THE ASTRONOMICAL JOURNAL VOLUME 81, NUMBER 8 AUGUST 1976

Radio source positions from very-long-baseline interferometry observations

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(Received 20 February 1976)

Accurate positions of compact radio sources have been determined from very-long-baseline interferometry (VLBI) observations based on the bandwidth-synthesis technique. The coordinates for 18 extragalactic sources were obtained from sets of observations spread over the period from April 1972 to January 1975; the scatter among the independent determinations of the source coordinates from the separate sets of observations is about 0."05, except for the declinations of near-equatorial sources where the scatter is about 0."15. Comparison of our positions with those determined with the Cambridge 5-km radio interferometer shows the rms scatter about the mean difference to be about 0."04 in each coordinate (no sources of low declination were in common). A similar comparison of our results with those obtained by the Jet Propulsion Laboratory from separate VLBI observations yields a slightly larger rms scatter, after exclusion of the declinations of the near-equatorial sources. We also obtained a position for the Galactic object, β Persei (Algol), which agrees well with the position given in the FK 4 catalogue: $\Delta\alpha(\mathrm{VLBI}-\mathrm{FK4}) = -0^{s}.001 \pm 0^{s}.007$ and $\Delta\delta = -0."12 \pm 0."09$.

INTRODUCTION

OBSERVATION of compact extragalactic radio sources via the technique of very-long-baseline interferometry (VLBI) offers the possibility to form an excellent approximation to an inertial frame through precise determination of the relative positions of such sources. VLBI holds the potential for the reduction of the uncertainty in these determinations to the milli-second-of-arc level. But the results published to date (see, e.g., Cohen and Shaffer 1971; Hinteregger *et al.* 1972; Cohen 1972; Rogers *et al.* 1973), although showing steady improvement down to an uncertainty level of a tenth of a second of arc, clearly fall well short of this goal.

Here we report results from an extended series of VLBI observations that yielded an additional twofold improvement: The coordinates of 18 compact extragalactic radio sources were determined with an uncertainty in each coordinate of about 0."05, except for the declination of near-equatorial sources for which the uncertainty is about threefold greater.

A unique aspect of the present work is the determination from VLBI observations of the coordinates of the Galactic source β Persei (Algol), a fundamental star in the FK4 catalogue (Fricke and Kopff 1963). This result allows the VLBI positions to be related directly to the stellar reference system.

I. OBSERVATIONS AND DATA REDUCTION

Source positions were determined from 18 separate sets of observations distributed between April 1972 and January 1975. Each set spanned one to four days and involved two, three, or four of the following five antenna systems: the 37-m-diameter antenna at the Haystack Observatory in Westford, Massachusetts; the 64-m-diameter antenna of the Jet Propulsion Laboratory in Goldstone, California; the 43-m-diameter antenna of the National Radio Astronomy Observatory in Green Bank, West Virginia; the 26-m-diameter antenna of the National Oceanic and Atmospheric Agency in Gilmore Creek, Alaska; and the 26-m-diameter antenna of the Chalmers University of Technology in Onsala, Sweden.

All observations were made at radio frequencies near 7850 MHz ($\lambda \simeq 3.8$ cm) with left-circular polarization (IEEE definition), and were recorded using the Mark I system (Clark *et al.* 1968). The duration of an individual observation was 3 min. A hydrogen-maser frequency standard was used at each site for each set of observations with only a few exceptions. The band-

TABLE I. Positions of extragalactic radio sources from VLBI observations.

