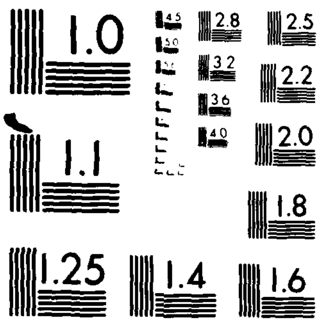
AD-A098 960 MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF EARTH A--ETC F/G 8/5
ANALYSIS OF LUNAR LASER RANGING DATA AND PERFORMANCE AND ANALYS--ETC(U)
NOV 80 C C COUNSELMAN, T A HERRING F19628-79-C-0064
UNCLASSIFIED AFGL-TR-81-0004 NL

END
DATE
FILMED
6 81
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

LEVEL

AFGL-TR-[illegible]

ANALYSIS OF LUNAR LASER RANGING DATA AND [illegible]

ANALYSIS OF VLBI OBSERVATIONS FOR GEODETIC [illegible]

C. C. Counselman III
T. A. Herring
R. B. Langley
I. I. Shapiro

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

27 November 1980

Final Report
15 February 1979 - 30 September 1980

Approved for public release; distribution unlimited.

Air Force Geophysics Laboratory
Air Force Systems Command
United States Air Force
Hanscom AFB, MA 01731

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-81-0004
2. GOVT ACCESSION NO.: AD-A098960
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): ANALYSIS OF LUNAR LASER RANGING DATA AND PERFORMANCE AND ANALYSIS OF VLBI OBSERVATIONS FOR GEODETIC PURPOSES
5. TYPE OF REPORT & PERIOD COVERED: Final rept. 15 Feb 1979 – 30 Sep 1980
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): C. C. Counselman, III, T. A. Herring, R. B. Langley, I. I. Shapiro
8. CONTRACT OR GRANT NUMBER(s): F19628-79-C-0064
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Dept. of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2309G1AX
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory, Hanscom AFB, MA 01731, Monitor: Theodore E. Wirtanen/LWG
12. REPORT DATE: 27 November 1980
13. NUMBER OF PAGES: 36
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number): Lunar Laser Ranging, Earth Rotation, UT1, Polar Motion, Variation of Latitude, Very Long Baseline Interferometry (VLBI), Geodesy, Intercontinental Distance Measurement
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

UT0 and variation of latitude have been determined from the McDonald Observatory lunar laser ranging (LLR) observations for the period October 1970 to October 1979. We have compared our estimates with those determined from the UT1 and pole position values obtained using other techniques.

In 1978, the distance between the Haystack Observatory in the United States and the Onsala Space Observatory in Sweden was

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

404184

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Continued from Block 20

determined by very long baseline interferometry (VLBI) with the "Mark-I" System; the estimated uncertainty was less than 10 cm. In 1979 and again in 1980, the distance between these observatories was redetermined with the "Mark-III" VLBI System. On each occasion, transatlantic distances were also determined by VLBI between one or both of these observatories and various other sites in the U.S. and Europe. Preliminary solutions using the November 1979 experiment data have indicated that the Mark-I derived baseline lengths are consistent with the Mark-III values within the quoted 10 cm precision of the Mark-I values.

In this report we present recent results from the analysis of lunar laser ranging (LLR) and very long baseline interferometry (VLBI) data.

I. Determinations of UT0 and Variation of Latitude from Lunar Laser Ranging Data

There now exists over ten years of lunar laser ranging data from observations made by the McDonald Observatory near Fort Davis, Texas. These data are currently being analyzed to estimate variations in the rotation of the earth. The primary earth rotation parameters are UT1 and the X and Y components of pole position. However the earth rotation parameters to which LLR observations are fundamentally sensitive are UT0 and variation of latitude. In this respect, the information content of LLR observations from a single station is the same as that of observations from a photographic zenith tube. In order to determine the primary earth rotation parameters, it is necessary to combine data from two or more stations. McDonald Observatory is currently the only station regularly providing scientifically useful data. Therefore, if we ignore other sources of data, we must content ourselves with determining UT0 and the variation of latitude specifically for McDonald Observatory. On the other hand, if an accurate set of pole position values is available from a separate source, it is possible to use them in conjunction with values of UT0 at McDonald Observatory to determine UT1. Similarly, if a set of UT1 values is available, it is possible to derive the X and Y components of pole position from the McDonald Observatory UT0 and variation of latitude values.

