HIGH PRECISION ASTROMETRY VIA VERY-LONG-BASELINE RADIO INTERFEROMETRY: ESTIMATE OF THE ANGULAR SEPARATION BETWEEN THE QUASARS 1038+528A AND B

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ABSTRACT

Dual-wavelength VLBI observations with the Mark III system of the two radio quasars 1038 + 528A and B yielded the following relative positions for the epoch 17 March 1981 (1950.0 coordinate system): $\Delta\alpha_{B-A} = 2^s.1205009 \pm 0^s.0000002$; $\Delta\delta_{B-A} = 27''.429228 \pm 0''.000003$ (λ 3.6 cm); $\Delta\alpha_{B-A} = 2^s.1204408 \pm 0^s.0000006$; $\Delta\delta_{B-A} = 27''.428622 \pm 0''.000009$ (λ 13 cm). The statistical standard errors represent fractional uncertainties of about 1 and 3 parts in 10^7 for λ 3.6 and λ 13 cm, respectively. The position of the brightest CLEAN component was chosen as the reference in each source at each wavelength. The difference found in the separations of these points at the two wavelengths, about $0''.0008$, is statistically very significant and probably represents the effect of wavelength-dependent opacity in the quasar 1038 + 528A (Marcaide and Shapiro 1983); plasma refraction contributes negligibly. Earlier, lower precision observations of these sources at these two wavelengths yielded relative positions consistent with those from the March 1981 epoch.

I. INTRODUCTION

A key kinematic question arises in studies of extragalactic radio sources with multiple compact components: which, if any, are stationary and which moving? Except for possible peculiar motions of the center of mass of a source and for possible variations of optical depth, one expects the core to appear stationary and any observed component motion to be identified with a "jet." No information is yet available on such "absolute" component motion in extragalactic radio sources. The most promising available means for measurement is very-long-baseline radio interferometry (VLBI). If a multicomponent radio source is separated by only a small angle from one with only a single compact component, then difference techniques can be used to determine the motions of the multiple components with respect to the presumably fixed single component of the reference source. This technique has been applied to 3C 345 (1641 + 399) with NRAO 512 (1638 + 398), 0.5 deg distant, as a reference (Shapiro *et al.* 1979). No useful results were obtained: the $\sim$2.5-yr span of the data in that study was insufficient to distinguish motions of $\sim 0''.0001$ per year or less.

We report here on first-epoch measurements of the relative positions of components in a pair of quasars, 1038 + 528A, B, whose separation in the sky is $\sim 33''$, about 60 times smaller than for the pair previously studied, implying a higher degree of cancellation in the effects of the instrumentation and of the propagation medium in the formation of difference observables. In fact, both sources are observable simultaneously at centimeter wavelengths from all telescopes available for VLBI, thus ensuring complete cancellation of the effect of instabilities in the frequency standards used, a major problem in the previous study (Shapiro *et al.* 1979).

The angular diameter distances of 1038 + 528A and B are 1.6 and 2.2 Gpc, respectively, based on estimated redshifts of $\sim$0.68 and $\sim$2.3 (Owen *et al.* 1980) and on values of $H_0 = 60$ km s^{-1} Mpc^{-1} and $q_0 = 0$. This pair of sources has the further characteristic that the essentially one-dimensional structures exhibited by the two members lie in almost orthogonal directions on the sky (Marcaide 1982; Marcaide and Shapiro 1983), thus facilitating the proper attribution of any observed component motions.

In the remainder of this paper we describe the observations (Sec. II), the difference observables (Sec. III), the data analysis (Sec. IV), and the astrometric results (Sec. V).

II. OBSERVATIONS

Using the new Mark III VLBI system, we observed 1038 + 528A and B simultaneously on 23–24 November 1979, 25–26 July 1980, and 17–18 March 1981, with different subsets of the following radio telescopes (with the abbreviation subsequently used, the antenna diameter, and its location given in parentheses): Deep Space Network (D, 64-m, California); Deep Space Network (M, 64-m, Spain); Effelsberg (B, 100-m, Federal Republic of Germany); Fort Davis (F, 26-m, Texas); Green Bank (G, 43-m, West Virginia); Haystack (K, 37-m, Massachusetts); Onsala (S, 25-m and X, 20-m, Sweden); Owens Valley (O, 40-m, California). Right-hand circular polarization was recorded at each telescope in each observation.

