

**POLAR MOTION AND UT1: COMPARISON OF VLBI, LUNAR LASER,  
SATELLITE LASER, SATELLITE DOPPLER, AND  
CONVENTIONAL ASTROMETRIC DETERMINATIONS**

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**ABSTRACT**

Very-long-baseline interferometry (VLBI) observations made with a 3900 km baseline interferometer (Haystack Observatory in Massachusetts to Owens Valley Observatory in California) have been used to estimate changes in the X-component of the position of the Earth's pole and in UT1. These estimates are compared with corresponding ones from lunar laser ranging, satellite laser ranging, satellite Doppler, and stellar observations.

## INTRODUCTION

Significant progress is being made in the technology of measuring the motion of the Earth's pole and the irregularities in the Earth's rotation. Very-long-baseline interferometry (VLBI), lunar laser ranging, satellite laser ranging, and satellite Doppler observations all have the potential of measuring the Earth's orientation with a precision far better than than obtainable with classical techniques. In this paper we compare the VLBI determinations of polar motion and Earth rotation with the corresponding results from other techniques and attempt to assess the current state of the art of such measurements.

## SENSITIVITY OF VLBI MEASUREMENTS TO POLAR MOTION AND UT1

VLBI delay observations of extra-galactic radio sources are insensitive to translations of the VLBI baseline, but are sensitive to some changes in the orientation of that baseline with respect to the (planar) radio wavefronts. To specify orientation in space, three angles are generally required; however, a baseline is one-dimensional and its orientation in space is specified by two angles. A rotation about an axis parallel to the baseline does not change the orientation of the baseline, but rather produces at most a translation of that baseline. VLBI observations are therefore insensitive to rotations about any axis parallel to the baseline. This result can be expressed analytically as follows: Define a cartesian coordinate system fixed to the rigid Earth, with the Z-axis in the direction of the reference pole, the X axis perpendicular to Z in the direction of the Greenwich meridian, and the Y axis completing a right-hand triad. The changes in the coordinates of the baseline vector caused by polar motion and variations in UT1 can be written as:

$$\Delta X = -\theta Y - xZ$$

$$\Delta Y = \theta X + yZ$$

$$\Delta Z = xX - yY$$

where  $\theta$  is UT1-UTC in radians, and  $x$  and  $y$  are the coordinates of the instantaneous pole, also in radians. Non-zero values for  $\Delta X$  and  $\Delta Y$  will introduce a sinusoidal signature in the delays observed for a non-polar source because of the rotation of the Earth. A non-zero value for  $\Delta Z$  will introduce a time-independent change in the delays, whose magnitude will depend on the declination of the source being observed. For the case of a polar baseline ( $X = 0$ ,  $Y = 0$ ) the sensitivity to  $\theta$  vanishes, and a change in pole position introduces a sinusoid in the delay observations whose amplitude and phase can be used to estimate the components of this change in pole position. For the case of an equatorial baseline oriented parallel to the plane of the Greenwich meridian ( $Y = 0$ ,  $Z = 0$ ) the sensitivity to the  $y$  component of the pole position vanishes.  $\theta$  will introduce a sinusoidal variation in the observed delays, and  $x$  will introduce a constant offset in those delays. For  $Y \neq 0$ , the VLBI observations will be sensitive to a change in the component of the pole that is in the direction of the

meridian whose plane is parallel to the baseline, and insensitive to a change in the component perpendicular to that plane. Thus for an equatorial baseline, the effects of polar motion and UT1 are separable.

The VLBI measurements discussed in this paper were obtained in 14 separate experiments spread between September 1976 and May 1978. 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. This baseline is nearly parallel to the Earth's equatorial plane, having a declination of less than  $7^\circ$ , and is even closer to parallel to the plane of the Greenwich meridian, making an angle of less than  $0.5^\circ$  with that plane. The interferometric observations are therefore sensitive to changes in the X-component of the position of the pole and to changes in UT1 and are practically insensitive to changes in the Y-component of the pole.

## POLAR MOTION

VLBI determinations of the X-component of the pole are shown in figure 1, displayed as differences from the corresponding values determined by the Bureau International de l'Heure (BIH). The VLBI values show peak-to-valley excursions from the BIH values of about 80 msec of arc, or a little more than two meters. The error bars shown are the formal standard errors, based on an adjustment of the measurement errors to yield an rms value of unity for the postfit residuals. Further analysis of these data, including detailed studies of effects of clock and atmosphere errors, as well as inclusion of some additional data from NRAO and Onsala (Sweden), may change these values by amounts up to a few times the formal standard errors.

