RADIO INTERFEROMETRIC DETERMINATION OF SOURCE POSITIONS UTILIZING DEEP SPACE NETWORK ANTENNAS—1971 TO 1980

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ABSTRACT

During the past decade, a series of observing sessions has been conducted by the Jet Propulsion Laboratory with NASA's Deep Space Network stations to develop a celestial radio reference frame based on the positions of compact extragalactic sources. Approximately 2400 observations were made between 1971 August and 1980 February, with more than half of them at dual frequencies (2.3 and 8.4 GHz), to eliminate the effects of charged particles. The resulting catalog includes 117 sources, distributed fairly uniformly over the celestial sphere north of $-40°$ declination. Most of these sources have formal positional uncertainties between 1 and 5 milliarcsec. Based on combined uncertainties, our positions for 44 sources were in fairly good agreement with the positions obtained from an independently measured radio source catalog. A similar comparison with a catalog of optical counterparts showed systematic differences in declination of about 0.″1.

I. INTRODUCTION

During the last few years, considerable progress (e.g., Thomas *et al.* 1976; Rogers *et al.* 1978, 1983; Ryan *et al.* 1978; Niell *et al.* 1979; Herring *et al.* 1981) has been made toward realizing the potential of radio interferometry for navigating spacecraft, for measuring both global rotational and crustal motions of the Earth with accuracies at the centimeter level, and for obtaining relative radio source positions at the milliarcsec level. Toward these goals, a series of observing sessions, primarily with NASA's Deep Space Network (DSN) has been conducted over the last decade to develop two generations of very long baseline interferometry (VLBI) systems.

Between 1971 and 1980, 48 interferometry sessions were carried out with eight different antennas on three continents, to measure delay rates or delays and rates. The selection of sources was based mainly on external requirements to develop two systems: a system to make rapid, routine measurements of Earth orientation, and a system to navigate spacecraft relative to extragalactic sources. The former system requires a large number of sources widely distributed over the sky, while the latter requires a concentration of sources near the ecliptic. The catalog contains a total of approximately 100 sources to meet both requirements.

A single multiparameter fit has been applied to our decade-long sequence of observations in order to estimate both astrometric and geophysical parameters. This paper focuses on the astrometric results of these experiments. The geophysical results are reported by Sovers *et al.* (1984). A catalog of 117 compact extragalactic sources has been obtained, with mean formal uncertainties in position of approximately 0.″005. A more complete description of the total effort may be found in Thomas *et al.* (1983).

II. SUMMARY OF EXPERIMENTS

In our early experiments, a prototype system (Thomas 1972) was used to record a single, narrowband channel at S band (2.3 GHz). In the later experiments, a second-generation system (Thomas 1981) recorded several time-multiplexed channels (each 2 MHz wide) at both S band and X band (8.4 GHz), so that delay could be obtained by means of bandwidth synthesis (BWS), a technique originated by Rogers (1970). With this BWS system, delay can be measured with a precision (i.e., system noise error) of approximately 100 ps, given a source strength of 0.5 Jy, an integration time of 3 min, two 64-m antennas with system temperatures of 35 K, a spanned bandwidth of 40 MHz, and a 4 Mbs recording rate time multiplexed among eight frequency channels (four at S and four at X band).

During the last ten years, 47 interferometry sessions have been carried out with six stations of NASA's Deep Space Network in Spain, California, and Australia, and one session with the 37-m antenna at Haystack Observatory in Massachusetts and the 40-m antenna at Owens Valley Observatory in California. Most of the 47 sessions involved the intercontinental baselines between the DSN complexes in Spain, California, and Australia. In all sessions, the sources were chosen to cover the full range of directions allowed under the constraint of mutual visibility to the two stations. Approximately half of the sources (53 of 117) were observed on both intercontinental baselines. This strategy greatly reduced the strong correlations between parameters found in single-baseline California-Australia solutions. It also removed the near singularity in declination determination for sources at zero declination in single-baseline solutions with the nearly east-west baseline (California-Spain).

Altogether, there were 2120 delay and 2364 delay rate observables for 117 sources obtained during 23 S-band sessions (1111 observables), 5 X-band sessions (736 observables), and 20 dual-band (S and X) sessions (2637 observables). Depending on the session, the station frequency standards were rubidium, cesium, or hydrogen masers. All but one (4C 55.16) of the sources observed in S-band-only sessions were also observed in the later dual-band sessions. Because the single-band observations were less accurate and less numerous, the source positions presented in this paper are predominantly determined by the dual-band data.

The primary sources of error in the data were as follows. In the S-band-only data, the uncorrected ionosphere was the dominant source of error, contributing an estimated uncertainty of approximately 0.2 to 0.5 ps/s to the delay rate observables and an estimated uncertainty of approximately 0.3 to 3.0 ns to the delay observables. The delay errors for the X-band data were a combination of system noise (0.1 to 0.7 ns), oscillator noise (0.03 to 0.5 ns), instrumental phase error (0.1

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to 0.3 ns), and ionosphere error (1/13 of the above S-band error). Changes in effective position due to source structure are expected to be negligible relative to these other errors, contributing delay errors of the order of 0.1 ns or less (Thomas 1980). For the S-X data, the errors were essentially the same as the X-band errors, except that the ionosphere error was reduced to a negligible level.

For each source, Table I gives the number of sessions in which that source was observed, the average epoch of these observations, and the number of delay and delay rate observables. Over the nine-year period, most sources were observed many times to provide adequate redundancy for repeatability tests and to enhance data reliability. Average observation epochs (calculated by weighting all observables equally) range from 1976.36 for NRAO 190 to 1980.15 for GC 1128 + 38.

III. DELAY MODEL AND FITTING TECHNIQUE

This section briefly summarizes the models used for the components of the observed delay (and by inference, delay rate) and outlines the multiparameter fitting technique. More detail on all aspects of the model and fitting technique can be found in Fanselow (1983), Sovers *et al.* (1984), and Thomas *et al.* (1983).

The geometric delay was evaluated in solar system barycentric (SSB) coordinates to facilitate both refinements in the model and future extension to sources moving within the solar system. Our present rotational model for the Earth obtains the Earth's ephemeris pole direction from the IAU 1976 precession expressions (Lieske *et al.* 1977) and the IAU 1980 expressions for nutation (Seidelmann 1982; Wahr 1981). Further, astronomical constants, time scales, and the fundamental reference frame are in accord with the IAU resolutions to be implemented in 1984 (Seidelmann 1982; Aoki *et al.* 1982), as summarized by Kaplan (1981).

To establish the origin of right ascension, we have adopted for the right ascension of 3C 273B a value ($12^h29^m06\overset{s}{.}6997$) currently used by other VLBI observing groups. We view this approach as a temporary convenience until it is possible to align our reference frame of radio sources with the celestial reference frame defined by the JPL planetary ephemeris. To obtain that alignment, the Astronomical Measurements Group at JPL is currently analyzing data from a number of radio interferometry experiments designed to measure the position of a spacecraft in orbit about a planet relative to nearby compact extragalactic radio sources (Newhall *et al.* 1984).

