ASTROMETRIC RESULTS OF 1978–1985 DEEP SPACE NETWORK RADIO INTERFEROMETRY: THE JPL 1987-1 EXTRAGALACTIC SOURCE CATALOG

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ABSTRACT

An astrometric radio reference frame has been determined from intercontinental dual-frequency radio interferometric measurements. These measurements were carried out on a regular basis during 1978–1985 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 estimates of 1300 parameters. The most significant of these are geophysical quantities and positions of extragalactic sources. The source catalog resulting from this analysis includes 106 sources fairly uniformly distributed over the celestial sphere, north of $-45°$ declination. Almost all of the resulting source positions have formal uncertainties between 0.5 and 3 milliarcseconds (mas), with rms values of 2 mas in both angular coordinates. Internal consistency checks, as well as comparisons with independently determined source catalogs of comparable quality, indicate that relative source coordinates determined by VLBI contain systematic errors at the level of 1 to 2 mas.

I. INTRODUCTION

This paper focuses on the astrometric results of very long baseline interferometry (VLBI) measurements on two intercontinental baselines (Goldstone, California, to Madrid, Spain, and to Tidbinbilla, Australia). A single multiparameter fit is made to a 7 yr span of data to estimate geophysical and astrometric parameters. Measurements of the orientation of the Earth's spin axis in inertial space (nutation and precession) are substantially improved in comparison to the data set yielding the previously published Jet Propulsion Laboratory (JPL) source catalog (Fanselow *et al.* 1984). There have been substantial improvements in both the quality and quantity of source coordinates in the catalog of extragalactic radio sources, which serves as a reference frame for interplanetary navigation. Typical formal uncertainties are reduced to the level of approximately 1 milliarcsecond (mas). Geophysical results of analysis of these data will be reported elsewhere by Sovers *et al.* (1988a,b).

Since publication of a paper describing intercontinental radio interferometry with Deep Space Network (DSN) antennas from 1971 to 1980 (Fanselow *et al.* 1984), the database has increased and modeling improved. By the end of 1985, the volume of data available for analysis and interpretation of geodetic and astrometric parameters had nearly tripled. This was accomplished despite the reduced availability of the DSN stations for VLBI reference-frame development during the 1980s due to demands for tracking the *Voyager* spacecraft and other interplanetary probes. The present database includes only dual-frequency measurements, and only observing sessions that employed hydrogen-maser frequency standards at all participating stations. For these reasons, the number of observations in the overlapping timespan (1978–1980) is approximately 20% smaller here than in the data used to produce the JPL 1983-3 catalog described in the paper by Fanselow *et al.* (1984).

Similar VLBI measurements by the National Aeronautics and Space Administration (NASA) Crustal Dynamics Project (CDP) have recently 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 Earth orientation parameters with submilliarcsecond formal uncertainties at 5 day intervals since the beginning of 1984 (Robertson *et al.* 1986). All of these data sets appear to be very close to fulfilling the long-promised potential of VLBI for milliarcsecond accuracy in determining positional angles. Concomitant advances in modeling have been made in refining existing tropospheric and Earth models and in identifying new effects that are significant at the centimeter level. The most significant model change since our 1984 paper is the use of the Lanyi (1984) instead of the Chao (1974) tropospheric mapping function. While a number of physical effects contributing centimeter-size motions of the Earth's crust are also now routinely incorporated in modeling, the state of understanding systematic errors in both modeling and instrumentation has probably not yet reached this level.

II. EXPERIMENTAL TECHNIQUE

A total of 51 observing sessions were carried out during 1978–1985, mostly of 24 hr duration. Some sessions in 1984 and 1985 involved three stations; thus the total number of baseline days was 61. Of these, 13 involved two stations within 20 km of each other at the Goldstone DSN complex in California. This leaves 48 intercontinental baseline days, divided between California–Spain (CS) and California–Australia (CA) as 24 CS (470 hr) and 24 CA (415 hr). There is thus a slight deficit of observing time on the longer CA baseline, which has the only substantial north–south component of the two. With the exception of one CS session, 64 m antennas were always employed in Spain and Australia; approximately half of the Goldstone measurements were made with the 64 m antenna, while the rest used either the 26 m or 34 m station.

Throughout the series of measurements described here, Mark II data-acquisition systems were employed. We used the bandwidth synthesis technique (Rogers 1970) with channels of 2 MHz bandwidth, spanning about 40 MHz in a given radio-frequency band. Simultaneous measurements were made at approximately 2.3 and 8.4 GHz (S and X band) to permit calibration of ionospheric delays. A somewhat more detailed description of experimental details was provided by Sovers *et al.* (1984).

The observational strategy continued to be essentially the same as that in our earlier work. Nearly concurrent pairs of sessions were scheduled on the CS and CA baselines. At-

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tempts were made to observe each source a number of times in a given session to cover the full range of mutual visibility, and when possible, each source was observed on both baselines. As new sources were included in the observing requirements, the observing schedules were modified. Many different schedules on each intercontinental baseline were used to obtain the data described in this paper. Most observing sessions included observations of 3C 273, the source used as the reference for right ascension.

III. DELAY MODEL AND FITTING ALGORITHM

With certain exceptions noted below, the theoretical model of delays and delay rates conforms to the description given in the paper reporting on the 1971–1980 DSN data. Details may be found in the description of the JPL VLBI software by Sovers and Fanselow (1987). In summary, the calculations are performed in solar system barycentric coordinates defined in terms of the mean equator of J2000.0. Astronomical constants conform to the 1984 IAU resolutions (Kaplan 1981), and we employ the Project MERIT standards (Melbourne *et al.* 1983) for Earth modeling, with the exception of ocean loading. The right-handed Earth-fixed coordinate system has its z axis along the 1903.0 mean spin axis, and the x axis in the Greenwich meridian. Despite the fact that our intrinsic data accuracy has not yet reached 1 cm, a number of centimeter-level contributions to the observables are now routinely included in the analysis. These include the pole tide (Wahr 1985) and ocean loading (Pagiatakis 1982). Plate-tectonic motion is not modeled; indeed, one of the primary motivations for our measurements is detection and quantitative estimation of the time dependence of the DSN station coordinates. For such studies, the uniformly smoothed Earth orientation series of Morabito *et al.* (1987) is adopted. These data are based on a combination of results of IRIS VLBI (Robertson *et al.* 1985), lunar laser ranging (Dickey *et al.* 1985), and *Lageos* satellite ranging (Tapley *et al.* 1985). Since a new station location is estimated for each observing session, the choice of UT1 and polar motion has no effect on the source position results. Tropospheric zenith delays are mapped to the desired elevations with the mapping function of Lanyi (1984). This function incorporates surface-temperature measurements, which are available for approximately half of the observing sessions, equivalent to approximately two-thirds of the observations. The three other parameters of the linearly modeled temperature profile required by this mapping function are fixed at their nominal values, and monthly average temperatures are used for the sessions with no temperature measurements.

A multiparameter least-squares fit with diagonal weighting (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 accounts for unmodeled or underestimated errors. These external adjustable error contributions were adjusted in order to make χ^2 per degree of freedom (χ^2_ν) close to 1 for each session. Such added delay error contributions were 100 ps for the majority of observing sessions, but ranged up to several hundred ps for some of the early data, as well as for a few of the poorer later sessions, and averaged 0.18 ns for delays and 0.13 ps/s for delay rates. No account was taken of correlation between observations on baselines involving the same station during three-station experiments (which comprise approximately one-quarter of the total observations). While it is expected that these correlations do not dominate the data analysis, their effects may be manifested in the formal parameter covariances. We have started to investigate this possibility, as well as introduction of colored noise models. Preliminary single-session fits suggest that correlations affect parameter estimates at a level well below the formal uncertainties.

