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RADIO-SOURCE POSITIONS FROM VLBI

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ABSTRACT

Positions of 85 compact extragalactic radio sources and the Galactic object Beta Persei (Algol) have been determined in the J2000.0 coordinate system from analysis of very-long-baseline interferometry (VLBI) observations made with the bandwidth-synthesis technique. Twenty-four of these sources were observed with the Mark I VLBI system in 37 sessions distributed between April 1972 and May 1978, and 82 of the sources were observed with the Mark III system in 85 sessions distributed between August 1979 and December 1982. Each session spanned at least 24 hr. Standard errors for the estimated positions on the sky of the ~ 10 sources frequently observed with the Mark I system are about 1 mas, except for the declinations of nearly equatorial sources, where these errors approach 5 mas. Corresponding uncertainties for the ~ 20 sources frequently observed with the Mark III system are 0.3 and 2 mas, respectively. Comparisons of our estimates of positions with those of the J2000.0 catalog of Fanselow *et al.* (1984) show rms differences of about 4 mas, within a factor of 2 of the root-sum-square of the relevant standard errors.

I. INTRODUCTION

Observations of compact extragalactic radio sources provide a means of defining a nearly inertial reference frame. Since the cores of such objects at distances greater than ~ 100 Mpc have, as yet, undetectable proper motion (Shapiro *et al.* 1979; Bartel *et al.* 1986), the relative positions of these cores define a celestial coordinate system which is useful for astrometry and spacecraft navigation as well as for geophysics, through measurements of global and regional tectonics and of universal time and polar motion. For example, the use of very-long-baseline interferometry (VLBI) to navigate the *Galileo* spacecraft to Jupiter requires a reference frame with relative positions known to 5 mas. To measure the length of a 4000 km baseline by VLBI with a standard error of 2 cm or less, the source positions must be known, or be determined simultaneously, with a standard error of 1 mas or less. Recent results from VLBI (see, for example, Fanselow *et al.* 1984) indicate that both the number and the accuracy of determinations of radio-source positions have improved to a level sufficient to define a fundamental celestial reference frame so that a radio catalog can now provide an important supplement to the conventional optical catalog of stellar positions.

Parts of the results reported here refine and extend those described by Rogers *et al.* (1973) and Clark *et al.* (1976). Their data were all obtained with the Mark I VLBI system. We have reanalyzed most of the same data with models appropriate for the J2000.0 coordinate system. In addition, the span of Mark I data that we analyzed was extended to May 1978 (see Ryan *et al.* 1986). We also analyzed a second, larger, data set that spans the interval from August 1979 to December 1982 and involves observations of some of the same strong sources; this second set was obtained with the Mark III system and was analyzed in a manner very similar to that used for the first set. The data obtained with the Mark III system yielded source positions markedly more precise than those obtained with the Mark I system.

II. THE VLBI NETWORK AND INSTRUMENTATION

The network of antennas used was extensive. The antennas are described in Table I. Observations with the Mark I system utilized from two to four of the antennas simultaneously. For Mark III observing sessions the number of antennas used simultaneously ranged from two to six. Baseline lengths ranged from 1.2 to 8204 km.

The Mark I system was described by Whitney *et al.* (1976). Mark I observations were made at radio frequencies near 7850 MHz with left-circular polarization (IEEE and

IAU definition) before September 1976 and at radio frequencies near 8450 MHz with right-circular polarization thereafter. Each observation "scan" lasted 3 min. With minor exceptions, hydrogen-maser frequency standards were used at each antenna. System temperatures ranged from 25 to 200 K. Signals were received in five time-multiplexed bands, each 350 kHz wide, to form a synthesized band up to 300 MHz wide, as described by Rogers (1970). A phase-calibration signal was injected at the receiver to remove instrumental dispersion and time variation in instrumental delay.

The Mark III system (Rogers *et al.* 1983; Clark *et al.* 1985) employed reception at two widely separated frequency bands simultaneously and provided considerably greater flexibility and sensitivity than the Mark I system. All operations except for mounting tapes were computer controlled. Signals were received simultaneously in up to 14 2 MHz-wide bands. Some of these bands were distributed to span widths of ~350 MHz, centered at 8400 MHz (*X* band); the remainder spanned ~85 MHz, centered at 2300 MHz (*S* band). The larger number of (narrow) bands sampled with the Mark III system at *X* band improved the delay resolution function (Rogers 1970) by lowering its sidelobes. Scan lengths varied from 100 to 400 s, depending on the flux density of the source and on interferometer sensitivity. System temperatures ranged from 120 to 300 K at *X* band and from 100 to 200 K at *S* band. The polarization of the received signals was always right-circular. Hydrogen-maser frequency standards were used for all observations at all antennas. A phase-calibration signal was injected at the receiver at both *X* band and *S* band to remove instrumental dispersion and time variation in instrumental delay. Meteorological sensors at each antenna provided information from which tropospheric delay was later estimated.

III. OBSERVATIONS AND DATA REDUCTION

The Mark I data were obtained in 37 irregularly separated observing sessions, each spanning one to four days. The unweighted mean epoch of all the sessions was 1975.2. Each of the 16 590 pairs of good data points consisted of a group delay (hereafter referred to as "delay") and a phase-delay rate (hereafter referred to as "delay rate") from two antennas. The definition of these astrometric observables and the data-reduction procedures used to generate them are described by Rogers *et al.* (1973), Shapiro (1976), and Whitney *et al.* (1976). The delay rates obtained from these Mark I observations were, however, not used (see below). The Mark III data were obtained in 85 separate observing sessions, each from one to seven days long, broken into approximately one-day sets, 107 altogether. The unweighted mean epoch of the one-day sets was 1981.9. The total number of pairs of good Mark III data points was 32 818. The data-reduction process used is described by Clark *et al.* (1985).

All of these astrometric data were placed in a data base (Ryan *et al.* 1980) for analysis. This data base is part of an integrated data analysis and data archiving system implemented on HP 1000 minicomputers. Detailed information on the epochs of observation sessions and on the antennas involved in each session is given in Table I.

With three exceptions described later, on each observing day 140 to 220 scans were made per antenna on a total of ten to 15 sources (not always the same sources in different sessions). An attempt was made in each day to observe each source a minimum of ten times, although sometimes fewer observations for sources at low declination were made because of limited mutual visibility. In general, different observation schedules were used for each session, although maximum hour-angle coverage of each source was always sought.