The tropospheric delay was based on a model developed by Chao (1974). In this model, the zenith delays were adjusted in the fit, but were constrained by treating Chao's monthly mean values as independent measurements with 3% accuracy. For single-band data, the ionospheric delays were approximately removed by means of a correction based on a mean-ionosphere model derived from Faraday rotation data measured by Klobuchar and Malik (1972). Dual-band (S-X) calibration of plasma effects was possible in most of the later experiments.

To model clock offsets and instabilities, a number of clock parameters were employed. In addition to clock effects, these parameters also absorbed uncalibrated instrumental effects. Quadratic clock models were required for three sessions, while piecewise linear fits were required in 23 of the 48 sessions. Typical time spans for these piecewise fits ranged between 3 and 12 hr.

A multiparameter weighted-least-squares program was used to fit simultaneously all of the delay and delay rate data and obtain estimates of the geophysical and astrometric parameters. The parameters available for adjustment included clock offsets and rates, polar motion, universal time, tropospheric delays, station locations, source positions, solid-Earth tides, the gamma factor of general relativity, and the precession constant. Formal uncertainties in the fitted parameters were obtained by covariance analysis after adjusting observable weights so that the normalized chi square for the fit residuals would equal unity. To generate the source positions reported in this paper, we applied a "standard" fit to the data in which (a) all parameters listed above, except for the precession constant, were estimated, and (b) a single Earth-fixed vector for each baseline was estimated for all sessions.

IV. RESULTS

In this section, we present the results for source positions as produced by the standard fit to the data, and the precession constant as obtained from a slight variant of that standard fit. Results for the other estimated parameters, as well as special fits to test data quality, are reported by Sovers *et al.* (1984) and Thomas *et al.* (1983). Our results for the geophysical, Earth-tide, and relativity parameters not presented in this paper were in agreement with other measurements of similar or better accuracy. In the standard fit, the rms residuals for all the data were 0.52 ns for delay and 0.30 ps/s for delay rate. The rms delay residuals for the dual-band data ranged between 0.19 and 0.76 ns for the various sessions, and between 0.52 and 1.08 ns for the single-band data.

a) Source Positions

The standard fit to our 1971–1980 data produced positions for the 117 sources presented in Table I. For completeness, the table lists all sources solved for in the standard fit, irrespective of magnitude of errors. The listed errors are 1σ formal uncertainties obtained from the parameter covariance matrix of the standard fit and thus may not properly account for systematic errors (for example, mismodeling of precession and nutation). The coefficient of correlation between the errors in right ascension and declination for each source is given in the last column.

Seven of the sources (3C 48, 3C 119, 3C 138, 3C 309.1, 3C 395, 3C 418, and DA 611) were observed only on short baselines, and thus have formal position errors exceeding $0\overset{''}{.}1$. One source (4C 55.16) was observed only once on an intercontinental baseline, and its position must therefore be regarded as provisional. Five other sources for which there are fewer than five delay observations may also lack adequate observational redundancy. One of these (P1130 + 009) is a zero-declination source observed only on the California-Spain baseline, which accounts for the large uncertainty in its declination.

The source positions presented in Table I, and denoted as JPL 1983-3, supersede all previous reports by JPL for the positions of these extragalactic radio sources. These new positions are substantially more accurate since they are based both on more data and on the most recent IAU-recommended models and astronomical constants.

The statistics of the JPL 1983-3 source catalog are more clearly displayed in Figs. 1–3. Figure 1 presents the source distribution in right ascension and declination, with error bars indicating formal uncertainties. Note the different

TABLE I. JPL 1983-3 radio source catalogue.†

IAU designation	Common name	Average obs. epoch	No. of sessions	Observations Delay	Delay rate	Right ascension h	m	s	Error(σ)	Declination d	m	s	Error(σ)	RA, dec correl.	
0008−264	P 0008−264	1980.05	3	8	8	0	11	1.24748	0.00039	−26	12	33.3891	0.0053	−0.660	
0104−408	P 0104−408	1979.43	7	21	21	1	6	45.10821	0.00023	−40	34	19.9636	0.0036	0.248	
0106+013	P 0106+01	1978.39	23	38	46	1	8	38.77105	0.00011	1	35	0.3175	0.0026	−0.283	
0111+021	P 0111+021	1980.04	3	6	6	1	13	43.14505	0.00168	2	22	17.3155	0.0254	−0.993	
0113−118	P 0113−118	1978.85	5	12	12	1	16	12.52213	0.00067	−11	36	15.4374	0.0103	−0.940	
0133+476	DA 55	1979.14	20	41	43	1	36	58.59495	0.00018	47	51	29.1053	0.0013	−0.185	
0134+329	3C 48	1979.64	3	3	3	1	37	41.34209	0.05828	33	9	35.4969	0.3769	−0.653	S
0202+149	P 0202+14	1980.02	6	13	13	2	4	50.41405	0.00012	15	14	11.0461	0.0024	−0.305	
0224+671	DW 0224+67	1977.48	24	39	62	2	28	50.05199	0.00032	67	21	3.0339	0.0019	−0.166	
0234+285	CTD 20	1980.02	6	13	13	2	37	52.40585	0.00014	28	48	8.9942	0.0021	−0.328	
0235+164	GC 0235+16	1980.04	6	11	11	2	38	38.93026	0.00012	16	36	59.2767	0.0023	−0.298	
0237−233	P 0237−23	1980.02	2	3	3	2	40	8.17473	0.00091	−23	9	15.7416	0.0126	−0.871	R
0300+470	OE 400	1978.39	10	19	19	3	3	35.24246	0.00024	47	16	16.2832	0.0019	−0.493	
0316+413	3C 84	1978.72	10	11	16	3	19	48.16043	0.00019	41	30	42.1074	0.0019	−0.321	
0332−403	P 0332−403	1977.84	5	17	17	3	34	13.65385	0.00037	−40	8	25.3968	0.0044	−0.341	
0333+321	NRAO 140	1977.61	25	34	50	3	36	30.10794	0.00016	32	18	29.3448	0.0017	−0.420	
0336−019	CTA 26	1979.52	9	13	15	3	39	30.93773	0.00013	−1	46	35.8003	0.0029	−0.303	
0355+508	NRAO 150	1978.60	6	26	26	3	59	29.74801	0.00026	50	57	50.1689	0.0022	−0.028	
0402−362	P 0402−362	1978.07	4	11	11	4	3	53.74940	0.00044	−36	5	1.9130	0.0054	−0.582	
0406+121	GC 0406+12	1980.03	6	12	12	4	9	22.00860	0.00014	12	17	39.8426	0.0055	−0.334	
0420−014	P 0420−01	1977.97	11	19	20	4	23	15.80052	0.00020	−1	20	33.0641	0.0037	−0.635	
0420+417	VRO 41.04.01	1979.72	7	9	10	4	23	56.10000	0.00026	41	50	2.7183	0.0033	−0.405	
0429+415	3C 119	1979.66	3	3	2	4	32	36.48679	0.28126	41	38	28.7575	1.6482	−0.982	S
0430+052	3C 120	1977.28	15	16	24	4	33	11.09592	0.00025	5	21	15.6144	0.0040	−0.746	
0434−188	P 0434−188	1980.02	3	5	5	4	37	1.48288	0.00057	−18	44	48.6197	0.0086	−0.886	
0438−436	P 0438−43	1977.87	5	20	20	4	40	17.17942	0.00033	−43	33	8.6053	0.0040	−0.067	
0440−003	NRAO 190	1976.36	19	16	34	4	42	38.66088	0.00051	−0	17	43.4243	0.0080	−0.926	
0451−282	P 0451−28	1980.02	3	5	5	4	53	14.64585	0.00048	−28	7	37.3195	0.0062	−0.719	
0518+165	3C 138	1979.55	1	2	2	5	21	10.04094	0.11462	16	38	21.9329	0.5140	−0.388	S
0528+134	P 0528+134	1980.03	7	14	14	5	30	56.41692	0.00012	13	31	55.1500	0.0022	−0.288	
0537−441	P 0537−441	1978.46	9	20	20	5	38	50.36073	0.00028	−44	5	8.9385	0.0037	0.113	
0552+398	DA 193	1977.55	17	27	33	5	55	30.80615	0.00022	39	48	49.1668	0.0019	−0.593	
0605−085	P 0605−08	1978.96	4	6	6	6	7	59.69928	0.00070	−8	34	49.9863	0.0100	−0.940	
0607−157	P 0607−15	1978.52	12	18	18	6	9	40.94952	0.00025	−15	42	40.6777	0.0044	−0.624	
0723−008	DW 0723−00	1979.99	5	8	8	7	25	50.63977	0.00020	−0	54	56.5434	0.0038	−0.674	
0727−115	P 0727−11	1977.93	12	20	21	7	30	19.11286	0.00024	−11	41	12.6139	0.0043	−0.642	
0735+178	P 0735+17	1977.85	16	20	24	7	38	7.39400	0.00022	17	42	18.9934	0.0036	−0.778	
0738+313	OI 363	1977.01	14	14	23	7	41	10.70376	0.00043	31	12	0.2264	0.0054	−0.850	
0742+103	DW 0742+10	1978.21	22	45	49	7	45	33.05953	0.00013	10	11	12.6897	0.0023	−0.465	
0748+126	P 0748+126	1980.00	5	10	10	7	50	52.04566	0.00017	12	31	4.8262	0.0031	−0.649	

