THE ASTROMETRIC POSSIBILITIES OF VERY-LONG-BASELINE INTERFEROMETRY

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I. INTRODUCTION

In the application of Very-Long-Baseline Interferometry (VLBI) to astrometric problems the fundamental observable is the difference in the arrival times of a wavefront at two widely separated receiving stations. Since the radio sources being observed are sufficiently distant that the arriving wavefront can be considered to be a plane wave, the differential arrival time is a measure of the component of the baseline in the direction of the source. Equivalently, if the baseline is known, the differential arrival time is sufficient to determine a circle on the sky containing the source. It is easy to show that a minimum of ten observations distributed among three different sources is sufficient to determine all of the source coordinates and the baseline coordinates simultaneously (Robertson, 1975).

The significance of the VLBI observations for astrometry results from the fact that the delays can be determined with a precision of about 0.1 nanosecond, equivalent to a few centimeters. For continental-scale baselines this translates into an angular precision for the resulting source coordinate determinations of the order of milliseconds of arc.

VLBI delay observations are of two general types, group delay and phase delay. Group delay observations are characterized by accuracies of the order of 0.1 nanoseconds and ambiguities spaced typically at about 100 nanosecond intervals. 100 nanoseconds represents about 30 meters of light-travel-time, and it is normally not difficult to resolve ambiguities at this level. The phase delay observations are characterized by accuracies of the order of 0.01 nanoseconds or less, and ambiguities of the order of 0.1 nanosecond. The usefulness of the extreme precision of the phase delay observations is seriously compromised by the difficulty of resolving ambiguities whose spacing represents only a few centimeters of light travel-time. These difficulties have proven so great that the phase delay observables have been used only for very special experiments, such as

H. K. Eichhorn and R. J. Leacock (eds.), Astrometric Techniques, 143–155.

observations of sources separated by less than one degree in the sky. For such observations, the difference phase ambiguities can be resolved, and a great deal of interesting information obtained (Shapiro, et al., 1979). This paper will focus on the results from group delay observations.

II. CURRENT ACCURACY LEVELS

There are several ways of demonstrating and displaying the state-of-the-art error level of VLBI observations and parameter estimates, the simplest being to note the size of the observation residuals. Figure 1 shows a typical set of delay residuals from observations taken on a 3100 km baseline

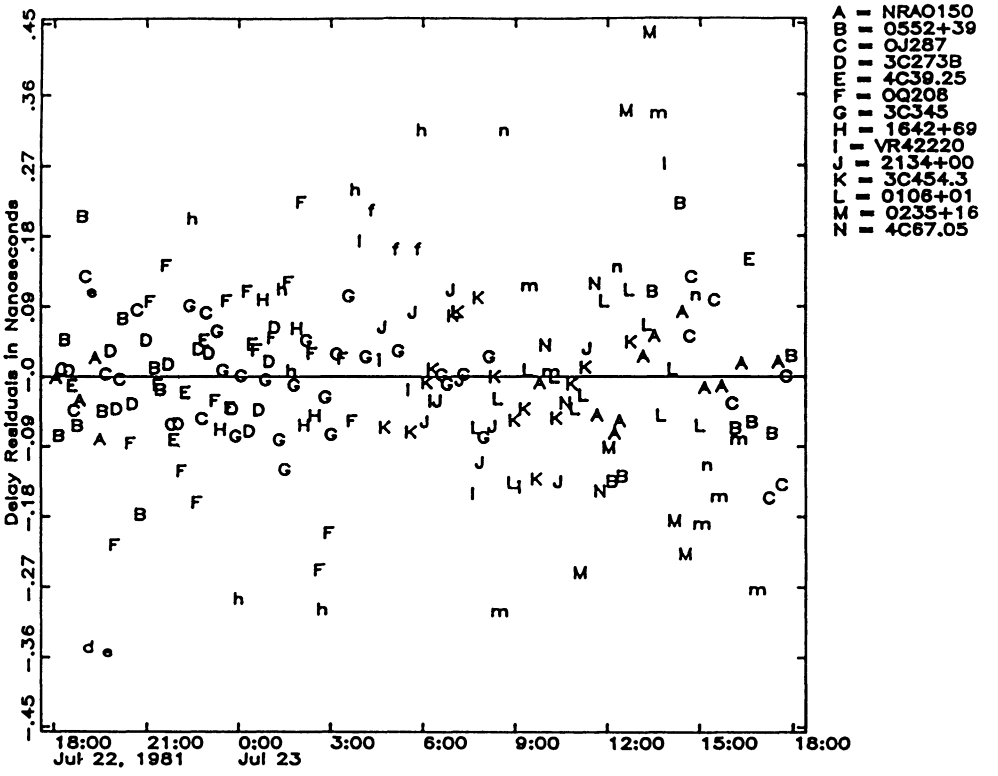

Figure 1. Delay residuals from observations with a 3100 km baseline.