TABLE I. Mark I and Mark III individual data sets: April 1972–December 1982.

DATE YY MM DD	EXPERIMENT PURPOSE	CONFIGUR-ATION	ANTENNAS H	W	O	N	F	T	C	E	G	A	S
72 4 14	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
72 5 9	G	MK 1	X	.	.	.	.	.	.	.	X	X	.
72 5 29	G	MK 1	X	.	.	.	.	.	.	.	X	X	.
72 6 6	G	MK 1	X	.	.	.	.	.	.	.	X	X	.
72 6 27	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
72 8 29	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
72 11 7	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
73 2 4	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
73 3 30	G	MK 1	X	.	.	.	.	.	.	.	X	.	.
73 4 11	G	MK 1	X	.	.	.	.	.	.	.	.	.	X
73 5 18	G	MK 1	X	.	.	.	.	.	.	.	.	.	X
73 8 10	GR	MK 1	X	.	.	X	.	.	.	.	X	.	X
73 10 12	GR	MK 1	X	.	.	X	.	.	.	.	X	.	X
74 1 22	GR	MK 1	X	.	.	.	.	.	.	.	X	.	X
74 3 4	GR	MK 1	X	.	.	X	.	.	.	.	X	.	X
74 4 29	GR	MK 1	X	.	.	X	.	.	.	.	X	.	X
74 7 8	GR	MK 1	X	.	.	X	.	.	.	.	X	.	X
74 10 27	GR	MK 1	X	X	.	X	.	.	.	.	X	.	.
75 1 14	GR	MK 1	X	.	.	X	.	.	.	.	X	.	.
75 5 27	GR	MK 1	X	.	.	.	.	.	.	.	X	.	.
75 10 15	GR	MK 1	X	.	.	X	.	.	.	.	X	.	.
76 4 20	GR	MK 1	X	.	.	.	.	.	.	.	X	.	.
76 9 9	G	MK 1	X	.	X	.	.	.	.	.	.	.	.
76 9 29	G	MK 1	X	.	X	.	.	.	.	.	.	.	.
76 10 4	G	MK 1	X	.	X	.	.	.	.	.	.	.	.
76 10 9	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
76 10 11	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
76 10 14	G	MK 1	X	.	X		.	.	.	.	.	.	.
76 12 13	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
76 12 15	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
77 3 27	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
77 6 26	G	MK 1	X	.	X	X	.	.	.	.	.	.	.
77 9 24	G	MK 1	X	.	.	X	.	X	.	.	.	.	.
77 12 13	G	MK 1	X	.	X	.	.	.	.	.	.	.	.
78 1 13	G	MK 1	X	.	X	.	.	.	.	.	.	.	.
78 2 24	G	MK 1	X	.	X	.	.	X	.	.	.	.	.
78 5 17	G	MK 1	X	.	X	X	.	X	.	.	.	.	.
79 8 3	GS	MK 3	X	.	X	X	.	.	.	.	.	.	.
80 4 11	G	MK 3	X	.	X	X	X	.	.	.	.	.	.
80 4 13	S	MK 3	X	.	X	X	X	.	.	.	.	.	.
80 7 26	G	MK 3	X	.	X	.	X	X	.	X	.	.	X
80 7 27	G	MK 3	X	.	X	.	X	X	.	X	.	.	X
80 9 26	M	MK 3	X	.	X	.	X	X	.	X	.	.	X
80 9 27	M	MK 3	X	.	X	.	X	X	.	X	.	.	X
80 9 28	M	MK 3	X	.	X	.	X	X	.	X	.	.	X
80 9 29	M	MK 3	X	.	X	.	X	X	.	.	.	.	X
80 9 30	M	MK 3	X	.	X	.	X	X	.	.	.	.	X
80 10 1	M	MK 3	X	.	X	.	X	X	.	.	.	.	X
80 10 2	M	MK 3	X	.	X	.	X	X	.	.	.	.	X
80 10 16	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 17	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 18	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 19	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 20	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 21	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 10 22	M	MK 3	X	.	X	.	X	X	X	.	.	.	X
80 11 3	P	MK 3	X	.	.	.	X	.	.	.	.	.	.
80 12 1	P	MK 3	X	.	.	.	X	X	.	.	.	.	X
80 12 19	P	MK 3	X	.	.	.	X	X	.	.	.	.	X
81 1 7	P	MK 3	X	.	.	.	X	.	.	.	.	.	.
81 1 22	P	MK 3	X	.	.	.	X	X	.	.	.	.	X
81 2 12	P	MK 3	X	.	.	.	X	.	.	.	.	.	.
81 2 27	P	MK 3	X	.	.	.	X	X	.	.	.	.	X
81 3 16	P	MK 3	X	.	.	.	X	.	.	.	.	.	.
81 5 13	P	MK 3	X	X	.	.	X	.	.	.	.	.	.
81 6 16	G	MK 3	X	X	X	.	X	.	.	.	.	.	.
81 6 17	S	MK 3	X	X	X	.	X	.	.	.	.	.	.
81 6 24	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81 7 1	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81 7 8	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81 7 15	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81 7 22	P	MK 3	.	X	.	.	X	.	.	.	.	.	.

TABLE I. (continued)

