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Determination of Intercontinental Baselines and Earth Orientation Using VLBI

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A series of experiments has been conducted during the last decade to explore the capability of very long baseline interferometry (VLBI) to measure the crustal and rotational motions of the earth with accuracies at the centimeter level. The observing stations are those of NASA's Deep Space Network in California, Spain and Australia. A multiparameter fit to the observed values of delay and delay rate yields radio source positions, polar motion, universal time, the precession constant, baseline vectors, and solid earth tides. Source positions are obtained with formal errors of the order of 0''.01. UT1-UTC and polar motion are determined at 49 epochs, with formal error estimates (1σ) for the more recent data of 0.5 msec for UT1-UTC and 2 to 6 mas for polar motion. Intercontinental baseline lengths are determined with formal errors of 5 to 10 cm. The Love numbers and earth tide phase lag agree with the commonly accepted values.

I. Introduction

Over the last few years, considerable progress has been made toward realizing the potential capability of radio interferometry to measure the crustal and rotational motions of the earth at the centimeter level (e.g., Refs. 1-5). Toward this goal, a series of experiments with NASA's Deep Space Network (DSN) antennas has been conducted over the last decade. In all, 48 sessions have been carried out using 8 different antennas on three continents. Delay and/or delay rate observables have been measured on two local baselines (at Goldstone, California and at Madrid, Spain), on a transcontinental baseline (California to Massachusetts, USA), and on two intercontinental baselines (Goldstone to Madrid and to Canberra, Australia). A multiparameter fit has been applied to these observables to extract astrometric and geophysical parameters. These parameters include source positions, polar motion, universal time, the precession constant, baseline vectors and solid earth tides. This article summarizes the geophysical results obtained from the intercontinental measurements.

II. Interferometry Technique

In the present experiments, two separate interferometry systems were employed. The prototype system used in the early measurements recorded a single narrowband (24 kHz) channel at S-band (2.3 GHz) and therefore could only measure delay rate accurately (Ref. 6). To obtain measurements of delay as well, a new system was developed and implemented in 1977 (Ref. 7). It records six time-multiplexed frequency channels to permit calculation of delay by bandwidth synthesis

(BWS), a technique pioneered by Rogers (Ref. 8). Three 2-MHz-wide channels are placed at S-band and three at X-band (8.4 GHz) to allow dual-frequency calibration of charged-particle delays. This new system can measure delay with a precision (system noise error) of approximately 100 psec, given a correlated source strength of 0.5 Jy, an integration time of 3 minutes, a spanned bandwidth of 40 MHz, and two 64-m DSN antennas with system temperatures of 35 K.

III. Summary of Experiments

The need to optimize determination of each class of astrometric and geophysical parameters imposes stringent and sometimes conflicting requirements on the design of a VLBI observing schedule. Maximum sensitivity to polar motion and UT1 requires concurrent or consecutive sessions (within 24-48 hours) on the California/Spain baseline (essentially east/west) and the California/Australia baseline (with a large north/south component). Development of a reference frame requires complete coverage of the sky and several observations of each source during the period of mutual visibility for each pair of stations. Establishing accurate positions of enough radio objects to provide "nearby" reference points for navigating interplanetary spacecraft, as well as for measurements of earth orientation with only 3 hours of VLBI data in a subsequent operational mode, requires approximately 100 sources. Observations which meet the above requirements have been carried out between August 1971 and February 1980. In all, 117 extragalactic radio sources were observed in 48 sessions, which ranged in length from 2 to 24 hours. Of the 2414 individual observations, 692 were made at S-band only, 366 at X-band only, and 1356 were dual-frequency. The observations included 2399 measurements of delay rate and 2152 of delay.

IV. Model and Fit to Experimental Data

In considering the multitude of effects contributing to the delay model for VLBI, it is helpful to group them as either modeled or unmodeled effects, with the models containing parameters that may be either adjusted or fixed at their a priori values. Modeled quantities that were fixed at their a priori values include nutation (Wahr series, Ref. 9) and the effects of the ionosphere. Effects of ocean loading and plate motion are unmodeled.