VLBI measurements alone are sensitive only to changes in the pole position and therefore the zero point of figure 1 is necessarily arbitrary. It was set by fixing the value of the X-component of the pole position at the BIH value for the experiment of October 4-5, 1976.

Figure 2 shows the two-day average values of the X-component of the pole position determined from satellite Doppler observations by the Defense Mapping Agency Hydrographic and Topographic Control (DMAHTC). Again, the values are differenced from those of the BIH and are plotted on the same scale as before. A clear systematic trend is present which appears to have an annual period with an amplitude of about 30 msec of arc; the point-to-point (short-period) scatter has an RMS of about 25 msec. In order to better exhibit the systematic trend, we smoothed these data by convolution with a Gaussian function whose full-width at half-maximum was 10 days. The result is shown in figure 3.

Figure 4 shows the corresponding determinations of the X-component of the position of the pole from laser ranging observations of the LAGEOS satellite. These values were supplied to us by D. Smith of NASA's Goddard Space Flight Center. Figure 5 shows these values smoothed by the same filter used to produce figure 3. Again, an annual trend seems to be present.

RADIO INTERFEROMETRY

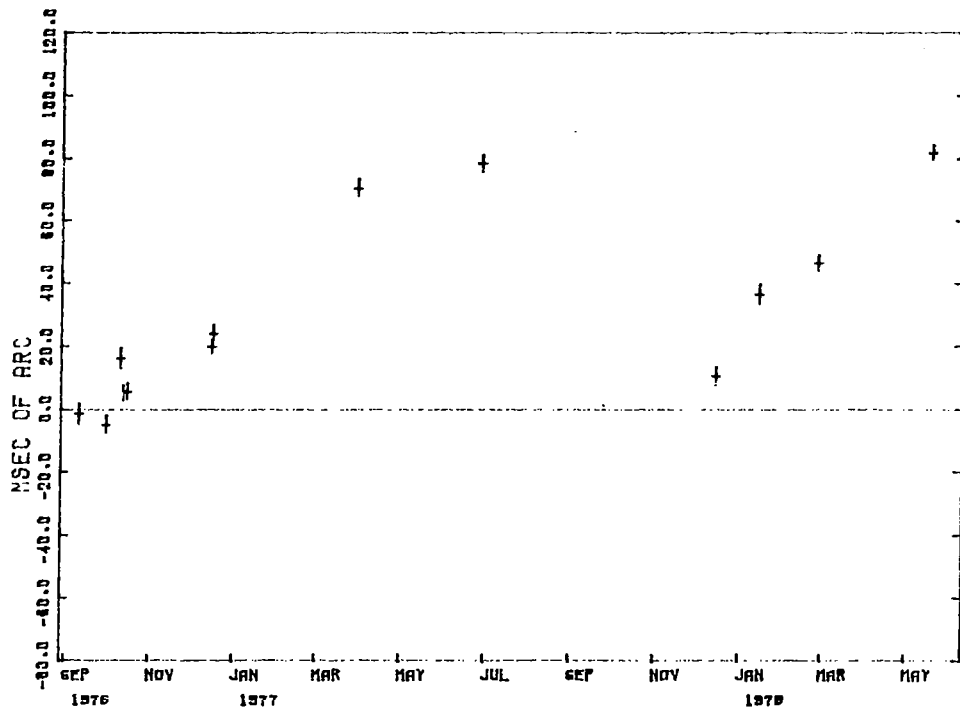


Figure 1.