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The largest and most sensitive array, used continuously for slightly over 12 hr on 17–18 March 1981, consisted of the telescopes K, G, B, O, D, M, and S. Observations were made at λ 3.6 and λ 13 cm simultaneously at each telescope, except at Onsala where only λ 13 cm was available; the only significant technical problems occurred at D where the first four hours were lost due to a mechanical problem with a hydraulic bearing and where a set-up error prevented use of the phase-calibration signal for the λ 3.6 cm observations (Marcaide 1982). The recorded bandwidth at each wavelength was 28 MHz. Each recording spanned about 13 min, with about 12 min between recordings being used to rewind and change tapes.

Observations for about 8 hr at λ 13 cm on 25–26 July 1980 involved K, B, O, S, and F, with each recording having a bandwidth of 28 MHz. However, much of the data was of poor quality due to faulty magnetic tapes used for recording and also to inadequate procedures used to clean the recording heads.

Observations at λ 3.6 cm on 23–24 November 1979 involved K, G, B, O, and X. The bandwidth recorded was 28 MHz. A necessary compromise in the schedule caused the observations to be split into two parts, separated by exactly one day (Marcaide 1982). Two hours of observation were lost at B due to technical difficulties; in addition, nearly two hours of data were lost from every telescope through an error in tape handling.

III. DIFFERENCE PHASE-DELAY OBSERVABLES

For a radio source of arbitrary structure the phase-delay observable is given approximately by

$$\tau(t) \simeq \frac{L}{c}\,[\cos D \cos\delta \cos(A_0 + \Omega t - \alpha) + \sin D \sin\delta] + \tau^{\rm pm}(\tau) + \tau^{\rm in}(\tau) + \tau^{s}(\tau) + \left(\frac{n}{f}\right), \qquad (1)$$

where c is the speed of light; L, A_0, and D are the length, right ascension at epoch, and declination, respectively, of the baseline vector; Ω is the magnitude of the angular velocity of the Earth; α and δ are the right ascension and declination, respectively, of the source; $\tau^{\rm pm}$, $\tau^{\rm in}$, and τ^{s} are the contributions to the fringe phase from the propagation medium, the instrumentation, and the source structure, respectively; n is an integer; and f is the radio frequency of the observation. The contribution $\tau^{s}(t)$ is referred to a specific reference point in the source, defined by α and δ, and can be determined from a brightness map of the source. In particular, we use the relation

$$\tau^{s}(t) = \frac{1}{2\pi f}\,{\rm Arg}\left\{\int \Delta\,(x,y) e^{2\pi i(ux+vy)} dx dy\right\}, \qquad (2)$$

where $\Delta\,(x, y)$ is the δ-function (CLEAN component) model of the source, x and y are the angular distances of CLEAN components from the reference point, in the directions of increasing right ascension and declination, respectively, and u and v represent the interferometer resolutions at epoch t in the x and y directions. The contributions $\tau^{\rm pm}(t)$ and $\tau^{\rm in}(t)$ can usually not be estimated accurately, nor can n; for these reasons the utility of phase delays for astrometry is limited. However, with observations made simultaneously of two sources, separated by $\Delta\alpha(\equiv\alpha_{\rm B} - \alpha_{\rm A}) \ll 1$ and $\Delta\delta\,(\equiv\delta_{\rm B} - \delta_{\rm A}) \ll 1$, as in our case, we can utilize effectively the difference phase delay:

$$\begin{aligned}\Delta\tau(t) &\equiv \tau_{\rm B}(t) - \tau_{\rm A}(t)\\ &\simeq [\tau^{g}_{\rm B}(t) - \tau^{g}_{\rm A}(t)] + [\tau^{s}_{\rm B}(t) - \tau^{s}_{\rm A}(t)]\\ &\quad + [\tau^{\rm pm}_{\rm B}(t) - \tau^{\rm pm}_{\rm A}(t)] + [\tau^{\rm in}_{\rm B}(t) - \tau^{\rm in}_{\rm A}(t)] + \frac{n'}{f}\\ &\equiv \Delta\tau^{g}(t) + \Delta\tau^{s}(t) + \Delta\tau^{c}(t),\end{aligned} \qquad (3)$$

where τ^{g} denotes the geometric term in Eq. (1), $\Delta\tau^{g}$ represents the difference in the geometric terms for A and B, $\Delta\tau^{s}$ the corresponding difference in structure terms, and $\Delta\tau^{c}$ the difference for the remaining terms. Values for $\Delta\tau^{s}$, as stated, can be determined from hybrid maps or phase-reference maps (Marcaide and Shapiro 1983), whereas $\Delta\tau^{c}$ is very nearly (n'/f) (n' an integer) since the propagation medium and the instrumentation effects cancel almost completely in this case (Marcaide 1982).

