RECENT RESULTS OF RADIO INTERFEROMETRIC DETERMINATIONS OF A TRANSCONTINENTAL BASELINE, POLAR MOTION, AND EARTH ROTATION

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ABSTRACT

Radio interferometric observations of extragalactic radio sources have been made with antennas at the Haystack Observatory in Massachusetts and the Owens Valley Radio Observatory in California during fourteen separate experiments distributed between September 1976 and May 1978. The components of the baseline vector and the coordinates of the sources were estimated from the data from each experiment separately. The root-weighted-mean-square scatter about the weighted mean ("repeatability") of the estimates of the length of the 3900 km baseline was approximately 7 cm, and of the source coordinates, approximately 0".015 or less, except for the declinations of low-declination sources. With the source coordinates all held fixed at the best available, a posteriori, values, and the analyses repeated for each experiment, the repeatability obtained for the estimate of baseline length was 4 cm. From analyses of the data from several experiments simultaneously, estimates were obtained of changes in the x component of pole position and in the Earth's rotation (UT1). Comparison with the corresponding results obtained by the Bureau

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International de l'Heure (BIH) discloses systematic differences. In particular, the trends in the radio interferometric determinations of the changes in pole position agree more closely with those from the International Polar Motion Service (IPMS) and from the Doppler observations of satellites than with those from the BIH.

For the past several years, our group has been involved in a major effort to improve the quality of data obtained by very-long-baseline interferometry (VLBI) through development of a third generation system referred to as the Mark III system. Portions of this system are presently in operation, and we expect the system to be in full operation by the end of 1979. The major improvements in the hardware and software already implemented can be cataloged as follows:

First: the use of wide-band parametric amplifiers which allow bandwidths of about 300 MHz to be synthesized, a tenfold increase over the previous limit. The significance of this increase in bandwidth lies in the fact that the uncertainty in the measurement of interferometric group delay is inversely proportional to the total bandwidth.

Second: the use of surface meteorological measurements with algorithms supplied by J. Marini of NASA's Goddard Space Flight Center. This combination has resulted in a significant decrease in the level of systematic errors caused by atmospheric effects.

Third: the use of equipment to calibrate instrumental effects, in particular the effect of the contribution to the measured delay of the path from the antenna feed horn to the recording apparatus. The uncertainty in such instrumental effects has thereby been reduced to the level of a few pico-seconds.

Fourth: the inclusion of several geophysical effects, resulting from the nonrigidity of the Earth, in the analysis programs (Woolard, 1959; Melchior, 1971; Guinot, 1970, 1974). These effects have an amplitude of a few hundredths of an arc second or less. Also we employed the value of the precession constant from the paper by Lieske _et_ _al_. (1977).

Fifth: the use of rewritten analysis programs. The inter-comparison of the new programs with the old indicates that there are no coding errors in the parts that were in common with effects on the interpretation of the observations larger than 1 mm. (This test does not address possible errors in the physical models on which both programs were based or in the additions noted above. For example, the precession-nutation algorithms employed are unlikely to be accurate at the millimeter level.)

Utilizing the above mentioned improvements in hardware, we undertook a series of VLBI experiments, starting in September 1976. These experiments utilized the 37-meter-diameter antenna at the Haystack Observatory in Massachusetts, and the 40-meter-diameter antenna at the Owens Valley

Radio Observatory in California, to observe extragalactic radio sources. We have used the data from these experiments to estimate the components of the baseline vector, the coordinates of the radio sources, and the changes in the x component of the position of the Earth's pole and in the Earth's rotation (UT1). (This particular baseline is not sensitive to changes in the y component of the position of the pole because any change in that component causes a nearly parallel displacement of the baseline vector and, therefore, has little effect on observations of very distant sources. In any event, a single baseline can yield information on only two of the three angles required to specify the orientation of the Earth in inertial space.)

We discuss here the observations made with this interferometer in fourteen experiments, the last of these being in May 1978. Each experiment spanned from 15 to 48 hours in which from 120 to 240 separate, three-minute, observations were made. The data from each session were first analyzed separately, and the following parameters were estimated: the vector components of the baseline, the epoch and rate offsets of the clock at Owens Valley relative to those offsets of the clock at Haystack, the zenith electrical path length of the atmosphere at each site, and the right ascension and declination of each source, with one right ascension held fixed to define the origin of right ascension. To test the consistency of the results, the repeatability of the estimates of baseline length was examined. Baseline lengths were selected for examination because the values of the direction components of the baseline vector are affected by errors in the values used for the pole position and for UT1; similarly, the estimated values for the source coordinates are affected by errors in the formulas used for precession and nutation, although the arc lengths between sources are free from such errors.

The estimate of the baseline length from each experiment is shown in Figure 1. The error bars represent formal standard errors based on measurement errors modified so that the root-weighted-mean-square scatter about the weighted mean (hereinafter "RMS scatter" or "repeatability") of the postfit residuals is unity. The RMS scatter of these baseline length values is 7 cm, or, expressed as a fraction of the 3900 km baseline, about 2 parts in 10^8. The values of the source coordinates from these solutions have an RMS scatter of $0\overset{''}{.}015$ or less, except for the declinations of the low-declination sources for which our observations have less sensitivity. The values for these coordinates appear to be somewhat more accurate than our previously published results (Clark et al., 1976) and will be discussed more fully in a separate paper.

