Reports

Transcontinental Baselines and the Rotation of the Earth Measured by Radio Interferometry

Abstract. *Nine separate very-long-baseline interferometry (VLBI) experiments, carried out in 1972 and 1973 with radio telescopes 3900 kilometers apart, yielded values for the baseline length with a root-mean-square deviation about the mean of less than 20 centimeters. The corresponding fractional spread is about five parts in 10^8. Changes in universal time and in polar motion were also determined accurately from these data; the root-mean-square scatter of these results with respect to those based on optical methods were 2.9 milliseconds and 1.3 meters, respectively. Solid-earth tides were apparently detected, but no useful estimate of their amplitude was extracted.*

The accurate measurement of distance has been of concern to civilized man since before the erection of the pyramids at Gizeh. The techniques used to attack this problem have evolved to a remarkable level of sophistication, especially during the last decade. One of the most promising of the new techniques, very-long-baseline interfrometry (VLBI), makes it possible to determine the vector separations of radio telescopes with high accuracy from interferometric observations of extragalactic radio sources. In this report, we present the results from a series of nine such VLBI experiments spanning the time interval from April 1972 to March 1973 and involving a single transcontinental baseline that extends from the antenna (37 m in diameter) of the Haystack Observatory, Westford, Massachusetts, to the antenna (64 m in diameter) of the Deep Space Network in Goldstone, California (*1*).

Each experiment encompassed a period of from 15 to 26 hours, with most being of 24 hours' duration. On the average, about 15 separate 3-minute observations were made of each of about ten radio sources in a single experiment. During each observation the radio receivers were switched (*1, 2*) rapidly among a number of channels, each 360 khz wide, spanning a total bandwidth of 23 Mhz (46 Mhz in the last experiment), centered near 7850 Mhz. The signals received at each site were recorded digitally on magnetic tape (*3*), with a hydrogen maser serving as the standard of time and frequency.

With this system we were able to determine, from a single observation, the differences between the group delays and the phase-delay rates of the signals propagating from the source to each site with errors of less than or equal to 0.15 nsec and 0.1 psec sec^{-1}, respectively ($\lesssim$ 5 cm in equivalent distance and 0.003 cm sec^{-1} in equivalent velocity), for any source with a correlated flux density of 3 jansky or more (1 jansky = 10^{-26} watt m^{-2} $hertz^{-1}$).

The delays and delay rates obtained from each separate experiment were analyzed to determine the components of the vector baseline, the source positions (*4*), the coefficients of a polynomial with two terms representing the relative epoch and rate differences of the clocks, and the zenith electrical path length of the atmosphere over each site (*5*). Changes in the relative weightings of the observations or increases beyond two in the number of terms in the clock-difference polynomial were found to yield results differing in almost all cases by less than twice the formal standard errors.

The baseline components from each experiment for an elevation angle–dependent weighting of the observations are given in Table 1. The baseline lengths are in remarkably good agreement, having a root-weighted-mean-square deviation about the weighted mean (hereinafter termed "rms") of less than 20 cm; the corresponding fractional spread is about five parts in 10^8. The baseline lengths from the last four experiments, which were superior to the others in the number of observations and the distribution in the sky of the sources observed, show an even smaller scatter. By contrast, the baseline directions for all experiments are much more widely spread. Such a pattern could be anticipated: any errors in the values of parameters used to describe the changes in the earth's orientation (*6*) with respect to the radio sources would manifest themselves in changes in baseline direction from experiment to experiment. However, the baseline length is invariant under rotation and so would be unaffected.