Source	Right ascension (1950.0)	Elliptic aberration[a]	Declination (1950.0)	Elliptic aberration[a]	Number of solutions[b]
3C 84	$3^h16^m29^s.550 \pm 0^s.002$[c]	$0^s.019$	41 19′51″.69±0″.07[c]	0″.16	12
NRAO 140	3 33 22.386±0.002	0.018	32 08 36.44±0.07	0.11	2
CTA 26	3 36 58.937±0.002	0.016	−01 56 16.79±0.20	−0.04	1
NRAO 150	3 55 45.235±0.004	0.027	50 49 20.11±0.04	0.16	8
3C 120	4 30 31.586±0.003	0.019	05 14 59.49±0.19	−0.01	14
OJ 287	8 51 57.231±0.003	0.021	20 17 58.45±0.07	−0.09	13
4C 39.25	9 23 55.297±0.004	0.023	39 15 23.73±0.03	−0.16	16
3C 273B	12 26 33.246[d]	0.002	02 19 43.31±0.13	−0.04	18
3C 279	12 53 35.834±0.002	−0.001	−05 31 07.99±0.14	0.00	13
OQ 208	14 04 45.625±0.001	−0.009	28 41 29.41±0.05	−0.18	6
OQ 172	14 42 50.496±0.020	−0.011	10 11 12.53±1.36	−0.08	1
NRAO 512	16 38 48.199±0.001	−0.025	39 52 30.23±0.01	−0.14	4
3C 345	16 41 17.635±0.002	−0.025	39 54 10.96±0.04	−0.13	15
3C 418	20 37 07.490±0.006	−0.032	51 08 35.66±0.03	0.11	6
PKS 2134+00	21 34 05.226±0.003	−0.017	00 28 25.03±0.23	−0.03	14
VRO 42.22.01	22 00 39.385±0.005	−0.020	42 02 08.40±0.04	0.15	16
CTA 102	22 30 07.827±0.006	−0.013	11 28 22.49±0.57	0.03	1
3C 454.3	22 51 29.533±0.003	−0.011	15 52 54.24±0.05	0.05	14

[a]The addition to our results of these contributions of elliptic aberration allows direct comparison with positions given in accord with conventional practice in optical astrometry.
[b]Each solution was based on the data from a single experiment of duration 1–4 days.
[c]The uncertainties given represent the root-weighted-mean-square (rms) spread of the individual solutions about the weighted mean, except when only one solution was available. In these latter cases, the uncertainties represent twice the formal standard errors which in turn are based on scaling the rms of the postfit residuals to unity.
[d]This value defines the origin of right ascension and is based on the result for the right ascension of 3C 273B obtained by Hazard *et al.*(1971).

width-synthesis technique, as in our prior work (Hinteregger *et al.* 1972; Rogers *et al.* 1973), was used throughout. The precise dates of the observations and detailed information on the equipment used are given by Robertson (1975).

The data-reduction procedures used to obtain the group delay and the fringe rate from each pair of Mark I recordings were as outlined by Rogers *et al.* (1973) and further described by Whitney *et al.* (1976). The algorithms and computer programs used in the estimation of the source positions from the group delays and fringe rates are given in Robertson (1975). Typically, for each set of data, we used a weighted-least-squares estimator to determine the values for the three components of each independent baseline, the clock epoch- and rate-offset parameters for each day for each baseline, the zenith electrical path length of the atmosphere for each site for each day, and the coordinates of the relevant sources. Although both the group delays and the fringe rates were utilized in the analysis to determine source positions, the fringe rates have, in all but one instance, only an insignificant effect on our results. The rate data will therefore be largely ignored in subsequent discussion.

II. RESULTS AND DISCUSSION

In the first part of this section, we discuss, in turn, the positions we obtained for extragalactic sources, the estimated uncertainties in these determinations, and the comparisons between our positions and those determined independently with different radio interferometric techniques. In the second part, we present our result for the position of Algol and compare it with the FK4 position.

Our estimates of the positions of the 18 observed extragalactic sources are gathered in Table I. Declinations were determined with respect to the equator of date, whereas right ascensions were determined with respect to an origin defined by the value given in Table I for 3C 273B. The source coordinates, with the effects of elliptic aberration removed, were referred back to the mean equator and equinox of 1950.0 via the standard formulas for precession and nutation.

The values shown in Table I for the source coordinates, with the exceptions to be discussed below, each represent the weighted mean of the estimates determined separately from the independent sets of observations. The number N of such independent estimates is given for each source in the last column of Table I. For $N > 1$, each uncertainty shown in Table I is the root-weighted-mean-square (rms) scatter about the weighted mean of the estimates from the independent sets of observations. Thus, the uncertainty given is not the standard error of the weighted mean which would be smaller by the factor $(N-1)^{-1/2}$. Because of the dominance of systematic errors in the individual results, as discussed below, the quoted uncertainties are more reliable indicators of the "true" 70% confidence limits on our coordinate determinations.