TABLE I. (continued)

IAU designation	Common name	Average obs. epoch	No. of sessions	Observations Delay	Observations Delay rate	Right ascension h	m	s	Error(σ)	Declination d	m	s	Error(σ)	RA, dec correl.	
0814+425	OJ 425	1977.83	19	23	27	8	18	16.00000	0.00023	42	22	45.4144	0.0018	−0.532	
0823+033	P 0823+033	1980.01	8	13	13	8	25	50.33852	0.00018	3	9	24.5131	0.0033	−0.644	
0827+243	B2 0827+24	1979.76	8	10	11	8	30	52.08663	0.00034	24	10	59.8106	0.0044	−0.841	
0831+557	4C 55.16	1977.58	6	4	7	8	34	54.90177	0.00182	55	34	21.1328	0.0228	−0.279	R
0836+710	4C 71.07	1979.64	8	15	15	8	41	24.36650	0.00043	70	53	42.1693	0.0020	0.319	
0851+202	OJ 287	1978.04	15	37	41	8	54	48.87506	0.00014	20	6	30.6364	0.0018	−0.469	
0859−140	P 0859−14	1977.80	11	16	16	9	2	16.83077	0.00082	−14	15	30.8847	0.0123	−0.953	
0859+470	OJ 499	1977.92	5	6	6	9	3	3.99137	0.00076	46	51	4.1265	0.0052	−0.650	
0923+392	4C 39.25	1978.52	29	78	83	9	27	3.01394	0.00013	39	2	20.8497	0.0012	−0.156	
0952+179	AO 0952+17	1979.98	5	5	5	9	54	56.82356	0.00078	17	43	31.2228	0.0126	−0.951	
1004+141	GC 1004+14	1980.01	6	16	15	10	7	41.49848	0.00047	13	56	29.5912	0.0064	−0.920	
1034−293	P 1034−293	1980.00	6	10	10	10	37	16.07922	0.00030	−29	34	2.8182	0.0042	−0.405	
1038+064	OL 064.5	1980.01	2	6	6	10	41	17.16237	0.00020	6	10	16.9223	0.0382	−0.597	
1040+123	3C 245	1980.03	6	7	6	10	42	44.60596	0.00036	12	3	31.2537	0.0049	−0.767	
1055+018	P 1055+01	1979.73	10	23	25	10	58	29.60516	0.00011	1	33	58.8175	0.0025	−0.281	
1104−445	P 1104−445	1977.74	10	15	15	11	7	8.69333	0.00047	−44	49	7.6226	0.0047	−0.398	
1111+149	GC 1111+14	1980.03	6	11	11	11	13	58.69532	0.00048	14	42	26.9450	0.0061	−0.901	
1116+128	P 1116+12	1980.11	3	4	4	11	18	57.30154	0.00031	12	34	41.7094	0.0064	−0.651	R
1123+264	P 1123+26	1980.02	8	21	21	11	25	53.71196	0.00019	26	10	19.9738	0.0023	−0.662	
1127−145	P 1127−14	1978.70	22	51	51	11	30	7.05233	0.00016	−14	49	27.3941	0.0033	−0.330	
1128+385	GC 1128+38	1980.15	1	3	3	11	30	53.28215	0.00047	38	15	18.5472	0.0037	−0.854	R
1130+009	P 1130+009	1980.05	3	3	3	11	33	20.05386	0.00741	0	40	53.4573	2.2097	−0.999	R
1144−379	P 1144−379	1978.73	15	40	40	11	47	1.37022	0.00022	−38	12	11.0304	0.0034	0.307	
1148−001	P 1148−00	1978.09	10	15	15	11	50	43.87056	0.00040	−0	23	54.2101	0.0064	−0.905	
1222+037	P 1222+037	1980.03	7	13	13	12	24	52.42221	0.00021	3	30	50.2808	0.0038	−0.738	
1226+023	3C 273	1978.62	20	54	57	12	29	6.69970	...	2	3	8.5915	0.0025	...	
1228+126	3C 274	1980.04	7	12	12	12	30	49.42342	0.00031	12	23	28.0376	0.0043	−0.850	
1244−255	P 1244−255	1980.02	6	16	16	12	46	46.80182	0.00025	−25	47	49.2953	0.0037	−0.333	
1253−055	3C 279	1978.24	6	14	14	12	56	11.16647	0.00038	−5	47	21.5320	0.0063	−0.884	
1308+326	B2 1308+32	1980.02	10	24	24	13	10	28.66381	0.00013	32	20	43.7789	0.0016	−0.356	
1313−333	OP−322	1978.15	9	16	16	13	16	7.98529	0.00031	−33	38	59.1781	0.0041	−0.328	
1334−127	DW 1335−12	1977.96	10	20	21	13	37	39.78287	0.00028	−12	57	24.7028	0.0043	−0.684	
1342+663	GC 1342+663	1980.12	3	5	5	13	44	8.67956	0.00053	66	6	11.6365	0.0025	−0.177	
1349−439	P 1349−439	1980.11	2	4	4	13	52	56.53523	0.00061	−44	12	40.4002	0.0057	−0.583	R
1354+195	P 1354+19	1980.02	11	22	22	13	57	4.43660	0.00017	19	19	7.3665	0.0027	−0.628	
1418+546	GC 1418+54	1980.13	2	6	6	14	19	46.59754	0.00020	54	23	14.7823	0.0015	−0.089	
1430−178	OQ−151	1980.05	4	9	9	14	32	57.68946	0.00054	−18	1	35.2438	0.0080	−0.872	
1458+718	3C 309.1	1979.61	4	7	7	14	59	7.33712	0.12839	71	40	20.4457	0.6308	−0.203	S
1502+106	OR 103	1979.35	18	39	40	15	4	24.97966	0.00011	10	29	39.1945	0.0023	−0.370	
1510−089	P 1510−08	1978.18	6	15	15	15	12	50.53332	0.00051	−9	5	59.8408	0.0079	−0.918	