In an effort to uncover any such errors in the description of the earth's orientation, we reprocessed the data from all nine experiments simultaneously, taking the optically determined orientation of the earth—specifically the values of polar motion and universal time—for 29 August 1972 as a reference and estimating the relative values for the other dates (*7*). These results for polar motion and variations in universal time are also shown in Table 1 and are compared there with the corresponding smoothed values determinted by the Bureau International de l'Heure (BIH) and, for universal time, with the U.S. Naval Observatory (USNO) values as well (*7*). Except for the 27 June 1972 experiment which was the least reliable (see below), the VLBI results agree reasonably well with those determined by the BIH, even though the BIH data for polar motion and universal time were each smoothed over periods of time long compared to the approximately 1 day consumed by each VLBI experiment. In particular, the rms spread of the difference is 2.9 msec for universal time and 1.3 m for the x-component of the polar motion (*8*). The small bias of −2.8 msec between the BIH and the VLBI determinations of universal time is clearly a function of the choice of the reference experiment. The bias between the BIH and the USNO values of universal time is nearly 5 msec for this limited set of data, with the largest single difference (11.4 msec) occurring coincidentally on the reference date of 29 August, 1972.

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Table 1. Results from nine VLBI experiments.

Date at start of observations	Baseline*†			Universal time (UT.1)†		x-Component of polar motion (8), BIH−VLBI (m)
	Length (m)	Hour angle (hr × 10⁹)	Declination (deg × 10⁵)	USNO−VLBI (msec)	BIH−VLBI (msec)	
14 Apr. 1972‡	3,899,998.51 ± 0.22	7,051,413.6 ± 0.3	−914,473.4 ± 1.8	10.7	1.1 ± 0.8	2.2 ± 0.3
9 May 1972	3,899,997.61 ± 0.76	7,051,414.6 ± 2.8	−914,487.1 ± 5.2	7.7	−3.2 ± 1.2	−1.6 ± 0.6
29 May 1972	3,899,998.64 ± 0.33	7,051,415.4 ± 0.8	−914,483.0 ± 1.4	3.6	−4.9 ± 0.8	−1.2 ± 0.3
6 June 1972	3,899,998.60 ± 0.45	7,051,413.7 ± 1.1	−914,482.8 ± 2.2	5.5	−1.6 ± 1.3	−2.0 ± 0.5
27 June 1972§	3,899,998.56 ± 0.28	7,051,412.1 ± 0.7	−914,477.8 ± 1.4	−4.9	−10.1 ± 4.8	−4.4 ± 1.5
29 Aug. 1972	3,899,998.77 ± 0.09	7,051,415.9 ± 0.3	−914,481.6 ± 0.6			
7 Nov. 1972	3,899,998.99 ± 0.15	7,051,415.5 ± 0.4	−914,482.1 ± 1.1	2.2	−1.5 ± 0.8	0.3 ± 0.2
4 Feb. 1973	3,899,998.83 ± 0.10	7,051,413.7 ± 0.4	−914,481.6 ± 0.4	6.3	0.4 ± 0.8	0.6 ± 0.2
30 Mar. 1973	3,899,998.99 ± 0.11	7,051,416.1 ± 0.3	−914,484.7 ± 0.5	3.2	−6.4 ± 0.6	−1.8 ± 0.2
Mean ± rms‖	3,899,998.82 ± 0.16	7,051,414.9 ± 1.2	−914,482.2 ± 2.0	5.1 ± 2.9	−2.8 ± 2.9	−0.2 ± 1.3
Survey−VLBI¶	−1.60	18.0	4.4			

* The baseline vector points from the intersection of the azimuth and elevation axes at Haystack to the corresponding point on the Goldstone antenna. The hour angle of the baseline vector is measured westward from the meridian that passes through the Haystack reference point and the mean pole of 1900–1905, defined by the International Latitude Service; the declination is with respect to a plane that passes through the Haystack reference point and is parallel to the equator defined by this mean pole. For this baseline, 10^{-6} hour $\simeq$ 1 m and 10^{-5} deg $\simeq$ 0.7 m. † The baselines were determined from separate solutions in which UT.1 and polar motion were both interpolated from the smoothed USNO and BIH values, respectivtly (7). The VLBI values for UT.1 and polar motion were obtained in a combined solution in which UT.1 and polar motion were set in accord with the USNO and BIH values only for 29 August 1972. The difference between the BIH and VLBI values (BIH − VLBI) for UT.1 (7) were obtained by adding the BIH − USNO values to the corresponding ones from the USNO − VLBI set and then subtracting 11.4 msec since the BIH − USNO value for 29 August 1972 is 11.4 msec (note that 1 msec $\simeq$ 0.46 m). All standard errors shown refer to the VLBI solutions and were obtained on the basis of setting the rms of the weighted postfit residuals equal to unity. ‡ For another purpose, about half the allotted time in these experiments was spent observing pairs of radio sources, the members of each being in nearly the same direction in the sky. These distributions of observations caused the results to be more sensitive to systematic errors. § There is a 5-hour gap in the data collected for this experiment (see text). ‖ Weighted mean and rms deviation. The mean for the baseline does not differ significantly from the result obtained from the combined solution. ¶ The survey values for each site, referred to the 1927 North American Datum and the 1866 Clarke Ellipsoid, were provided by R. A. Ballew (Defense Mapping Agency Aerospace Center, St. Louis, Missouri). The large difference in hour angle between the survey and VLBI values may be attributable to a difference in reference systems.