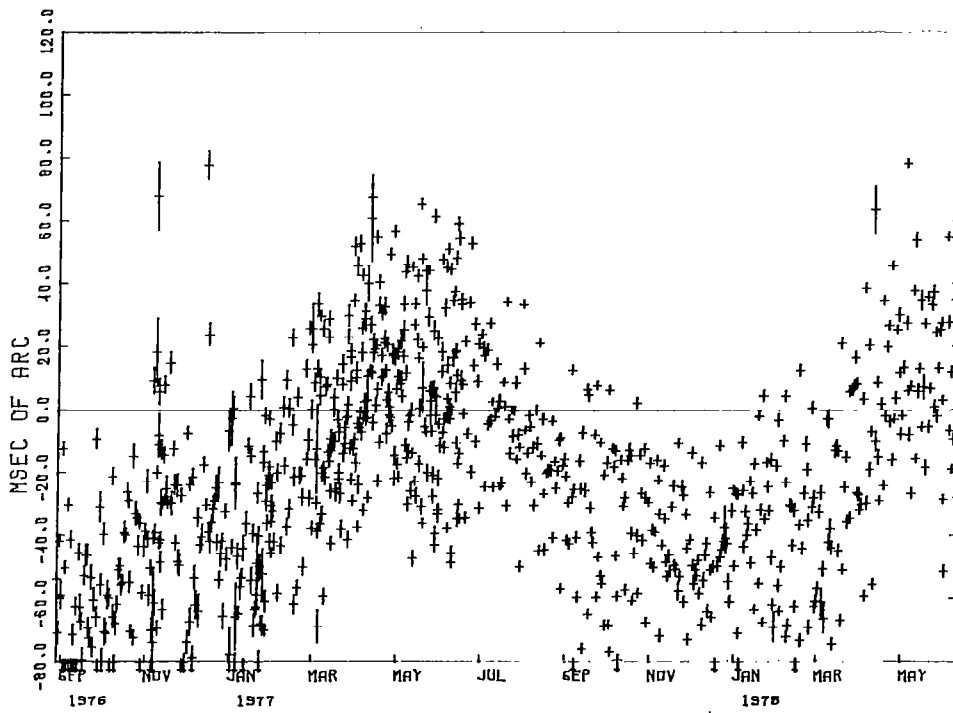


Figure 2.

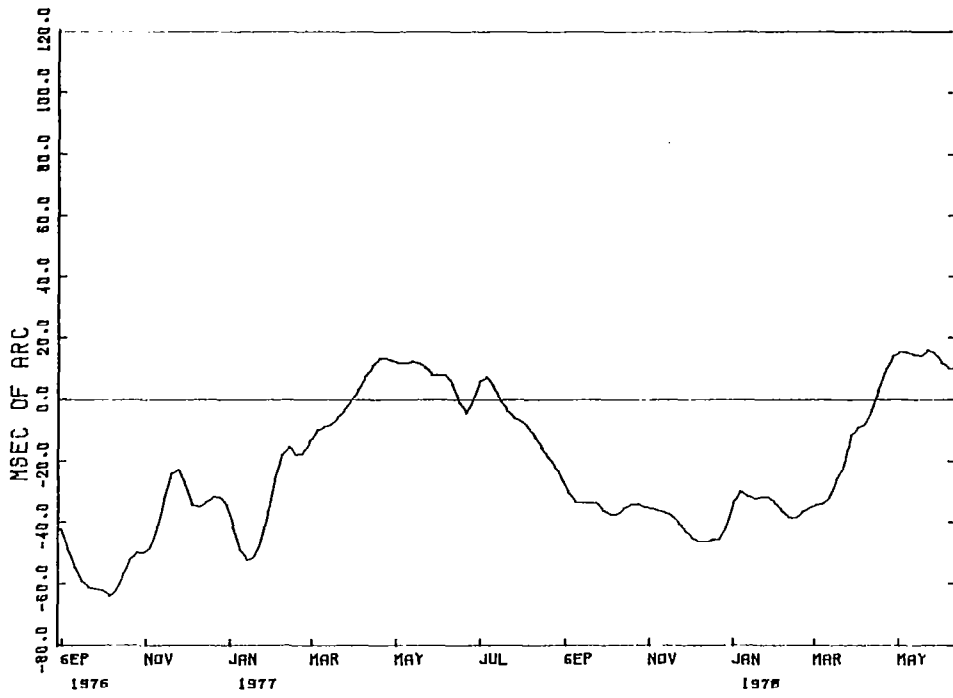


Figure 3.