TABLE I. (continued)

IAU designation	Common name	Average obs. epoch	No. of sessions	Observations Delay	Delay rate	Right ascension h	m	s	Error(σ)	Declination d	m	s	Error(σ)	RA, dec correl.	
1519−273	P 1519−273	1980.03	6	15	15	15	22	37.67553	0.00022	−27	30	10.7888	0.0035	−0.140	
1555+001	DW 1555+00	1976.86	14	22	34	15	57	51.43417	0.00033	−0	1	50.4202	0.0052	−0.857	
1611+343	DA 406	1977.37	16	30	44	16	13	41.06409	0.00025	34	12	47.9083	0.0026	−0.717	
1633+382	GC 1633+38	1980.04	10	32	32	16	35	15.49283	0.00013	38	8	4.4985	0.0013	−0.178	
1638+398	NRAO 512	1979.50	16	54	53	16	40	29.63258	0.00015	39	46	46.0279	0.0014	−0.255	
1641+399	3C 345	1978.28	19	54	72	16	42	58.80982	0.00013	39	48	36.9928	0.0012	−0.127	
1656+053	DW 1656+05	1978.85	9	12	16	16	58	33.44732	0.00061	5	15	16.4384	0.0093	−0.951	
1717+178	GC 1717+17	1980.07	8	19	19	17	19	13.04836	0.00022	17	45	6.4353	0.0037	−0.689	
1730−130	NRAO 530	1979.13	14	28	28	17	33	2.70553	0.00018	−13	4	49.5459	0.0038	−0.492	
1738+476	OT 465	1978.70	4	6	6	17	39	57.12573	0.00078	47	37	58.3764	0.0045	−0.858	
1741−038	P 1741−038	1977.44	13	25	35	17	43	58.85676	0.00027	−3	50	4.6251	0.0046	−0.776	
1749+701	1749+701	1979.45	11	16	16	17	48	32.83874	0.00060	70	5	50.7750	0.0032	−0.382	
1807+698	3C 371	1978.96	18	48	57	18	6	50.67971	0.00026	69	49	28.1088	0.0011	0.171	
1821+107	P 1821+10	1980.06	7	14	14	18	24	2.85523	0.00013	10	44	23.7699	0.0048	−0.349	
1901+319	3C 395	1979.61	4	5	5	19	2	55.83919	0.08750	31	59	40.3951	0.7979	0.923	S
1921−293	OV−236	1978.47	4	11	9	19	24	51.05563	0.00044	−29	14	30.1129	0.0055	−0.682	
1933−400	P 1933−400	1979.86	4	7	7	19	37	16.21676	0.00059	−39	58	1.5527	0.0061	−0.628	
1958−179	OV−198	1979.30	8	18	17	20	0	57.09073	0.00037	−17	48	57.6760	0.0055	−0.774	
2021+614	OW 637	1978.47	11	18	19	20	22	6.68158	0.00095	61	36	58.8193	0.0055	0.501	
2029+547	OW 551	1980.02	3	8	8	20	31	47.95843	0.00040	54	55	3.1494	0.0037	−0.301	
2030+121	P 2029+121	1980.06	9	14	14	20	31	54.99410	0.00019	12	19	41.3436	0.0034	−0.630	
2037+511	3C 418	1979.64	3	5	5	20	38	36.94366	0.06543	51	19	11.8560	0.4130	0.765	S
2113+293	B2 2113+29B	1979.83	11	19	19	21	15	29.41343	0.00015	29	33	38.3663	0.0024	−0.295	
2134+004	P 2134+004	1977.17	14	26	40	21	36	38.58616	0.00017	0	41	54.2151	0.0038	−0.641	
2145+067	P 2145+06	1978.52	21	31	39	21	48	5.45853	0.00011	6	57	38.6057	0.0024	−0.319	
2149+056	OX 082	1980.06	8	16	16	21	51	37.87530	0.00017	5	52	12.9557	0.0034	−0.595	
2155−152	OX−192	1978.66	4	6	6	21	58	6.28154	0.00072	−15	1	9.3262	0.0109	−0.935	
2200+420	VRO 42.22.01	1978.05	27	46	60	22	2	43.29125	0.00016	42	16	39.9839	0.0014	−0.227	
2230+114	CTA 102	1978.45	10	13	13	22	32	36.40896	0.00050	11	43	50.9053	0.0068	−0.931	
2234+282	GC 2234+28	1980.04	10	23	22	22	36	22.47076	0.00013	28	28	57.4169	0.0018	−0.296	
2243−123	OY−172.6	1979.27	14	22	22	22	46	18.23184	0.00014	−12	6	51.2763	0.0033	−0.299	
2245−328	P 2245−328	1979.55	7	20	20	22	48	38.68551	0.00024	−32	35	52.1860	0.0036	−0.088	
2251+158	3C 454.3	1977.56	17	37	50	22	53	57.74779	0.00015	16	8	53.5658	0.0027	−0.540	
2253+417	GC 2253+41	1980.11	3	11	11	22	55	36.70799	0.00019	42	2	52.5371	0.0030	0.026	
2320−035	P 2320−035	1980.00	5	8	7	23	23	31.95363	0.00021	−3	17	5.0215	0.0044	−0.617	
2345−167	P 2345−16	1977.98	16	20	24	23	48	2.60846	0.00035	−16	31	12.0232	0.0052	−0.743	
2352+495	DA 611	1979.66	3	5	5	23	55	9.45244	0.07304	49	50	8.4831	0.2230	0.162	S

+ In J2000.0 barycentric coordinates.
S Short-baseline data only.
R Inadequate redundancy : fewer than 5 delay observations.

