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EXTRAGALACTIC RADIO SOURCES: ACCURATE POSITIONS FROM VERY-LONG-BASELINE INTERFEROMETRY OBSERVATIONS

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ABSTRACT

Relative positions for 12 extragalactic radio sources have been determined via wide-band very-long-baseline interferometry ($\lambda \simeq 3.8$ cm). The standard error, based on consistency between results from widely separated periods of observation, appears to be no more than 0″.1 for each coordinate of the seven sources that were well observed during two or more periods. The uncertainties in the coordinates determined for the other five sources are larger, but in no case exceed 0″.5.

Subject heading: radio sources

I. INTRODUCTION

Extragalactic objects can provide an excellent approximation to an inertial reference frame for a wide variety of astronomical and geophysical purposes. To best utilize this frame one must determine the relative positions of these sources as accurately as possible. The potential of very-long-baseline interferometry (VLBI) for such determinations has long been recognized; its realization is taking somewhat longer than first envisioned. Previous publications (Cohen and Shaffer 1971; Hinteregger *et al.* 1972; Cohen 1972) have shown the steady improvement in accuracy from several arc seconds to several tenths of an arc second uncertainty. Here we report another step forward in accuracy: From a suite of twelve observed extragalactic radio sources we have determined positions for seven with uncertainties no greater than about 0″.1 in either coordinate. This limit on the error is based, for each source, on the consistency attained in results from several different VLBI experiments, widely separated in time. The uncertainties in the coordinates determined for the other five sources are larger since each was observed either in only one experiment or with relatively restricted hour-angle coverage. However, in no case does the error estimate in a source coordinate exceed 0″.5.

II. OBSERVATIONS AND DATA REDUCTION

The source positions to be discussed are based on observations made in (i) a 2-week 1969 experiment involving three interferometer elements: the 43-m-diameter National Radio Astronomy Observatory telescope in Green Bank, West Virginia; the 37-m-diameter Haystack Observatory telescope in Tyngsboro, Massachusetts; and one of the 28-m-diameter radio telescopes of the Owens Valley Radio Observatory in California (Whitney 1973); and (ii) three 1-day 1972 experiments involving Haystack and the 64-m-diameter Deep Space Net radio telescope in Goldstone, California.

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TABLE 1

Source Coordinates from VLBI Observations*

Source	α (1950.0)	Elliptic Aberration†	δ (1950.0)	Elliptic Aberration†
3C 84	$03^{h}16^{m}29^{s}.539$	$0^{s}.019$	$41°19'51''.75$	$0''.16$
3C 120	04 30 31.586 ± 0.005	0.019	05 14 59.2 ± 0.1	−0.01
OJ 287	08 51 57.232 ± 0.005	0.021	20 17 58.45 ± 0.1	−0.09
4C 39.25	09 23 55.296 ± 0.004	0.023	39 15 23.73 ± 0.04	−0.16
3C 273B	12 26 33.246‡	0.002	02 19 43.2 ± 0.1	−0.04
3C 279	12 53 35.831 ± 0.004	−0.001	−05 31 08.0 ± 0.1	0.00
OQ 208	14 04 45.626	−0.009	28 41 29.4	−0.18
3C 345	16 41 17.634 ± 0.004	−0.025	39 54 11.00 ± 0.07	−0.13
PKS 2134 + 00	21 34 05.222 ± 0.005	−0.017	00 28 25.2	−0.03
VRO 42.22.01	22 00 39.394 ± 0.007	−0.020	42 02 08.3 ± 0.1	0.15
CTA 102	22 30 07.82	−0.013	11 28 22.8	0.03
3C 454.3	22 51 29.530 ± 0.009	−0.011	15 52 54.24 ± 0.03	0.05

* Coordinate determinations for which no uncertainties are quoted were based on only a single set of observations or had formal errors greater than $0''.1$; the errors in these coordinates are probably no more than a few tenths of an arc second.

† The addition of these contributions of elliptic aberration to our results allows direct comparison with positions given in accord with the conventional practice in astrometry.

