DEVELOPMENT OF A RADIO-ASTROMETRIC CATALOG BY MEANS OF VERY LONG BASELINE INTERFEROMETRY OBSERVATIONS*

J. L. Fanselow, O. J. Sovers, J. B. Thomas, F. R. Bletzacker, T. J. Kearns, E. J. Cohen, G. H. Purcell, Jr., D. H. Rogstad, L. J. Skjerve, L. E. Young

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91103.

ABSTRACT

The Jet Propulsion Laboratory of the California Institute of Technology has been developing a radio-astrometric catalogue for use in the application of radio interferometry to interplanetary navigation and geodesy. The catalogue consists of approximately 100 compact extragalactic radio sources whose relative positions have formal uncertainties of the order of 0."01. The sources cover nearly all of the celestial sphere above -40° declination. By using the optical counterparts of many of these radio sources, we have tied this radio reference frame to the FK4 optical system with a global accuracy of approximately 0."1. This paper describes the status of this work.

INTRODUCTION

Development of a radio-astrometric catalog is an essential element in the application of radio interferometry to both spacecraft navigation and geodesy. For this reason, the Jet Propulsion Laboratory of the California Institute of Technology has been developing a catalog of precise positions for compact extragalactic radio sources. Our goal has been a catalog of approximately 100 sources, uniformly distributed over the celestial sphere. In order to support the navigation of the Voyager mission, an accuracy in these positions of approximately 0."01 is required in 1980. Further, it is required that this catalog have negligible (0."1) mean offset in right ascension relative to the FK4 system, since all interplanetary navigation to date has been based on that system.

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

E. M. Gaposchkin and B. Kołaczek (eds.), Reference Coordinate Systems for Earth Dynamics, 351–357.

INSTRUMENTATION AND DATA REDUCTION

The observations on which the results of this paper are based were obtained over the period from 1971 to March 1980. Throughout the nine years of this development, the interferometry instrumentation has been steadily improved, so that the nine most recent measurements employ dual frequency observations at S- and X-band (13 and 3.6 cm wavelengths, respectively), hydrogen maser frequency standards, and a 4 Mbs data acquisition system. The data were obtained during observing sessions of 8 to 24 hours in duration, utilizing antennas of the Deep Space Network. These DSN facilities provided an 8400 km baseline from Califonia to Spain, and a 10,600 km baseline from Califonia to Australia. A total of 44 such observing sessions are included in the results presented here. Altogether the observations include 3941 independent measurements, of which 1844 are measurements of delay and 2097 are of delay rate.

For convenience in processing this large amount of data, we have separated the data into two time sequences, with each sequence containing about half the data. Sequence #1 contains all data obtained prior to January 1, 1979, while sequence #2 is all data collected after that date. In the last step of this processing, we fit all observations of a given sequence with an analytic model, using a conventional least squares technique to adjust selected parameters of that model. In sequence #1 we solved for the values of 431 parameters, including 136 parameters for source positions. In sequence #2, 148 of the 273 solve-for parameters pertained to source positions. The list of sources observed in sequence #2 was not identical to that observed in sequence #1, as we were attempting to expand the number of sources in our catalog. However, in sequence #2 we have reobserved 33 of the sources from sequence #1 so as to provide overlap between the two parts of the catalog. In each sequence, the sources observed were fairly well distributed over the entire celestial sphere.

The delay model used in processing consisted of geometric, clock, ionospheric and tropospheric components. In the geometric component, the adjusted parameters included baseline, source position, UT1 and polar motion. Precession, nutation, solid earth tides and gravitational bending were all modeled but no associated parameters were adjusted. One of the major deficiencies in our model was the use of the standard nutation series, which has known errors as large as approximately 0"02 in magnitude. We also had to "patch in" an improved precession rate in order to fit the data. Both of these deficiencies will be corrected in the near future as we incorporate better Earth models. With regard to the clock model, we typically had to assign only one epoch offset and one rate offset to each baseline for each observing session. On occasion, however, we had to introduce discontinuities in epoch and rate within a session. In the case of the

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ionosphere, a simple diurnal model was used whenever we were observing at only one radio frequency. For those observations involving dual frequencies, the effect of the ionosphere, as well as all other charged particle contributions to the measurements, were removed by exploiting the dispersive character of a plasma at these frequencies. All of the data in sequence #2 were obtained on the basis of this dual frequency technique. For the troposphere, a monthly-mean model was used as a priori, but the zenith troposphere delay was adjusted for each station under the constraint of that a priori.