DATE YY	MM	DD	EXPERIMENT PURPOSE	CONFIGURATION	H	W	O	N	F	T	C	E	G	A	S
82	1	6	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	1	13	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	1	20	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	1	27	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	2	1	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	2	10	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	2	17	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	2	24	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	3	3	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	3	10	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	3	24	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	3	29	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	4	7	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	4	13	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	4	26	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	5	3	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	5	10	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	7	29	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	8	5	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	8	26	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	9	2	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	9	9	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	9	16	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	9	23	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	9	30	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	10	15	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	10	21	P	MK 3	.	X	.	.	X	X	.	.	.	.	X
81	10	28	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	11	4	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	11	10	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	11	18	G	MK 3	X	X	X	X	X	X	.	.	.	.	X
81	11	19	G	MK 3	X	X	X	X	X	X	.	.	.	.	X
81	11	24	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	12	2	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	12	16	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
81	12	22	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	5	17	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	6	2	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	6	7	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	6	16	G	MK 3	.	X	X	.	.	X	.	.	.	.	X
82	6	17	S	MK 3	.	X	X	.	.	X	.	.	.	.	X
82	6	18	G	MK 3	X	X	X	.	.	X	.	.	.	.	X
82	6	19	G	MK 3	X	X	X	.	.	X	.	.	.	.	X
82	6	20	G	MK 3	X	X	X	.	X	X	.	.	.	.	X
82	6	21	G	MK 3	.	X	X	.	X	X	.	.	.	.	X
82	6	28	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	7	12	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	7	19	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	7	26	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	8	4	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	8	9	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	8	16	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	8	23	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	8	30	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	9	7	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	9	13	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	9	20	P	MK 3	.	X	.	.	X	X	.	.	.	.	X
82	9	27	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	10	4	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	10	13	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	10	18	P	MK 3	.	X	X	.	X	X	.	.	.	.	X
82	10	25	P	MK 3	.	X	X	.	X	.	.	.	.	.	.
82	11	1	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	11	8	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	11	15	P	MK 3	.	X	.	.	X	X	.	.	.	.	X
82	11	22	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	11	29	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	12	6	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	12	15	G	MK 3	.	X	X	X	X	X	.	.	.	.	X
82	12	16	G	MK 3	.	X	X	X	X	X	.	.	.	.	X
82	12	20	P	MK 3	.	X	.	.	X	.	.	.	.	.	.
82	12	27	P	MK 3	.	X	.	.	X	.	.	.	.	.	.

Notes to TABLE I

Experiment purposes:

G-Geodesy
R-Source structure
M-MERIT short campaign
P-POLARIS
S-Source survey

Antennas:
A—A 26 m-diameter antenna near Gilmore Creek, Alaska, operated by the National Oceanic and Atmospheric Administration.
C—A 25 m-diameter antenna near Chilbolton, England, operated by the Appleton Laboratories.
E—A 100 m-diameter antenna near Effelsberg, Federal Republic of Germany, operated by the Max Planck Institut für Radioastronomie.
F—A 26 m-diameter antenna near Fort Davis, Texas, operated by the Harvard College Observatory.
G—A 64 m-diameter antenna in the Goldstone tracking complex, near Barstow, California, operated by the Deep Space Network.
H—A 37 m-diameter antenna near Westford, Massachusetts, operated by the Northeast Radio Observatory Corporation.
N—A 43 m-diameter antenna near Green Bank, West Virginia, operated by the National Radio Astronomy Observatory.
O—A 40 m-diameter antenna near Big Pine, California, operated by the California Institute of Technology.
S—A 26 m-diameter antenna near Onsala, Sweden, operated by the Onsala Space Observatory and used for *X* band Mark I observations and *S* band Mark III observations.
T—A 20 m-diameter antenna located 607 m from the 26 m-diameter antenna near Onsala, Sweden, operated by the Onsala Space Observatory and used for the last three Mark I observing sessions and all *X* band Mark III observations.
W—An 18 m-diameter antenna near Westford, Massachusetts, operated by the Northeast Radio Observatory Corporation.

Notation:
An X denotes participation by the corresponding antenna.

always sought. Because of antenna constraints, circumpolar sources were rarely observed for an entire day. Not all observations were made using all antennas available. Especially in the Mark III era, the array was sometimes divided into subsets of antennas with each subset observing a different source in order to increase hour-angle coverage and to allow antennas at longitudes intermediate between those in California and those in Europe to observe nearer the horizon to separate better the signatures of various effects on the observables.

During three observing sessions we used special survey schedules to check various sources for suitability for astrometric and geodetic studies. These sources were chosen for their flat spectra and high flux density (> 1.5 Jy) in hopes of finding strong emitters without discernible structure. For each of these sessions up to 40 sources were observed, including "standard" sources used to "control" the reference frame.

The basic data-analysis techniques and models used are described in detail by Robertson (1975), Ma (1978), Herring *et al.* (1981), Rogers *et al.* (1983), and Clark *et al.* (1985). The definition of the J2000.0 reference frame includes formulas for precession (Lieske *et al.* 1977; Lieske 1979) and sidereal time (Aoki *et al.* 1981), a precise ephemeris of the Earth's motion with respect to the solar system barycenter (in our case, Ash 1972), and consideration of gravitational ray deflection. In addition, we used the 1980 IAU theory of nutation (Wahr 1981; Seidelmann *et al.* 1982).

Much of the Mark I data were taken in observing sessions designed to measure source structure rather than astronomical or terrestrial positions. During the period 1973–1975, most of the sessions spanned several days. However, the clock behavior at some of the antennas was poor, wandering many nanoseconds erratically over one day. Each Mark I observing session was analyzed as a single ("individual") data set, regardless of the actual length of the session, in order to improve the significance of the results from each individual data set. The quality of the Mark III data is much higher because of better overall system performance, and all the Mark III data were therefore divided into one-day sets, even when individual sessions of observations were longer. Each data set was first edited and analyzed separately. The root-mean-square (rms) scatter of the postfit delay residuals ranged from a minimum of <0.1 ns for some of the Mark III data sets to a maximum of ~ 2 ns for some of the Mark I data sets. Suitable parametrizations for the zenith electrical path length through the atmosphere at each antenna and for the station clock there (one offset and rate for each day for each antenna except the reference, but with diurnal sinusoids, quadratic terms, and shorter intervals used as necessary) were saved in the data base for future reference. All measurement variances, originally based on signal-to-noise ratios, were modified by adding a baseline-dependent constant so that the reduced χ^2 was unity for the data from each baseline for each data set; these constants were also saved in the data base.

Using arc-parameter elimination (Brownd 1978), we combined the data sets sequentially on an HP 1000 minicomputer to obtain two "global" solutions, one for the Mark I data and one for the Mark III data. Each step involved adding a data set to the combined global matrix (CGM) from the previous step, with the initial CGM empty. The CGM retains information only about global parameters, i.e., those whose values are to be estimated from the ensemble of data. In our solutions, only source and antenna positions were global parameters. Only the global parameters and the local parameters for a single data set, i.e., those relating to clocks, zenith electrical paths, universal time, and polar motion, are involved in the normal matrix of each step. Two or three Earth-orientation parameters were estimated for each data set, depending on the geometry of the baselines involved. Moreover, the global parameter estimates are available at each step. The local parameters can be generated correctly only by a "back" solution. The parameter estimates resulting from the back solution are those that would have been obtained from a conventional least-squares solution. The weighted rms of the postfit residuals from the global Mark I solution was 0.3 ns. The corresponding weighted rms from the global Mark III solution was 0.1 ns for the delays and 0.1 ps/s for the delay rates.

