2.7 if the three outliers are included). The sizable x and y rotations point to the need for reconciling nutation modeling (see Sec. 5 below), while the z rotation is exactly equal to the rotation that was applied in the process of generating GSFC 1989 to align it with the FK5 system. The magnitudes of the differences indicate that realistic errors are probably close to the formal uncertainties, with the exception of the three sources noted above.

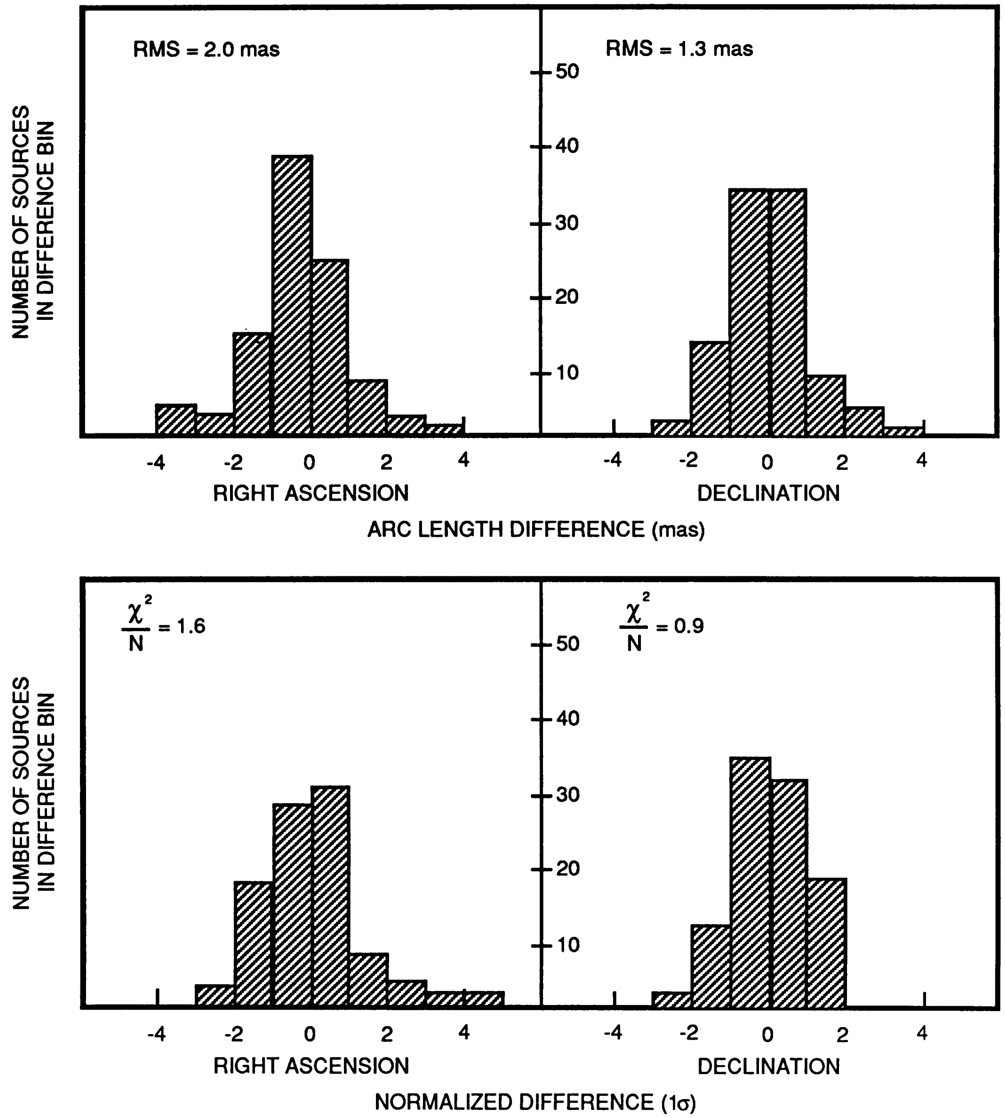

Figure 3. Histograms of differences between coordinates of 98 sources common to the JPL 1989-5 and GSFC 1989 catalogs. For the two lower plots, the differences are normalized by root-sum-squared formal uncertainties.