Values of n' can be estimated for each measurement by use of the fringe rates, as discussed in Sec. IV (see, also, Shapiro *et al.* 1979). Thus, we are left essentially with samples of $\Delta\tau^{g}$ from which to estimate $\Delta\alpha$ and $\Delta\delta$. To second-order accuracy in $\Delta\alpha$ and $\Delta\delta$, we can write:

$$\begin{aligned}\Delta\tau^{g}(t) = \frac{L}{c}\Big\{&\cos D \sin(A_0 + \Omega t - \alpha)\\ &\times [\Delta\alpha \cos\delta - \Delta\alpha\,\Delta\delta \sin\delta]\\ &- \cos D \cos(A_0 + \Omega t - \alpha)\\ &\times [\Delta\delta \sin\delta + \tfrac{1}{2}((\Delta\alpha)^2 + (\Delta\delta)^2)\cos\delta]\\ &+ \sin D\left[\Delta\delta \cos\delta - \frac{(\Delta\delta)^2}{2}\sin\delta\right]\\ &+ O\,\{(\Delta\alpha)^3, (\Delta\delta)^3, \Delta\alpha(\Delta\delta)^2, \Delta\delta(\Delta\alpha)^2\}\Big\},\end{aligned} \qquad (4)$$

where α and δ correspond to the A quasar. This observable yields very accurate estimates of $\Delta\alpha$ and $\Delta\delta$. Less accurate results are obtainable from difference phase-delay rates, the time derivative of Eq. (4).

IV. DATA ANALYSIS

We first describe the data analysis for the 1981 experiment. The recorded data were cross correlated in the Haystack Mark III processor (Rogers *et al.* 1983) and the VLBI group delay, (ambiguous) phase delay, and phase-delay rate were estimated for each source for each 13-min observation.

The group delays from observations of 1038 + 528A and the calibrator source 0923 + 392 (4C39.25) (Marcaide 1982) were used with our standard analysis technique (see, for example, Herring *et al.* 1981) to determine the position of the A quasar as well as the orientation of the Earth (UT1 and pole position) and the location of M, the only one not sufficiently well known from our other VLBI observations.

To determine the relative position of the A and B quasars, we used a multistage procedure. First, we formed the phase-delay-rate observable by differencing the phase-delay rates for the A and B quasars at each epoch for which values of both were available, and, with these observables, we again used our standard analysis procedure (see, also, Shapiro *et al.* 1979) to estimate the relative position of A and B. Second, from this estimate, we predicted the difference phase delays for each epoch for which phase-delay measurements were available for A and B. These predictions were of sufficient accuracy to allow us to determine n' correctly for almost all measurements, thus allowing us to construct the corresponding, mostly unambiguous, difference phase delays [see Eq. (4)]. Some of the difference phase delays were still in error, but by only one or two ambiguity intervals. Third, we removed the structure-phase contributions from these difference delay observables [see Eqs. (1)–(4)] using the brightest CLEAN component as a reference (Marcaide 1982), and, fourth, used the corrected observables to estimate $\Delta\alpha$ and $\Delta\delta$. The postfit residuals showed clearly those errors in n' remaining in the difference observables. Fifth, these errors were removed and the resultant difference delays checked for consistency by subjecting all to the "closure test": the sum of differenced delays obtained simultaneously from each independent closed loop of antenna pairs (Rogers *et al.* 1974) should be almost exactly zero. All the data passed this check. Sixth, we used the corrected observables to again estimate $\Delta\alpha$ and $\Delta\delta$, obtaining postfit residuals that were all smaller than about one twentieth of the ambiguity interval. The statistical standard errors from this analysis are over 400 times smaller than the corresponding uncertainties from the analysis that utilized the difference phase-delay rates.