between Massachusetts and west Texas. The full scale variation is about .45 ns or about 15 centimeters, and the RMS residual size is about 0.1 ns or about 3 centimeters. Another way of demonstrating error levels is to examine some of the resulting parameter estimates. Figure 2 shows the baseline length residuals from more than 100 observing sessions on the same 3100 km baseline. The root-mean-square (RMS) residual size is about 2 centimeters.

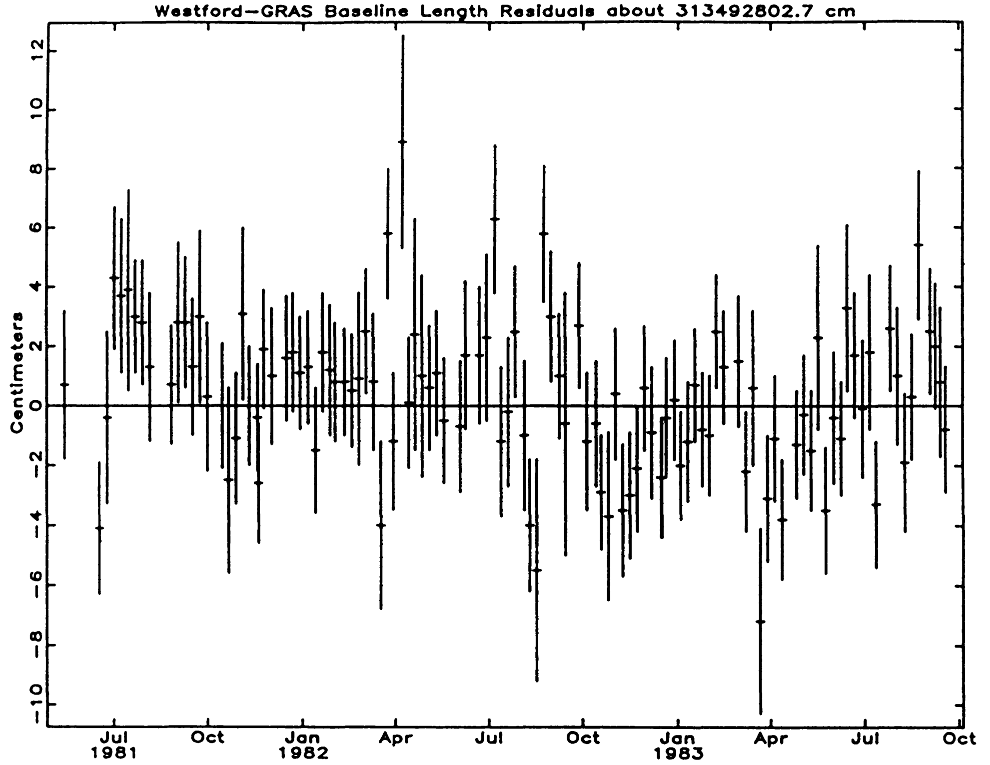

Figure 2. Determinations of the length of the baseline between the Westford antenna in Massachusetts and the G. R. Agassiz Station in West Texas.

The sources of the errors in the VLBI observables can be classified into three broad categories: 1. Instrumental errors, including clock errors and variations in the receiver-recorder equipment chain; 2. propagation medium effects; 3. effects of non-pointlike structure in the radio sources. Of the three effects, propagation medium effects are believed to dominate. Studies have indicated that source structure effects should be at the sub-centimeter level for reasonable choices of sources to be observed (Cotton, 1980). The most dramatic demonstration of the fact that the instrumental errors are already at the sub-centimeter level comes from observations of a short (1.2 km) baseline between the Haystack and the Westford antennas in Massachusetts. Over baselines as short as this the effects of the propagation medium largely cancel because both antennas are effectively looking through the same atmosphere. The baseline determinations from these experiments have indeed shown an internal consistency at the sub-centimeter level in all vector components, and further were shown to agree with a classical survey at about the same level (Rogers, et al., 1978; Carter, et al., 1980). These results indicate that the instrumental errors in the VLBI observing procedures are below the centimeter level.