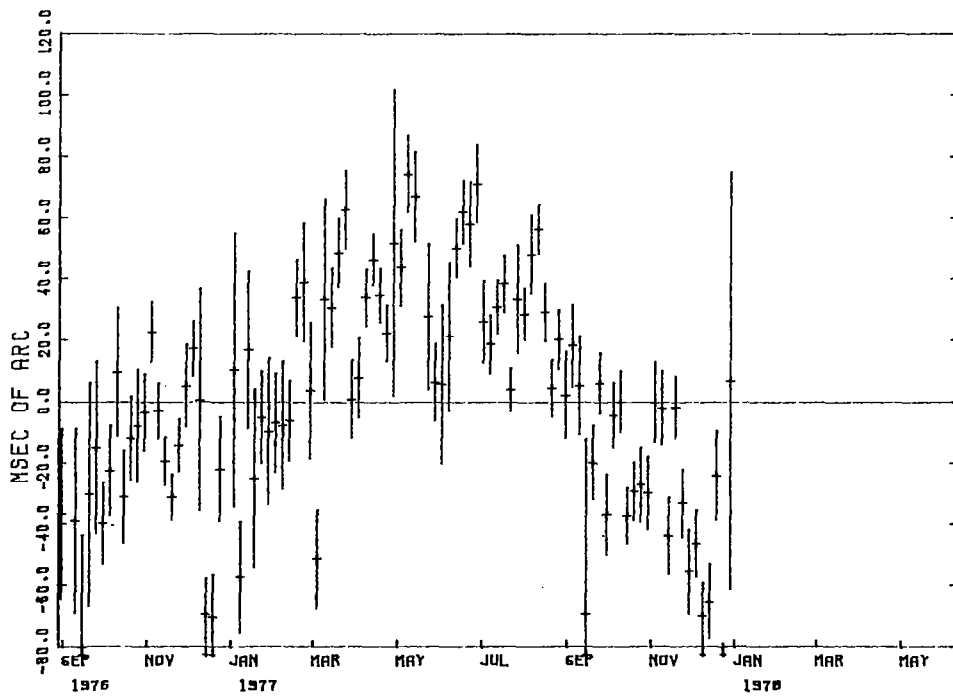


Figure 4.

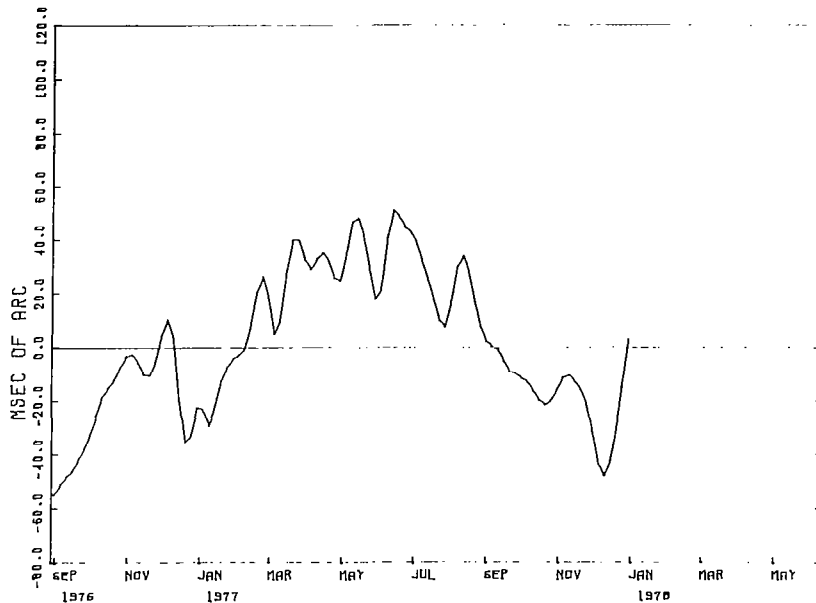


Figure 5.

Figure 6 shows the corresponding determination of the X-component of the position of the pole as determined by the International Polar Motion Service (IPMS) in Misuzawa, Japan. The IPMS employs only classical optical observations (PZT, VZT, etc.). Even here, the annual trend away from the BIH is clear.

Each of the figures of differences in estimates of pole position has a different bias. This bias can be removed by re-defining the "zero point." (In fact, this procedure was used for the Doppler, satellite laser, and IPMS values, but for different spans of data.) Shifting each set of differences shown in our figures by the mean value of its difference from the corresponding values from the Doppler set yields figure 7. The consistency of the amplitudes and phases of the annual terms is quite clear.

In order to evaluate quantitatively the short-term differences between the results from the different techniques, we can calculate the RMS deviation about the mean of the differences between the corresponding members of each pair of results, for the dates in common. The results of these calculations are tabulated in matrix form in table 1. The first value in the matrix indicates a 9 msec RMS difference between the VLBI and the Doppler estimates of the position of the pole. Since the expected standard error in the Doppler estimates of  $\sim 10$  msec, and the average formal standard error of the VLBI estimates is  $\sim 3$  msec, the RMS difference is about what one would expect. Although, admittedly, there are only 13 VLBI estimates, this RMS difference does indicate that the systematic errors in the Doppler estimates are not contributing significantly to the total errors. The other values in the table are consistent with the errors in the satellite laser ranging estimates of the pole position being  $\sim 12$  msec, the corresponding IPMS errors  $\sim 15$  msec, and the BIH errors  $\sim 25$  msec.