Table 4. Catalog Comparison: JPL 1989-5 *vs.* GSFC 1989

	All	Omit 3
Number of common sources	98	95
RMS uncertainty for common sources		
JPL 1989-5 : RA, dec. (mas)	1.7 1.7	1.7 1.7
GSFC 1989 : RA, dec. (mas)	1.2 0.6	1.2 0.6
Rotational offsets (mas) x	−2.1	−2.1
y	0.6	0.6
z	5.1	5.1
χ^2 per degree of freedom	1.7	1.1
RMS difference (mas) : RA	2.0	2.0
dec.	1.3	1.3
χ^2 per degree of freedom : RA	1.6	1.2
dec.	0.9	0.9
Δ(RA) *vs.* δ slope (μas/deg)	19±4	19±4

The sole indicator of systematic errors is the apparently highly significant slope of RA differences *vs.* declination. This amounts to ≈2 mas over the entire range of observed declinations, and is comparable to the RMS arclength difference. In previous JPL-GSFC comparisons, a similar systematic trend was seen in declination differences (Sovers et al., 1988). It is not clear whether the revised treatment of the RA origin in the GSFC fit is responsible for this change. The apparently high degree of significance of the $\Delta\alpha$ *vs.* δ slope is likely to be reduced when correlations between all source coordinates are included in the comparison, by analogy with the reduction of the significance of the $\Delta\delta$ *vs.* δ trend in the 1988 comparison.

5. Future Prognosis

Future joint analyses of DSN, CDP, and IRIS data might shed light on the remaining discrepancies between magnitudes of formal uncertainties and catalog differences. Analyses of 1984-1989 IRIS data, as well as of a considerable fraction of the CDP observations of astrometric quality dating back to 1979, are nearly complete at JPL. This is being done with independent parametrization and independent software (Masterfit: Sovers and Fanselow, 1987). Results of the new southern astrometric program (Russell and Johnston, 1989) will densify sky coverage and contribute significant numbers of source positions in the previously unexplored region of the celestial sphere below −45° declination. Plans are to eventually combine the several hundred thousand VLBI observations from all these programs to generate a definitive extragalactic reference frame.

Preliminary work exposes one danger of such an undertaking: if the position of a source is very different in fits to two individual data sets, the discrepancy may enter either the fit residuals or bias other estimated parameters in the combined fit. Only to the extent that it is practical to examine such details of large-scale combined fits will it be possible to have complete confidence in the resulting uncertainty estimates.

Uncertainties due to defects in the current IAU nutation model may misalign the entire VLBI reference frame by several milliarcseconds, as was seen in the presence of GSFC-JPL rotational offsets in Table 4. That such rotations are entirely due to errors in nutation modeling was demonstrated by adding the CDP session of 1980/10/17 (the GSFC nutation reference day) to the fit producing JPL 1989-5. The x and y rotational offsets between this modified JPL 1989-5 and GSFC 1989 are reduced to below 0.5 mas. Naturally, errors in celestial pole coordinates on the reference day will be directly reflected in misalignment of the radio source catalog.

Fixing the origin of right ascension is the second aspect of correctly orienting a radio source catalog. There are two parts to this problem: connecting the radio frame to the optical FK5 frame on the one hand, and to the frame of the planetary ephemerides on the other hand. Hipparcos data and observations of radio stars will contribute to the former, while analyses of planetary probe orbits, planetary occultation measurements, and VLBI and timing experiments on pulsars will yield ties to the ephemeris frame. VLBI data themselves have some sensitivity to absolute right ascensions (*e.g.*, through the Sun's gravitational bending and aberration effects). It appears, however, that such internal ties will not be possible at the several mas level, due to insufficient sensitivity.

6. Acknowledgments

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7. References

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Discussion

CHANDLER: You mentioned the Phobos "lander" data—are these the data from the Soviet Phobos mission in Mars orbit (rather than something from the future)?

SOVERS: I am not directly involved in this work, but my information is that analysis of tracking data for the Phobos mission through mid-1989 is underway.

XU: What is the origin of RA you have used for your VLBI catalogue?

SOVERS: It was the usual value of the right ascension of 3C273, determined by Hazard *et al.* from lunar occultation measurements in the 1970s. This has been used as an RA reference point in all VLBI analyses until very recently.