It is convenient to resolve the remaining propagation medium errors into two basic components, the dispersive ("ionosphere") component and the non-dispersive ("troposphere") component. The dispersive component has a magnitude of about 15 to 30 cm in the zenith direction at X-band (8 ghz), with an order of magnitude variation between day and night. This error source is removed with centimeter accuracy by the use of dual-frequency observations. The remaining non-dispersive component of the atmosphere, with a magnitude of about 1.5 meters at the zenith, is probably the major source of errors in the VLBI observables. We can model the effects of this component using surface meteorological data and remove about 90% of its effects, but the remaining error has proven remarkably resistant to attack. Considerable resources have been expended to try to use water vapor radiometry to remotely monitor the water vapor portion of the troposphere effects, but these efforts have not produced a convincing demonstration that such measurements have actually reduced the errors in the VLBI parameter estimates. Troposphere sensing and/or modeling is the area in which a major breakthrough of any sort would probably have the greatest effect in improving the results from VLBI observations.

III. GEOGRAPHIC REQUIREMENTS FOR BASELINES

For general astrometric work it is not sufficient to simply have baselines capable of high resolution angular determinations. The geographic distribution of the baselines is also important. The ideal antenna distribution would consist of a grid of antennas covering the entire globe. However, given that such a network is beyond our financial and computational resources and is likely to remain so for the foreseeable future, it is important to identify the desirable characteristics of the geographic distributions of the baselines which we can construct. Sensitivity to source right ascensions will scale linearly with cylindric radius of the baseline, the component of the baseline parallel to the plane of the equator. For declination sensitivity, the situation is a bit more complex. A perfectly equatorial baseline will have a sensitivity to declination which is proportional to the sine of the declination, i.e., it will have no sensitivity to declinations at the celestial equator, and maximum sensitivity near the poles. In addition, a purely equatorial baseline suffers from a degeneracy such that the length of the baseline cannot be separated from a linear combination of all of the source declinations. Both of these problems can be eliminated by the use of a baseline with a significant polar component. A purely polar baseline would have a sensitivity to declinations which scales as the cosine of the declination and would be maximally sensitive to declinations at the celestial equator and have no sensitivity at the celestial poles. Thus equatorial and polar baselines are complementary in their sensitivity to source declinations. A purely polar baseline would, of course, have no sensitivity to source right ascensions at all. Astrometry with VLBI therefore requires a minimum of two baselines, one with a significant equatorial component and one with a significant polar component.

The next factor which needs to be considered is the length of the baselines. The angular sensitivity of any interferometer is, of course, proportional to its length. But as the length of the baseline exceeds an Earth radius the duration of mutual visibility of a source declines drastically, compromising the angular precision of the resulting source coordinate estimates. A baseline length of the order of an Earth radius is about optimal for astrometric work.

Figure 3 shows the stations used to obtain the results discussed in this paper. Notice that there is a preponderance of east-west lines. The largest east-west distance is almost an order of magnitude larger than the largest north-south distance. Current astrometric position determinations are somewhat compromised by this lack of north-south baselines.

IV. ONGOING PROJECTS - POLARIS, IRIS, MERIT

The enabling legislation for the U.S. National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration charges the NGS to monitor "variations in latitude and longitude." In pursuit of this objective the NGS operated visual zenith telescope (VZT) optical observatories for the International Latitude Service at Gaithersburg, Maryland, and Ukiah, California, from 1899 until 1982. By the middle 1970's it was realized that modern techniques could perform the same task with very much higher precision and accuracy and probably at lower cost as well. After a careful and detailed examination of the various competing new techniques it was determined that VLBI had substantial advantages over the other techniques in accuracy, reliability, long-term stability and cost (Carter and Strange, 1979). The fact that VLBI alone among the new techniques promised significant new results for astrometry as well as improved determinations of precession and nutation was regarded as an important fringe benefit. The NGS launched project POLARIS (POLar motion Analysis by Radio Interferometric Surveying) in 1977 with the objective of creating a three station VLBI network capable of monitoring polar motion and UT1 with an accuracy of 10 centimeters and a time resolution of about 24 hours.