‡ Reference right ascension (Hazard *et al.* 1971).

In each experiment, a wide-band synthesis technique (Rogers 1970; Hinteregger *et al.* 1972) was used which is especially potent for the determination of declinations for sources lying near the equatorial plane. The bandwidth spanned was 35 MHz in 1969 and 23 MHz in 1972. All observations were centered at a frequency near 8,000 MHz ($\lambda \simeq 3.8$ cm), and each observation, of 3 minutes extent, was recorded using the Mark I system (Clark *et al.* 1968). Hydrogen-maser frequency standards were used at each site for each experiment.

These data were reduced using a sequence of programs: VLBI 1, 2, and 3 (see, e.g., Hinteregger *et al.* 1972; Hinteregger 1972; Whitney 1973). The first program carries out the "raw" correlations and is, in effect, a data compressor. The second program determines the values of group delay and phase-delay rate (proportional to fringe rate) for each pair of the 3-minute tape recordings; in some cases successive sets of pairs were processed coherently. The data sets from each of the four experiments were processed separately in the third program, which takes the data on group delay and phase-delay rate as input and computes the weighted least-squares solution for the source positions and other unknown parameters. The latter included clock epoch- and rate-offset parameters for each day, an atmospheric parameter for each site for each day (the zenith electrical path length), and the three components of each independent baseline vector for each experiment. The right-ascension origin for all observation periods was set in accord with the value given by Hazard *et al.* (1971) for 3C 273 B. We could have incorporated an *a priori* covariance matrix for this purpose, but the small improvement perhaps attainable in relating our reference system to the FK 4 did not seem worth the effort. The declination origin was defined by the Earth's equatorial plane of date. The parametrized theoretical model, used in the comparison with the delay and delay-rate data, included all important motions of the sites with respect to the sources as well as simple algorithms to account for the Earth's atmosphere and ionosphere. Standard expressions were used for precession, nutation, polar motion, and UT.1 variations (Ash 1972); the largest few terms for solid-Earth tides were also incorporated.

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III. RESULTS AND INTERPRETATION

Our results for source positions, referred back to 1950.0 coordinates, are displayed in table 1. The standard errors shown were determined from the scatter in the results from the separate observing periods, except where judgment was used to raise such errors. No errors are given for coordinates that either were determined from only one observing period or had formal errors greater than 0.″1 due to restricted hour-angle coverage. Nonetheless, the errors in these latter coordinates are estimated to be bounded by fairly small values as indicated in the table.

In table 2 we display the results for the separate determinations of the coordinates from these four quasi-independent experiments. Because *a priori* values were used for precession and nutation, which define the change in the direction in inertial space of the Earth's spin axis between one experiment and the next, we might expect the scatter to be increased due to errors in these various quantities. Any unexpectedly large error in these quantities would increase the scatter in our results, especially the comparison between the 1969 and 1972 source-position estimates. Thus, under this hypothesis, different experiments would yield results differing by an overall rotation. To test this possibility, we computed arc lengths between appropriate source pairs since arc lengths are invariant under rotation. All pairs in which each individual coordinate had a formal error no greater than 0.″1 were included. The resultant scatter in arc lengths for this subset of source pairs yielded an unbiased estimate of the standard error of each arc length of 0.″14, or about $\sqrt{2}$ times the standard error for the position of each individual source, leading us to the expected conclusion that our present results are not limited by errors in the model of the motion of the Earth's spin axis in inertial space. Note, however, that the comparison of the source positions determined from the different experiments cannot disclose inadequacies in the models for polar motion and UT.1, except for variations occurring within a single experiment, because these quantities affect only the determination of the direction of the baseline in inertial space. The comparisons of the various solutions for the baseline vector bear on polar motion and UT.1 and will be discussed in a separate publication.