The rms scatter estimates of uncertainty given in the table can be contrasted with corresponding ones based on the postfit residuals or on the signal-to-noise ratios achieved in individual observations. An rms scatter result was typically found to be about twice the formal standard error that corresponded to a value of unity for the weighted postfit residuals of the group delays from a single experiment. The achievement of this value of unity, on the other hand, typically required a doubling of the uncertainties expected on the basis of the signal-to-noise ratios for individual measurements of group delays.

Trends often present in the postfit residuals (Robertson 1975) for a given source are also indicative of the influence of systematic errors and lend further support to our choice of the rms scatter uncertainty over either the twofold smaller formal standard error or the fourfold smaller one based on the signal-to-noise ratios from the measurements. The causes of such systematic errors are presumably combinations of the effects of the instabilities of the frequency standards employed, the variations in the propagation medium, and the drifts in the phase responses of the receiver systems. It was not possible to pinpoint the contributions from each cause for each set of observations. However, in some of the sets of observations, the effects of long-term (on the order of hours) clock "wander" were unmistakable. In analyzing data from sites so affected, we therefore made use of a differencing technique (Shapiro *et al.* 1974; Robertson 1975) in which the group delays from neighboring observations were subtracted to form new observables that were effectively freed from the long-term components of the clock drifts.

For the sources observed in only one set of observations ($N = 1$), the rms-scatter approach to the estimate of the errors in the coordinates is clearly inappropriate. In order to place the uncertainties in the estimates of the coordinates for these sources on a basis comparable to the uncertainties given for the coordinates of the other sources, we multiplied the formal standard errors by 2 (see above). We also note that for the single source for which $N = 2$, the rms scatter was, respectively, somewhat less and somewhat greater than twice the average formal standard error in right ascension and declination.

Overall, we note that for 11 of the 17 sources the uncertainties in the right-ascension coordinates are under 0."05, and in only one case was 0."1 reached or exceeded; for that source, OQ 172, only a single 3-min observation had been made. (Thus, in this case, and only in this case, the fringe rate played an important role.) With regard to the declinations, eight of the 18 uncertainties are less than or equal to 0."05; of the other ten uncertainties, three are 0."07 and five are two- or threefold higher due primarily to the declinations being 5° or under in absolute value. The remaining two larger uncertainties are for OQ 172, observed only once, and for CTA 102 which was observed in only one set of observations and has a declination of only 11°.

The accuracy of these determinations of relative positions does not seem to have been degraded by errors in the standard expressions for precession and nutation. Arclengths between the positions of pairs of sources remain invariant under rotations of the coordinate system and these arclengths, for the selected cases investigated, showed rms scatters consistent with those exhibited by the individual coordinates. Errors in precession and nutation would in any event affect our results only insofar as the errors in the precession and nutation changed during the approximately 3-yr period covered by our observations. Errors involved in the transformation to 1950.0 coordinates can be removed simply by transforming back to the corresponding coordinate system for an epoch, say, at the midpoint of our observation period. Of course, at any time when more accurate expressions for the precession and nutation become available, the data can be reprocessed and all effects of such errors thereby removed. Any inadequacies in our models for polar motion and UT.1 are unimportant for the determination of source positions since we solved independently for the baseline coordinates from each set of observations. Only the very small changes in the errors in our models for polar motion and UT.1 over the course of a single set of observations affect our results for source positions.

TABLE II. Comparison of VLBI and Cambridge 5-km interferometer[a] positions for extragalactic radio sources.

Source	$\Delta\alpha$(VLBI−Cambridge) (0.s001)	$\Delta\delta$(VLBI−Cambridge) (0."01)
3C 84	7	−8
NRAO 140	2	−8
OJ 287	3	−25[b]
4C 39.25	6	−1
OQ 208	−1	−4
NRAO512	6	0
3C 345	8	1
VRO 42.22.01	5	−5
CTA 102	21[b]	8
3C 454.3	12	6

[a] Elsmore and Ryle (1975).
[b] See text for discussion.