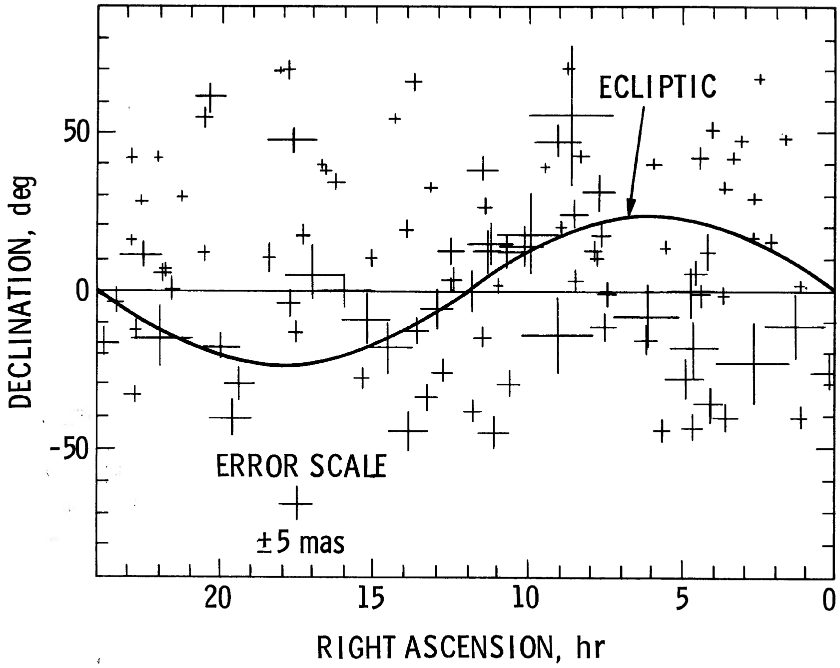

FIG. 1. Source positions and their formal errors obtained by the standard fit to 1971–1980 VLBI data.

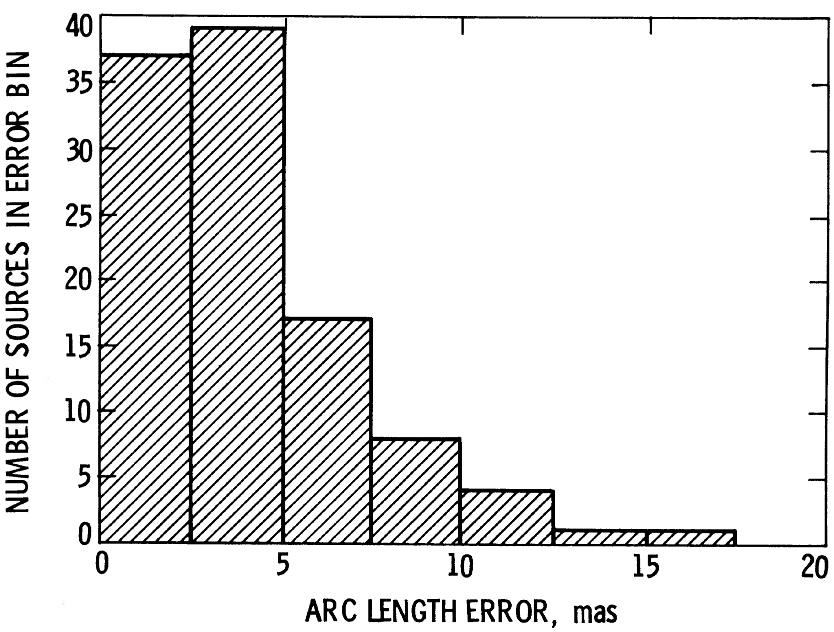

FIG. 2. Histogram of right ascension formal errors obtained by the standard fit to 1971–1980 data.

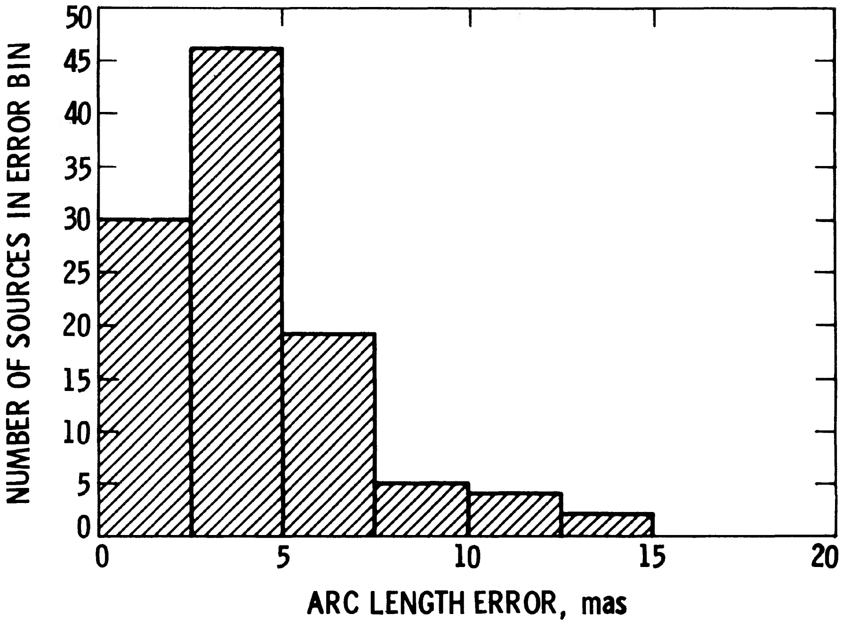

FIG. 3. Histogram of declination formal errors obtained by the standard fit to 1971–1980 data.

scales for position and uncertainty. In Figs. 2 and 3, histograms of the arc length errors for right ascension and declination indicate that the mean position error (1σ) is approximately 5 mas for each coordinate. Ten right ascension and 11 declination measurement errors exceed 20 mas and are not shown on these plots.

An additional model adjustment was performed to determine the repeatability of source positions over a long period of time and to test the validity of the formal error estimates. The data were divided into two segments: observations made before 1979 January, and observations made thereafter. The average measurement times in these two segments were approximately 1977.5 and 1979.9. All 17 sources with more than ten delay and ten delay rate observations in each segment were assigned independent position parameters in the two segments. A fit was then performed in which all other parameters were solved for as in the standard fit. In Table II, columns 4 and 5 show the right ascension (α) and declination (δ) differences, $\Delta\alpha$ and $\Delta\delta$, for the two position estimates of these 17 sources. Columns 6 and 7 give the formal errors of the differences ($\sigma_{\Delta\alpha}$, $\sigma_{\Delta\delta}$), while the last two columns give the differences normalized by these formal errors. No systematic trends in the position differences are evident outside of formal errors. A chi square analysis indicates that the scatter of the differences is somewhat smaller than the formal uncertainties would predict. In all, the positions produced by the two segments of data appear to be in good agreement at the level of the formal uncertainties.