Strictly speaking, the scatter in our results for source positions establishes only consistency, not accuracy. We do not really know the "true" accuracy; there are some small systematic errors involving the atmosphere, the ionosphere, clock drift, and instrumental calibration that are still under study and whose quantitative effects on source positions cannot yet be estimated reliably, either individually or in toto. The nonrandomness of these effects is manifested by the clear, albeit small, systematic trends present in the postfit residuals from the Goldstone-Haystack experiments. In contrast to the 1969 experiment, these were not even near to being limited by signal-to-noise ratios.

Although our results are ostensibly the most accurate available, it is of obvious interest to compare them with others. Such comparisons are also given in table 2. We see that in most cases the differences are less than twice the rms of the quoted standard errors. The average of the right ascensions determined by Cohen (1972) is seen to be only slightly different from the average of our corresponding results, despite the difference in the definition of the origin of right ascension. Our generally smaller uncertainties in declination determinations, especially for low declination sources, are attributable to our use of the wide-band synthesis technique which provides accurate group delays as well as the phase-delay rates, utilized alone by Cohen. Except for the declination of VRO 42.22.01, the short-baseline results of Adgie, Crowther, and Gent (1972) and of Brosche, Wade, and Hjellming (1973) seem to be in at least as good agreement with ours as with each other's. Kristian and Sandage's (1970) right-ascension values, except for 3C 120, seem systematically lower than ours—

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TABLE 2

COMPARISON OF SOURCE COORDINATES DETERMINED BY DIFFERENT TECHNIQUES*

Source	α (1950.0)	δ (1950.0)	Technique†	Reference
3C 84...........	$03^h16^m29^s.539$	$41^\circ19'51''.75$	VLBI	TP1‡
	29.568 ± 0.007	51.84 ± 0.1	VLBI	C
	29.58 ± 0.04	52.1 ± 0.4	SBI	A
	29.548 ± 0.014	52.19 ± 0.12	P	AK
3C 120..........	04 30 31.582	05 14	VLBI	TP1
	31.588	59.19	VLBI	TP3
	31.588	59.21	VLBI	TP4
	31.605 ± 0.007	60.19 ± 0.3	VLBI	CN
	31.57 ± 0.03	60.1 ± 0.4	SBI	A
	31.605 ± 0.024	60.10 ± 0.3	P	CR
	31.60 ± 0.015	58.9 ± 0.3	P	KS
OJ 287	08 51 57.237	20 17	VLBI	TP2
	57.229	58.47	VLBI	TP3
	57.229	58.42	VLBI	TP4
	57.258 ± 0.012	58.7 ± 0.3	VLBI	CN
	57.29 ± 0.03	58.3 ± 0.4	SBI	A
	57.257 ± 0.02	58.22 ± 0.3	P	CR
4C 39.25.........	09 23 55.293	39 15 23.80	VLBI	TP1
	55.301		VLBI	TP2
	55.293	23.66	VLBI	TP3
	55.295	23.73	VLBI	TP4
	55.33 ± 0.04	23.5 ± 0.4	SBI	A
	55.29 ± 0.01	24.3 ± 0.2	SBI	B
3C 273B.........	12 26 33.246§	02 19	VLBI	TP1
	33.246§		VLBI	TP2
	33.246§	43.1	VLBI	TP3
	33.246§	43.2	VLBI	TP4
	33.242 ± 0.01	42.6 ± 1.1	VLBI	CN
	33.246 ± 0.01	43.38 ± 0.1	P‖	HD
3C 279	12 53 35.83	−05 31	VLBI	TP1
	35.831	08.0	VLBI	TP2
	35.835	08.3	VLBI	TP3
	35.831	07.9	VLBI	TP4
	35.825 ± 0.01	07.65 ± 0.45	VLBI	CN
	35.82 ± 0.02	07.4 ± 0.6	SBI	B
	35.67 ± 0.10	05.7 ± 1.9	SBI	H
	35.82 ± 0.02	07.65 ± 0.25	P	KS
OQ 208..........	14 04 45.629	28 41 29.41	VLBI	TP4
	45.65 ± 0.03	29.2 ± 0.4	SBI	A
3C 345	16 41 17.632	39 54 11.05	VLBI	TP1
	17.636	10.95	VLBI	TP4
	17.613 ± 0.01	11.15 ± 0.15	VLBI	CN
	17.64 ± 0.04	10.6 ± 0.4	SBI	A
	17.61 ± 0.01	11.3 ± 0.2	SBI	B
	17.606 ± 0.013	10.72 ± 0.12	P	AK
	17.56 ± 0.03	10.7 ± 0.3	P	KS
PKS 2134+00....	21 34 05.218	00 28	VLBI	TP1
	05.225	25.2	VLBI	TP4
	05.212 ± 0.01	28.6 ± 4.4	VLBI	CN
	05.23 ± 0.03	25.7 ± 0.4	SBI	A
VRO 42.22.01	22 00 39.40	42 02 08.2	VLBI	TP1
	39.402	08.19	VLBI	TP2
	39.390	08.34	VLBI	TP3
	39.386	08.42	VLBI	TP4
	39.365 ± 0.01	08.53 ± 0.15	VLBI	CN
	39.31 ± 0.04	09.0 ± 0.4	SBI	A
	39.37 ± 0.01	08.8 ± 0.2	SBI	B
CTA 102	22 30 07.82	11 28 22.78	VLBI	TP3
	07.83 ± 03	23.1 ± 0.4	SBI	A
	07.79 ± 0.07	21.6 ± 1.6	SBI	H
	07.78 ± 0.03	22.8 ± 0.3	P	KS

