Reports

Precision Geodesy via Radio Interferometry

Abstract. *Very-long-baseline interferometry experiments, involving observations of extragalactic radio sources, were performed in 1969 to determine the vector separations between antenna sites in Massachusetts and West Virginia. The 845.130-kilometer baseline was estimated from two separate experiments. The results agreed with each other to within 2 meters in all three components and with a special geodetic survey to within 2 meters in length; the differences in baseline direction as determined by the survey and by interferometry corresponded to discrepancies of about 5 meters. The experiments also yielded positions for nine extragalactic radio sources, most to within 1 arc second, and allowed the hydrogen maser clocks at the two sites to be synchronized a posteriori with an uncertainty of only a few nanoseconds.*

Very-long-baseline interferometry (VLBI) holds promise for the direct detection of intercontinental drift and for a marked improvement in the measurement of all global motions of the earth's crust (*1*). The promise is a long way from fulfillment. In this report, we present results from the first precision determinations of vector baselines by use of the VLBI technique (*2*).

To estimate the vector separation between two widely spaced antennas by using interferometric observations of distant radio sources, we measure the differences in the arrival times of the signals received at the separate antennas (*3, 1*). The accuracy of such differenced delay measurements is directly proportional to the width of the spectral band over which the observations extend (*4, 5*). To encompass a sufficiently wide band, we have developed frequency-switching equipment (*3*) to permit sequential sampling in frequency. Up to 110 Mhz have been spanned in this manner to yield differenced delays with errors under 1 nsec (approximately 30 cm or less).

Two experiments were performed with each designed to determine the baseline between the 43-m-diameter antenna of the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia, and the 37-m-diameter antenna of the Haystack Observatory in Tyngsboro, Massachusetts. In both experiments hydrogen maser frequency standards and NRAO Mark I recording systems (*6*) were used at the two sites.

In the first experiment, conducted on 11 to 13 January 1969, L-band receivers were used, the system temperature at Haystack being about 250°K and that at NRAO 110°K. A band 110 Mhz wide was sampled in six steps [the total local-oscillator (L.O.) frequencies were 1599.9, 1659.4, 1659.9, 1662.4, 1669.9, and 1709.9 Mhz]. To achieve this wide effective bandwidth by frequency switching, two Hewlett-Packard HP5100 synthesizers at each site were programmed digitally. One was used as the reference for the first L.O., and the other directly as the second L.O. To determine the differenced delay from the fringe phases obtained from the various narrow frequency bands, we measured the necessary phase characteristics of the receivers (*5*).

In the second experiment, conducted in early October 1969, observations were made at both L-band and X-band, but not simultaneously (*7*), the X-band system temperature being about 170°K at each site. Also, an attempt was made to simplify the apparatus. The phase-locked first L.O. was not switched in frequency, nor were the radio-frequency amplifers retuned. A somewhat reduced effective bandwidth of 36 Mhz was achieved by switching only a single synthesizer used directly as the second L.O. Data were obtained at a set of X-band frequencies (7797.1, 7823.1, 7827.1, 7829.1, 7832.1, and 7833.1 Mhz) and at a similarly spaced set of L-band frequencies that yielded good delay resolution even though only six sample bands were used (*8*). The highest sidelobes of the delay resolution function (*3*) had an amplitude 67 percent of that of the main lobe. By contrast, the amplitude of the highest sidelobes in the January experiment was 80 percent of that of the main lobe.

Each pair of magnetic-tape recordings of the signals from the radio

Table 1. Coordinates of radio sources from VLBI experiments. The origin of right ascension was defined by those of 3C345 and CTA102 in solution A and by those of 3C345 and 3C454.3 in solution B (see Table 2). The coordinate changes shown are in the sense of new minus old. The errors given are the formal standard errors based on the postfit residuals. The "true" standard errors may be severalfold larger. The relatively large uncertainties in the coordinates determined from solution A for PKS 1127-14 and 3C279 are due mostly to the poor distribution in time of the observations of each.