Comparison of the coordinates shown in Table I with those we reported previously for 12 of the same extragalactic sources (Rogers *et al.* 1973) shows the agreement to be very good. The differences were less than, or comparable to, the root sum square (rss) of the quoted uncertainties in all cases but that of the declination of 3C 120, for which the difference was about 1.4 times the rss of the uncertainties. Of course, in drawing conclusions from this good agreement, one must bear in mind that the two sets of determinations are not independent: The second includes most of the data from the first.

The most accurate published values for the positions of extragalactic radio sources, other than ours, are probably those of Elsmore and Ryle (1975). We therefore compared our positions with theirs for the ten sources that were in common in the two sets. This comparison is displayed in Table II. The agreement is good in almost all cases. The disagreement between the declinations obtained for OJ 287 is surprisingly large, about threefold larger than the rss of the uncertainties given for each. Furthermore, in not one of our 13 independent determinations did the declination even reach within 0."05 of the Cambridge value. One might suspect that this difference is due to a genuine difference between the centers of brightness of the unresolved components of the source as viewed by interferometers of resolving powers differing by a factor of order 1000. However, militating against such a possibility is our result (Wittels *et al.* 1975) that OJ 287 is almost completely unresolved, yielding typically a normalized fringe amplitude of about 0.9 with our interferometers. Conceivably, the difference might be due instead, or in part, to the difference in radio frequencies employed: the Cambridge group observed at a frequency of about 5 GHz as compared with our 8 GHz. Perhaps most likely, the uncertainty assigned by at least one of the two groups has been underestimated.

The only other coordinate value represented in Table II differing by as much as three times the rss of the uncertainties is the right ascension of CTA 102, but here any conclusion must be constrained by the fact that we have only one independent VLBI determination.

Omitting from consideration the declination of OJ 287 and the right ascension of CTA 102, we computed the weighted mean of the differences between the VLBI and the Cambridge coordinates and obtained

$$\overline{\Delta\alpha}(\text{VLBI} - \text{Cambridge}) \simeq 0\overset{s}{.}006 \simeq 0\overset{''}{.}08,$$

$$\overline{\Delta\delta}(\text{VLBI} - \text{Cambridge}) \simeq -0\overset{''}{.}02.$$

The bias between the right ascension values may be due, at least in part, to different definitions of origin. Elsmore and Ryle (1975) used the right ascension of Algol to define the origin in their system. The uncertainty of about $0\overset{''}{.}09$ in our single determination of Algol's right ascension, given below, is consistent with this interpretation of the bias. The bias between the declination values is clearly insignificant for the present level of accuracy and sample size.

With the right ascension bias removed, and still omitting α_{CTA102} and δ_{OJ287}, we find that the root-weighted-mean-square differences in $\Delta\alpha \cos\delta$ and $\Delta\delta$ are

$$\sigma(\Delta\alpha \cos\delta) \simeq 0\overset{s}{.}003 \simeq 0\overset{''}{.}04,$$

$$\sigma(\Delta\delta) \simeq 0\overset{''}{.}04,$$

in accord with the uncertainties given for the individual estimates.

Another comparison was made with the results (Fanselow 1973) obtained independently at the Jet Propulsion Laboratory from VLBI observations made at a radio frequency of about 2.3 GHz. These observations, however, involved only fringe-rate data which are very insensitive to declinations for near-equatorial sources; we therefore restricted our comparison of the declinations to those exceeding 10°. For the nine sources in common, and the seven declinations exceeding 10°, we obtained

$$\overline{\Delta\alpha}(8\text{ GHz} - 2.3\text{ GHz}) \simeq 0\overset{s}{.}002 \simeq 0\overset{''}{.}02,$$

$$\overline{\Delta\delta}(8\text{ GHz} - 2.3\text{ GHz}) \simeq 0\overset{''}{.}01,$$

and

TABLE III. Position of Galactic radio source β Persei (Algol) from VLBI observations.