Project POLARIS began observations in late 1980 using the Haystack antenna in Massachusetts and the G. R. Agassiz Station (GRAS, formerly known as the Harvard Radio Astronomy Station, HRAS) in Fort Davis, Texas. In June 1981, the Haystack observatory was replaced by the nearby Westford observatory. This interferometer is more than 3100 kilometers in length, and is oriented predominantly east-west (the baseline is inclined to the Earth's equatorial plane by only 20 degrees), and is therefore very sensitive to changes in the rotational orientation of the Earth (Carter and Robertson, 1982). The third station, in Richmond, Florida, began operations in late 1983.

The POLARIS observing sessions are 24 hours in duration. In a typical observation, the telescopes simultaneously observe a radio source for 2

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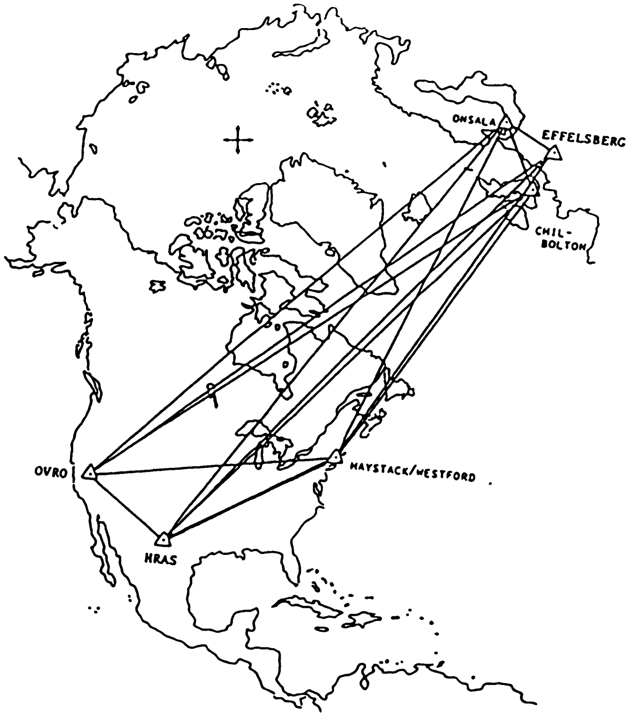

Figure 3. Geographic distribution of the baselines employed for the observations discussed in this paper.

to 3 minutes before shifting to another source. More than 200 observations on a set of 14 sources may be accumulated during a session. Observations are made at 14 different frequency channels, six near 2200 Megahertz (S-band) and eight near 8400 Megahertz (X-band), recording 4-million bits per second on each channel. A single observation involves the collection of approximately 10 billion (10^{10}) bits at each station. The methods and procedures used by the NGS to process the POLARIS observations are described in detail in (Robertson and Carter, 1982a; 1982b).

It was realized from the outset that restricting the POLARIS project to stations within the United States would seriously limit the accuracy of its determinations of Earth orientation. Negotiations were therefore started with scientists and organizations in other countries in order to expand the geographic coverage of the network. The resulting project, code-named IRIS (for International Radio Interferometric Surveying) began with the cooperation of Sweden's Onsala Space Observatory in the POLARIS observing sessions on a monthly basis. The Wettzel station in the Federal Republic of Germany began IRIS observations in late 1983, and is participating on a continuing basis at five-day intervals. Other groups in Japan and the People's Republic of China have expressed an interest in joining such cooperative observations, and we look forward to further expanding the geographic coverage of the continuing VLBI observing program.

In 1978 the International Astronomical Union initiated project MERIT (Monitor Earth Rotation and Intercompare Techniques of observation and analysis) in order to compare the reliability and accuracy of modern techniques for determining Earth orientation. The project encompassed a short test observing campaign in the fall of 1980, whose results are summarized in (Calame, 1982), and a long observing campaign which began in September, 1983, and will run through October, 1984. The POLARIS and IRIS projects are major contributors to the polar motion and UT1 results of the MERIT campaign.