To examine how the repeatability of the baseline results might have been affected by the prior availability of sufficiently accurate values of the source coordinates, we obtained new solutions with each source coordinate fixed at the weighted mean of its values from the 14 separate solutions, thereby reducing the number of parameters estimated in each solution from about 30 to about 10. We would expect the RMS

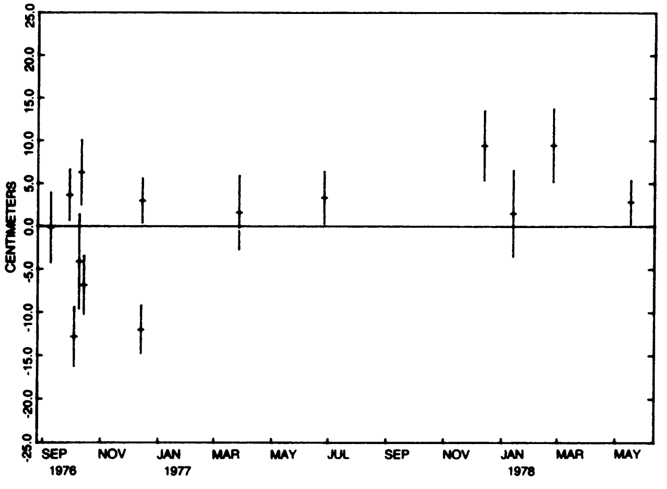

Figure 1. Differences between the estimates of baseline length and their weighted mean from 14 experiments with the Haystack-Owens Valley interferometer. The weighted mean of these estimates of baseline length was 392,888,164.4 cm. The value of the speed of light used to convert light travel time to centimeters was 2.99792458 x 10^{10} cm/s. The source coordinates were also estimated in these analyses.

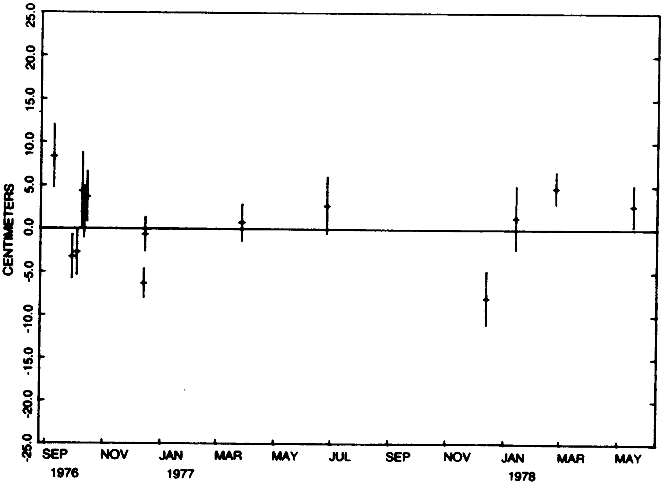

Figure 2. Same as Figure 1, but with each source coordinate kept fixed at the same value for all analyses (see text). The weighted mean of these length estimates was 392,888,162.6 cm.

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scatter to be reduced, provided that any systematic errors affecting the data and the model are sufficiently benign. The estimates of baseline length from these solutions are shown in Figure 2; the RMS scatter is indeed reduced, to about 4 cm, and the mean itself, as one might expect, changed little, by only 1.8 cm. These results indicate that at present VLBI can be used to determine lengths of transcontinental baselines with a repeatability of about 4 cm.

It is not possible from VLBI data alone to determine the point at which the rotation pole of the Earth pierces its crust. It is possible, however, to measure changes in this position from the position at some arbitrary epoch, the position of the pole at that epoch being used to define the orientation of the baseline in the Earth-fixed frame. The ability to determine these changes is, therefore, related to the ability to determine the orientation of the baseline. An examination of the relevant error ellipsoids indicates that, for our interferometer, the inherent sensitivity of the VLBI data to baseline orientation is about a factor of four less than their sensitivity to baseline length. We would expect, therefore, that uncertainties in the determinations of changes in the position of the pole from these data would be no greater than about 30 cm, equivalent to about 0".01 uncertainty in the determination of the direction of the pole.

To determine changes in the position of the pole, we combined all of the data in a single analysis and estimated these changes and all other relevant parameters simultaneously. For one experiment, conducted on 4 October 1976, the position of the pole was fixed at the value determined by the BIH, as recorded in their Circular D publications, in order to define the orientation of the baseline. Our results for the position of the pole from the other 13 experiments are shown in Figure 3 in the form of the difference between the VLBI and the BIH values.