There are eight categories of modeled and adjusted parameters: station locations, tropospheric delays, clock offsets and rates, polar motion and UT1, source positions, the precession constant, the gamma factor of general relativity, and solid earth tides. The solution provided a catalog of approximately 100 positions of radio sources with declinations ranging between -40° and $+70^\circ$ (with formal error estimates of the order of $0''.01$). A number of discontinuities and nonlinearities in the station clocks were detected and modeled in many of the sessions. There were 114 parameters describing delay due to the troposphere; these were constrained to agree with the Chao monthly mean model (Ref. 10) to within 3%. The long span of data enables us to solve for the luni-solar precession constant, in addition to UT1 and polar motion at 49 epochs.

A rotation about the polar axis of 2.37 milliarcsecond/year (mas/yr) is included in the model to correct UT1 for the new IAU expressions for Greenwich mean sidereal time and precession (Ref. 9). The BIH Circular D provides a reference point for earth orientation: the values of both components of polar motion and two values of UT1 (one for each intercontinental baseline) are constrained on December 20-21, 1979, during which period there were two intercontinental observing sessions. In total, the fit to the 1971-1980 data includes 744 adjusted parameters.

The observables in the fit were weighted in inverse proportion to the sum of squares of known random error sources, plus an additional noise term which is adjusted to make chi-square per degree of freedom equal to 1 for each session. The software used to perform parameter estimation is based on the square-root-information-filter method (Ref. 11) implemented for the VAX 11/780 computer. Approximately 8 CPU hours are required for a solution for the 1971-80 data. RMS residuals for the grand fit are 0.5 nsec for delay and 0.3 psec/sec for delay rate. The resulting geophysical parameters are discussed in some detail in the next section.

V. Results

A. Earth Orientation

The solution for universal time and polar motion produced the average formal error estimates given in Table 1 as functions of the date of observation. Clearly, the quality of the data improved substantially as the interferometric system evolved, with the 1980 data exhibiting formal uncertainties of 6 to 20 cm.

Figures 1 and 2 show comparisons of our x and y polar motion values for the latter part of the data (1977-80) with BIH Circular D. Taking into account the 4 mas error of the BIH data (Ref. 12), there are no outstanding discrepancies with the possible exception of three points that differ by ~ 1.5 to 2σ. For the UT1 results similarly plotted in Fig. 3, short-period tidal fluctuations have been removed from the VLBI data in order to permit comparison with the heavily smoothed BIH values. The solid curve represents lunar laser ranging (LLR) data as smoothed over a 15-day interval by Fliegel et al. (Ref. 13). These data originally consisted of several hundred points in the range of the plot.

Figure 3 shows that the UT1 values measured by VLBI, LLR and BIH generally agree with one another if the BIH values are assigned errors of approximately 2 msec, and the LLR values errors of 1 msec or less. Both the VLBI and LLR results suggest the same oscillation of ~2 msec amplitude about the BIH values. The three points of large discrepancy (~2 to 3σ) between VLBI and LLR in February 1977 and February 1980 require further investigation.

The value obtained for the luni-solar precession constant is smaller than the 1976 IAU value by 3.7 ± 0.9 mas/yr. This discrepancy may indicate the need for a revision of either the precession constant or of the long-period (18.6-year) term in the nutation series. Such an inference is supported by calculations in which the fit was repeated with a modified nutation constant, and the precession constant was solved for. The rms delay residual for the 1971-80 VLBI data reaches a minimum when the amplitude of the 18.6-year term in the Wahr nutation series is increased by ~7 mas (to 9″.210 in obliquity), at which point the precession constant equals the 1976 IAU value within its error estimate.

B. Baselines and Earth Tides

On the premise that our data, especially the 1971-1977 portion, lack quality sufficient to detect plate motion, each station was initially assumed to have a single location for the entire span of data. Table 2 shows the lengths of the two intercontinental baselines obtained from such fits in 1978 and at present. Comparison of baseline lengths in this table is complicated by the substantially different modeling used in the two calculations (e.g., the 1978 fit did not use the Wahr nutation series). In spite of the lack of separation of the effects of improved data quality and improved modeling, Table 2 shows the qualitative enhancement in system performance over the past decade. The decrease by nearly a factor of 3 in the formal baseline errors between 1978 and the most recent solution suggests that future improved experiments will permit detection of plate motion within the next few years

A useful test of internal consistency is to divide the data into parts and to determine if fits to the parts lead to consistent values for theoretically constant parameters. To test baseline repeatability, the span of data was divided into two portions containing nearly equal numbers of observations: 1971-78 (average epoch 1978.2) and 1979-80 (average epoch 1979.9). All of the data were again simultaneously fit, but the Spanish and Australian 64-m antennas were each allowed to have different locations in the two spans of data. As shown in Table 3, the resulting baseline lengths for the two parts are in good agreement.