The weighted mean of the results for the baseline components are also compared in Table 1 with the corresponding components determined from classical land surveys of the two sites. The baseline lengths agree remarkably well; the large difference in the baseline hour angles may be due at least in part to a difference in the orientations of the reference systems, but this possibility has not yet been explored. We also have not yet made any attempt to estimate the magnitude of the solid-earth tides, which have a maximum predicted effect on the delay observable of about 0.5 nsec ($\simeq$ 15 cm). However, it appears that we have detected their influence since the rms of the postfit residuals for the 29 August 1972 experiment—the one most suitable for such detection (see below)—were reduced by 14 percent when the tidal effects on the theoretical value of the observable were included (*9*).

For all the analyses described, the postfit residuals exhibit some systematic trends, with those from 27 June 1972 being largest, partly because of a 5-hour gap in the data for this experiment. The rms values of these sets of residuals range from slightly above the level expected solely from signal-to-noise considerations up to severalfold greater (*10*). Contributions to such systematic errors stem primarily from inadequacies in the model for the propagation medium, drifts in the phase delays in the receiver systems, and unmodeled variations in the clock differences. It was not possible in these experiments to separate reliably the contributions from each of these sources of error (*11*).

In future experiments we will be able to improve significantly the phase calibration of the VLBI instrumentation with equipment that has recently been installed at both sites. We also anticipate that two hydrogen-maser frequency standards might soon be available at each site to provide a partial check on clock performance.

Farther in the future lies the possibility of monitoring the effects of the propagation medium. We require the capability to observe simultaneously at two widely separated frequency bands in order to determine the electrical path length of the ionosphere, and we intend to use a water-vapor radiometer system (*12*), in conjunction with surface meteorological data, to determine the corresponding length added by the neutral atmosphere at each site. With these modifications we expect to reduce the errors in baseline estimates to the centimeter range (*13*).

We close with a remark on the statement, often repeated by some VLBI enthusiasts, that the absolute accuracy achievable in baseline determinations is virtually independent of the baseline length. This statement contrasts with the fact of life known to all geodesists: uncertainties always increase with increasing baseline length. How can this apparent paradox be resolved? In VLBI, the accuracy of the measurements of delays and delay rates may indeed be independent of baseline length. But the accuracy of the baseline deduced from such measurements will depend importantly on its length. As the length increases, uncertainties in the model of the propagation medium, the source positions, the source structures (*13*), and the precession, nutation, rotation, polar motion, and solid-body tides of the earth all have increasingly important effects on the accuracy of the baseline determination. Thus, the reduction of errors in this determination to the centimeter range with VLBI, although feasible, is more difficult to accomplish for transcontinental than for shorter baselines.