Of the 6802 delay and delay-rate pairs, 1293 were also included in the earlier fit to 1971–1980 data which generated the JPL 1983-3 catalog (Fanselow *et al.* 1984). Our new catalog is therefore not totally independent of the results presented there. The fit included session-specific parameters describing clock epochs and rates (an average of 4 hr of observations per clock section), a troposphere zenith delay at each station every 3 hr, 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, with the exception of the R.A. of 3C 273.

Specifications of the Earth-fixed coordinate frame and of the origin of right ascension were performed as follows. Absolute geocentric coordinates of the Goldstone station DSS 13 were adopted from the DSN station location set LS 111A of Moyer (1971). These are considered to have potential errors ranging from 1 m in the radius off the spin axis to ~ 10 m in z height. As in the case of UT1 and polar motion, the choice of *a priori* reference station coordinates has no effect on source positions in the standard fit. The value $12^h29^m6\overset{s}{.}6997$ at J2000.0 was adopted for the right ascension of the reference source 3C 273. It is obtained by transforming the occultation measurements of Hazard *et al.* (1971) to the J2000 frame, and its use has been customary in recent VLBI work. Observations of 3C 273 reveal changing structure on the 5 mas level (Unwin *et al.* 1985; Cohen *et al.* 1987). The impact of this structure on source coordinates is being evaluated (Ulvestad 1987), and is expected to degrade absolute locations, while affecting relative source positions to a lesser extent. Switching the reference source to GC 0235 + 16 yields source positions that differ by 0.2 mas (rms) from those obtained with 3C 273, apparently indicating that the choice of R.A. reference is not a problem at the milliarcsecond level.

A number of variants of the standard fit were also performed. Searches for manifestation of mismodeling included separate fits to the CS and CA data, separate fits to delay and delay-rate data, separate fits to data from each of the three California stations, fits to alternate observing sessions, fits in which observations at elevation angles lower than 10° at either or both stations were deleted, a solution for independent positions of 32 sources in three subsets of the 1978–1985 timespan, and fits in which parameters of the tropospheric mapping function were estimated. The adequacy of the models of nutation, precession, and general relativistic bending was tested in turn by solving for parameters in the standard descriptions of these effects. Only those results of these variant fits that are most pertinent to the characterization of source coordinate errors will be presented in the next section. Further details of the various analyses of subsets of the data will be given in a JPL report (Sovers *et al.* 1988c).

IV. RESULTS

In this section, we present the results for source positions from the standard fit, which form a source catalog named JPL 1987-1. This apellation is somewhat of a misnomer, with the year referring to the time of analysis rather than observation. The rms residuals in the standard fit were 0.37 ns for delay and 0.14 ps/s for delay rate. These are considerably smaller than those in the fit producing the previously published JPL 1983-3 source catalog (Fanselow *et al.* 1984), mainly due to elimination of the early (1971–1978) single-frequency measurements. Some searches for systematic errors involving various subsets of the 1978–1985 data gave negative results, while subsets of higher-elevation-angle observations indicated systematic errors in source positions. Such considerations are discussed in Sec. V below. The uniform distribution of observations of 32 sources over a long timespan allowed estimates to be made of source-position reproducibility. Other variations of the standard fit show definite indications that the standard models of precession and nutation need to be revised. Such results are presently being analyzed, and will be presented in a forthcoming paper (Sovers *et al.* 1988b). Finally, comparisons were made between the JPL 1987-1 catalog and independently measured compilations of source positions, in an effort to further characterize the level of systematic mismodeling.

The standard fit to 1978–1985 DSN data produced positional coordinates of 128 sources. Another 20 sources were observed, but the quality and/or quantity of the observations precluded the possibility of solving for their positions. The 128 sources whose positions were determined are divided into two groups. The main part of the 1987-1 catalog is presented in Table I (106 sources), while for completeness, a supplementary group of 22 sources is tabulated in Table II. This subgroup had fewer than ten intercontinental baseline observations per source, with consequent larger formal errors. It contains sources that are no longer being observed, as well as sources that we have just started observing, but for which we do not yet have adequate coverage. Note that the entire 1987-1 catalog is the result of a single fit to all available dual-frequency data. In particular, sources that were not observed after 1977 have not been carried over from the 1983-3 catalog.

Two identifications are given for each source: the IAU name based on 1950 positional coordinates, and the name in common use in JPL VLBI processing. Along with the average observation epoch, the number of successful observations (intercontinental plus short-baseline) of each source, positional coordinates and (1σ formal) uncertainties, we have also tabulated the correlation coefficient between R.A. and declination in the standard fit, and a "success rate." Almost all R.A.–Dec. correlations are negative because of the orientation of the CA baseline. This is strikingly evident in Fig. 1, which is a schematic representation of our source coordinates and their error ellipses. The success rate represents the fraction of originally scheduled observations that are included in the final fit. It thus accounts for attrition due to experimental problems at the stations, correlator problems, and effects of insufficient source flux due to weak signals, source structure, and flux variability. It is a rough indicator of the suitability of a source for a highly accurate extragalactic reference frame. For our measurements, the average success rate is approximately 80%.

Figure 2 shows histograms of the (1σ) formal uncertainties in right ascension and declination for JPL 1987-1 (the R.A. uncertainties have been multiplied by $\cos\delta$). It may be seen that the distributions peak somewhat below 1 mas. As in all VLBI-derived measurements published to date, the median of the right ascension errors appears to be lower than that of the declination errors, with a considerably more sharply peaked error distribution. This disparity is partially due to the greater east–west versus north–south average extension of current baselines. Root-mean-square uncertainties, however, are nearly equal for R.A. 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 peaks at higher uncertainties come from infrequently observed sources, some of which entered the observing schedules in 1982 or later, and others that are no longer observed.

It is important to re-emphasize that the positional coordinates presented here are relative to the 1980 IAU models of precession and nutation. Herring *et al.* (1986a,b) have reported evidence of significant shifts in nutation parameters relative to the 1980 IAU model. Similar evidence is present in the DSN data: source positions obtained by estimating daily nutation angles differ from positions based on 1980 IAU nutation by statistically significant offsets of 0.9 and 2.0 mas (rms) in R.A. and Dec. Results of our estimates of the precession constant, along with the in- and out-of-phase nutation amplitudes in longitude and obliquity with 18.6 yr, annual, and semiannual periods from the DSN VLBI data set, will be reported by Sovers *et al.* in a forthcoming publication (1988b). Users of the JPL 1987-1 catalog are cautioned that deviations from the 1980 IAU model can lead to errors in source positions in the range of 1 to 2 mas. If the source coordinates are transformed from J2000 to dates that are far from the mean observation epoch (1983), our preliminary estimate of the precession correction (-1.6 mas/yr) leads to very sizable errors (≈ 30 mas at J2000).