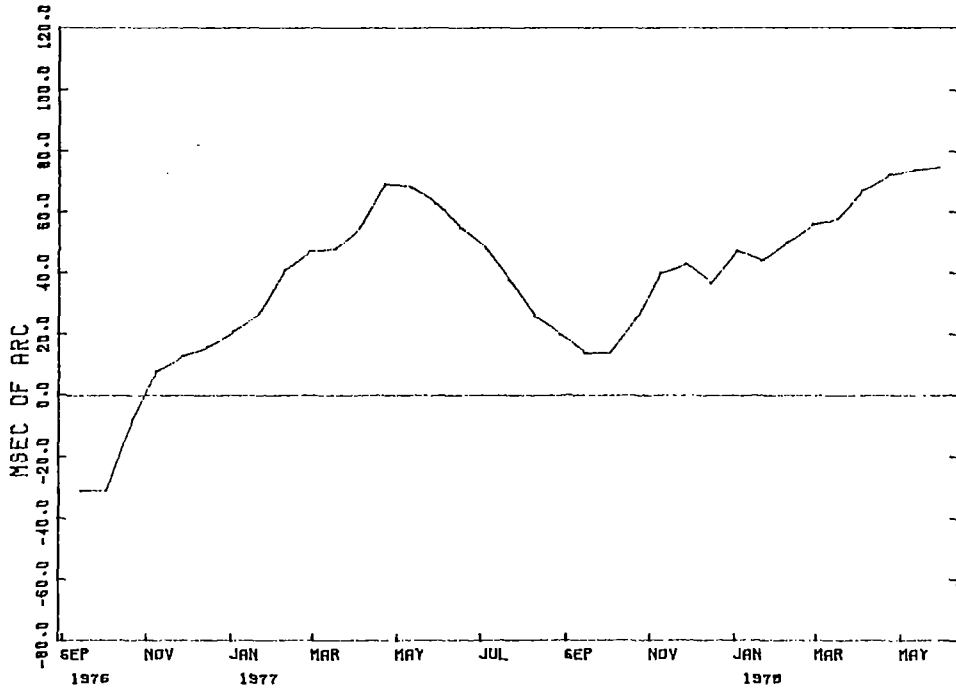


Figure 6.

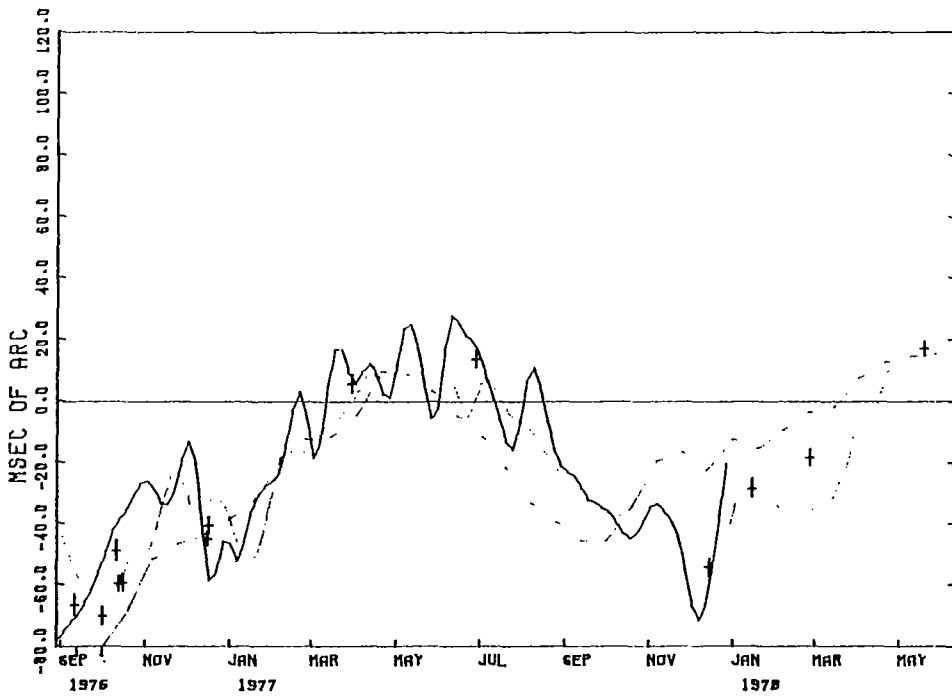


Figure 7.