Also plotted in Figure 3 are the differences from the BIH values of the x component of the pole position determined by the IPMS from optical observations (tabulated at intervals of 0.05 years), and by the Polar Monitoring Service of the Defense Mapping Agency Topographic Center from satellite Doppler observations (tabulated at intervals of 5 days), both as recorded in the Series 7 publications of the U. S. Naval Observatory. The standard deviations for the IPMS data are typically about 50 cm or 0".015. The changes with time for all three sets have a common trend, systematically different from the BIH values. This common trend appears to have persisted at least through May 1978. Thus, the VLBI results seem to agree with both the IPMS results and the Doppler results better than any one of the three sets agrees with the BIH values. The RMS scatter of the differences between the VLBI and BIH determinations shown in Figure 3 is 0".030; the corresponding scatter for the Doppler results is 0".020; and for the IPMS results 0".027. This scatter in the VLBI results is about 30 percent less than that obtained previously (Shapiro et al., 1974; Robertson, 1975) from the analysis of VLBI observations made in 1972 and 1973.

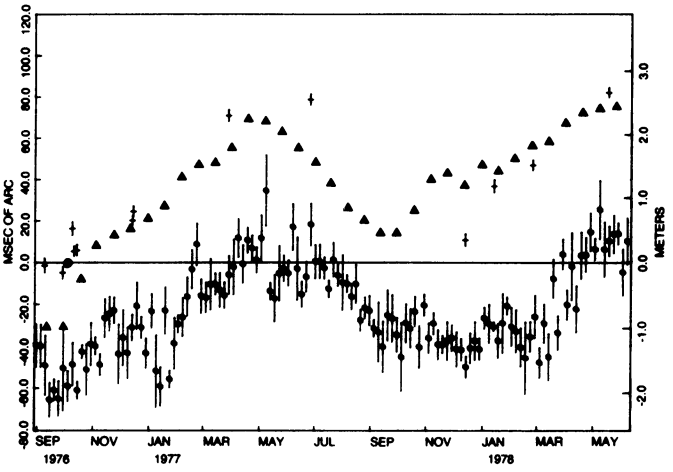

Figure 3. x-component of the pole position, from VLBI observations (+) of extragalactic radio sources, from Doppler observations (¢) of satellites, and from IPMS optical observations (▲) of Galactic stars, all relative to the values obtained by the BIH (see text). In the analysis of the VLBI data, the pole position was fixed at the BIH value for the experiment of 4 October 1976 (●).

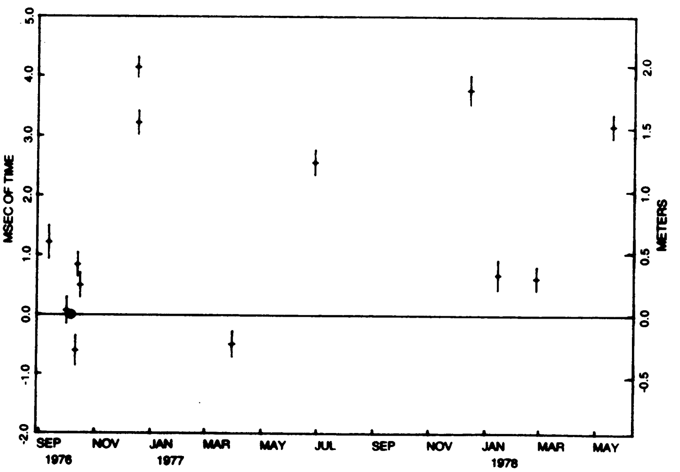

Figure 4. Comparison of the VLBI and BIH determinations of UT1. The VLBI value for UT1 for the experiment of 4 October 1976 was fixed at the BIH value (●).

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Figure 4 shows the corresponding comparison of the VLBI and BIH results for UT1, obtained from the same analysis, with UT1 having been set at the BIH value for 4 October 1976. The RMS scatter here, about $0\overset{s}{.}002$, is again less than that obtained previously (Shapiro _et al_., 1974; Robertson, 1975) and is about the same as the scatter seen in the UT1 determinations from lunar laser ranging (King _et al_., 1978; see also Stolz _et al_., 1976).

In this paper we have summarized our current ability to determine baseline lengths, pole position, and Earth rotation with VLBI. Another paper presented at this conference (Carter _et al_., 1979) addresses plans we have for the improvement of both the quality and the quantity of such determinations.

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DISCUSSION

J. D. Mulholland: The equations given by Johnston suggest that your claim to solve directly for UT1 assumes that the Z-component of the baseline is known without error.

W. E. Carter: The determination of UT1 is relatively insensitive to small errors in Z.

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A. R. Robbins: I believe that tapes have to be played back in real time for cross-correlation, and that very few organizations can carry this out. Consequently it takes a very long time to get results from experiments. Can you comment on this?

W. E. Carter: The Mark III VLBI system, which will be utilized in project POLARIS, has been designed with a high degree of automation of the data handling and processing which will allow the solutions to be completed in a matter of days after receipt at the processing facility. In the future, communications satellites may be utilized, and the results could be determined nearly in real time.

K. Johnston: What form of atmospheric correction did you apply to the data? If H_2O radiometers had been used to measure the H_2O atmospheric content along the line of sight, how would this have improved the accuracy of your results?

W. E. Carter: Only surface meteorological measurements were used with a model derived by J. Marini at NASA. It appears that H_2O radiometers may reduce the uncertainty in the atmospheric corrections to the sub-centimeter level.