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References and Notes

1. For results from two 1969 VLBI experiments over an 845-km baseline, see H. F. Hinteregger *et al.*, *Science* **178**, 396 (1972). A. R. Whitney [thesis, Massachusetts Institute of Technology (1974)] has described a three-site transcontinental VLBI experiment carried out in 1969. Similar techniques were also used in 1972 by a group from the Jet Propulsion Laboratory [J. B. Thomas, J. L. Fanselow, P. F. MacDoran, D. J. Spitzmesser, L. Skjerve, *Jet Propulsion Lab. Tech. Rep. 32-1526* (1974), p. 36] to determine a 16-km baseline.
2. A. E. E. Rogers, *Radio Sci.* **5**, 1239 (1970).
3. We used the Mark I recording system described by C. Bare, B. G. Clark, K. I. Kellermann, M. H. Cohen, D. L. Jauncey, *Science* **157**, 189 (1967).
4. A. E. E. Rogers, C. C. Counselman III, H. F. Hinteregger, C. A. Knight, D. S. Robertson, I. I. Shapiro, A. R. Whitney, T. A. Clark, *Astrophys. J.* **185**, 801 (1973).
5. The theoretical expressions used to model the observables contained the standard descriptions for the motions of the sites with respect to an inertial reference frame [see, for example, M. E. Ash, *Lincoln Lab. Tech. Note 1972-5* (1972)]. We intend to refine this model by incorporating the small diurnal effects usually omitted; however, their omission does not significantly affect the interpretation of the data discussed herein.
6. Here we refer only to variations in the speed of the earth's rotation and to shifts in the orientation of the earth with respect to its spin axis, the latter's direction in inertial space being characterized with sufficient accuracy for the present purposes (*4*). For the first published discussion of the determination of the earth's rotation via VLBI, see T. Gold [*Science* **157**, 302 (1967)] and G. J. F. MacDonald (*ibid.*, p. 304).
7. For the separate baseline determinations, we used the smoothed values for polar motion as determined by the BIH and the smoothed values for the variation of universal time (UT.1) with respect to atomic time as determined by the USNO. Both sets of data are tabulated at 10-day intervals in the *U.S. Nav. Observ. Time Service Announce. (Ser. 11) No. 221* (30 July 1973) and *No. 222* (22 Aug. 1974). A four-point Everett formula was used to interpolate between the tabular values. These same smoothed values were used in the comparison with the results from the simultaneous solution; in addition, for the comparison of the UT.1 values with the corresponding BIH values, we used the smoothed values of the latter as tabulated at 5-day intervals in the *Bur. Int. Heure Circ. D65–D68* (1972–1973), and interpolated with the four-point formula.
8. Our baseline is sensitive to only one component of polar motion, almost precisely the conventional "*x*-component."
9. We modeled the solid-earth tides using the constants given in table 3a in P. Melchoir, *Earth Tides* (Pergamon, Oxford, 1966), p. 33. The resultant computer program used to calculate these tides was found to be in reasonably good agreement with one provided by J. C. Harrison (University of Colorado, Boulder): The maximum difference was less than 10 percent of the maximum effect on the delay observable.
10. The smallest postfit residuals, obtained on 29 August 1972, were 0.25 nsec and 0.2 psec sec^{-1} rms for the delays and delay rates, respectively. The largest corresponding rms values, 1.4 nsec and 0.4 psec sec^{-1}, accompanied the 27 June 1972 experiment.
11. Several attempts were made in the analysis to isolate these various contributions. (i) The postfit residuals were studied as a function of elevation angle to separate errors introduced by the propagation medium, but no clear-cut pattern was found. (ii) New observables were formed from pairs of the original observables by taking the differences and sums of adjacent observations. By "down weighting" in a new analysis the "sum" observables, which would be affected by the long-term (> 30 minutes) relative drifts in the clocks at the two sites, with respect to the "difference" observables, which would be sensitive mainly to the short-term (10 to 20 minutes) relative drifts, we hoped to uncover inadequacies in our model of the long-term behavior of the clocks used at the two sites. However, the postfit residuals for the difference observables were not sufficiently small with respect to those for the sum observables to allow us to draw any reliable conclusions about the contribution of clock errors to our results.
12. See, for example, L. W. Schaper, D. H. Staelin, J. W. Waters, *Proc. Inst. Electr. Electron. Eng.* **58**, 272 (1970).
13. For fractional errors of five parts in 10^9 or less, source structure at the milliarcsecond level must be taken into account [see, for examples, C. A. Knight, D. S. Robertson, A. E. E. Rogers, I. I. Shapiro, A. R. Whitney, T. A. Clark, R. M. Goldstein, G. E. Marandino, N. R. Vandenberg, *Science* **172**, 52 (1971); A. R. Whitney, I. I. Shapiro, A. E. E. Rogers, D. S. Robertson, C. A. Knight, T. A. Clark, R. M. Goldstein, G. E. Marandino, N. R. Vandenberg, *ibid.* **173**, 225 (1971); M. H. Cohen, W. Cannon, G. H. Purcell, D. B. Shaffer, J. J. Broderick, K. I. Kellermann, D. L. Jauncey, *Astrophys. J.* **170**, 207 (1971); and I. I. Shapiro *et al.*, *ibid.* **183**, L47 (1973)].