The anomalously large RMS difference between the VLBI and the BIH estimates is due to the distribution of the VLBI values in time. The epochs of most of the VLBI observations were close to the extrema of the annual error in the BIH estimates.

Table 1  
RMS Deviations about the Mean of the Differences between the Determinations  
of the X-Component of the Pole by Various Monitoring Techniques

	VLBI	Doppler	Satellite Laser	IPMS	BIH
VLBI	—				
Doppler	9 ms	—			
Satellite Laser	12 ms	14 ms	—		
IPMS	16 ms	15 ms	18 ms	—	
BIH	30 ms	23 ms	24 ms	27 ms	—
Corrected BIH	16 ms	11 ms	17ms	19 ms	15 ms

In May 1979, the BIH altered this picture by announcing that it would introduce an ad hoc correction to its X-component values in the form of an annual term and a semi-annual term. The form of the correction is displayed in figure 8. After application of this correction, the RMS difference between the BIH estimates and those from the other techniques are displayed in the last line of table 1. The errors in the BIH estimates of the X-component of the position of the pole appear to have been reduced by the correction to about the level of the errors in the IPMS values.

## UT1

Figure 9 displays the differences between the VLBI determinations of (UT1-UTC) and the BIH determinations. As with the values of pole position, completion of a more detailed analysis of the VLBI observations may lead to changes in these estimates of (UT1-UTC) by amounts up to several times the formal standard errors. Nonetheless, the general trends in the differences from the BIH estimates are probably significant.

Lunar laser ranging data have also been employed to determine variations in UT1. The UT1 variations were modeled as a piece-wise linear function, as described by King *et al.* (1978). To compare the lunar laser ranging values with the VLBI values, the laser values were converted to UT1 from UT0 at the McDonald Observatory by using the estimate of the position of the Earth's pole as determined from the Doppler observations. Figure 10 shows the lunar laser values compared to the VLBI values which have been adjusted to allow for a different value used for the precession constant in the lunar laser program.



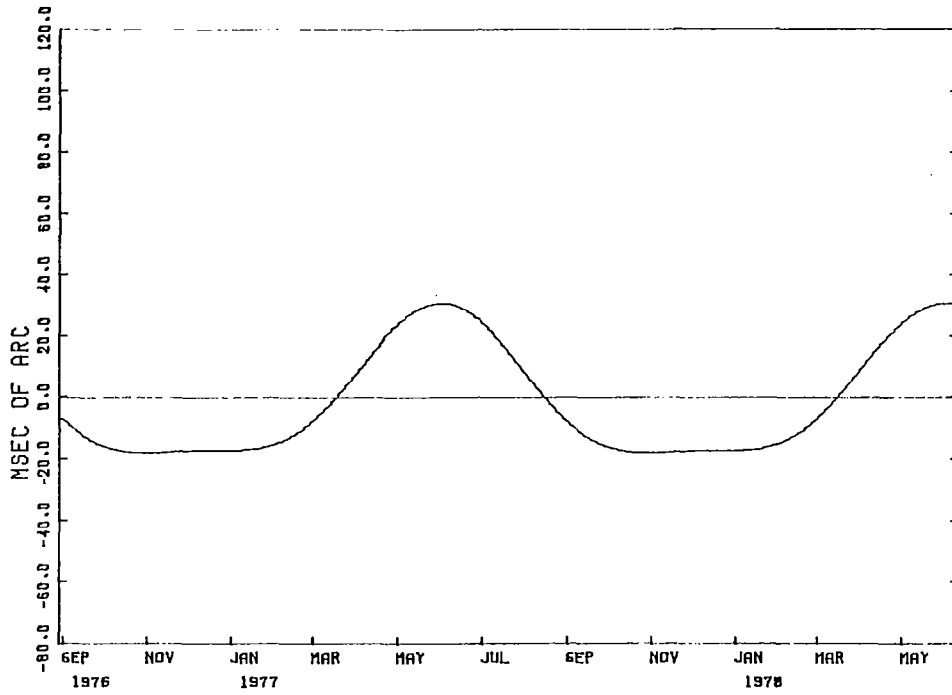


Figure 8.