The source positions obtained in the standard fit are sensitive to the value of the gamma factor of general relativity (Misner *et al.* 1973) used to describe the retardation of signals by the massive bodies of the solar system. In practice, the only significant contribution is that of the Sun, and inclusion of this effect is crucial for a good fit to the data. When a supplementary fit to the 1978–1985 data is performed, solving explicitly for γ, the resulting value is 0.988 ± 0.012, in agreement with Einstein's theory of general relativity ($\gamma = 1$). Our formal uncertainty of 1.2% is not as small as the realistic errors of 0.2%–0.5% which were attained in analyses of specially designed experiments on the Mars *Viking* landers and orbiters (Shapiro *et al.* 1977; Cain *et al.* 1978). It compares with the formal error of 0.5% obtained by Robertson and Carter (1984) from analysis of 41 000 geodetic VLBI observations.

V. ERROR ANALYSES

Two types of systematic error investigations were conducted: (1) searches for errors by comparing parameters determined from different subsets of the data and alternative tropospheric mapping models, and (2) comparisons of the 1987-1 source positions and related parameters to those determined from independent data. As shown below, the two investigations led to an overall systematic error assessment of 1 to 2 mas in both right ascension and declination.

a) Internal Accuracy Tests

The VLBI data that determined the current catalog were divided into elevation-angle subsets to test for tropospheric mismodeling. The 1987-1 source coordinates were differ-

TABLE I. JPL 1987-1 radio source catalog.

IAU name	Common name	Observing epoch	No. of obsvs.	Success rate, %	Right ascension, h m s	error ms	Declination, d m s	error mas	RA, dec correl.
0008-264	P 0008-264	1982.15	20	80	0 11 1.24672	0.12	-26 12 33.3734	2.0	-0.529
0019+058	P 0019+058	1983.70	41	62	0 22 32.44128	0.04	6 8 4.2715	1.6	-0.338
0104-408	P 0104-408	1980.64	23	96	1 6 45.10822	0.19	-40 34 19.9557	2.1	-0.435
0106+013	P 0106+01	1983.19	133	81	1 8 38.77113	0.04	1 35 0.3200	1.0	-0.305
0111+021	P 0111+021	1982.77	33	40	1 13 43.14512	0.14	2 22 17.3179	2.3	-0.848
0119+041	GC 0119+04	1984.13	14	53	1 21 56.86177	0.12	4 22 24.7377	2.3	-0.793
0133+476	DA 55	1982.55	83	84	1 36 58.59476	0.07	47 51 29.1023	0.7	-0.342
0202+149	P 0202+14	1983.25	69	77	2 4 50.41399	0.04	15 14 11.0450	1.0	-0.440
0212+735	0212+735	1983.93	60	94	2 17 30.81326	0.10	73 49 32.6234	0.4	-0.141
0224+671	DW 0224+67	1981.64	27	75	2 28 50.05179	0.26	67 21 3.0325	1.4	-0.246
0234+285	CTD 20	1983.43	118	90	2 37 52.40576	0.04	28 48 8.9919	0.7	-0.346
0235+164	GC 0235+16	1983.32	85	86	2 38 38.93021	0.04	16 36 59.2753	0.8	-0.430
0239+108	OD 166	1983.81	55	81	2 42 29.17103	0.05	11 1 0.7285	1.2	-0.477
0256+075	OD 094.7	1983.66	33	52	2 59 27.07676	0.05	7 47 39.6417	2.1	-0.357
0300+470	OE 400	1983.61	75	89	3 3 35.24220	0.06	47 16 16.2779	0.6	-0.268
0316+413	3C 84	1980.04	11	73	3 19 48.16024	0.15	41 30 42.1080	1.8	-0.524
0332-403	P 0332-403	1983.30	34	77	3 34 13.65485	0.17	-40 8 25.3949	1.9	-0.289
0333+321	NRAO 140	1982.84	89	75	3 36 30.10770	0.05	32 18 29.3446	0.8	-0.445
0336-019	CTA 26	1980.78	16	89	3 39 30.93771	0.09	-1 46 35.7983	1.9	-0.648
0402-362	P 0402-362	1983.40	40	90	4 3 53.74980	0.13	-36 5 1.9056	1.7	-0.181
0406+121	GC 0406+12	1983.28	76	79	4 9 22.00881	0.04	12 17 39.8492	1.2	-0.417
0420-014	P 0420-01	1983.83	77	92	4 23 15.80087	0.04	-1 20 33.0639	1.1	-0.279
0430+052	3C 120	1983.55	44	72	4 33 11.09564	0.06	5 21 15.6226	1.6	-0.546
0434-188	P 0434-188	1983.48	41	73	4 37 1.48278	0.09	-18 44 48.6109	1.8	-0.536
0438-436	P 0438-43	1982.63	29	94	4 40 17.17995	0.16	-43 33 8.5972	1.8	-0.171
0454+844	0454+844	1983.57	34	95	5 8 42.36429	0.34	84 32 4.5454	0.6	-0.105
0528+134	P 0528+134	1983.45	92	93	5 30 56.41687	0.04	13 31 55.1516	0.9	-0.403
0537-441	P 0537-441	1982.93	39	89	5 38 50.36127	0.17	-44 5 8.9314	1.9	-0.257
0552+398	DA 193	1983.61	91	89	5 55 30.80562	0.05	39 48 49.1675	0.6	-0.263
0607-157	P 0607-15	1982.01	15	45	6 9 40.95024	0.33	-15 42 40.6808	5.0	-0.951
0723-008	DW 0723-00	1983.70	85	91	7 25 50.64003	0.05	-0 54 56.5432	1.2	-0.506
0727-115	P 0727-11	1983.59	71	94	7 30 19.11261	0.04	-11 41 12.6003	1.3	-0.219
0735+178	P 0735+17	1983.86	71	82	7 38 7.39382	0.04	17 42 19.0000	0.9	-0.436
0742+103	DW 0742+10	1983.15	121	86	7 45 33.05960	0.03	10 11 12.6923	0.9	-0.392
0745+241	B2 0745+24	1984.37	50	81	7 48 36.10934	0.05	24 0 24.1108	1.1	-0.350
0748+126	P 0748+126	1983.12	64	79	7 50 52.04583	0.04	12 31 4.8283	1.0	-0.464

TABLE I. (continued)