The Spanish baseline errors in Table 3 again show the improvement of data quality with time. It is of interest to note that, even though our results are consistent with no motion, the differences for both the Spanish and Australian baselines in Table 3 are more consistent with the motion inferred from paleomagnetic data (Refs. 14, 15). For a 1.7-year span, Morabito's application (Ref. 15) of Minster and Jordan's model (Ref. 14) indicates changes of +4 and −6 cm respectively for the Spanish and Australian baselines.

Assuming that the vertical and horizontal Love numbers and the solid-earth-tide-phase lag values are identical at all stations we obtain 0.63 ± 0.03, 0.063 ± 0.017, and −1.7 ± 1.6 degrees respectively. These agree well with the commonly accepted values of 0.603 – 0.611, 0.0832 – 0.0842, and 0 degrees (Refs. 16, 17).

VI. Conclusions

The radio interferometric system under development at JPL during the past decade has improved continually in quality. By 1980 it had reached the point where earth orientation parameters could be determined with formal uncertainties of 6 to 20 cm, and source positions with formal uncertainties of the order of 0″.01. Formal uncertainties of 5 to 10 cm in intercontinental baseline lengths promise detection of plate-tectonic motion in the near future.

The present set of results represents very nearly our final fit to the 1971-80 data. Minor changes in the model, such as improved ephemerides and earth tide models, as well as adoption of the J2000 system, will probably not have significant repercussions.

References

1. Thomas, J. B., et al., "A Demonstration of an Independent-Station Radio Interferometry System with 4-cm Precision on a 16-km Baseline," *J. Geophys. Res.*, 81, pp. 995-1005, 1976.

2. Rogers, A. E. E., et al., "Geodesy by Radio Interferometry: Determination of a 1.24-km Base Line with 5-mm Repeatability," *J. Geophys. Res.*, 83, pp. 325-334, 1978.

3. Ryan, J. W., et al., "Precision Surveying Using Radio Interferometry," *J. Surveying and Mapping Division,* Proc. ASCE, Vol. 104, No. SU1, pp. 25-34, 1978.

4. Niell, A. E., et al., "Comparison of a Radio Interferometric Differential Baseline Measurement with Conventional Geodesy," *Tectonophysics*, 52, pp. 49-58, 1979.

5. Herring, T. A., et al., "Geodesy by Radio Interferometry: Intercontinental Distance Determinations with Subdecimeter Precision," *J. Geophys. Res.*, 86, pp. 1647-1651, 1981.

6. Thomas, J. B., *An Analysis of Long Baseline Radio Interferometry*, Technical Report 32-1526, Volume VII, 37-50, Volume VIII, 29-38, Volume XVI, 47-64, Jet Propulsion Laboratory, Pasadena, Calif., 1972.

7. Thomas, J. B., *An Analysis of Radio Interferometry with the Block 0 System,* Publication 81-49, Jet Propulsion Laboratory, Pasadena, Calif., 1981.

8. Rogers, A. E. E., "Very Long Baseline Interferometry with Large-Effective Bandwidth for Phase-Delay Measurements," *Radio Science*, 5, p. 1239, 1970.

9. Kaplan, G. H., "The IAU Resolutions on Astronomical Constants, Time Scales, and the Fundamental Reference Frame," USNO Circular No. 163, United States Naval Observatory, Washington, D.C., 1981.

10. Chao, C. C., *The Tropospheric Calibration Model for Mariner Mars 1971*, Technical Report 32-1587, pp. 61-76, Jet Propulsion Laboratory, Pasadena, Calif., 1974.

11. Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation,* New York, Academic Press, 1977.