The effect of charged particles in the propagation medium was treated differently in the two global solutions. Because only one synthesized frequency band was recorded by the Mark I system, Mark I observations could not be corrected for charged-particle retardation from the delay data themselves (see below). Since group delay and phase delay (and therefore phase-delay rate) are affected by the charged particles in opposite senses, it is possible in principle to measure the change in the effect of the ionosphere through the course of an observing session, although its total effect is not accessible. However, the delay rates were subject to fluctuations from clock behavior to a degree that made them of marginal use for determining charged-particle effects. Hence, only uncorrected delays were used in the Mark I global solution.

The dual-band receivers and multichannel recorders we used for Mark III observations allow simultaneous recording of X band and S band radio frequencies. Since the charged-particle contribution to the electrical path-length scales approximately as the inverse square of the observing frequency, and since no other effect has the same signature, a new observable virtually free of charged-particle (largely ionospheric) effects can be computed from a linear combination of the S band and X band delays (see, for example, Herring 1983). All the Mark III data included in this paper were corrected in this manner. On some occasions, most notably in November 1981, S band data were lost at Onsala because of severe weather which resulted in a shutdown of the 26 m antenna on which the S band receiver was mounted; since the Onsala data could not then be calibrated for charged-particle effects, they were not used. Although the data from April 1980 were included, their calibration may have small errors because of the small, 12.5 ns, S band delay ambiguity which may not have always been correctly eliminated; an error of one ambiguity interval at S band introduces an error in the "corrected" delay of ~ 1 ns.

There are two other differences between the Mark I and the Mark III data. The tropospheric calibrations for Mark I data were calculated from whatever information was recorded at the weather service station nearest each observatory. The Mark III data were calibrated using meteorological data (pressure, temperature, relative humidity/dew point) from each site which were recorded automatically during the observations. In addition, the calibration for the variation in electrical length of the cable used in the phase-calibration system was applied to the Mark III, but not to the Mark I, data. The cable-calibration system was developed late in the history of the Mark I system and was never used routinely. The (uncorrected) diurnal cable variation recorded during Mark III observations was as large as 2 ns but was typically less than 200 ps. The effect was largest during July 1980 at Owens Valley when the cable between the control room and the antenna was above ground.

IV. RESULTS

The results for source positions are presented in order of increasing right ascension in Tables II and III; also given are our estimates of the "true" standard errors and the number of observations. These errors are twofold higher than the statistical standard errors obtained from the respective global solutions as will be discussed below. The conventional IAU names given for the sources are based on their B1950.0 positions. The origin of right ascension of our VLBI reference frame is arbitrary since no VLBI measurements sensitive to the ecliptic have been included. Following past practice (Rogers *et al.* 1973; Clark *et al.* 1976; Kaplan *et al.* 1982; Fanselow *et al.* 1984), we take the J2000.0 right ascension of 1226 + 023, freed from the effects of elliptic aberration, to be $12^h29^m6.6997^s$, consistent with the B1950.0 value of Hazard *et al.* (1971). Since the origin of right ascension is arbitrary the stated standard errors in right ascension apply only to the relative values of right ascension.

Table II gives the 24 J2000.0 positions derived from Mark I delay data. Table III shows the 82 positions derived from Mark III data. The average level of the standard errors decreases by about a factor of 2 from the earlier to the later data.

Figures 1 and 2 show the distribution of errors as a function of sky position. There are two causes for the larger uncertainties: (1) Declinations less than ~ 20 deg are more poorly determined. Sources with such declinations have restricted windows of mutual visibility, especially in networks including the European antennas. More important, the relatively small spin-axis ("z") components of the baselines involved reduce the sensitivity of the observations to the declination for a near-equatorial source. The sensitivity of the

TABLE II. Source positions (J2000.0) from Mark I data (1).

IAU Name	Right Ascension h	m	s	Declination °	'	"	Standard Error (2) RA ms	D mas	Number of Observations	Correlation of RA-D Estimates
0106+013	1	8	38.769	1	35	.5	2.	200	8	-.87
0224+671	2	28	50.057	67	21	3.05	2.	10	71	-.70
Beta Pers	3	8	10.127	40	57	20.34	6.	40	17	-.67
0316+413	3	19	48.1608	41	30	42.113	.1	1	2783	.04
0333+321	3	36	30.1080	32	18	29.38	.6	10	33	-.47
0336-019	3	39	30.938	- 1	46	35.8	2.	200	15	-.99
0355+508	3	59	29.7482	50	57	50.167	.1	1	1381	.13
0430+052	4	33	11.0956	5	21	15.631	.1	8	1195	-.58
0851+202	8	54	48.8751	20	6	30.633	.1	3	534	-.14
0923+392	9	27	3.0141	39	2	20.844	.1	1	1735	.14
1127-145	11	30	7.049	-14	49	27.1	2.	200	9	-.71
1226+023	12	29	6.6997	2	3	8.592	(3)	7	1730	
1228+126	12	30	49.423	12	23	28.03	.7	30	91	-.64
1253-055	12	56	11.1664	- 5	47	21.528	.1	9	865	-.41
1404+286	14	7	.3941	28	27	14.68	.3	10	65	-.34
1633+382	16	35	15.4926	38	8	4.496	.4	6	172	-.48
1638+398	16	40	29.6325	39	46	46.034	.4	6	269	-.43
1641+399	16	42	58.8094	39	48	36.995	.1	1	1884	.12
1807+698	18	6	50.675	69	49	28.15	4.	40	10	-.57
2037+511	20	38	37.0338	51	19	12.675	.4	6	167	.19
2134+004	21	36	38.5862	0	41	54.24	.1	10	977	-.63
2200+420	22	2	43.2912	42	16	39.992	.2	1	1464	.07
2230+114	22	32	36.405	11	43	51.3	2.	200	11	-.84
2251+158	22	53	57.7480	16	8	53.582	.1	3	1104	-.19

Notes to TABLE II

(1) The positions given are free from the effects of elliptical aberration, as specified for J2000.0 coordinates.
(2) The standard errors given are twice the statistical standard errors from the global solution.
(3) The right ascension of 1226 + 023 defines the origin of right ascension.