The data analysis for the July 1980 and November 1979 observations was very similar to the analysis described for the March 1981 observations with the following exceptions: (1) The position of the A quasar was not estimated from either set of data, the position obtained from the March 1981 experiment having been used instead because of its higher expected accuracy; (2) For the correction of the structure-phase contribution, we used our results from March 1981 for the B quasar at λ 3.6 and λ 13 cm and for the A quasar at λ 13 cm since the amount and quality of the earlier data were insufficient for the construction of useful brightness maps. We inferred *a posteriori* that this usage was justified because systematic trends that would have been expected from use of an inadequate model of source structure, were not present in the postfit residuals.

V. RESULTS

Our results for the coordinates of the A quasar, the location of M, and the coordinates of the Earth's spin

TABLE I. Parameters used in analysis of VLBI observables.

Source coordinates[a] (1950.0)						
	Right ascension			Declination		
Name	(hr)	(min)	(s)	(deg)	(min)	(arcsec)
0923 + 392	09	23	55.2943	39	15	23.828
1038 + 528A[b, c]	10	38	43.1205 ± 0.0002	52	49	10.425 ± 0.002

Station coordinates and electrical path length of atmosphere

Name[d]	Cylindrical radius (km)	West longitude (deg)	Distance from equatorial plane[e] (km)	Atmospheric delay (zenith) (ns)
B	4063.232206	− 6.8836561	4900.432515	7.9
D	5204.002092	116.8894679	3677.052301	7.0
G	5003.001571	79.8357523	3944.130869	7.6
K	4700.479739	71.4881411	4296.882102	8.0
M[b]	4862.447432	4.2479652	4115.110773	7.6
O	5085.453720	118.2826645	3838.602933	7.0

Miscellaneous parameters

	Earth tides			Earth rotation[b, c, f]
	Love number			UT1
Precession constant	Radial	Horizontal	Lag angle	(s)
5027″.878 cy⁻¹(1950.0)	0.584	0.045	0 deg	− 0.0019 ± 0.0005

[a] Elliptic aberration removed.
[b] These values were obtained from the analysis of the group-delay observations (see text).
[c] The uncertainties shown are the statistical standard errors, determined by scaling the measurement standard deviations uniformly such that the root-weighted-mean-square of the postfit residuals is unity.
[d] See text for definition of station symbols.
[e] Speed of light: $c = 299792.458$ km/s.
[f] Correction to the 17 March 1981 (smoothed) value obtained from circular D, published by the Bureau International de l'Heure (BIH). The values obtained at this epoch for pole position were consistent, within their large uncertainties, with those of the BIH.

TABLE II. Relative position of 1038 + 528A and B.

Radio wavelength	Epoch of measurement	Position of $B-A$ (1950.0)[a] Right ascension (s)	Declination (arcsec)
3.6 cm	23–24 Nov 1979	2.1205005 ± 0.0000007	27.429246 ± 0.000005
	17–18 Mar 1981	2.1205009 ± 0.0000002	27.429228 ± 0.000003
13 cm	25–26 Jul 1980	2.120434 ± 0.000002	27.42850 ± 0.00003
	17–18 Mar 1981	2.1204408 ± 0.0000006	27.428622 ± 0.000009

[a] Relative to the position in each source of the brightest CLEAN component (Marcaide 1982; Marcaide and Shapiro 1983).

vector obtained from the March 1981 group-delay observations are shown in Table I, along with the values used for other relevant parameters which were obtained from other observations. In Table II we present our estimates of $\Delta\alpha$ and $\Delta\delta$ from the March 1981 observations; these estimates are based on the parameters given in Table I. The statistical standard deviations shown were obtained by increasing the measurement standard errors threefold from their originally assigned, signal-to-noise ratio values in order for χ^2 per degree of freedom to be unity. The root cause for this increase is unknown; the postfit residuals offer few clues (see Fig. 1).