Our formal errors for the effective proper motion of these 17 sources range between 0.8 and 7.2 mas/yr, with a typical value of 2.5 mas/yr. Comparison of our measured position differences with the formal uncertainties indicates that no proper motion was evident, as expected, at our level of sensitivity.

b) Catalog Comparisons

In an effort to uncover possible systematic mismodeling and to test further the formal source position uncertainties, we compared our source positions with two recent catalogs: the radio catalog of Ma *et al.* (1981, 1984) and the optical catalog of de Vegt and Gehlich (1982). With regard to the comparison of the two radio catalogs, the antennas, baseline lengths and orientations, data acquisition hardware, and the data reduction software of the two VLBI systems are completely independent. Thus, the only errors we should have in common are those that are technique specific and those arising from deficiencies in the generally accepted models of Earth motion.

The JPL 1983-3 catalog has 44 sources in common with the preliminary radio catalog of Ma *et al.* (denoted GSFC – 821007). That catalog from the Goddard Space Flight Center is based on some 24 000 pairs of delay and delay rate observations between antennas in the U. S. A. and Europe from 1979 August to 1982 June. For GSFC – 821007, we followed the recommendation of Ma (private communication) and assigned "realistic" errors equal to twice the formal uncertainties. On the average, the formal 2σ uncertainties of GSFC – 821007 are considerably smaller than the formal 1σ uncertainties of JPL 1983-3 for right ascension, and comparable for declination (except for the larger GSFC declination errors near zero declination).

The differences in the right ascensions measured by the two groups have been corrected by an average offset $0^{\mathrm{s}}00013 \pm 0^{\mathrm{s}}00010$ computed by a weighted average of the initial right ascension differences. This correction accounts for errors that might corrupt the alignment provided by the common specification of the right ascension of 3C 273. For example, the intrinsic accuracy of the 3C 273 data is about 1 mas for the JPL catalog and a few tenths of a milliarcsecond for the GSFC catalog. Further, source structure effects can cause misalignment due to variations in the effective position of the reference source with change in fringe pattern (i.e., for different baselines) and due to changes in brightness distribution with time. Calculations based on 3C 273 brightness distribution measurements at 10.65 GHz by Pearson *et al.* (1981) indicate that errors due to these two structure effects

TABLE II. Source position repeatability results.

Source	Average epoch		Difference+ (mas)		Errors (mas)		Diff/error	
	Part 1	Part 2	$\Delta\alpha$	$\Delta\delta$	$\sigma_{\Delta\alpha}$	$\sigma_{\Delta\delta}$	$\Delta\alpha/\sigma_{\Delta\alpha}$	$\Delta\delta/\sigma_{\Delta\delta}$
P 0104−408	78.74	80.06	−1.7	2.3	3.9	3.0	−0.43	0.77
P 0106+01	77.24	79.93	1.6	−0.3	4.6	4.6	0.36	−0.07
DA 55	77.74	79.92	3.2	3.7	3.5	3.8	0.92	1.31
DW 0224+67	76.34	79.84	0.5	−1.3	3.4	4.0	0.15	−0.32
NRAO 140	75.86	79.94	−1.9	3.9	4.1	3.5	−0.47	1.12
DW 0742+10	77.73	80.00	5.3	−6.6	3.6	3.8	1.47	−1.76
4C 39.25	77.85	80.02	2.2	0.3	2.1	2.1	1.06	0.14
P 1127−14	77.98	80.01	1.7	0.4	4.4	4.3	0.39	0.09
P 1144−379	78.12	80.00	0.1	−0.3	3.4	2.9	0.03	−0.10
OR 103	77.95	80.00	1.8	1.5	7.2	7.3	0.25	0.21
NRAO 512	77.83	80.04	−4.2	2.7	4.9	4.9	−0.86	0.55
3C 345	76.06	80.01	−1.5	0.7	2.8	3.4	−0.53	0.21
NRAO 530	78.31	79.95	−1.8	12.0	6.9	6.9	−0.26	1.73
3C 371	77.09	79.98	−6.5	2.2	4.7	4.0	−1.37	0.55
P 2145+06	76.62	80.03	−0.9	2.4	4.6	4.8	−0.20	0.51
VRO 42.22.01	76.82	79.92	−0.6	3.8	3.0	2.8	−0.20	1.38
OY−172.6	78.64	80.02	3.5	−4.0	4.7	4.8	0.75	−0.83
		RMS =	2.8	3.8		χ^2/N =	0.50	0.79

+ Difference : 1971−78 position minus 1979−80 position.

are of the order of 1 mas or less. The alignment correction noted above is consistent with these error estimates.

Figure 4 shows histograms of both the absolute and the error-normalized differences in positions measured by the two groups. All four histograms in Fig. 4 are reasonably close to Gaussian shapes, with rms differences of 3.5 mas (RA) and 7.1 mas (Dec) for the "absolute" histograms and with values of 1.1 and 1.5 for the normalized chi square for right ascension and declination, respectively. To reduce the normalized chi square to 1.0, our formal uncertainties for right ascension and declination would have to be increased by factors of 1.1 and 1.3, respectively.

A graphic representation of the source position differences betwen the two radio catalogs is given in Fig. 5. For each of the 44 common sources, a closed circle is plotted at the source position, and a vector is drawn with components equal to the error-normalized differences in right ascension and declination, in the sense GSFC − 821007 minus JPL 1983-3. Note the different scale for the vector differences. As indicated above, the right ascension differences have been corrected for an average offset.

Among the coordinates that differ by more than 0″01 between JPL and GSFC are both the right ascension and the declination of P1741 − 038, and the declinations of P1055 + 01, GC 1342 + 663, P1510 − 08 and DW 1656 + 05. The only serious disagreement is for P1741 − 038, for which the normalized differences are 2.8σ and 2.5σ for right ascension and declination, respectively.

The error vectors in Fig. 5 indicate that systematic errors of the order of the RSS formal uncertainties (~ 5 mas) were marginally evident, particularly for right ascension. A fit to the differences with functions of the form $\Delta\alpha = A \sin\alpha \tan\delta + B$ and $\Delta\delta = A \cos\alpha$ indicated that the systematic differences can not be explained solely by an error in the precession constant. The cause of these apparent systematic differences is currently not known.