The significance of these observing programs to the general astronomical community extends beyond improvements to the tabulated polar motion and UT1 series. The entire set of observed data taken under these projects is considered to be in the public domain, and is available to interested investigators. We would like to encourage independent reductions of the data in order to refine the data reduction procedures and to improve the general level of confidence in the results.

V. APPLICATIONS - STAR COORDINATES, POLAR MOTION, EARTH ROTATION, NUTATION

There are several general classes of applications of VLBI to astrometric problems. The first and most direct application involves the estimation of source coordinates. Table 1 shows the source coordinates resulting from a combined solution using more than 40,000 delay and delay rate observations from the POLARIS and IRIS projects. The errors tabulated are the one-sigma formal errors based on the post-fit observation residuals, and are generally at the level of a few tenths of a millisecond of arc. The actual errors are apt to be a factor of two or three larger than the formal errors. Table 1 demonstrates the precision which is routinely available from VLBI group delay observations.

Figure 4 shows some of the results obtained from using the POLARIS observations to monitor the orientation of the Earth. The figure shows the determinations of UT1 from VLBI and Satellite Laser Ranging (SLR) observations. In order to display the short term fluctuations, both series are displayed as differences from the BIH Circular D series (BIH Annual Report, 1982). The SLR observations have been modified by processing them through a high-pass filter to remove spurious long-period fluctuations with amplitudes of several milliseconds caused by unmodeled time variations in the geopotential (Carter, et al., 1984). The seasonal and short period agreement between the series is very good. The RMS difference between the two is only 0.7 milliseconds, and the large excursions on time scales of months are tracked by both series of observations. The spike seen by both techniques in early 1983 is correlated with anomalous global wind circulation patterns associated with the El Nino phenomenon which produced violent storms along the Pacific coast during this period.

https://doi.org/10.1017/S007418090007649X Published online by Cambridge University Press

Table 1. Source coordinate determinations from the POLARIS-IRIS observations

Source	Rt. Asc. h	m	s	sigma s	Declination °	'	"	sigma "
0106+013	1	8	38.77099	0.00001	1	35	0.3234	0.0007
0212+735	2	17	30.81343	0.00003	73	49	32.6235	0.0001
4C67.05	2	28	50.05170	0.00003	67	21	3.0310	0.0002
0234+285	2	37	52.40567	0.00001	28	48	8.9923	0.0002
0235+164	2	38	38.93002	0.00001	16	36	59.2796	0.0005
NRAO150	3	59	29.74731	0.00002	50	57	50.1632	0.0001
0528+134	5	30	56.41670	0.00002	13	31	55.1479	0.0009
0552+398	5	55	30.80565	0.00001	39	48	49.1661	0.0001
0742+103	7	45	33.05961	0.00008	10	11	12.6872	0.0024
OJ287	8	54	48.87488	0.00001	20	6	30.6403	0.0003
4C39.25	9	27	3.01383	0.00001	39	2	20.8513	0.0002
3C273B	12	29	6.6997	---	2	3	8.5959	0.0007
OQ208	14	7	0.39426	0.00001	28	27	14.6890	0.0002
1637+574	16	38	13.45608	0.00002	57	20	23.9798	0.0002
1642+690	16	42	7.84812	0.00003	68	56	39.7567	0.0002
3C345	16	42	58.80977	0.00001	39	48	36.9950	0.0001
1741-038	17	43	58.85589	0.00004	3	50	4.6124	0.0021
1928+738	19	27	48.49450	0.00014	73	58	1.5726	0.0009
2134+00	21	36	38.58611	0.00001	0	41	54.2201	0.0008
VR422201	22	2	43.29123	0.00001	42	16	39.9829	0.0001
3C454.3	22	53	57.74780	0.00001	16	8	53.5653	0.0003

Figure 5 shows the correlation between the Earth rotation values and values computed from atmospheric data. Measurements of the global zonal wind patterns have been used to calculate the total angular momentum of the atmosphere. These calculations can be used to infer changes in the rotation of the Earth if we assume that the total angular momentum of the atmosphere and the solid crust of the Earth is conserved. In other words, we must assume that other transfers of angular momentum, such as to the oceans or the liquid core, are small. The figure shows determinations of the variations in the length-of-day (LOD) from VLBI, SLR and the atmospheric angular momentum computations. The maximum seen in the LOD determinations in early 1983 is associated with the El Nino phenomenon, and represents one of the highest values of atmospheric angular momentum observed in this century.