One of our goals is to provide a catalog with the smallest possible rotation in right ascension relative to the FK4 system. Thus, we employed the following two-step process in the final reduction of our data:

(1) A preliminary multiparameter adjustment was performed. In this adjustment the right ascensions of those sources that had suitably measured optical counterparts were statistically constrained to the FK4 system on the basis of the apriori errors in the right ascensions of these counterparts. This procedure is mathematically equivalent to adding to our observations a set of measurements of right ascension specific to the subset of sources with optical counterparts. This parameter adjustment step resulted in an uncertainty in right ascension alignment given approximately by:

$$\sigma_a \approx \left(\sum_{i=1}^{N} \frac{1}{\sigma_1^2} \right)^{-\frac{1}{2}}$$

where σ_i is the uncertainty in right ascension of the i^{th} optical counterpart, and where the summation is over the N optical counterparts.

(2) A final multiparameter adjustment was then made. In this step all constraints on the source positions were removed except for the constraint on the right ascension of a "mean reference" source. The reference source was tightly (0".0000002) constrained to the right ascension obtained for that particular source in the previous estimation step. The selection of this source was relatively arbitrary, although it appears that a source at about 30° declination was best for the particular baselines involved in these experiments.

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This procedure produces a global minimization of the right ascension offset between the FK4 system and the radio reference system. Currently, we believe the accuracy of this alignment is approximately $0\overset{\prime\prime}{.}1$. Another advantage of this procedure is that the intrinsic precision (i.e. relative position error) is directly printed out in the final fit as the right ascension error of each source. At this point in the analysis of the data, we have executed this procedure only for sequence #1 of the data, and have chosen NRAO 140 as the "mean reference" source. In the subsequent processing of the data in sequence #2, we adopted this reference position without resorting to another preliminary fit. However, for the final analysis of this data, the procedure outlined above eventually will be performed for the entire data set as a single unit.

RESULTS

The position catalog we have obtained has been designated JPL 1980-1 and is listed in Table I. In presenting this catalog, we have excluded all sources that were observed fewer than 3 times. One source was observed 67 times, though more typically each source was observed 10-40 times. The source positions are given in 1950.0 solar-system-barycentric coordinates while the position errors are the formal uncertainties obtained by adjusting chi-square for the fit residuals to 1.0. For convenience, we have listed the "elliptical aberration" terms that must be added to our results to obtain the coordinates conventionally used in optical catalogues. In all, 109 sources are listed, with most of the positions having formal uncertainties less than $0\overset{\prime\prime}{.}01$. One check on the quality of the data is to compare common source positions between the two sequences of data. When the 33 common sources were compared, almost all of the differences were less than about $0\overset{\prime\prime}{.}03$, with the larger differences resulting primarily from inadequate observations in one of the two sequences. As a test of the formal uncertainties, these position differences were compared with the errors obtained from the formal uncertainties. We found that an additional error of about $0\overset{\prime\prime}{.}01$ had to be root-sum-squared with the formal uncertainties in order to make the total errors statistically consistent with the position differences.

SUMMARY AND PLANS FOR THE FUTURE

Radio-astrometric positions have been obtained for 109 extragalatic radio sources. The formal uncertainties in these positions fall primarily in the range $0\overset{\prime\prime}{.}003$-$0\overset{\prime\prime}{.}02$ while the accuracy is presently estimated to be approximately $0\overset{\prime\prime}{.}01$ - $0\overset{\prime\prime}{.}02$. This work is part of an ongoing effort to develop an astrometric catalog of extragalactic radio sources distributed over the entire celestial sphere with positional accuracies of $0\overset{\prime\prime}{.}01$ or better. Improvements in the hardware and modeling scheduled for 1981 should allow us to improve the accuracy of the current catalog to the level of $0\overset{\prime\prime}{.}003$-$0\overset{\prime\prime}{.}005$ within the next year or two.