Source	VLBI solution	A priori position (1950.0 epoch) Right ascension (hr	min	sec)	Declination (deg	min	sec)	Reference	Right ascension change (arc sec)	Declination change (arc sec)	Differenced delay observations (No.) VLBI A	VLBI B
CTA21	A	3	16	09.12	16	17	40.3	(*20*)	+0.0 ± 0.2	−0.2 ± 0.4	5	
3C84	B	3	16	29.57	41	19	52.1	(*21*)	−1.4 ± 0.1	−0.8 ± 0.06		36
3C120	B	4	30	31.60	5	14	59.5	(*20*)	−0.9 ± 0.1	+0.0 ± 0.2		19
3C147	A	5	38	43.52	49	49	42.4	(*20*)	−1.4 ± 0.2	+0.5 ± 0.2	5	
4C39.25	B	9	23	55.34	39	15	24.4	(*22*)	−1.5 ± 0.1	−0.8 ± 0.2		20
PKS 1127-14	A	11	27	35.65	−14	32	54.8	(*20*)	+1.3 ± 0.9	−2.3 ± 2.0	6	
3C273B	A	12	26	33.29	2	19	42.0	(*23*)	−1.0 ± 0.2	+1.9 ± 0.6	12	
3C273B	B	12	26	33.29	2	19	42.0	(*23*)	−1.0 ± 0.1	+1.4 ± 0.3		32
3C279	A	12	53	35.82	−5	31	07.6	(*24*)	−0.3 ± 0.7	+0.6 ± 1.5	8	
3C279	B	12	53	35.82	−5	31	07.6	(*24*)	+0.3 ± 0.2	−0.9 ± 0.6		12
3C345		16	41	17.57	39	54	10.6	(*20*)			3	23
CTA102		22	30	07.77	11	28	22.8	(*20*)			5	
3C454.3	A	22	51	29.50	15	52	53.7	(*20*)	−0.0 ± 0.2	−0.0 ± 0.2	7	31
											51	173

sources, made simultaneously at the two sites, was of approximately 3 minutes duration and constituted one observation. These observations were reduced in three stages on a general purpose digital computer. In the first, or data compression stage, the separate 16-bit segments (approximately 22 μsec) of data from the participating sites were cross-correlated by using seven adjacent delays centered on the a priori value. In the second stage, the differenced delay and delay-rate observables were estimated for each pair of tapes (*5*). Estimates were also made of the statistical measurement errors for each pair of tapes through separate processing of interleaved portions of the data. The standard errors in the differenced delay measurements were found to vary from about 0.5 to 2 nsec, the average being somewhat under 1 nsec in both experiments (*9*). The errors in differenced delay rate were about 1 and 0.2 psec/sec or less for the L-band and the X-band measurements, respectively. Both delay and delay-rate errors were in reasonably good accord with the theoretical calculations.

In the final program, estimates of the model parameters were made from the observables with a weighted-least-mean-square algorithm. These parameters included: (i) the relative location of the interferometer elements, with one site taken as the origin (*10*); (ii) the source positions, with the right ascension of one source taken as the origin of right ascension (*11*); and (iii) the coefficients of a power series that describe clock synchronization as a function of time. In the determination of the theoretical values of the observations, the program includes the effects of precession, nutation, polar motion, and deviations of U.T.1 (universal) from A.1 (atomic) time, as well as of the atmosphere and ionosphere (*12*).

The data from the 1969 experiments were analyzed in many different ways to estimate the components of the baseline vector, primarily to expose possible systematic errors and to develop a reliable indication of the true accuracy of the results. For independent comparison, we had values from special geodetic surveys; the baselines determined from these surveys coincided at each end with the precise positions to which the interferometric data apply.

We now discuss, in turn, the results from the January and October experiments. The January data set consisted of 51 differenced delay and 52 delay-rate observations, but the delay rates have little effect on the baseline solution. From these data we estimated 25 parameters: 3 components of the baseline vector, 10 clock parameters (*13*), and 12 source coordinates (*14*) (see Table 1). The baseline solution, labeled VLBI A, is given in Table 2. The postfit differenced delay and delay-rate residuals exhibit no obvious systematic trends. All but three of the delay residuals are under 1 nsec; the delay-rate residuals are also quite small, mostly under 2 psec/sec. Since the number of delay observations is little more than twice the number of parameters, we reduced the number of unknowns to 13 by deleting the seven observations obtained on 11 January and by using initial coordinates for all sources except 3C273 and 3C147 (*15*). The vector baseline obtained was within 1 m of the VLBI A baseline in all components.

Table 2. Haystack-Green Bank baseline from VLBI experiments. The reference point at Haystack is the intersection of the azimuth and elevation axes of the antenna. At Green Bank, the reference point is the intersection of the polar axis with a line perpendicular to both the polar and declination axes. The baseline vector points from Haystack to Green Bank. The hour angle is measured from the Haystack meridian, defined by the International Latitude Service mean pole of 1900–1905; the declination is measured from a plane that passes through Haystack and is parallel to the equator defined by this mean pole. The uncertainties shown are the formal standard errors, based on the postfit residuals. The "true" standard errors may be severalfold larger due to systematic errors. The differences in all baseline components are expressed in meters to facilitate comparison.