14. We thank J. I. Levine for the design, construction, and checkout of the digital correlator used in the data reduction. We also thank R. A. Ballew, G. Catuna, R. Clauss, C. F. Martin, L. Skjerve, and the staffs of the Haystack Observatory and the Goldstone Tracking Station for their indispensable aid. The experimenters at the Massachusetts Institute of Technology and the Haystack Observatory were supported in part by the Advanced Research Projects Agency and the National Science Foundation under grant GA-36283X. This report 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. Radio astronomy programs at the Haystack Observatory are conducted with support from the National Science Foundation under grant GP-25865.

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Io: A Surface Evaporite Deposit?

Abstract. *A model is suggested for Io's surface composition involving evaporite salt deposits, rich in sodium and sulfur. According to this model, these deposits were produced as a result of the migration of salt-saturated aqueous solutions to Io's surface from a warm or hot interior followed by loss of the water to space. This model satisfies cosmochemical constraints based on Io's initial composition, current density, and thermal history. Salt-rich assemblages are easily derivable from the leaching of carbonaceous chondritic material; the chemical and optical properties of such deposits, after modification by irradiation, can be used to explain Io's overall albedo and spectral reflectance, its dark reddish poles, and the observed sodium emission as well as or better than other currently suggested materials.*

Any hypothesis for Io's surface composition must explain the spectral curves of Io and the other Galilean satellites in a manner consistent with what is known of their cosmochemical setting in the solar system. Io has long been noted for its unusual optical properties, particularly its high visual albedo and its very low blue and ultraviolet reflectance (*1, 2*). The high albedo, polarimetric evidence (*3*), and the high derived value for the phase integral ($q \sim 0.7$) (*1, 4*) all suggest that Io's surface is covered by low-opacity, multiply scattering material. We hypothesize that the surface of Io is largely covered with an evaporite salt deposit, produced by the migration to the surface of salt-rich aqueous solutions from Io's interior with subsequent water loss to space from the surface. First, we will discuss relevant data from mineralogical and chemical studies of meteorites which suggested our (evaporite) hypothesis. Then we will compare the visible and near-infrared spectrum of Io with our spectra for laboratory samples that seem appropriate for testing our hypothesis. Finally, we will show that our hypothesis is consistent with what is known of the cosmochemical history of the Galilean satellites.

Studies of the mineralogy and chemistry of carbonaceous chondritic meteorites would appear to be pertinent to Io since models for temperature and pressure gradients in the preplanetary nebula (*5*) and derivative chemical models for the initial condensation of solid material (*6*) suggest that carbonaceous chondritic material condensed in the asteroid belt and beyond. Supportive evidence from a comparison of asteroid and meteorite spectra has recently been reported (*7*).

Meteoritical studies are supportive of our hypothesis in that they provide direct evidence of salt production in the parent bodies of carbonaceous chondrites (*8*). In the type I carbonaceous chondrites, epsomite ($MgSO_4 \cdot XH_2O$), bloedite ($MgSO_4 \cdot Na_2SO_4 \cdot XH_2O$), and gypsum ($CaSO_4 \cdot 2H_2O$) have been identified (*8*). In some specimens salt deposits virtually fill the pores, and in some specimens of the Orgueil meteorite up to 15 percent by weight of epsomite is present (*8*). Moreover, studies by Edwards and Urey of the alkali metals in the various types of chondrites suggested to them that the