	Coordinate in 1950.0 system	Elliptic aberration[a]	Proper motion[b]
Right ascension	$03^h04^m54\overset{s}{.}338 \pm 0\overset{s}{.}006$	$0\overset{s}{.}017$	$0\overset{s}{.}008$
Declination	$40°\,45'\,52\overset{''}{.}19 \pm 0\overset{''}{.}08$	$0\overset{''}{.}16$	$0\overset{''}{.}06$

[a] The addition of the elliptic aberration to our results yields values compatible with the conventional practice in optical astrometry.

[b] The subtraction of these values of proper motion were used in the conversion of our 1975.04 position for Algol to the 1950.0 position given in the table.

$$\sigma(\Delta\alpha \cos\delta) \simeq 0\overset{s}{.}004 \simeq 0\overset{''}{.}06,$$

$$\sigma(\Delta\delta) \simeq 0\overset{''}{.}05,$$

where these quantities were calculated as for the comparison of our results with those of Elsmore and Ryle. We note that the Jet Propulsion Laboratory solution for the source coordinates incorporated, as *a priori* constraints, the corresponding optical positions and their uncertainties, thus yielding an origin for the right ascension coordinate different in principle from ours. The small average difference obtained in the comparison may therefore be somewhat fortuitous. Similarly, the mean difference in the declination values is smaller than could be expected on the basis of the uncertainties in our individual determinations. The rms scatter for the comparison of right ascensions is also smaller than the value expected from the uncertainties accompanying the Jet Propulsion Laboratory's individual estimates. On the other hand, the rms scatter for the comparison of declinations is close to the value expected.

In addition to the determination of the positions of extragalactic sources, we also obtained a result for the Galactic radio source β Persei (Algol). This source, which flares from time to time (Hjellming 1972), was detectable during our scheduled observations in mid-January 1975 and allowed us to make useful VLBI observations over a period of about 8 h (Clark *et al.* 1976). The values we obtained for the right ascension and declination are given in Table III with the basis for the quoted uncertainties being as described above for $N = 1$. Comparison with the FK4 catalogue position (Fricke and Kopff 1963) for Algol yields

$$\Delta\alpha(\text{VLBI} - \text{FK4}) = -0\overset{s}{.}001 \pm 0\overset{s}{.}007,$$

$$\Delta\delta(\text{VLBI} - \text{FK4}) = -0\overset{''}{.}12 \pm 0\overset{''}{.}09,$$

where the quoted uncertainties include contributions from the random errors in the FK4 catalogue position as given by Fricke and Kopff (1963). Since the more distant companion, Algol C, was separated by only $0\overset{''}{.}06$ from the close binary pair, Algol AB, during our observations (Bachmann and Hershey 1975), we could not determine the origin of the radio flare within the Algol system. However, Ryle and Elsmore (1973) concluded from four separate determinations of the position of Algol that the close pair AB was the source of the radio emission.

Our results for the position of Algol therefore indicate that, at least to within 0".1, our choice of origin for the right ascension coordinate is consistent with that of the FK4 catalogue.

ACKNOWLEDGMENTS

We are indebted to the staffs of the participating observatories for their important aid. Some of the observations reported here were made as part of the Quasar Patrol sponsored by the National Aeronautics and Space Administration and the Jet Propulsion Laboratory. The experimenters at the Massachusetts Institute of Technology were supported in part by the National Science Foundation, Grant DES74-22712, and in part by the National Aeronautics and Space Administration, Grant NAS 5-22843. Radio astronomy programs at the Haystack Observatory are conducted with support from the National Science Foundation, Grant MPS 71-02109 A07. This work also represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by the National Aeronautics and Space Administration. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. The VLBI program at the Onsala Space Observatory is supported in part by the Swedish Natural Science Research Council and the Swedish Board for Technical Development. The successful use of the National Oceanic and Atmospheric Agency's facility in Gilmore Creek, Alaska, was accomplished with the invaluable aid of W. K. Klemperer and W. W. Warnock.

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