12. Dickey, J. O., "Analysis of Lageos Polar Motion Results Using Lunar Laser Ranging," *EOS 62,* p. 841, 1981.

13. Fliegel, H. F., Dickey, J. O., and Williams, J. G., "Intercomparison of Lunar Laser and Traditional Determinations of Earth Rotation," IAU Colloquium Proc. No. 63, O. Calame, ed., Grasse, France, 1981.

14. Minster, J. B., and Jordan, T. H., "Present-Day Plate Motions, *J. Geophys. Res.,* 83, pp. 5331-5354, 1978.

15. Morabito, D. D., Claflin, E. S., and Steinberg, C. J., "VLBI Detection of Crustal Plate Motion Using DSN Antennas as Base Stations," *DSN Progress Report 42-56*, pp. 59-75, Jet Propulsion Laboratory, Pasadena, Calif., 1980.

16. Wahr, J. M., "The Tidal Motions of a Rotating, Elastic and Oceanless Earth," pp. 162-171, Thesis, University of Colorado, 1977.

17. Lambeck, K., *The Earth's Variable Rotation: Geophysical Causes and Consequences*, pp. 13, 111, Cambridge University Press, 1980.

Table 1. Earth orientation parameter formal errors in fit to 1971–1980 VLBI data

Year	Polar motion, mas		UT1, msec
	x	y	
1971-4	• • •	• • •	2.1
1977	10	4	0.9
1978	10	3	0.7
1979	6	2	0.5
1980	6	2	0.5

Table 2. Baseline length results from VLBI data

Date	California to	
	Spain	Australia
1971–78	8 390 429.66 ± 0.16 m	10 588 965.85 ± 0.26 m
1971–80	8 390 429.84 ± 0.05 m	10 588 966.32 ± 0.11 m

Table 3. Baseline consistency test results

Average date	California to	
	Spain	Australia
1978.2	8 390 429.78 ± 0.09 m	10 588 966.36 ± 0.11 m
1979.9	8 390 429.85 ± 0.05 m	10 588 966.27 ± 0.11 m
Difference	7 ± 10 cm	−9 ± 15 cm