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TABLE 1

JPL SOURCE POSITION CATALOG 1980-1 (1950.0 SOLAR-SYSTEM – BARYCENTRIC COORDINATES)

SOURCE	1950.0 SSB POSITION				E TERMS	
	RIGHT ASCENSION	ERROR	DECLINATION	ERROR	R.A.	DECL.
	H M SEC	SEC	D M ARC SEC	ARC SEC	SEC	ARC SEC
P 0008-264	00 08 28.89062	0.00074	-26 29 14.7068	0.0098	-0.00398	-0.1761
P 0104-408	01 04 27.57593	0.00053	-40 50 21.4313	0.0066	0.00263	-0.2442
P 0106+01	01 06 04.51802	0.00028	01 19 01.0517	0.0051	0.00215	-0.0207
P 0111+021	01 11 08.57066	0.00204	02 06 24.7017	0.0313	0.00265	-0.0161
P 0113-118	01 13 43.21948	0.00074	-11 52 04.5578	0.0118	0.00297	-0.0977
DA 55	01 33 55.09519	0.00028	47 36 12.5292	0.0028	0.00724	0.2273
P 0202+14	02 02 07.38976	0.00027	14 59 50.7876	0.0056	0.00784	0.0558
DW 0224+67	02 24 41.13548	0.00050	67 07 39.3413	0.0031	0.02483	0.2741
CTD 20	02 34 55.57744	0.00027	28 35 11.1996	0.0050	0.01203	0.1198
GC 0235+16	02 35 52.62012	0.00027	16 24 03.8667	0.0066	0.01110	0.0579
P 0237-23	02 37 52.77814	0.00115	-23 22 06.2887	0.0157	0.01179	-0.1455
OE 400	03 00 10.08884	0.00060	47 04 33.4153	0.0055	0.01868	0.1882
3C 84	03 16 29.54633	0.00033	41 19 51.6859	0.0040	0.01869	0.1564
P 0332-403	03 32 25.21858	0.00091	-40 18 23.9515	0.0099	0.01999	-0.1861
NRAO 140	03 33 22.38543	0.00000	32 08 36.4807	0.0036	0.01809	0.1104
CTA 26	03 36 58.93966	0.00034	-01 56 16.9227	0.0068	0.01559	-0.0370
NRAO 150	03 55 45.22857	0.00058	50 49 20.0966	0.0038	0.02673	0.1598
P 0402-362	04 02 02.57565	0.00094	-36 13 11.7743	0.0107	0.02144	-0.1545
GC 0406+12	04 06 35.45953	0.00029	12 09 49.2242	0.0084	0.01799	0.0178
VRO 41.04.01	04 20 27.90873	0.00035	41 43 07.8786	0.0053	0.02470	0.1123
P 0420-01	04 20 43.52420	0.00059	-01 27 28.7187	0.0085	0.01846	-0.0337
3C 120	04 30 31.58567	0.00064	05 14 59.5673	0.0091	0.01908	-0.0112
P 0434-188	04 34 48.94761	0.00091	-18 50 48.1149	0.0126	0.02033	-0.0862
P 0438-43	04 38 43.16141	0.00092	-43 38 53.4625	0.0098	0.02687	-0.1437
NRAO 190	04 40 05.27323	0.00071	-00 23 20.5961	0.0126	0.01951	-0.0298
P 0451-28	04 51 15.10887	0.00081	-28 12 29.3160	0.0100	0.02276	-0.1017
P 0528+134	05 28 06.73759	0.00027	13 29 42.2652	0.0053	0.02214	-0.0017
P 0537-441	05 37 21.05095	0.00063	-44 06 44.6034	0.0065	0.03038	-0.0891
DA 193	05 52 01.37457	0.00058	39 48 21.9227	0.0048	0.02889	0.0277
P 0605-08	06 05 36.01023	0.00164	-08 34 20.2896	0.0216	0.02271	-0.0368
P 0607-15	06 07 25.96313	0.00052	-15 42 03.2793	0.0079	0.02336	-0.0424
DW 0723-00	07 23 17.81774	0.00042	-00 48 55.0426	0.0076	0.02246	-0.0277
P 0727-11	07 27 58.07964	0.00074	-11 34 52.5369	0.0106	0.02284	-0.0150
P 0735+17	07 35 14.10394	0.00061	17 49 09.3584	0.0082	0.02335	-0.0502
OI 363	07 38 00.15143	0.00077	31 19 02.1767	0.0087	0.02594	-0.0655
DW 0742+10	07 42 48.44300	0.00029	10 18 32.7510	0.0043	0.02241	-0.0435
P 0748+126	07 48 05.03818	0.00035	12 38 45.5747	0.0061	0.02246	-0.0484
OJ 425	08 14 51.63812	0.00057	42 32 07.9250	0.0043	0.02854	-0.1099