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TABLE 2 (*Continued*)

Source	α (1950.0)	δ (1950.0)	Technique†	Reference
3C 454.3.........	$22^h51^m29^s.53$	15°52′54″.23	VLBI	TP1
	29.52	54.27	VLBI	TP2
	29.534	54.22	VLBI	TP4
	29.524 ± 0.01	54.36 ± 0.2	VLBI	CN
	29.54 ± 0.03	54.9 ± 0.4	SBI	A
	29.60 ± 0.10	56.3 ± 3.1	SBI	H
	29.533 ± 0.011	54.98 ± 0.15	P	AK
	29.485 ± 0.035	54.45 ± 0.4	P	KS

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* Our results are freed from all effects of aberration (see table 1). The photographic positions, on the other hand, are affected by elliptic aberration, whereas some of the other radio positions may not be; the references are not all clear on this point.

† *Symbols.*—TP1 ≡ This paper, 1969 October 1–15 (includes data from Hinteregger *et al.* 1972). TP2 ≡ This paper, 1972 April 14–15. TP3 ≡ This paper, 1972 June 6–7. TP4 ≡ This paper, 1972 August 29–30. CN ≡ Cohen 1972. A ≡ Adgie *et al.* 1972. H ≡ Hunstead 1972; note that these observations were obtained at a radio frequency of only 408 MHz. HD ≡ Hazard *et al.* 1971. B ≡ Brosche *et al.* 1973. AK ≡ Argue and Kenworthy 1972. CR ≡ Couper 1972. KS ≡ Kristian and Sandage 1970. VLBI ≡ Very-long-baseline interferometry. SBI ≡ Short-baseline (radio) interferometry. P ≡ Photography.

‡ All entries describing our results had formal errors of 0″.1 or less. Missing entries for single coordinates stem from those whose formal errors are greater than 0″.1 due usually to a restricted distribution of observations in hour angle; the absence of both coordinates usually signifies that the source was not observed in that experiment.

§ This value was used to define our origin of right ascension (see table 1).

‖ Based on radio occultation as well as photographic data.

possibly an origin problem—whereas their declinations agree with ours to within their estimated uncertainties. Couper's (1972) estimate for the declination of 3C 120 seems anomalously high (as does Cohen's) relative to ours. Finally, we should point out that our coordinates refer to the unresolved radio component of these, in some cases, extended sources. At some higher levels of accuracy, depending on source extension, we may therefore expect to see systematic differences appearing between the VLBI, the short-baseline radio, and the optical positions.

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