These Earth rotation determinations were produced in large part with observations on a single baseline between the Westford station in Massachusetts and the G. R. Agassiz station in Texas. Regular observations with more baselines, including stations in Europe, began in late 1983. These observations should produce substantially improved determinations of UT1 and polar motion parameters.

Figure 6 shows the determinations of the X-component of polar motion from the POLARIS observations. The smoothed curve was generated by

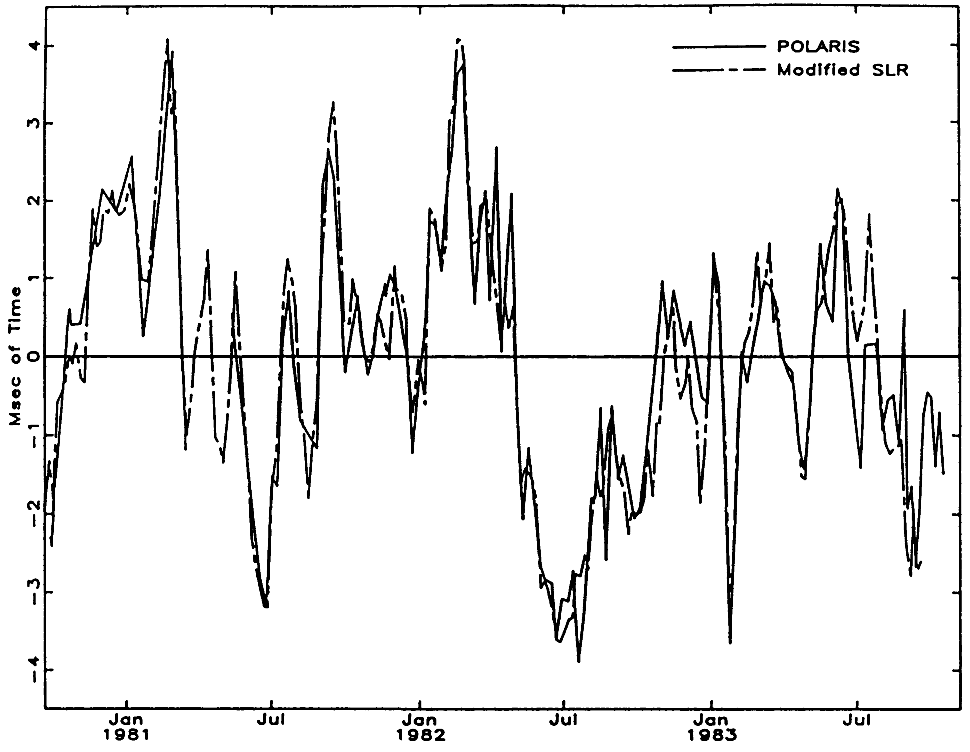

Figure 4. UT1 determinations from VLBI and SLR observations. Both series are shown as differences from the BIH Circular D series, and the SLR determinations have been processed through a high-pass filter to remove spurious long-term drifts.

convolution of the raw values with a Gaussian curve with a full-width at half-maximum of 20 days. Because most of these observations were made with the single Westford-GRAS baseline, the Y-component is generally not available.

These same VLBI observations can be used to determine the orientation of the Earth's spin axis in space (precession and nutation). Figure 7 shows the determinations of the nutation in longitude, and figure 8 shows the corresponding determinations in obliquity. As with the pole values, the smooth curves in both figures were generated by convolution with a Gaussian curve with a full-width at half maximum of 20 days. There is a hint of periodicity in the residuals, with an annual signature. We expect the newer data which contains more and longer baselines will substantially improve determinations of these parameters.