IAU name	Common name	Observing epoch	No. of obsvs.	Success rate, %	Right ascension, h m s	error ms	Declination, d m s	error mas	RA, dec correl.
0814+425	OJ 425	1983.48	58	91	8 18 15.99973	0.05	42 22 45.4147	0.6	-0.194
0823+033	P 0823+033	1983.48	85	81	8 25 50.33845	0.03	3 9 24.5203	1.1	-0.354
0827+243	B2 0827+24	1980.19	11	55	8 30 52.08640	0.28	24 10 59.8172	3.9	-0.880
0836+710	4C 71.07	1980.88	17	55	8 41 24.36625	0.35	70 53 42.1704	2.0	0.230
0851+202	OJ 287	1983.82	106	91	8 54 48.87500	0.03	20 6 30.6417	0.7	-0.311
0923+392	4C 39.25	1982.91	114	89	9 27 3.01390	0.05	39 2 20.8514	0.6	-0.270
1004+141	GC 1004+14	1980.00	15	56	10 7 41.49854	0.47	13 56 29.5949	6.3	-0.959
1034-293	P 1034-293	1983.47	49	89	10 37 16.07950	0.12	-29 34 2.8094	1.7	-0.394
1038+064	OL 064.5	1983.73	70	72	10 41 17.16254	0.04	6 10 16.9224	1.5	-0.371
1055+018	P 1055+01	1983.16	93	92	10 58 29.60524	0.03	1 33 58.8234	1.0	-0.287
1104-445	P 1104-445	1983.39	26	97	11 7 8.69384	0.22	-44 49 7.6140	2.1	-0.432
1111+149	GC 1111+14	1980.02	11	44	11 13 58.69545	0.47	14 42 26.9480	5.9	-0.940
1123+264	P 1123+26	1983.09	76	85	11 25 53.71198	0.04	26 10 19.9771	0.9	-0.277
1127-145	P 1127-14	1981.20	40	76	11 30 7.05242	0.14	-14 49 27.3862	2.3	-0.781
1128+385	GC 1128+38	1983.89	66	82	11 30 53.28263	0.05	38 15 18.5457	0.8	-0.040
1144-379	P 1144-379	1982.23	65	95	11 47 1.37067	0.10	-38 12 11.0223	1.6	0.080
1148-001	P 1148-00	1982.99	27	48	11 50 43.87087	0.08	-0 23 54.2062	2.7	-0.499
1222+037	P 1222+037	1982.62	47	80	12 24 52.42190	0.04	3 30 50.2923	1.3	-0.428
1226+023	3C 273	1983.12	127	93	12 29 6.69970	....	2 3 8.5986	1.0	...
1228+126	3C 274	1980.03	12	44	12 30 49.42339	0.31	12 23 28.0427	4.1	-0.941
1244-255	P 1244-255	1982.97	53	89	12 46 46.80206	0.07	-25 47 49.2883	1.6	-0.232
1253-055	3C 279	1983.61	58	91	12 56 11.16661	0.03	-5 47 21.5278	1.3	-0.183
1308+326	B2 1308+32	1983.22	111	90	13 10 28.66383	0.04	32 20 43.7820	0.6	-0.107
1313-333	OP-322	1982.54	27	81	13 16 7.98591	0.19	-33 38 59.1713	2.2	-0.594
1334-127	DW 1335-12	1984.19	65	93	13 37 39.78283	0.03	-12 57 24.6943	1.4	-0.232
1342+662	GC 1342+662	1983.51	34	64	13 43 45.95954	0.11	66 2 25.7432	0.7	-0.085
1342+663	GC 1342+663	1983.50	104	73	13 44 8.67964	0.09	66 6 11.6416	0.4	-0.100
1349-439	P 1349-439	1983.61	23	72	13 52 56.53511	0.21	-44 12 40.3875	2.0	-0.377
1354+195	P 1354+19	1983.06	84	90	13 57 4.43661	0.04	19 19 7.3718	0.9	-0.349
1418+546	GC 1418+54	1983.56	92	89	14 19 46.59734	0.06	54 23 14.7853	0.5	-0.065
1430-178	OQ-151	1980.66	11	50	14 32 57.69004	0.48	-18 1 35.2412	7.2	-0.964
1502+106	OR 103	1983.13	121	90	15 4 24.97976	0.03	10 29 39.1990	1.0	-0.226
1504-167	P 1504-167	1984.15	63	86	15 7 4.78704	0.04	-16 52 30.2673	1.6	-0.110
1510-089	P 1510-08	1984.07	81	91	15 12 50.53293	0.04	-9 5 59.8292	1.3	-0.193
1519-273	P 1519-273	1982.89	47	89	15 22 37.67604	0.12	-27 30 10.7848	1.9	-0.509
1555+001	DW 1555+00	1983.57	63	66	15 57 51.43398	0.04	-0 1 50.4136	1.3	-0.346

TABLE I. (continued)

IAU name	Common name	Observing epoch	No. of obsvs.	Success rate, %	Right ascension, h m s	error ms	Declination, d m s	error mas	RA, dec correl.
1611+343	DA 406	1983.59	85	94	16 13 41.06416	0.04	34 12 47.9074	0.7	-0.137
1633+382	GC 1633+38	1982.84	106	92	16 35 15.49289	0.04	38 8 4.4991	0.6	-0.141
1638+398	NRAO 512	1982.01	98	89	16 40 29.63263	0.05	39 46 46.0278	0.6	-0.173
1641+399	3C 345	1983.49	254	93	16 42 58.80982	0.04	39 48 36.9930	0.5	-0.068
1656+053	DW 1656+05	1980.90	15	45	16 58 33.44777	0.41	5 15 16.4362	6.4	-0.951
1657-261	P 1657-261	1984.05	30	63	17 0 53.15433	0.06	-26 10 51.7268	1.7	-0.221
1706-174	OT-111	1983.92	34	54	17 9 34.34548	0.06	-17 28 53.3651	1.7	-0.380
1717+178	GC 1717+17	1980.28	20	48	17 19 13.04856	0.19	17 45 6.4342	3.3	-0.778
1730-130	NRAO 530	1983.39	111	82	17 33 2.70587	0.04	-13 4 49.5476	1.3	-0.149
1738+476	OT 465	1983.75	62	84	17 39 57.12887	0.06	47 37 58.3608	0.8	-0.157
1741-038	P 1741-038	1983.69	95	92	17 43 58.85618	0.03	-3 50 4.6174	1.1	-0.209
1749+701	1749+701	1982.82	97	71	17 48 32.83993	0.11	70 5 50.7675	0.5	-0.171
1807+698	3C 371	1982.69	121	86	18 6 50.68020	0.10	69 49 28.1083	0.5	0.083
1821+107	P 1821+10	1981.70	23	57	18 24 2.85537	0.08	10 44 23.7719	3.8	-0.448
1908-201	OV-213	1984.08	18	48	19 11 9.65288	0.18	-20 6 55.1068	2.7	-0.820
1921-293	OV-236	1983.92	42	80	19 24 51.05619	0.11	-29 14 30.1208	1.7	-0.377
1958-179	OV-198	1983.50	54	77	20 0 57.09062	0.06	-17 48 57.6729	1.5	-0.369
2029+121	P 2029+121	1981.95	21	54	20 31 54.99421	0.13	12 19 41.3428	2.6	-0.720
2113+293	B2 2113+29B	1982.57	66	80	21 15 29.41339	0.04	29 33 38.3676	0.9	-0.172
2134+004	P 2134+004	1983.43	67	83	21 36 38.58646	0.04	0 41 54.2134	1.2	-0.407
2145+067	P 2145+06	1983.21	140	92	21 48 5.45873	0.03	6 57 38.6038	0.9	-0.219
2149+056	OX 082	1982.84	65	76	21 51 37.87540	0.05	5 52 12.9565	1.4	-0.502
2155-152	OX-192	1983.42	27	70	21 58 6.28195	0.15	-15 1 9.3263	2.4	-0.812
2200+420	VRO 42.22.01	1982.83	100	80	22 2 43.29129	0.05	42 16 39.9815	0.6	0.051
2216-038	P 2216-03	1984.11	47	85	22 18 52.03784	0.04	-3 35 36.8802	1.2	-0.212
2223-052	3C 446	1983.86	55	83	22 25 47.25938	0.04	-4 57 1.3903	1.1	-0.194
2230+114	CTA 102	1983.37	81	82	22 32 36.40891	0.04	11 43 50.9054	0.9	-0.346
2234+282	GC 2234+28	1982.98	98	84	22 36 22.47081	0.04	28 28 57.4141	0.7	-0.215
2243-123	OY-172.6	1983.07	73	77	22 46 18.23209	0.04	-12 6 51.2758	1.3	-0.220
2245-328	P 2245-328	1982.24	40	84	22 48 38.68583	0.15	-32 35 52.1830	2.0	-0.511
2251+158	3C 454.3	1983.51	103	89	22 53 57.74796	0.04	16 8 53.5614	0.9	-0.311
2253+417	GC 2253+41	1983.12	57	68	22 55 36.70773	0.07	42 2 52.5353	1.2	-0.215
2320-035	P 2320-035	1983.19	56	61	23 23 31.95381	0.04	-3 17 5.0220	1.6	-0.287
2345-167	P 2345-16	1982.40	28	84	23 48 2.60852	0.20	-16 31 12.0187	2.9	-0.868

TABLE II. Supplementary source list from JPL 1987-1.