TABLE III. Source positions (J2000.0) from Mark III data (1).

IAU Name	Right Ascension h	m	s	Declination °	'	"	Standard Error (2) RA ms	D mas	Number of Observations	Correlation of RA-D Estimates
0016+731	0	19	45.7865	73	27	30.021	.4	2.	20	.07
0048-097	0	50	41.3174	- 9	29	5.227	.1	8.	17	-.67
0106+013	1	8	38.77104	1	35	.322	.02	1.	1651	-.28
0133+476	1	36	58.5948	47	51	29.102	.1	2.	35	.03
0212+735	2	17	30.81341	73	49	32.6225	.07	.2	1086	-.05
0224+671	2	28	50.05165	67	21	3.0306	.05	.3	759	-.00
0229+131	2	31	45.89398	13	22	54.719	.04	2.	90	-.38
0234+285	2	37	52.40566	28	48	8.9911	.03	.5	1262	-.19
0235+164	2	38	38.93003	16	36	59.2779	.02	.8	830	-.28
0300+470	3	3	35.24218	47	16	16.2769	.05	.5	202	.00
0316+413	3	19	48.1601	41	30	42.103	.1	2.	36	.01
0333+321	3	36	30.1076	32	18	29.343	.1	3.	25	-.29
0336-019	3	39	30.93773	- 1	46	35.804	.08	6.	27	-.66
0355+508	3	59	29.74730	50	57	50.1625	.03	.2	2441	.02
0420-014	4	23	15.80060	- 1	20	33.063	.07	5.	37	-.67
0430+052	4	33	11.09536	5	21	15.619	.07	4.	77	-.47
0458-020	5	1	12.80978	- 1	59	14.255	.05	3.	65	-.32
0454+844	5	8	42.365	84	32	4.542	1.	2.	13	.20
0528+134	5	30	56.41668	13	31	55.149	.03	1.	246	-.45
0552+398	5	55	30.80560	39	48	49.1653	.02	.3	2928	-.03
0605-085	6	7	59.699	- 8	34	49.980	1.	9.	18	-.66
0707+476	7	10	46.1048	47	32	11.142	.3	5.	13	-.06
0716+714	7	21	53.4486	71	20	36.362	.5	3.	19	.27
0723-008	7	25	50.6401	- 0	54	56.579	.1	7.	20	-.65
0735+178	7	38	7.3937	17	42	18.994	.1	5.	13	-.38
0736+017	7	39	18.0339	1	37	4.62	.1	12.	17	-.70
0742+103	7	45	33.05943	10	11	12.691	.07	3.	80	-.63
0748+126	7	50	52.0456	12	31	4.832	.1	8.	13	-.37
0804+499	8	8	39.6662	49	50	36.526	.2	3.	20	-.01
0814+425	8	18	15.9995	42	22	45.411	.1	3.	25	-.26
0828+493	8	32	23.2167	49	13	21.035	.2	3.	20	.33
0851+202	8	54	48.87486	20	6	30.6394	.02	.6	2217	-.06
0917+624	9	21	36.2310	62	15	52.177	.3	3.	18	-.04
0923+392	9	27	3.01376	39	2	20.8510	.02	.3	2223	.04
0953+254	9	56	49.87533	25	15	16.048	.05	2.	96	-.59
0954+658	9	58	47.2449	65	33	54.811	.5	4.	8	.08
1055+018	10	58	29.6050	1	33	58.828	.1	7.	19	-.70
1144+402	11	46	58.2975	39	58	34.304	.3	4.	4	-.79
1150+812	11	53	12.498	80	58	29.150	1.	4.	11	.21
1219+285	12	21	31.69042	28	13	58.499	.05	2.	113	-.52
1226+023	12	29	6.6997	2	3	8.597	(3)	1.	1833	

TABLE III. (continued)

IAU Name	Right Ascension h	m	s	Declination °	'	"	Standard Error (2) RA ms	D mas	Number of Observations	Correlation of RA-D Estimates
1253-055	12	56	11.1666	- 5	47	21.54	.1	13.	37	-.60
1308+326	13	10	28.6637	32	20	43.782	.1	3.	23	-.49
1342+663	13	44	8.679	66	6	11.66	1.	13.	9	-.42
1354+195	13	57	4.43660	19	19	7.367	.08	3.	53	-.75
1404+286	14	7	.39424	28	27	14.6886	.02	.5	2231	.07
1418+546	14	19	46.5971	54	23	14.788	.2	2.	9	-.36
1502+106	15	4	24.97971	10	29	39.197	.06	3.	71	-.68
1510-089	15	12	50.53283	- 9	5	59.825	.09	6.	32	-.65
1538+149	15	40	49.4916	14	47	45.88	.5	24.	3	-.96
1548+056	15	50	35.26919	5	27	10.448	.08	5.	35	-.59
1555+001	15	57	51.4338	- 0	1	50.41	.2	16.	13	-.81
1606+106	16	8	46.2032	10	29	7.77	.2	14.	6	-.89
1611+343	16	13	41.06412	34	12	47.910	.09	2.	33	-.24
1633+382	16	35	15.49277	38	8	4.5017	.06	.9	84	-.46
1637+574	16	38	13.45603	57	20	23.9800	.05	.5	548	-.06
1638+398	16	40	29.6326	39	46	46.027	.2	4.	15	-.14
1642+690	16	42	7.84801	68	56	39.7568	.05	.2	1242	.23
1641+399	16	42	58.80975	39	48	36.9947	.02	.3	3541	.23
1656+053	16	58	33.4472	5	15	16.448	.1	7.	20	-.57
1739+522	17	40	36.9775	52	11	43.407	.2	2.	24	-.26
1741-038	17	43	58.85600	- 3	50	4.613	.04	3.	145	-.50
1749+701	17	48	32.8399	70	5	50.769	.6	3.	13	-.41
1749+096	17	51	32.81848	9	39	.730	.05	3.	72	-.61
1803+784	18	0	45.6834	78	28	4.020	.4	1.	33	-.06
1807+698	18	6	50.6804	69	49	28.107	.4	2.	18	-.35
1823+568	18	24	7.0680	56	51	1.492	.1	2.	32	-.04
1842+681	18	42	33.6412	68	9	25.230	.5	2.	24	-.40
1923+210	19	25	59.6050	21	6	26.172	.2	7.	6	-.82
1928+738	19	27	48.4946	73	58	1.572	.2	1.	78	-.16
2007+777	20	5	30.9982	77	52	43.249	.5	1.	26	-.18
2005+403	20	7	44.9449	40	29	48.610	.4	5.	9	.40
2021+614	20	22	6.6818	61	36	58.809	.2	2.	28	-.17
2037+511	20	38	37.0346	51	19	12.665	.1	1.	13	-.16
2121+053	21	23	44.51733	5	35	22.096	.07	4.	36	-.55
2134+004	21	36	38.58615	0	41	54.217	.02	1.	1084	-.31
2145+067	21	48	5.45862	6	57	38.606	.06	3.	43	-.57
2200+420	22	2	43.29120	42	16	39.9827	.03	.3	2385	.07
2216-038	22	18	52.03765	- 3	35	36.878	.05	3.	111	-.61
2223-052	22	25	47.25928	- 4	57	1.392	.09	7.	16	-.52
2243-123	22	46	18.23189	-12	6	51.282	.08	6.	24	-.61
2251+158	22	53	57.74784	16	8	53.5643	.02	.7	1946	-.07