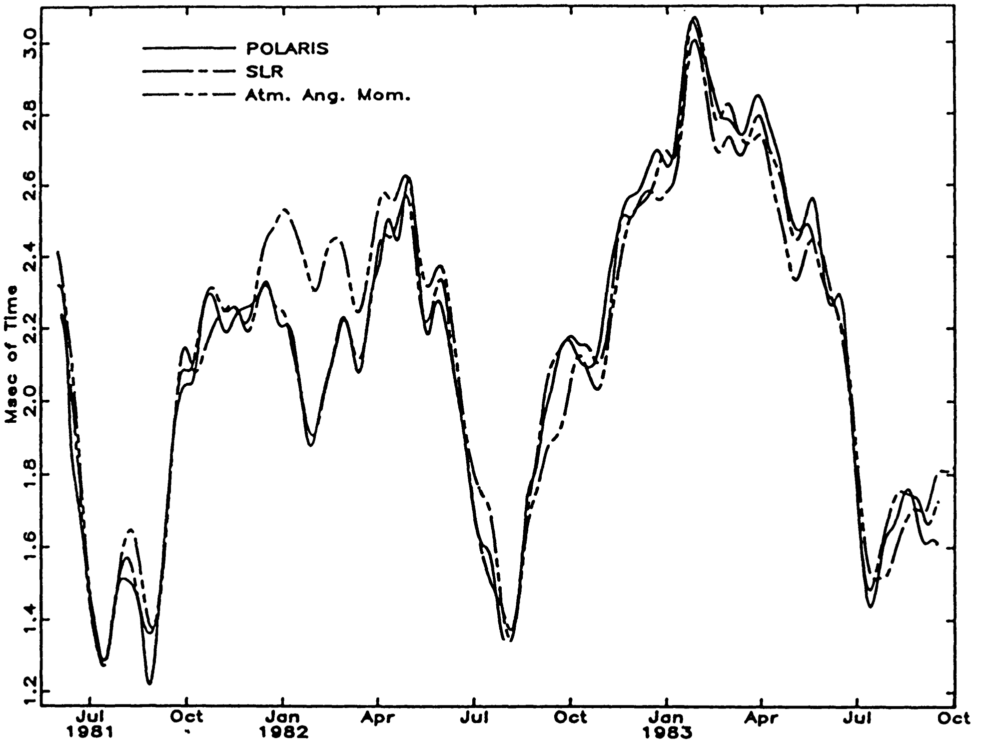

Figure 5. Variations in the length-of-day estimated from VLBI, SLR and atmospheric angular momentum data.

VI. CONCLUSIONS

VLBI is proving to be a powerful tool for determining source coordinates and Earth rotation parameters with accuracies at the level of several milliseconds of arc. Several observation programs are operating and producing a wealth of data of continuing interest to the astrometric community. The major problems with the current data set are related to unmodeled effects of the neutral atmosphere and to inadequate distribution of baselines, especially north-south baselines. In spite of these problems, the precision which the current observations can attain in measurements of source positions is beyond anything attainable by any other ground-based observation technique. Indeed, VLBI is one of the few ground-based techniques which will be able to compete in accuracy with space-based telescopic observations.

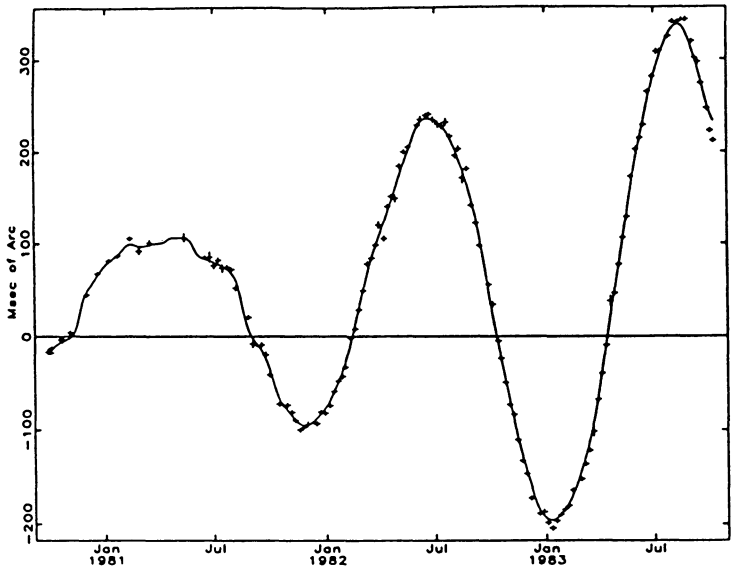

Figure 6. X-Component of the pole position from the POLARIS VLBI observations.