IAU name	Common name	Observing epoch	No. of obsvs.	Success rate, %	Right ascension, h m s	error ms	Declination, d m s	error mas	RA, dec correl.
0113-118	P 0113-118	1981.49	10	63	1 16 12.52261	0.72	-11 36 15.4378	10.3	-0.980
0201+113	P 0201+113	1983.90	10	29	2 3 46.65734	0.13	11 34 45.3629	22.0	-0.557
0237-233	P 0237-23	1980.01	3	30	2 40 8.17469	0.87	-23 9 15.7355	12.0	-0.901
0342+147	0342+147	1985.74	2	43	3 45 6.41780	5.81	14 53 49.5343	89.3	-0.998
0400+257	CTD 26	1982.50	1	11	4 3 5.58660	0.73	26 0 1.4993	9.6	-0.080
0420+417	VRO 41.04.01	1980.01	9	60	4 23 56.00988	0.22	41 50 2.7185	3.3	-0.483
0440-003	NRAO 190	1979.53	7	32	4 42 38.66087	0.52	-0 17 43.4203	8.1	-0.970
0451-282	P 0451-28	1980.01	5	71	4 53 14.64608	0.46	-28 7 37.3155	5.7	-0.896
0507+179	P 0507+17	1985.52	13	93	5 10 2.36907	0.44	18 0 41.5819	6.3	-0.919
0600+177	0600+177	1985.58	9	77	6 3 9.13061	0.20	17 42 16.8029	3.9	-0.742
0605-085	P 0605-08	1979.54	5	86	6 7 59.69912	0.44	-8 34 49.9764	6.7	-0.942
0657+172	0657+172	1985.56	12	100	7 0 1.52567	0.17	17 9 21.6989	3.3	-0.734
0738+313	OI 363	1978.95	4	36	7 41 10.70310	0.52	31 12 0.2340	6.2	-0.882
0859-140	P 0859-14	1980.30	7	67	9 2 16.83057	1.41	-14 15 30.8724	21.4	-0.992
0859+470	OJ 499	1982.79	5	40	9 3 3.99286	1.29	46 51 4.1212	6.5	-0.779
0952+179	AO 0952+17	1979.97	5	23	9 54 56.82361	0.77	17 43 31.2270	12.6	-0.962
1040+123	3C 245	1980.02	6	22	10 42 44.60597	0.35	12 3 31.2586	4.8	-0.821
1116+128	P 1116+12	1980.10	4	17	11 18 57.30158	0.30	12 34 41.7143	6.3	-0.698
1749+096	OT 081	1985.74	3	75	17 51 32.81845	0.20	9 39 0.7298	8.0	-0.498
1933-400	P 1933-400	1980.10	6	26	19 37 16.21717	0.56	-39 58 1.5464	5.5	-0.809
2029+547	OW 551	1981.34	12	42	20 31 47.95846	0.32	54 55 3.1490	3.6	-0.264
2355-106	P 2355-106	1985.74	2	33	23 58 10.88244	0.26	-10 20 8.4817	68.9	-0.398

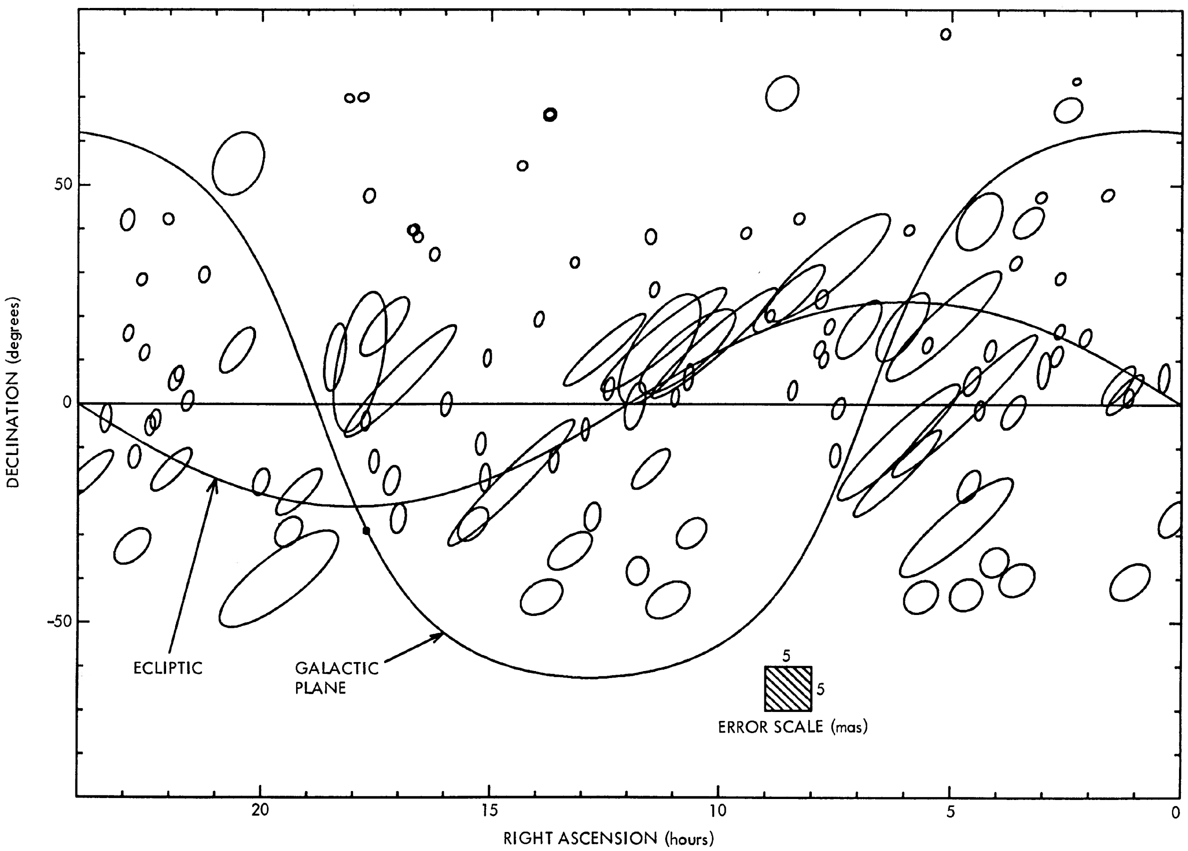

FIG. 1. Schematic source positional coordinates and formal 1σ error ellipses for the JPL 1987-1 catalog. Note the different scales for positions and uncertainties.