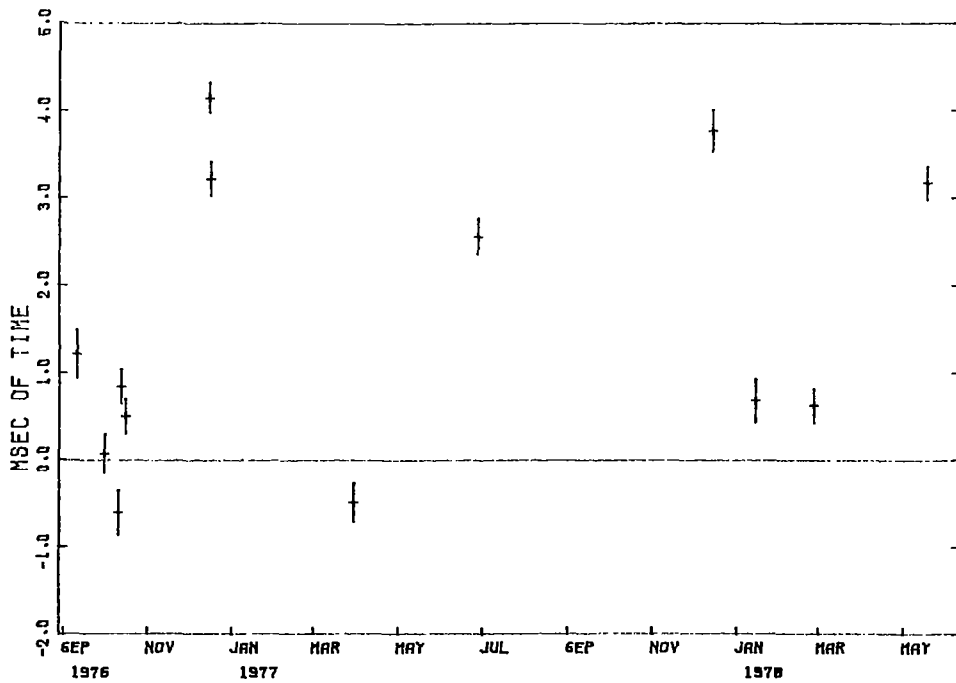


Figure 9.

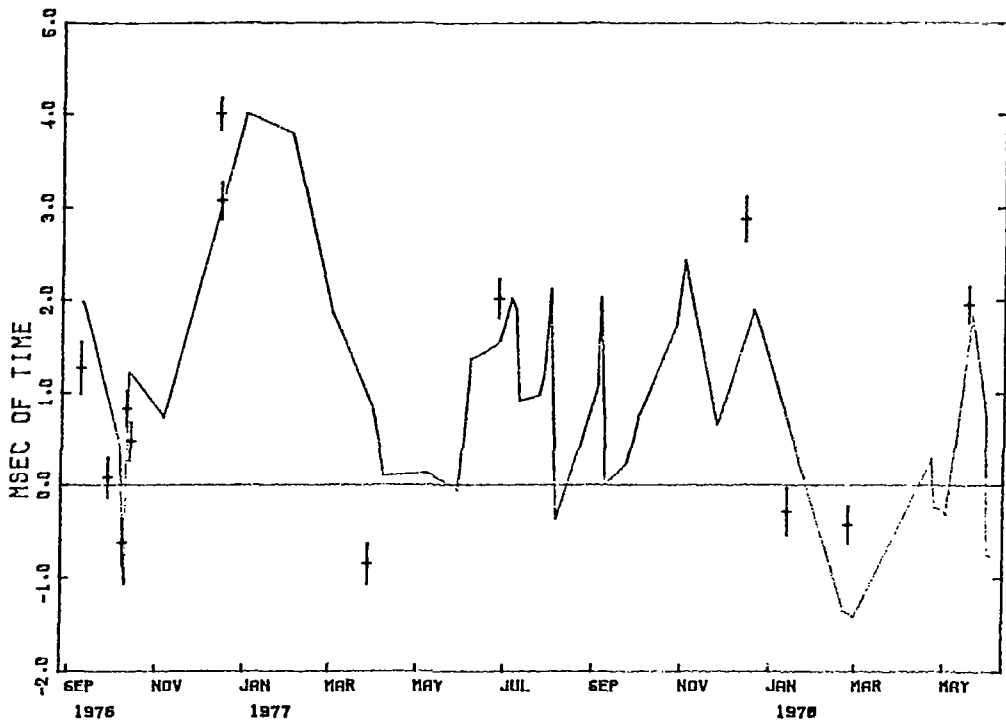


Figure 10.