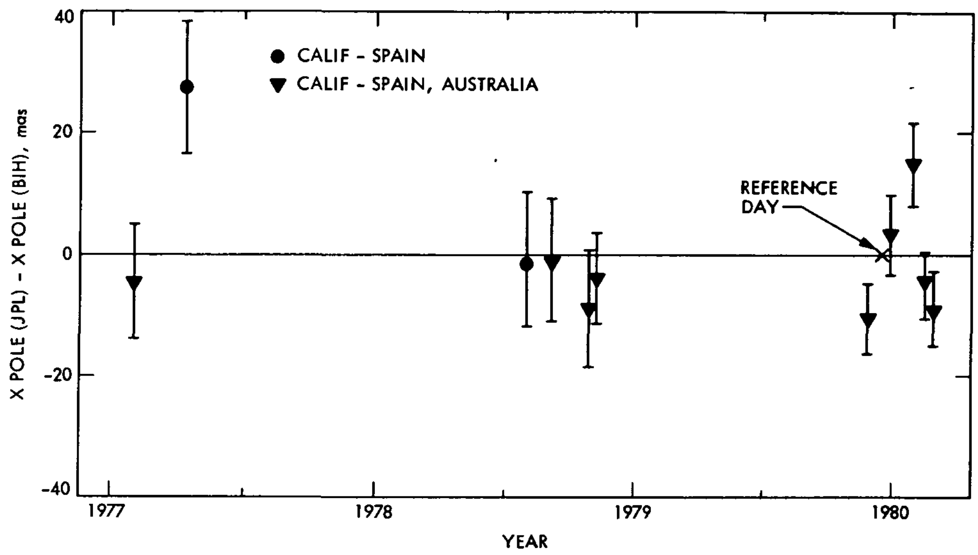

Fig. 1. Polar motion x-component results from 1977–1980 VLBI data

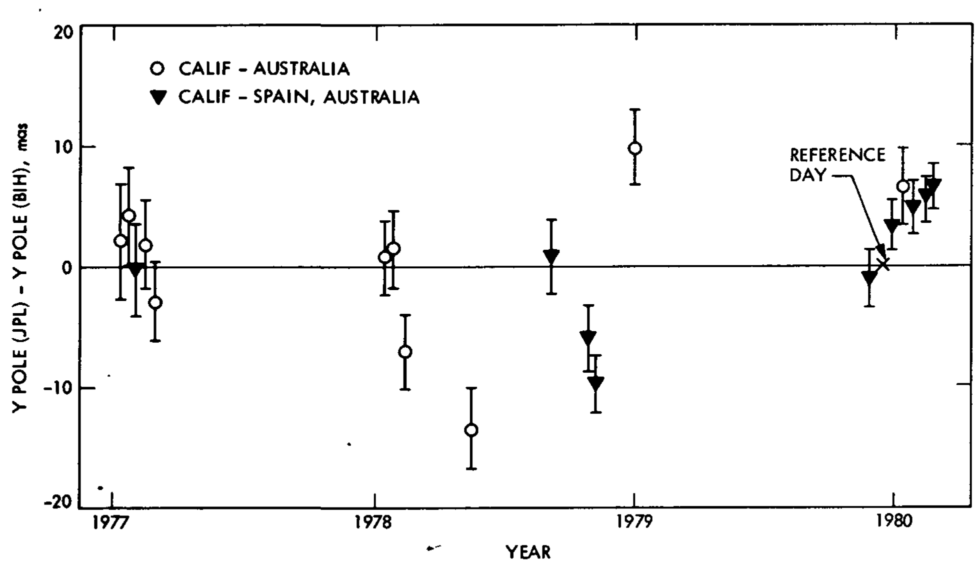

Fig. 2. Polar motion y-component results from 1977–1980 VLBI data

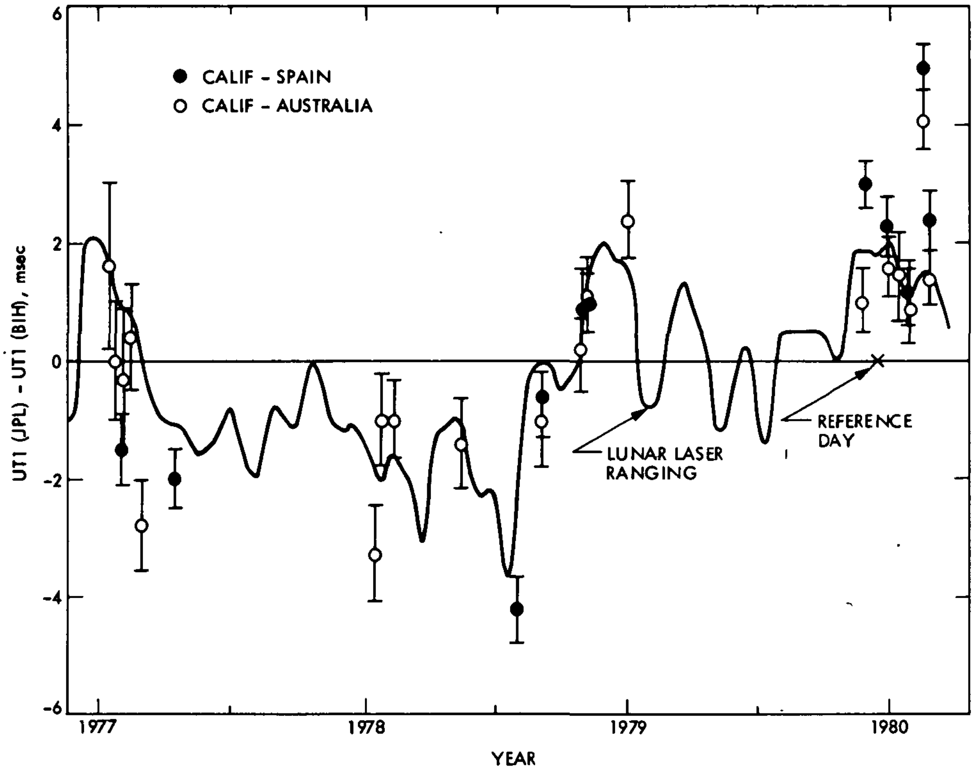

Fig. 3. UT1 results from 1977–1980 VLBI data. Short-period tidal terms have been removed to permit comparison with BIH values