Source	Length (m)	Hour angle (hr	min	sec)	Declination (deg	min	sec)
Geodetic survey	845,129.7	4	44	9.81	−24	40	12.0
VLBI A (January 1969)	845,132.1 ± 0.5	4	44	9.68 ± 0.01	−24	40	12.8 ± 0.2
VLBI B (October 1969)	845,130.8 ± 0.3	4	44	9.72 ± 0.005	−24	40	13.2 ± 0.2
VLBI A − VLBI B	1			−2 m		2 m	
Geodetic − VLBI B	−1			5 m		5 m	

The October data obtained on the Haystack–Green Bank baseline consisted of 173 differenced delay and 187 delay-rate measurements, about 70 percent from X-band and the remainder from L-band observations. Here 31 parameters were estimated: 3 baseline coordinates, 18 clock parameters, and 10 source coordinates (*16*). The resultant baseline solution, VLBI B, is also given in Table 2. The postfit differenced delay and delay-rate residuals are mostly under 2 nsec and 1 psec/sec, respectively. Some small systematic trends are visible; these may well be due to some as yet unrecognized clock discontinuities that occurred during some of the days of observation (*17*).

The agreement between the baselines obtained from the January and October data is quite good. All the baseline components are consistent to within 2 m, even though the solutions were not specially chosen for the property. The main limitations on the baseline accuracy achieved in these experiments are imposed, in their most probable order of importance, by the clock discontinuities, the measurement accuracy, and the propagation-medium corrections; means now exist to decrease substantially the effects of each. Further analysis of the 1969 data may also disclose additional small systematic errors that might be affecting our results (thus, Table 2 shows the hour angle difference to be nearly four times larger than the combined standard error).

The VLBI solutions are compared in Table 2 with the results from a special geodetic survey (*18*). The baseline lengths agree to within 2 m. The comparison in direction shows a discrepancy of about 5 m. It is difficult to obtain a reliable estimate of the accuracy of the survey results. But when account is taken of the possible differences in orientation of the coordinate systems used for VLBI and for the survey, as well as of the effect of internal survey errors (*19*), we find that agreement to better than 3 m cannot be expected. The "extra" 2 m have yet to be explained.

None of the corrections to the source coordinates in the VLBI B solution and few of those in the VLBI A solution (see Table 1) are greater than 1.5 arc seconds. The adjusted coordinates of the two sources estimated in both the VLBI A and the VLBI B solutions agree to within the sum of the formal standard errors. The predominantly negative corrections to the right ascensions of the sources probably indicate that the (arbitrary) origin we chose for this coordinate (*11*) differs from the conventional origin, determined by the equinox, by a major fraction of an arc second. However, in view of the possible presence of small systematic errors, it is premature to attach much significance to any of our coordinate adjustments.

In both experiments the estimates of the coefficients of the power series representing differences in clock readings at the two sites provided a posteriori synchronization of the clocks. The corrections were of the order of 250 μsec in January and 10 μsec in October, with formal standard errors of a few nanoseconds or less. Thus, remote clock synchronization at the nanosecond level can be accomplished through VLBI. On a time scale of hours, each of the hydrogen maser standards was stable to at least a few parts in 10^{13} in these two experiments. Because of the discontinuities, little of use can be said about stabilities on longer time scales.