To compare with the epoch 1950.0 optical catalog of de Vegt and Gehlich (1982), we chose to transform JPL 1983-3 back to the 1950.0 frame using the reverse of the prescriptions of Kaplan (1981) for transforming radio catalogs. The resulting position differences for the 14 sources common to the two catalogs are plotted in Figs. 6 and 7, along with RSS errors. In both coordinates, the differences exceed the formal uncertainties. The rms angular right ascension difference is 0″09 (after removal of a right ascension time offset of 0ˢ06) while the rms declination difference is 0″13. The systematic variation of the declination differences with right ascension can be approximated by a sinusoid of the form $\Delta\delta = -0''13 \cos\alpha$. Since such a signature could be caused by a precession error, we attempted to fit simultaneously the differences for both coordinates with the functions mentioned above in the radio catalog comparison. The fit indicated that a precession error alone could not explain the signatures in both coordinates. At this time, the differences between these two catalogs remain unexplained. Systematic variations in declination differences were also present in a comparison of one of our older radio catalogs (JPL 1980-2) with these same optical positions. Unlike the present positions, JPL 1980-2 was based on older precession and nutation expressions and reference frame.

c) Nutation and Precession

The long time span of these data also provided an opportunity to solve for the precession constant. When we modified

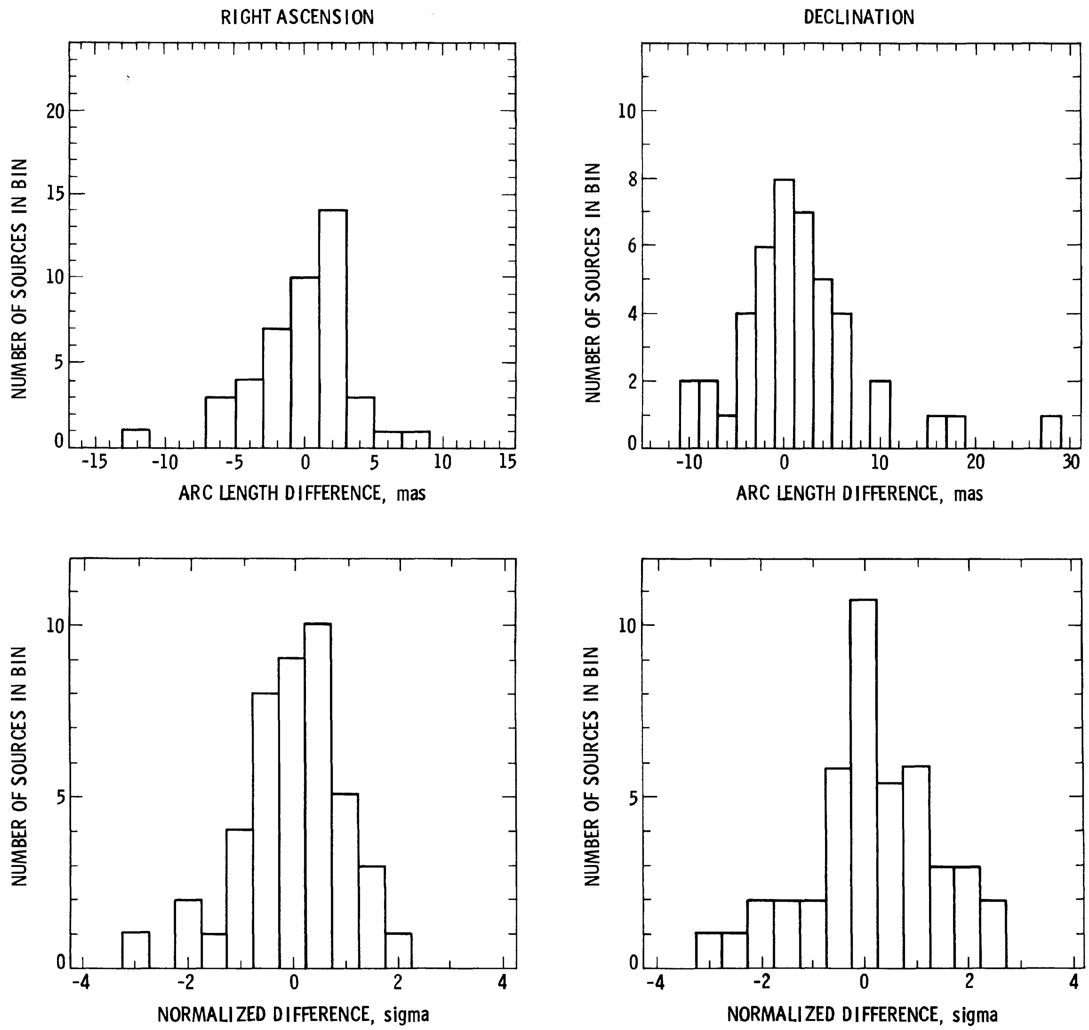

FIG. 4. Histograms of source position differences: GSFC-821007 minus JPL 1983-3.

our standard fit to solve also for a residual precession rate of the Earth, we obtained a value for the luni-solar precession constant that was smaller than the 1976 IAU value by 3.8 mas/yr, with a formal uncertainty of 0.9 mas/yr. Our estimate of the precession constant is potentially sensitive to possible systematic errors caused by the ionosphere in the S-band data collected during the first 6.5 years of our 8.5-yr data span. Since our formal uncertainty does not account properly for this influence, we estimate that a more realistic value of our precession error is 2 mas/yr. When this error is root-sum squared with the estimated error of 1.5 mas/yr (Fricke 1981) in the IAU value, fair agreement (1.5σ) is found between the two measurements. As a check on the influence of the ionosphere, we also obtained a solution for the precession constant based on our S-X data alone. The result was smaller than the IAU value by 4.0 mas/yr with a formal uncertainty of 1.5 mas/yr, in agreement with the result from all of our data. Since our data span a time interval small compared to the 18.6-yr nutation period, there is a high degree of correlation between the effect of an error in our estimate of the precession constant and the effect of an error in the 18.6-yr nutation term. Thus, our present data can not indicate whether the difference applies to the precession model or to the nutation model.

Whether this difference persists as we add new data, and whether it applies primarily to precession or nutation modeling, should become evident as the span of data approaches a significant fraction of the 18.6-yr period. Estimates of the nutation and precession constants by the JPL group analyzing lunar laser ranging data (Dickey *et al.* 1984) have yielded values of $+7 \pm 5$ mas for the correction to the amplitude of the 18.6-yr nutation term, and -1 ± 3 mas/yr for the correction to the precession rate.