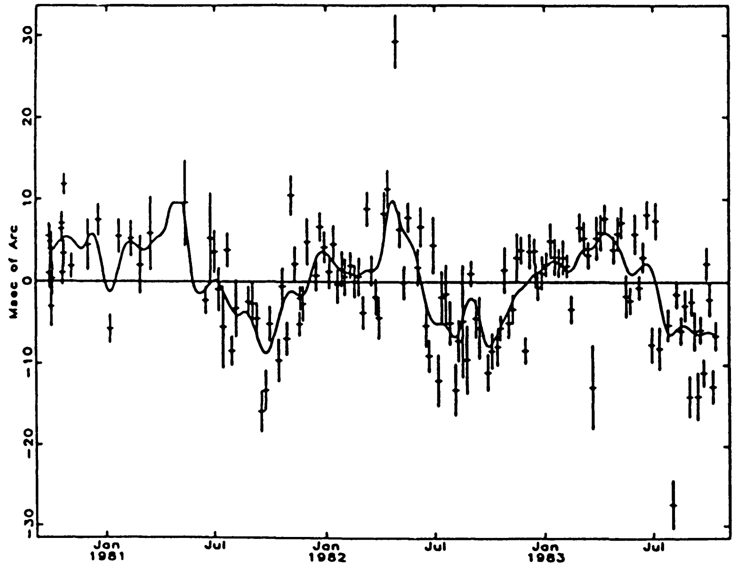

Figure 7. VLBI estimates of corrections to the IAU 1984 model for nutation in longitude.

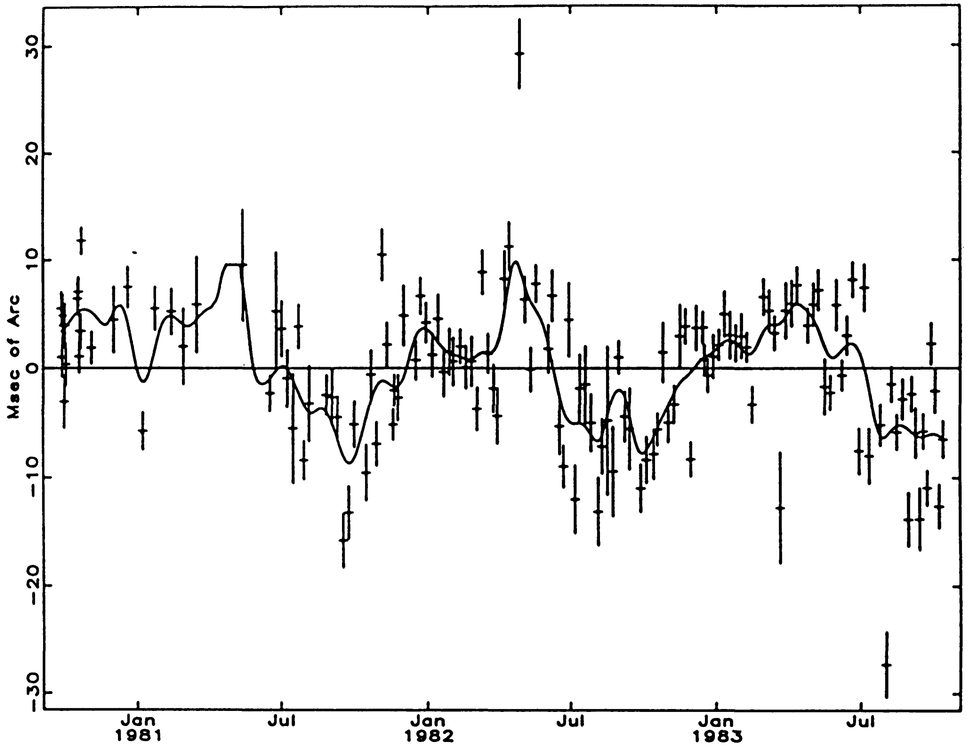

Figure 8. VLBI estimates of corrections to the IAU 1984 model for nutation in latitude.

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Discussion:

de VEGT: Is your quoted correction to precession related to the new (1984) precession constant?

ROBERTSON: Yes.

EICHHORN: You make the statement that "the precision for the baseline translates to a few milliarcseconds". What exactly does this mean?

ROBERTSON: This reflects the error in the angular precision of the baseline as seen from the source. A few centimeters error in the baseline corresponds to a few milliarcseconds.

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