Notes to TABLE III

(1) The positions given are free from the effects of elliptical aberration, as specified for J2000.0 coordinates.
(2) The standard errors given are twice the statistical standard errors from the global solution.
(3) The right ascension of 1226 + 023 defines the origin of right ascension.

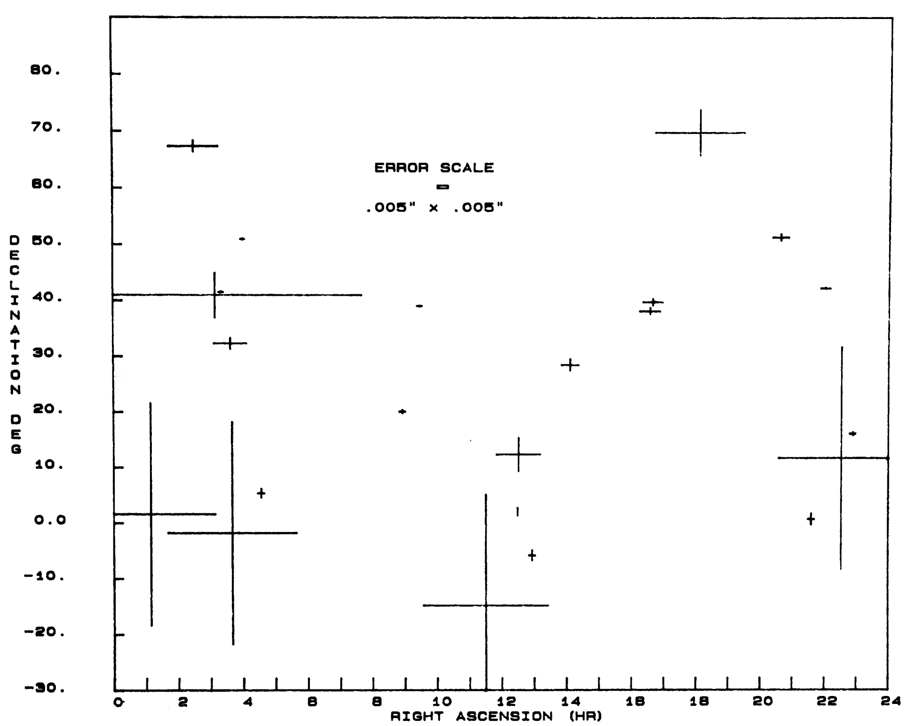

FIG. 1. Mark I source-position uncertainties. Horizontal bars are standard errors for estimates of right ascension multiplied by cosine of declination. Vertical bars are standard errors for estimates of declination. The magnitudes of the correlations between the estimates of right ascension and those of declination for a single source range from 0.04 to 0.99. The largest magnitude of correlation between the coordinates of different sources is 0.90.

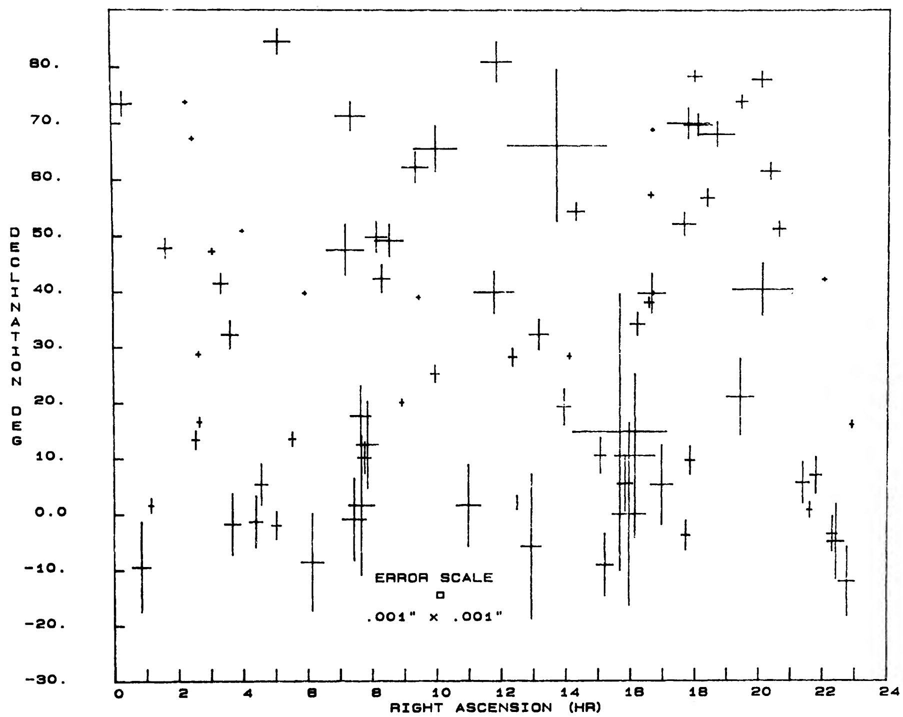

FIG. 2. Mark III source-position uncertainties. Horizontal bars are standard errors for estimates of right ascension multiplied by cosine of declination. Vertical bars are standard errors for estimates of declination. The magnitudes of the correlations between the estimates of right ascension and those of declination for a single source range from 0.004 to 0.96 (0.89 for sources observed more than 5 times). The largest magnitude of correlation between the coordinates of different sources is 0.84.

variable part of a delay observable to the source declination vanishes at zero declination, whereas the sensitivity of the constant part is proportional to the z component of the baseline. (2) The total number of observations of many of the sources is relatively small. Only the compact sources with the highest correlated flux densities have been observed frequently; these number only 23. The other sources have been observed only in survey sessions or have been introduced gradually as formerly strong emitters such as 0430 + 052 have weakened or expanded.