Our estimates of $\Delta\alpha$ and $\Delta\delta$ from the July 1980 and November 1979 experiments are also presented in Table II. It is seen that the results from observations at the same wavelength agree in all cases to within four times the root-sum-square of the individual standard deviations, which are dominated by the low accuracies achieved with the data from the earlier observations. Comparison of the results from the different wavelengths of observation shows that the arclength between the position of the brightest CLEAN component in A and that in B is shorter at λ 13 cm than at λ 3.6 cm by $\sim$ 0".0008, a difference far larger than could be accounted for by statistical errors. Elsewhere we concluded (Marcaide 1982; Marcaide and Shapiro 1983) that (i) this difference is due to the wavelength dependence of opacity, which causes the spatial location of the peak brightness to be wavelength dependent, and (ii) the effect of plasma on this difference is negligible.

What can we conclude about the utility of the high precision we have obtained? We must contrast this nearly *microarcsecond* precision with the *milliarcsecond* dimensions of the source structure to which our observations are sensitive. [The milliarcsecond-dimension hybrid maps we obtained for these sources from our VLBI observations are given and discussed by Marcaide (1982) and by Marcaide and Shapiro (1983) and are not presented here.] The implications are painful. Even if the brightness distributions of the sources were in reality to remain strictly constant and if our interferometer array and schedule of observations, in sidereal time, were to remain the same from one epoch to the next, we might *appear* to be detecting proper motion: Because of differences in equipment performance, the hybrid brightness maps we would produce might be different for different epochs and lead to different corrections and hence to different relative positions. Because map making is still more an art than a science, estimates of true map uncertainties, given those of the data, cannot yet be made satisfactorily. This circumstance could make it difficult to determine whether any detected proper motion were real or an artifact. Moreover, if indeed the brightness distributions do change detectably, as already found for many compact extragalactic radio sources, then we would likely detect apparent proper motions. Even if our reference points were in reality fixed in space, the errors in the differences in the maps obtained from data at different epochs might lead to such apparent motions. It thus may be difficult to use the extraordinary precision already demonstrated to draw any reliable conclusions, at this nearly microarcsecond level of precision,

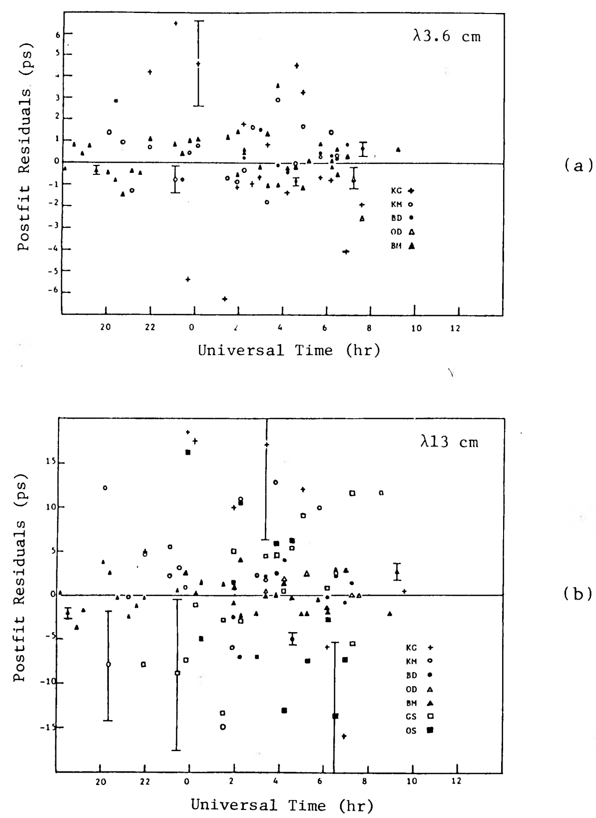

FIG. 1. Typical postfit residuals from the analysis of the difference phase-delay observables from the 17–18 March 1981 VLBI observations of 1038 + 528A, B. (a) λ 3.6 cm; (b) λ 13 cm.

about actual motion of the centers of brightness of components, to say nothing of motion of the centers of mass of these sources. On the other hand, we have demonstrated that astrometry, at least for sources close together on the sky, can be perfected down to limits placed only by knowledge of the brightness distributions of the sources. Thus, if one, and only one, of a pair of sources were noticeably time dependent (perhaps even superluminal), then we would be able to tell, by referring to the position of the other, which parts of the time-varying source, if any, remain stationary at the milliarcsecond level or somewhat below. Further advances may depend on the availability of VLBI arrays that can be used to determine these brightness distributions more accurately, as for example the array proposed in the *Astronomy Survey Committee's Report* (1982).

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