V. CONCLUSIONS

The decade long span of intercontinental VLBI data has yielded a radio source catalog, JPL 1983-3, which consists of 117 extragalactic sources whose relative positions have been measured with an average formal uncertainty of 5 mas. For 44 common sources, our source positions are in fair agree-

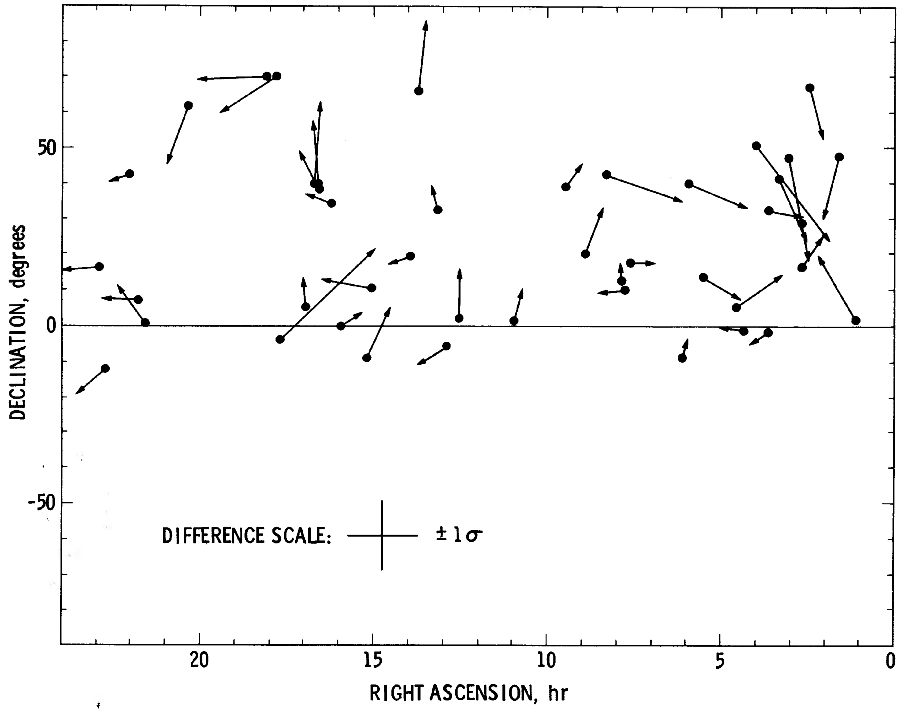

FIG. 5. Source position difference vectors for the GSFC-821007 minus JPL 1983-3 catalogs. The difference for each coordinate of each source is normalized by the corresponding RSS error estimate for that coordinate difference.

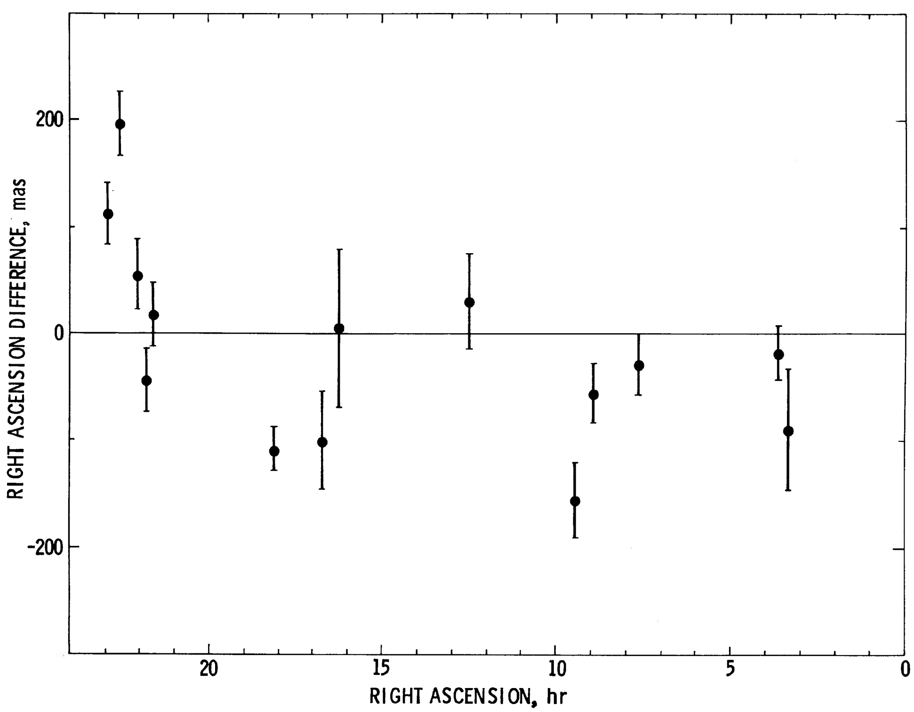

FIG. 6. Right ascension differences (de Vegt and Gehlich minus JPL 1983-3) versus right ascension.

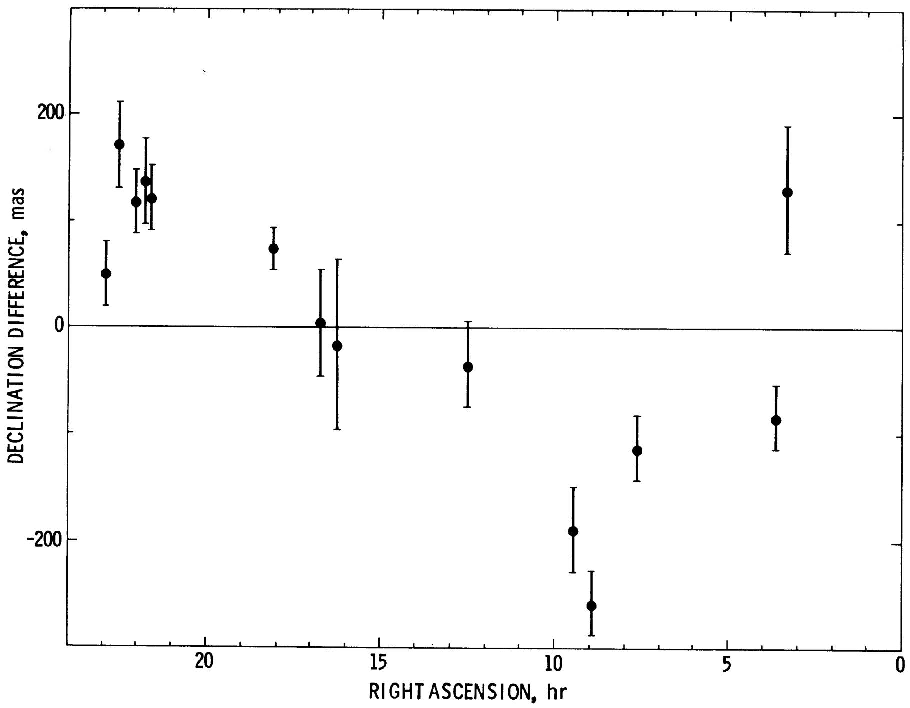

FIG. 7. Declination differences (de Vegt and Gehlich minus JPL 1983-3) versus right ascension.

ment with the positions determined by Ma (1981, 1984). In contrast, comparison with a catalog of optical counterparts shows systematic discrepancies of the order of 0".1. A fit to our current data produced an estimate for the luni-solar precession constant that is smaller than the IAU value by 3.8 mas/yr, with an estimated accuracy of 2 mas/yr. When our error is root-sum squared with the estimated error of 1.5 mas/yr in the IAU value, one finds that there is fair agreement between the two values. The difference is large enough, however, to provide strong motivation to improve the accuracy of our result through more measurements.

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