V. INTERNAL CONSISTENCY

The consistency of the Mark III positions was tested by comparing arclengths between each element of every pair of sources whose positions we estimated using data obtained from different time intervals. This comparison should be unaffected by errors either in precession or in the long-period components of nutation. The arclengths should be invariant since the sources have no detectable proper motion. A similar test was not performed with the Mark I data because of their poorer accuracy and lack of ionosphere correction.

Table IV shows the distribution of the Mark III observations by year (with the few observations from 1979 included with those for 1980). Table V shows the comparison of arclengths between those sources which were each observed during each of two years. For all such comparisons for pairs of sources the rms differences in arclength lie between 3 and 5 mas. For the most frequently observed pairs of sources the rms differences of the arclengths are twofold lower. The reduced χ^2s of the year-to-year variation of arclengths between sources indicate that the statistical standard errors are far too small. One possible cause is errors in short-period terms in the nutation series. The sources are not observed uniformly in time throughout the year and the source-position determinations would be distorted differently depending on the exact distribution of observations (Herring *et al.* 1985).

We also combined the individual Mark I and Mark III data sets into several larger, but disjoint, sets from which separate solutions were made. These solutions are tabulated and described in Table VI. The source positions from the separate solutions were then compared in pairs and the results are presented in Table VII. For each source the differences in coordinates between solutions were decomposed into arclength components parallel and perpendicular to the equator: $\Delta\alpha \cos\delta$ and $\Delta\delta$, respectively. After the mean offsets for these arclength components were removed, the weighted rms differences between solutions were calculated. The reduced χ^2s in Table VII are based on the root-sum-squares of the statistical standard errors from the separate solutions. The position differences and corresponding reduced χ^2s are largest for the comparison of Mark III data obtained before and after 1981.0. These large values may be caused by a rotation of the entire coordinate system over time, which could be a result of an error in the constant of precession or in the coefficient of a long-period term in nutation, or some combination. With the data available, it is not possible to separate usefully the two effects, and we chose not to solve at this time for any such correction. Based on these comparisons we have assigned our estimated true standard errors in Tables II and III at twice the value of the statistical standard errors.

TABLE IV. Number of sources and arcs observed with Mark III, by year.

	1980	1981	1982
Total number of sources observed	49	49	37
Number of arcs formed	1176	1176	666
Number of sources observed more than 50 times each	20	21	18
Number of arcs formed	190	210	153
Total number of observations	12 378	8376	12 064

TABLE V. Comparison of arclengths determined from data from different years.

	1980–1981	1980–1982	1981–1982
All sources:			
Number of common arcs	231	190	253[a]
Mean difference in arclength (mas)	− 0.4	− 1.3	1.5
rms difference in arclength (mas)	3.3	3.2	4.5
Reduced χ^2	14	3.9	14
Sources observed more than 50 times each:			
Number of common arcs	105	66	105
Mean difference in arclength (mas)	− 1.0	− 0.6	1.7
rms difference in arclength (mas)	2.1	1.2	2.0
Reduced χ^2	16[b]	6.8[c]	18[d]

[a] The arcs for 0420 − 014 and 1055 + 018 are not included. When these arcs are included, the reduced χ^2 is 102.
[b] The reduced χ^2 is 8.6 if the arcs for 0106 + 013 are ignored.
[c] The reduced χ^2 is 3.1 if the arcs for 0106 + 013 are ignored.
[d] The reduced χ^2 is 9.4 if the arcs for 0528 + 134 are ignored.

Several other solutions were made from the Mark III data to test the effects of changes in modeling. In one such solution we estimated an offset in nutation in both obliquity and longitude for each individual data set. Effects of errors of short period in the nutation series tend thereby to be removed from the estimates of source positions. In another solution we adjusted the antenna positions for each individual data set. Because of plate motions, the relative positions of the antennas are not fixed, and solving for antenna positions as global parameters might introduce some errors since sources observed at different epochs are being measured with interferometers at slightly different relative locations. Two types of solution were made to test the effects of the troposphere, one in which the observations below 15° elevation were not used and one in which a new tropospheric mapping function was used. This mapping function retains the general continued fraction form of the Marini model applied in the normal analysis but uses different constants based on ray traces for a variety of atmospheric conditions (Davis *et al.* 1985). The results from all of these solutions are presented in Table VIII. The adjustment of nutation offsets for each data set, equivalent in aggregate to the adjustment of the coefficients of the nutation series, introduces the largest rms changes. Herring *et al.* (1985) have found a significant correction in an annual nutation term which, if omitted as in our analysis, might lead to such a spread in our results because of the distribution of our observations throughout the year.

VI. COMPARISONS

The Mark III positions, listed in Table III, are expected to be the most accurate and have been compared with the Mark I positions in Table II and with positions from the J2000.0 source catalog in Fanselow *et al.* (1984). The results are summarized in Table IX.

The comparison of the Mark I and the Mark III positions shows larger than expected differences. In particular, there are three sources (0923 + 392, 2200 + 420, and 2251 + 158) with differences in the direction perpendicular to the equator that are anomalously large compared to the root-sum-square of their respective uncertainties. Without these sources, the weighted mean offset perpendicular to the equator is − 3.1 mas with corresponding weighted rms difference of 4.6 mas and reduced χ^2 of 2.9. If the uncertainties of the remaining 17 Mark I positions are increased by a factor of 2, then both reduced χ^2s are close to unity. The mean offset perpendicular to the equator is probably due in large part to the absence of any ionosphere correction for the Mark I data. Neglecting the delay arising from the ionosphere causes both baseline lengths, including their z components, and source declinations to be greater than their ionosphere-corrected values. This effect was demonstrated by a

TABLE VI. Subsets of test data used in analysis.