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TABLE 1 - CONT'D

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SOURCE	1950.0 SSB POSITION				E TERMS	
	RIGHT ASCENSION	ERROR	DECLINATION	ERROR	R.A.	DECL.
	H M SEC	SEC	D M ARC SEC	ARC SEC	SEC	ARC SEC
P 0823+033	08 23 13.52100	0.00038	03 19 15.5035	0.0065	0.02073	-0.0368
B2 0827+24	08 27 54.37577	0.00051	24 21 07.8035	0.0068	0.02250	-0.0875
4C 55.16	08 31 04.33624	0.00147	55 44 41.5632	0.0287	0.03617	-0.1428
4C 71.07	08 36 21.48266	0.00066	71 04 22.6662	0.0032	0.06203	-0.1609
OJ 287	08 51 57.23118	0.00048	20 17 58.5891	0.0046	0.02063	-0.0894
OJ 499	08 59 39.95317	0.00093	47 02 57.0712	0.0139	0.02778	-0.1586
P 0859-14	08 59 54.93147	0.00100	-14 03 38.8076	0.0143	0.01950	0.0186
4C 39.25	09 23 55.29490	0.00024	39 15 23.8158	0.0024	0.02258	-0.1608
AO 0952+17	09 52 11.78721	0.00092	17 57 44.7993	0.0149	0.01635	-0.1042
GC 1004+14	10 04 59.77021	0.00068	14 11 11.0960	0.0092	0.01506	-0.0920
P 1034-293	10 34 55.81427	0.00065	-29 18 26.9805	0.0084	0.01399	0.1164
OL 064.5	10 38 40.87423	0.00041	06 25 58.6886	0.0575	0.01196	-0.0610
3C 245	10 40 05.98969	0.00056	12 19 15.1695	0.0077	0.01204	-0.0904
P 1055+01	10 55 55.30470	0.00033	01 50 03.6896	0.0057	0.01039	-0.0383
P 1104-445	11 04 50.35912	0.00091	-44 32 53.0777	0.0093	0.01346	0.1971
GC 1111+14	11 11 21.30050	0.00069	14 58 47.8907	0.0085	0.00932	-0.1087
P 1116+12	11 16 20.76764	0.00050	12 51 06.9046	0.0118	0.00876	-0.0983
P 1123+26	11 23 14.86160	0.00034	26 26 50.2673	0.0042	0.00883	-0.1683
P 1127-14	11 27 35.66118	0.00037	-14 32 54.3755	0.0057	0.00775	0.0534
GC 1128+38	11 28 12.50587	0.00074	38 31 51.9262	0.0252	0.00951	-0.2236
P 1144-379	11 44 30.85450	0.00046	-37 55 30.7109	0.0058	0.00747	0.1804
P 1148-00	11 48 10.12252	0.00065	-00 07 13.0260	0.0089	0.00554	-0.0279
P 1222+037	12 22 19.09700	0.00042	03 47 27.2259	0.0070	0.00220	-0.0510
3C 273	12 26 33.24591	0.00030	02 19 43.4662	0.0045	0.00178	-0.0424
3C 274	12 28 17.56987	0.00054	12 40 01.9607	0.0072	0.00164	-0.1026
P 1244-255	12 44 06.71495	0.00056	-25 31 26.6764	0.0076	0.00004	0.1215
3C 279	12 53 35.83516	0.00080	-05 31 07.8978	0.0119	-0.00091	0.0044
B2 1308+32	13 08 07.56619	0.00030	32 36 40.5509	0.0037	-0.00279	-0.2073
OP-322	13 13 20.04572	0.00076	-33 23 09.7439	0.0087	-0.00343	0.1627
DW 1335-12	13 34 59.81113	0.00065	-12 42 09.6906	0.0091	-0.00511	0.0455
GC 1342+663	13 42 41.06705	0.00117	66 21 13.5572	0.0054	-0.01428	-0.3145
P 1349-439	13 49 52.53598	0.00132	-43 57 54.2530	0.0127	-0.00892	0.2071
P 1354+19	13 54 42.09628	0.00035	19 33 44.1912	0.0051	-0.00730	-0.1360
GC 1418+54	14 18 06.21090	0.00053	54 36 58.4161	0.0056	-0.01564	-0.2722
OQ-151	14 30 10.65791	0.00089	-17 48 24.2834	0.0131	-0.01065	0.0664
OR 103	15 02 00.17377	0.00030	10 41 17.9005	0.0048	-0.01310	-0.0804
P 1510-08	15 10 08.91683	0.00072	-08 54 47.5743	0.0103	-0.01369	0.0144
P 1519-273	15 19 37.25585	0.00057	-27 19 30.3141	0.0079	-0.01607	0.0969