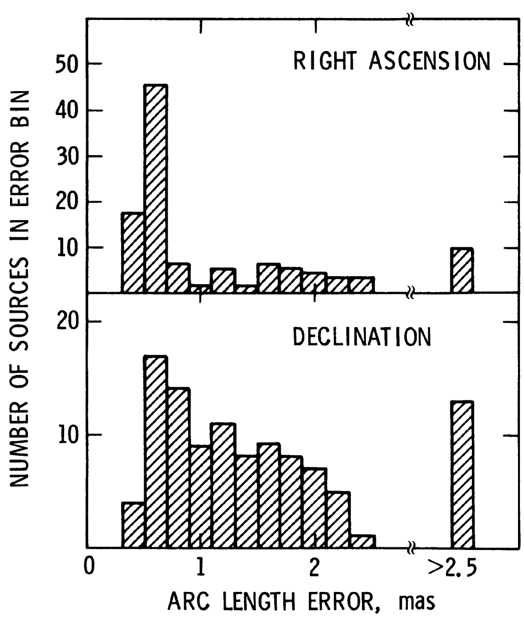

FIG. 2. Histogram of source-position formal uncertainties for 106 sources in the JPL 1987-1 catalog. The right ascension uncertainties are scaled by the cosine of declination.

enced from those determined only by observations taken above 10° elevation at both stations, with uncertainties of the differences calculated by differencing the two uncertainties in quadrature. The declination difference is plotted versus declination in Fig. 3. Given the DSN baselines, low-declination sources are observed at lower elevation angles, and the variation of declination difference with declination serves as a sensitive probe of troposphere systematics. The line shown was fit to the declination differences. Its slope is $\mu = 12 \pm 5$ μas/deg. Because the slope is more than twice its formal error, it is an indication of a potential systematic error at the approximate level of the departure of the line from zero at the left-hand side of Fig. 3 (≈ 2 mas). It should be noted that including all correlations among the points was critical to the correct determination of the slope and its error. There is no readily identifiable trend of the largest correlation coefficients with declination. Approximately half of the sources with correlations exceeding 0.9 are in the midrange of declination, 15°–45°.

Both systematic and random error sources must be considered as candidates for contributing to the slope in Fig. 3. Inaccuracies in tropospheric mapping are a primary concern. For example, the lack of surface meteorological input to the tropospheric mapping function for about one-third of the observations could account for some of the slope. When no surface meteorological data are used in evaluating the troposphere mapping function, the slope increases to a value

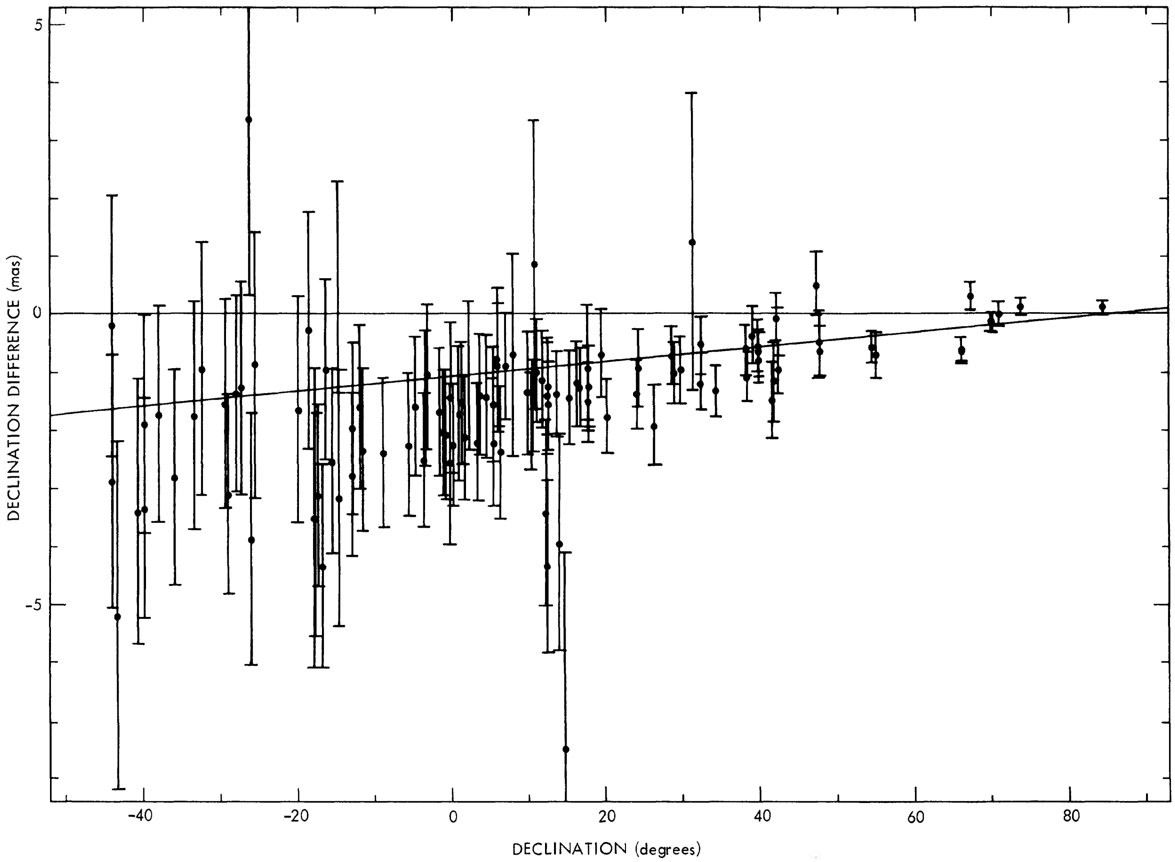

FIG. 3. Differences in source declination: standard fit to the 1978–1985 DSN VLBI data minus a fit including only measurements in which both stations observed above 10° elevation. The slope of the weighted linear least-squares fit is 12 ± 5 μas/deg.

of 18 ± 5 μas/deg. Other examples of potential elevation-dependent systematic error sources are instrumental phase shifts which are dependent on antenna orientation, and deformation of the antenna due to gravity. Calibration tests indicate that the instrumental errors are in the 5 mm range, which corresponds to an angular error of ≈ 0.2 mas over the entire declination range on intercontinental baselines. Although the systematic errors mentioned seem too small to cause the trend in Fig. 3, they will be further tested in future short-baseline experiments.

An acknowledged source of random error is tropospheric fluctuations. This stochastic delay error is not rigorously treated by the additive noise procedure currently used to force the reduced χ^2 of the catalog fit to unity. That is, the delay and delay-rate covariances used in the standard VLBI fit were diagonal. Because tropospheric fluctuations introduce off-diagonal terms in the observation covariance matrix (Treuhaft and Lanyi 1987), the source coordinate values and covariances used in the linear fit of Fig. 3 are still deficient. The apparent significance of the $\Delta\delta$ vs δ slope may be an indication of that deficiency. This possibility will be tested as software becomes available for including the correlation terms in the fit for the source coordinates. While tropospheric fluctuations are expected to give the largest contribution to the off-diagonal observable covariance, hydrogen-maser clock wandering and other stochastic instrumental instabilities may also contribute to the slope observed in Fig. 3.