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References and Notes

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4. These differenced delays are determined from the variation of fringe phase with frequency and therefore are group delays, not phase delays.
5. For a detailed discussion, see H. F. Hinteregger, thesis, Massachusetts Institute of Technology (1972).
6. C. C. Bare, B. G. Clark, K. I. Kellermann, M. H. Cohen, D. L. Jauncey, *Science* **157**, 189 (1967).
7. We intended to eliminate effects of charged particles on the delay and delay-rate measurements by taking observations simultaneously at L-band and at X-band. However, the necessary modifications to the configuration at Haystack could not be implemented for this experiment.
8. The set of relative frequencies chosen, [0,1,4, 6,24,36] Mhz, constitutes two overlapping Arsac arrays [J. Arsac, thesis, University of Paris (1966)]. One array has a unit spacing of 1 Mhz and the other a unit spacing of 6 Mhz; the arrays have two elements, 0 and 6 Mhz, in common. The Arsac array, [0,1,4,6] Mhz, uniformly samples all spacings from 1 to 6 Mhz.
9. The measurement errors are inversely related to the correlation amplitudes (and to the effective bandwidth). In the January experiment, for example, these varied from 0.3 to 1 percent and were quite constant for each source observed. The corresponding spread in differenced delay errors was from 1.5 to 0.5 nsec. The measurement errors in the October experiment at X-band were, on the average, not much larger, because the correlation amplitudes were about a factor of 2 higher, and thereby almost compensated for the decrease by a factor of 3 in the effective bandwidth.
10. The VLBI observations of extragalactic radio sources are sensitive to changes in both the length and the direction of each baseline, but not to a parallel displacement. Therefore, with no loss in generality, we can take the coordinates of one site as fixed.
11. The plane normal to the earth's rotation axis defines the declination origin, but there is no corresponding natural way to define the origin of right ascension for VLBI observations. We fixed the right ascension of at least one source at its a priori value for this analysis; for longer baselines, where the source coordinates play a relatively more important role, an a priori covariance matrix would be employed.
12. The neutral atmosphere was modeled in the manner described by H. Hopfield [*J. Geophys. Res.* **74**, 4487 (1969)]; the corrections to the observables were determined for the measured or extrapolated values of surface temperature, pressure, and humidity for each site. The ionospheric corrections involved a simple model that employed the values for the integrated electron content deduced by J. Klobuchar (personal communication) from observations of the Faraday rotation of radio signals transmitted from a satellite in synchronous orbit. The individual atmospheric corrections varied in magnitude from about 0.1 to 3 nsec for the differenced delay measurements, and from about 0.05 to 1 psec/sec for the corresponding delay-rate data. The ionospheric corrections varied in magnitude over approximately the same range for the L-band observations, and were about 20 times lower at X-band.
13. The hydrogen maser frequency standards in use at both sites were in a relatively poor state of repair at the time of this experiment. As a result, a number of discontinuities in clock offset occurred that required parametrization.
14. All source coordinates were estimated except those for 3C345 and CTA 102 (see Table 2) since their positions previously determined by radio and optical methods agreed to within 0.2 arc second (*20, 24*).
15. The coordinates for 3C273 and 3C147 were not held fixed at their initial values (*20, 23*) since we believed that they were the most likely to be in error. In the case of 3C273, our belief was confirmed after the completion of our analysis. The lunar occultation data on which the entry for 3C273 in Table 2 was based were re-reduced with more data added [C. Hazard, J. Sutton, A. N. Argue, S. M. Kenworthy, L. V. Morrison, C. A. Murray, *Nature* **233**, 89 (1971)] and yielded a revised position in close agreement with our result. There is no significant difference in declination; the difference in right ascension is 0.5 arc second with respect to the new occultation value, but only 0.15 arc second with respect to one of the two optical determinations presented by Hazard *et al.* There are no new determinations with which to compare the coordinates of 3C147, which is known to have a complex structure at least on the level of a few tenths of an arc second [W. Donaldson and H. Smith, *Mon. Not. Roy. Astron. Soc.* **151**, 253 (1971)].
16. The coordinates of 3C345 and 3C454.3 were held fixed at Wade's positions [see Table 2 and (*14*)]. A separate clock offset in epoch and in rate for each day's observations was used, yielding the total of 18 clock parameters.
17. Again in October, the hydrogen maser at Green Bank was not in good health (*13*); at Haystack a maser built by H. Peters was borrowed from Goddard Space Flight Center for the occasion. Since 1969 the masers permanently located at the two sites have been refurbished.
18. The survey was performed under the direction of the First Geodetic Survey Squadron, Warren Air Force Base, Wyoming.
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25. We thank J. K. Alexander, N. Brenner, L. W. Brown, J. C. Carter, J. Edrich, R. J. Greenberg, E. Johnson, J. Klobuchar, H. H. Malitson, C. F. Martin, H. Peters, R. Preston, R. Reasenberg, and the staffs of the Haystack and National Radio Astronomy Observatories, and of the Computer Facility at Goddard Space Flight Center for their important aid. We also thank W. E. Howard III of the National Radio Astronomy Observatory and D. L. Jauncey of Cornell University for the use of the Mark I VLBI recording systems. The experimenters at Massachusetts Institute of Technology were supported in part by the National Science Foundation and in part by the Advanced Research Projects Agency. Research at the Haystack Observatory is supported by NSF grant GP-25865 and NASA grant NGR22-174-003, contract NAS-7830. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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Quaternary Paleotemperatures and the Duration of the High-Temperature Intervals

Abstract. *Oxygen isotopic analysis of Caribbean cores P6304-4 and P6304-7, and the close correlation of these cores with other Caribbean and Atlantic cores previously analyzed, make possible the reconstruction of a paleotemperature curve of considerable detail. This curve demonstrates again the unusualness of the present interval of high temperature within the framework of Quaternary climatic evolution, and the need for a close study of man's impact on climate.*

According to the classical picture, still adopted in some contemporary textbooks (*1*), the Quaternary consisted of four major glaciations each lasting approximately 100,000 years, separated by interglacials ranging in length from 100,000 to 300,000 years. The classical picture, as recorded in (*2*), is illustrated in Fig. 1.

Oxygen isotopic analyses of deep-sea cores, together with absolute dating by the ^{14}C and $^{230}Th/^{231}Pa$ methods, has revealed a completely different picture (*3–6*), with more numerous,