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	RIGHT ASCENSION	ERROR	DECLINATION	ERROR	R.A.	DECL.
	H M SEC	SEC	D M ARC SEC	ARC SEC	SEC	ARC SEC
DW 1555+00	15 55 17.71303	0.00061	00 06 43.6138	0.0087	-0.01686	-0.0290
DA 406	16 11 47.94478	0.00057	34 20 20.0350	0.0060	-0.02170	-0.1427
GC 1633+38	16 33 30.65680	0.00027	38 14 10.2645	0.0033	-0.02440	-0.1368
NRAO 512	16 38 48.20296	0.00026	39 52 30.2680	0.0032	-0.02534	-0.1361
3C 345	16 41 17.63965	0.00024	39 54 10.9820	0.0026	-0.02551	-0.1341
DW 1656+05	16 56 05.64376	0.00132	05 19 47.1145	0.0208	-0.02037	-0.0429
GC 1717+17	17 17 00.35082	0.00043	17 48 08.6088	0.0068	-0.02221	-0.0661
NRAO 530	17 30 13.55741	0.00045	-13 02 45.8174	0.0077	-0.02217	-0.0033
OT 465	17 38 36.35562	0.00118	47 39 28.8671	0.0083	-0.03244	-0.0908
P 1741-038	17 41 20.64125	0.00067	-03 48 48.8811	0.0100	-0.02197	-0.0223
1749+701	17 49 03.47807	0.00087	70 06 39.7254	0.0045	-0.06503	-0.0866
3C 371	18 07 18.63145	0.00043	69 48 57.1646	0.0019	-0.06517	-0.0616
P 1821+10	18 21 41.68538	0.00033	10 42 43.9245	0.0103	-0.02307	-0.0344
OV-236	19 21 42.25872	0.00121	-29 20 26.3558	0.0132	-0.02579	-0.0520
P 1933-400	19 33 51.14815	0.00099	-40 04 47.4408	0.0107	-0.02909	-0.0689
OV-198	19 58 04.63144	0.00065	-17 57 16.9631	0.0095	-0.02272	-0.0604
OW 637	20 21 13.36085	0.00104	61 27 17.9739	0.0071	-0.04349	0.1094
P 2029+121	20 29 32.70544	0.00038	12 09 28.6943	0.0067	-0.02090	0.0039
OW 551	20 30 29.14186	0.00057	54 44 49.0654	0.0056	-0.03532	0.1081
B2 2113+29B	21 13 20.60309	0.00029	29 21 06.5346	0.0046	-0.02081	0.0765
P 2134+004	21 34 05.22698	0.00052	00 28 24.9999	0.0084	-0.01682	-0.0267
P 2145+06	21 45 36.09733	0.00028	06 43 40.8124	0.0049	-0.01614	0.0001
OX 082	21 49 07.71970	0.00036	05 38 06.7847	0.0069	-0.01585	-0.0042
OX-192	21 55 23.25930	0.00081	-15 15 30.1166	0.0130	-0.01588	-0.0941
VRO 42.22.01	22 00 39.38807	0.00026	42 02 08.3514	0.0029	-0.02010	0.1516
CTA 102	22 30 07.82046	0.00079	11 28 22.6653	0.0102	-0.01286	0.0286
GC 2234+28	22 34 01.74630	0.00027	28 13 23.0082	0.0042	-0.01393	0.1110
OY-172.6	22 43 39.80604	0.00036	-12 22 40.3085	0.0064	-0.01173	-0.0912
P 2245-328	22 45 51.51834	0.00056	-32 51 44.3630	0.0072	-0.01342	-0.1852
3C 454.3	22 51 29.53403	0.00047	15 52 54.1807	0.0061	-0.01121	0.0549
GC 2253+41	22 53 19.86196	0.00036	41 46 50.9891	0.0065	-0.01424	0.1802
P 2320-035	23 20 57.53518	0.00050	-03 33 33.6885	0.0091	-0.00813	-0.0483
P 2345-16	23 45 27.69119	0.00068	-16 47 52.6153	0.0102	-0.00606	-0.1229

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