To test the effect of tropospheric-mapping inaccuracies on source positions, differences were calculated between the JPL 1987-1 positions and those given by a number of variant fits to the 1978–1985 data. The standard fit employed the Lanyi mapping function with daily average temperatures of each site when available; otherwise, monthly average temperatures were used. Variations included: (a) a fit in which the default temperature of 292 K was used for sessions without surface meteorology, (b) a fit in which monthly mean temperatures replaced surface meteorological calibrations, (c) a fit in which the default surface temperature of 292 K was used for all sessions, (d) a fit in which the Lanyi mapping function was replaced by the CfA (Davis *et al.* 1985) function, and (e) a fit in which the Lanyi mapping function was replaced by the Chao (1974) function. Root-mean-square positional differences between the catalogs obtained from these fits and JPL 1987-1 are uniformly 0.1–0.2 mas, with the exception of those for the catalog based on the Chao mapping function (0.5 and 1.2 mas for R.A. and declination, respectively). Coordinate shifts induced by changes in tropospheric mapping thus show that deficiencies in atmospheric modeling probably amount to < 0.2 mas, while much larger errors can result from the use of the less adequate Chao mapping function. Other variant fits involving various subsets of the data will be discussed in a forthcoming report (Sovers *et al.* 1988c).

In addition to elevation subsets, the data were divided into temporal subsets to compare the stability of source coordi-

TABLE III. Differences of source coordinates among three time periods.

Source	$\Delta\alpha_{21}$		$\Delta\delta_{21}$		$\Delta\alpha_{32}$		$\Delta\delta_{32}$		μ_α		μ_δ	
P 0106+01	1.3±2.2		5.2±3.6		-0.8±1.3		-3.6±2.5		0.0±0.5		0.3±0.9	
DA 55	-1.0	2.6	-3.0	1.9	4.9	1.7	-0.4	1.7	0.9	0.6	-0.8	0.5
P 0202+14	-1.1	2.3	2.3	3.2	-2.4	2.0	0.1	2.6	-0.6	0.6	0.5	0.8
CTD 20	-0.8	2.6	-1.0	2.5	2.3	1.4	-2.8	1.6	0.5	0.6	-0.9	0.6
GC 0235+16	-1.1	2.3	1.1	2.8	2.9	1.5	-4.4	2.0	0.4	0.6	-0.8	0.7
NRAO 140	-4.5	2.7	1.5	2.3	1.9	1.7	-1.1	2.3	-0.5	0.7	0.2	0.6
GC 0406+12	2.4	2.6	8.7	5.9	1.7	1.4	-1.9	3.1	1.0	0.6	1.1	1.4
P 0528+134	-1.7	2.2	4.3	3.0	0.0	1.3	-2.3	2.1	-0.4	0.5	0.4	0.7
DW 0742+10	1.1	2.5	0.0	3.2	-0.2	1.1	-1.7	2.1	0.1	0.5	-0.4	0.7
P 0823+033	-2.2	3.0	5.4	4.1	-0.5	1.1	-2.5	2.6	-0.5	0.6	0.5	1.0
4C 39.25	-1.2	2.3	-0.2	2.0	1.1	1.5	0.4	1.7	-0.0	0.6	0.0	0.5
P 1055+01	-0.2	1.8	3.7	3.5	0.2	0.9	-3.9	2.5	0.0	0.4	-0.1	0.8
P 1123+26	-0.8	2.9	1.5	2.9	0.2	1.3	0.9	2.8	-0.1	0.6	0.5	0.8
P 1144-379	1.1	3.6	9.8	5.1	0.1	2.9	-12.7	3.9	0.3	0.9	-0.3	1.2
3C 273	...	...	4.0	3.6	...	...	-5.7	2.3	...	...	-0.6	0.8
P 1244-255	3.5	4.0	6.0	5.0	0.7	2.1	-11.1	3.8	0.9	0.9	-1.0	1.2
B2 1308+32	-0.6	2.2	2.6	2.1	0.4	1.2	1.6	1.5	0.0	0.5	0.9	0.5
P 1354+19	-0.5	2.8	4.9	3.3	1.0	1.2	0.8	2.5	0.3	0.6	1.3	0.8
OR 103	1.5	2.1	4.9	3.3	-0.7	0.9	-1.9	2.2	0.0	0.4	0.6	0.8
P 1519-273	13.5	5.0	2.5	5.9	-5.0	4.9	-9.5	5.4	2.2	1.0	-1.3	1.3
GC 1633+38	-1.2	2.3	1.8	2.0	0.0	1.4	0.8	1.4	-0.3	0.6	0.6	0.5
NRAO 512	-1.4	2.4	1.5	2.0	0.8	1.6	2.1	2.0	-0.1	0.6	0.7	0.5
3C 345	-3.0	2.3	1.5	1.9	1.1	1.4	0.8	1.2	-0.4	0.6	0.5	0.4
NRAO 530	5.9	3.2	6.2	5.3	-1.6	1.2	-7.5	3.1	0.2	0.6	-0.8	1.2
3C 371	2.7	2.0	0.6	1.4	-6.2	1.5	1.9	1.3	-0.6	0.5	0.5	0.4
OV-198	0.3	6.6	7.8	6.9	0.8	2.1	-9.6	3.6	0.4	1.2	-1.5	1.5
P 2145+06	4.3	2.2	1.0	3.3	0.2	1.0	-4.4	2.0	0.8	0.5	-0.9	0.8
OX 082	2.5	3.0	4.9	4.3	1.1	1.9	-8.2	3.6	0.8	0.7	-0.3	1.1
VRO 42.22.01	1.1	2.6	-3.4	2.1	1.1	1.6	2.7	2.0	0.5	0.6	-0.4	0.6
GC 2234+28	1.1	2.4	-1.5	2.5	0.6	1.4	0.7	1.6	0.4	0.6	-0.1	0.6
OY-172.6	4.2	2.6	5.2	4.7	-1.9	1.7	-5.4	3.3	0.5	0.6	-0.0	1.1
GC 2253+41	-4.8	2.9	-1.2	3.5	2.0	1.9	-1.3	3.4	-0.6	0.7	-0.5	0.9
Rms	3.4		4.2		2.1		4.9		0.5		0.6	
χ_ν^2		1.1		1.2		1.5		2.6		0.8		1.0

nates at different epochs. The 1978–1985 DSN observations were divided into three time periods: 1978–1980, 1981–1983, and 1984–1985, with measurements showing some clustering within each period. Average epochs are close to 1980.0, 1983.2, and 1984.5 for all sources. Three separate fits were done, with estimated parameters as in the standard fit.

Comparisons of the resulting source coordinates were made for the 32 sources that have at least ten intercontinental observations in each of the three timespans. After removal of rotational offsets amounting to <3 mas (presumably mainly due to precession errors), adjacent pairs of catalogs yield differences and time rates of change, which are presented in Table III. Here the differences in right ascension and declination between adjacent periods ($\Delta\alpha_{ij}$,$\Delta\delta_{ij}$, mas) and the time rates of change of R. A. and Dec. (μ_α,μ_δ, mas/yr) are shown, together with their formal uncertainties, rms values, and χ^2 per degree of freedom, χ_ν^2. Coordinate differences are defined in the sense $\Delta\alpha_{ij} = \alpha_i - \alpha_j$, where i and $j = 1,2,3$ correspond to the average epochs in increasing time order. Linear fits to each set of three values of each coordinate determine the time rates of change. Generally, the improvement of data quality between 1978 and 1985 is evident in the smaller formal errors in the 8485–8183 ($\Delta\alpha_{32}$, $\Delta\delta_{32}$) vs 8183–7880 ($\Delta\alpha_{21}$, $\Delta\delta_{21}$) shifts. While there are a number of cases of $>2\sigma$, and two of $>3\sigma$ differences ($\Delta\alpha_{32}$ of 3C 371 and $\Delta\delta_{32}$ of P1144 − 379), none of these sources show consistent shifts between both pairs of epochs. It remains to be determined whether these shifts can be explained by known source-structure effects or flux time variability. Root-mean-square differences are approximately 2–4 mas for both sets of epochs, and χ_ν^2s are somewhat in excess of 1. Most of this discrepancy is due to the few outliers. Only one time rate exceeds 2σ: μ_α of P1519 − 273.