Mark I	
Set 1	Sep. 1976–May 1978
Set 2	Jan. 1974–Mar. 1976
Set 3	Apr. 1972–Oct. 1973
Set 4	odd numbered individual data sets
Set 5	even numbered individual data sets
Set 6	Jan.–Jun., all years
Set 7	Jul.–Dec., all years
Mark III	
Set 1	1981–1982
Set 2	1979–1980
Set 3	odd numbered individual data sets
Set 4	even numbered individual data sets
Set 5	Jan.–Jul., all years
Set 6	Aug.–Dec., all years
Set 7	Apr.–Sep., all years
Set 8	Oct.–Mar., all years

TABLE VII. Comparison of solutions from different subsets of data.

Mark I comparisons	1–2	2–3	1–3	4–5	6–7
Number of sources	12	15	11	19	17
Mean $\alpha \cos \delta$ offset (mas)	1.8	− 1.6	3.3	− 2.4	− 0.9
Mean δ offset (mas)	0.6	2.0	3.3	2.6	− 6.2
rms $\alpha \cos \delta$ difference (mas)	5.3	9.8	3.3	4.7	5.1
rms δ difference (mas)	10.5	18.7	4.4	15.2	12.0
$\alpha \cos \delta$ reduced χ^2	1.3	1.4	1.6	0.7	1.2
δ reduced χ^2	1.8	1.4	1.5	2.1	2.2
Mark III comparisons	1–2	3–4	5–6	7–8	
Number of sources	22	24	25	18	
Mean $\alpha \cos \delta$ offset (mas)	0.2	− 1.2	− 0.4	− 0.4	
Mean δ offset (mas)	− 0.2	− 0.4	− 1.2	0.4	
rms $\alpha \cos \delta$ difference (mas)	2.4	0.7	0.3	0.9	
rms δ difference (mas)	3.7	3.7	1.4	1.1	
$\alpha \cos \delta$ reduced χ^2	4.5	1.2	0.8	2.5	
δ reduced χ^2	2.7	1.4	1.4	1.1	

TABLE VIII. Description of Mark III solutions based on different models.

Solution A—no estimate of nutation; assumes no site movement between sessions.
Solution B—nutation offset estimated for each session; assumes no site movement between sessions.
Solution C—nutation offset estimated for each session; assumes no site movement between sessions; 15 deg elevation cutoff.
Solution D—nutation offset and site positions estimated for all sessions except reference session.
Solution E—nutation offset and site positions estimated for all sessions except reference session; alternate troposphere mapping function used.

Solutions compared	A–B	B–C	B–D	D–E
Number of sources	21	21	25	24
Mean $\alpha \cos \delta$ offset (mas)	0.0	0.1	−0.0	0.0
Mean δ offset (mas)	−0.2	−0.2	−0.1	0.1
rms $\alpha \cos \delta$ difference (mas)	0.5	0.2	0.2	0.2
rms δ difference (mas)	0.8	0.5	0.5	0.3

TABLE IX. Comparison of J2000.0 positions from Mark III and other catalogs (Mark III − catalog).

Catalog	Sources in common	Weighted mean arclength offset: parallel to equator (mas)	Weighted mean arclength offset: perpendicular to equator (mas)
Mark I	20	−2.0	−2.2
Fanselow *et al.*	47	−1.6	−0.1

Catalog	Weighted rms difference[a]: parallel to equator (mas)	Weighted rms difference[a]: perpendicular to equator (mas)	Reduced χ^{2a}: parallel to equator	Reduced χ^{2a}: perpendicular to equator
Mark I	4.2	7.0	3.6	10
Fanselow *et al.*	2.5	4.0	1.1	2.2

[a] Weighted mean arclength offsets removed.

solution using Mark III data without ionosphere correction.

Our Mark III catalog and the Fanselow *et al.* catalog were based on disjoint observations made with dissimilar equipment over different intervals of time. The ~2400 observations for the latter catalog were obtained between 1971 and 1980 from *S* band and *X* band Mark II VLBI observations, some made simultaneously at both bands. The antennas they used (with the exception of one session) are in California, Spain, and Australia; the southern hemisphere antenna allowed better precision to be obtained in estimates of declination. Because of their use of a narrower synthesized bandwidth, the rms's of their postfit residuals (0.5 ns in delay and 0.3 ps/s in delay rate) are larger than ours. The agreement in positions in the direction parallel to the equator is consistent with the root-sum-square of the respective uncertainties. The poorer agreement in the direction perpendicular to the equator may arise from the quite different *z* components of the interferometers used and the high correlation between the estimates of baseline *z* component and source declination, which makes these estimates especially sensitive to the effects of systematic errors.

VII. CONCLUSIONS

The accuracy of source positions derived from the first few years of Mark III data is at least as high as that in other catalogs of radio sources. Slightly more than three years of data have allowed us to produce a catalog of positions of 82 sources with standard errors generally less than 4 mas. Data being acquired by the Crustal Dynamics Project of the National Aeronautics and Space Administration (NASA) now involve a wider network of antennas, including several in the Pacific with a larger spread in latitude, which will allow us to improve the determination of the declination of many of these and other sources.

The data from the interferometers involving the Massachusetts and Texas antennas were obtained under the auspices of the National Oceanic and Atmospheric Administration/National Geodetic Survey as part of their POLARIS program. The other Mark III data were obtained under the auspices of the NASA Crustal Dynamics Project. In all cases the data were obtained in cooperation with the involved North American and European radio observatories and we thank the staffs of the participating observatories for their indispensable aid. Haystack Observatory is operated with support from the National Science Foundation (NSF), grant GP 25865; the National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under contract with the NSF; Onsala Space Observatory is supported by a grant from the Swedish Natural Science Research Council; and Owens Valley Radio Observatory is sustained by a grant from the NSF. The Goldstone Tracking Station is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS7-100 with NASA. Some experiments were carried out under the Quasar Patrol, approved by the Radio Astronomy Experiment Selection Panel for use of the Goldstone Tracking Station. Experimenters at the Center for Astrophysics were supported in part by U.S. Air Force contract F19628-83-K-0031; NASA contracts NAS5-27230 and NAS5-27571; and NSF grants NSF-EAR-83-02221, NSF-EAR-83-06380, and NSF-AST-83-00796. The Mark III VLBI system for geodesy was developed with primary support from NASA's (then) Office of Applications and with additional funds or subsystems provided by NRAO, NSF, the U.S. Air Force, and the U.S. Geological Survey.

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