The RMS differences between the lunar laser and the BIH values and between the VLBI and the BIH values are both 1.6 msec, but the difference between the VLBI and the lunar laser values is only 0.8 msec.

Although the general agreement between the VLBI and the lunar laser values is good, more regular monitoring of Earth rotation with VLBI is necessary to establish the significance of any small ( $>2$  msec) differences between the BIH values and those from VLBI and lunar laser ranging.

The BIH has also published an annual and a semi-annual correction term for its UT1 values. The form of this correction is shown in figure 11. With this correction included, the RMS differences between the BIH and the VLBI and lunar laser results are 1.3 msec and 1.1 msec, respectively, still larger than the corresponding difference between the VLBI and the lunar laser ranging estimates of UT1.

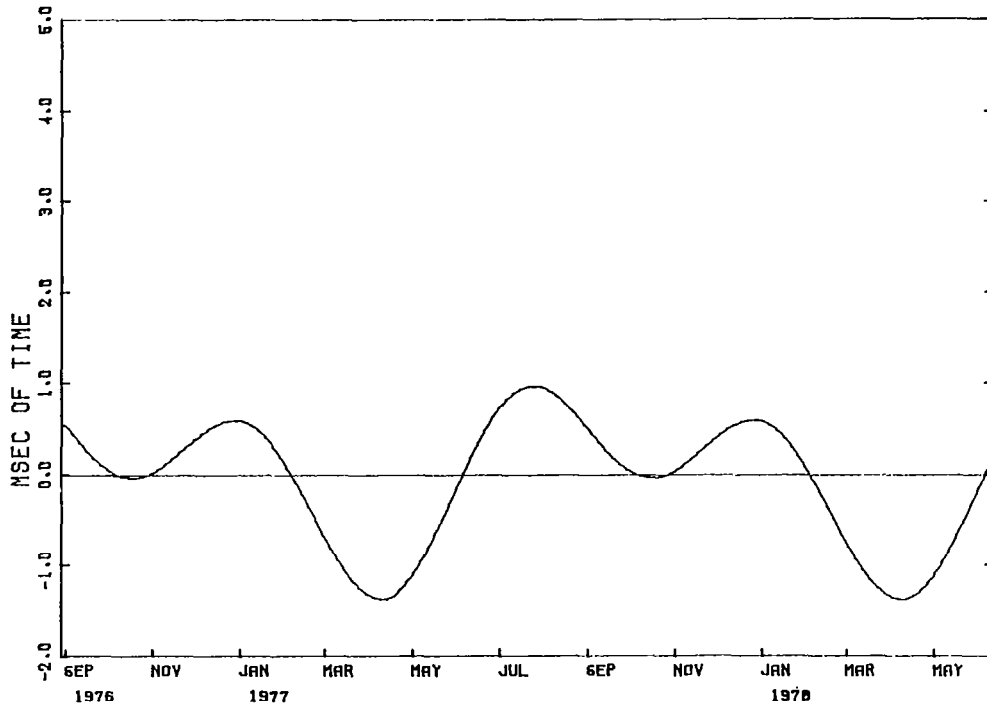


Figure 11.

## CONCLUSIONS

The determination of the position of the Earth's pole from satellite Doppler and satellite laser ranging observations are approaching an accuracy of  $\sim 10$  msec of arc (30 cm). The VLBI determinations may have better accuracy, although a determination of whether the VLBI accuracy is indeed better, and by how much, must await the collection and analysis of a far larger set of VLBI data.

The comparison of lunar laser ranging and VLBI determinations of UT1 suggests that the RMS of the uncertainties in each set are under 1 msec.

All of these comparisons have been hampered by the paucity of VLBI data. To rectify this problem, the National Geodetic Survey has undertaken Project POLARIS whose object is to obtain VLBI data at least several times per week, starting in 1982.

**REFERENCE**

King, R. W., C. C. Counselman, and I. I. Shapiro, Universal Time: Results from Lunar Laser Ranging, J. Geophys. Res., 83, 3377-3381, 1978.

**A REVIEW OF CONNECTED ELEMENT RADIO INTERFEROMETRY  
DIRECTED AT ESTABLISHING  
AN ALMOST INERTIAL REFERENCE FRAME**

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**ABSTRACT**

The present status of connected element radio interferometry towards establishing an accurate grid of positions of extragalactic radio sources is reviewed. Many of the problems being encountered are, in general, also faced by very long baseline interferometry (VLBI).