The rms time rates of change (μ_α,μ_δ) calculated from linear fits to the 32 sets of coordinates are 0.5 and 0.6 mas/yr for right ascension and declination, respectively, with χ_ν^2s close to 1. This is an indication of the stability of the JPL reference frame, exclusive of long-term nutation and precession effects.

b) External Accuracy Tests

All of the above internal consistency tests probe the precision of the catalog. The question of its accuracy is addressed below by comparing our source coordinates to independent determinations. There are two independent VLBI programs currently yielding extragalactic source catalogs of comparable quality to JPL 1987-1. One is based on Crustal Dynamics Project (CDP) data analyzed at Goddard Space Flight Center (GSFC) (Ma *et al.* 1986), and the other on IRIS data (Robertson *et al.* 1986). Both programs employ databases containing an order of magnitude more observations than the JPL DSN data. Since the GSFC catalogs use IRIS data as part of their database, these catalogs are not totally independent. For comparisons of source coordinates, we chose two recent GSFC catalogs, denoted GSFC8708 and GSFC8708N (Ma 1987), and two IRIS catalogs, denoted IRIS86 and IRIS87 (Robertson *et al.* 1986; Carter *et al.* 1987). Only the JPL and GSFC8708 source positions are based on the current IAU conventions, while nutation angles were estimated for each session in the fits producing GSFC8708N, IRIS86, and IRIS87. The JPL VLBI program employs completely independent hardware, baselines, observing schedules, and correlation and parameter-estimation software. A recent detailed comparison of the modeling software (Sovers and Ma 1985) concluded that the GSFC and JPL models agree at the 1 to 2 cm level or better (≈ 0.5 mas on intercontinental baselines). Comparison of results may therefore be valuable in identifying residual systematic errors in the VLBI technique.

As may be seen from Table IV, for the sources that the catalogs have in common, the respective rms formal coordinate uncertainties are ≈ 2 mas for the 61 sources from the GSFC and JPL lists, and ≈ 1 mas for 18–23 sources from the IRIS and JPL catalogs. This indicates that the quality of the source positions used in the comparisons is essentially comparable. Prior to comparing positional coordinates, we removed a three-dimensional rotation for each pair of catalogs, in order to allow for the different Earth-fixed coordinate systems and/or nutation origins. The results are shown in Table IV for the catalog differences JPL 1987-1 minus GSFC and IRIS. The offsets are right-handed rotations about the axes of the right-handed celestial coordinate system, applied to the GSFC and IRIS catalogs prior to comparison. The formal uncertainties of the rotational offsets are approximately 0.2 mas. The normalized chi-squares in Table IV are based on root-sum-squared 1σ formal uncertainties for catalog pairs, with the full covariance matrices employed for the JPL 1987-1 and GSFC coordinates, and a diagonal matrix for IRIS. Replacement of complete by diagonal covariance for JPL 1987-1 changed the rotational offsets by 0.5 mas or less, and μ and its error by as much as a factor of 2; the corresponding effect with the GSFC covariance is nearly negligible. We therefore expect that the values in Table IV would undergo very small changes if the full IRIS covariance were used.

Right ascension and declination rms differences range from 1.5 to 3.7 mas, and their χ^2_ν values, as well as those for the rotational transformation, indicate that one or both sets of formal uncertainties are underestimates of the true errors. The hypothesis that declination systematics are due to the preponderance of low-elevation observations in the DSN data is supported by the values of μ in the last line of Table IV. For example, the $\Delta\delta$ vs δ slope μ for 1987-1 minus GSFC8708 ($16 \pm 10\,\mu$as/deg) has the same sign as that for 1987-1 minus the catalog obtained from the same DSN data with observations only $>10°$ elevation ($\mu = 12 \pm 5$ μas/deg). The corresponding slopes for GSFC8708N and IRIS86 are similar. The magnitudes of the slopes are in qualitative proportion to the disparity in fractions of low-elevation observations in the three data sets, since there are smaller proportions of observations below 20° elevation in both the GSFC and IRIS data. The IRIS87 catalog includes five new low-declination sources that were not present in previous IRIS observations, and is based on a different treatment of the R.A. reference point. It is seen from Table IV that the trend in $\Delta\delta$ vs δ has essentially disappeared with the latest IRIS catalog.

In addition to comparison of different radio interferometric measurements of extragalactic radio sources, compari-

TABLE IV. Source catalog comparisons with JPL 1987-1.

Catalog	GSFC8708	GSFC8708N	IRIS86	IRIS87
Number of common sources	61	61	18	23
Rms uncertainty for common sources				
JPL 1987-1 : RA, dec. (mas)	1.8 2.0	1.7 2.0	1.2 0.9	1.3 1.2
GSFC/IRIS : RA, dec. (mas)	2.0 1.6	2.0 1.6	0.6 1.0	0.5 0.9
Rotational offsets (mas) x	0.4	2.5	1.0	0.8
y	-1.3	0.1	0.0	-2.3
z	0.7	0.7	1.1	1.0
χ^2 per degree of freedom	2.5	2.5	2.2	2.6
Rms difference (mas) : RA	1.8	3.7	1.5	1.8
dec.	3.3	3.5	2.0	1.8
χ^2 per degree of freedom : RA	1.3	1.4	1.4	1.4
dec.	1.2	1.3	1.3	1.2
μ, $\Delta\delta$ *vs.* δ slope (μas/deg)	16±10	16±10	22±14	-3±12

sons with catalogs of optical counterparts may be valuable in exposing the inadequacies of both techniques. Unfortunately, however, present formal uncertainties of the optical measurements are nearly two orders of magnitude larger than those of VLBI source positions. Consequently, such comparisons only reflect on the optical accuracies. The results of Fanselow *et al.* (1984) and, more recently, Walter and West (1986), which suggest a sinusoidal dependence of declination differences on right ascension for optical minus JPL 1983-3 catalogs, remain quite similar for JPL 1987-1.

VI. CONCLUSIONS

The 7-yr-long span of dual-frequency DSN VLBI data has yielded a source catalog, JPL 1987-1, containing 106 sources to serve as an extragalactic reference frame. Average formal positional uncertainties are approximately 2 mas, and their distributions peak at somewhat less than 1 mas. Differences with independently measured source positions for up to 61 sources are approximately 2 mas in R.A., and 2–3.5 mas in declination, with the values of χ^2 per degree of freedom being less than 1.5. These results, as well as internal-consistency studies, indicate that VLBI measurements suffer from partially identified sources of systematic error at the level of 1 to 2 mas.

While strong evidence is found for a long-term drift of the Earth's rotation axis in inertial space relative to the 1980 IAU precession and nutation models, the source positions presented here are based on the 1980 IAU model. Users of the JPL 1987-1 catalog are therefore cautioned that deviations from the 1980 IAU model lead to source-position errors when they are transformed from J2000 to dates that are far from the mean observation epoch. The gravitational-bending parameter γ is determined with a formal uncertainty of 1.2%, and is in agreement with the value of 1 given by Einstein's general relativity theory. From time variation of source coordinates of 32 sources, it is expected that the present extragalactic reference frame is stable at the 0.5 mas/yr level, exclusive of precession errors.

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