Our initial approach in determining earth rotation values from the LLR data was to determine only UT0 and by using pole position data from the traditional astronomical techniques, determine UT1. We realized that the quality of the pole position data used would, in part, determine the quality of the UT1 estimates. In this regard it is worth noting that recently significant differences have been found between the values of pole position and UT1 obtained using traditional techniques as reported by the Bureau International de l'Heure (BIH) and those obtained from other sources [Stolz et al., 1976; Harris and Williams, 1977; King et al., 1978; Robertson et al., 1980; Bureau International de l'Heure, 1979]. The discovery of these differences has resulted in the establishment of a new BIH system, the "1979 BIH System" [Bureau International de l'Heure, 1979]. The 1979 BIH System was adopted in an attempt to "correct" the BIH results to bring them into better agreement with those obtained from the other sources. Results in this system are related to results in the 1968 BIH System by the following relationships:

$$X_{1979} - X_{1968} = 0\overset{''}{.}024 \sin[\frac{2\pi}{365.24}(MJD - 43932)]$$
$$+ 0\overset{''}{.}007 \sin[\frac{4\pi}{365.24}(MJD - 43979)]$$

$$Y_{1979} - Y_{1968} = 0$$

$$UT1_{1979} - UT1_{1968} = 0\overset{s}{.}0007 \sin[\frac{2\pi}{365.24}(MJD - 44048)]$$

$$+ 0\overset{s}{.}0007 \sin[\frac{4\pi}{365.24}(MJD - 44019)] \quad .$$

The discovery of the "errors" in the BIH results shows the importance of developing and refining alternative techniques for determining pole position and UT1.

Our first step in determining UT0 was to use the MIT Planetary Ephemeris Program (PEP) to estimate tabular values of a continuous piece-wise-linear model of UT0 with respect to a set of _a priori_ reference values. The model has the form

$$f(t) = g_i + \frac{g_{i+1} - g_i}{t_{i+1} - t_i}(t - t_i) \ ,$$

$$t_i \leq t \leq t_{i+1}; \ i = 1, 2, 3, \ldots, n-1 \ ,$$

where $g_i \equiv f(t_i)$ are the unknown tabular points which are estimated simultaneously with all other parameters affecting the observations. The time intervals between successive tabular points need not be uniform; they were chosen at approximately monthly intervals to nearly coincide with the center of the usable LLR data for each lunation. The number of tabular points was 96.

The continuous piece-wise-linear model provides corrections to the reference values of UT0. These corrections contain no information on variations with periods less than about one month. In a subsequent step, we estimated the high frequency variations in UT0. We took the postfit range residuals from the first step and analyzed them separately for one observing day at a time to obtain an incremental correction to the estimate of UT0 for each day. We estimated two parameters, a range bias and a correction to UT0 for each day on which there were two or more observations of a single reflector spanning a period of 1.5 hours or more. Raw estimates of corrections to UT0 were obtained for 636 dates between October 1970 and October 1979. The raw daily estimates were smoothed by convolving the weighted raw values with a Gaussian-shaped smoothing window:

$$y_i^* = \sum_{j=1}^{n} w_j y_j e^{-(x_i - x_j)^2/a^2}$$

where the weights, w_j, are given by

$$w_j = (\sigma_j^2 \sum_{i=1}^{n} \sigma_i^{-2} e^{-(x_i - x_j)^2/a^2})^{-1}$$

with the σ_i being the standard deviations of the raw estimates. The smoothing parameter, $\underline{a}$, determines the degree of smoothing obtained. It is proportional to the full-width-at-half-maximum (FWHM) of the Gaussian window:

$$\mathrm{FWHM} \simeq 1.665\, a.$$

Filters with FWHM of about 4.1, 8.3 and 16.7 days have been used.

We interpolated among the smoothed values, using cubic polynomials, to obtain estimates of UT0 at 5-day intervals corresponding to the dates of the published BIH values. We then combined our UT0 values with BIH values of pole position to create UT1. A comparison of these values with smoothed BIH values in the 1979 system has revealed significant differences while a comparison with a limited number of preliminary VLBI (D. S. Robertson, personal communication, 1980) and raw BIH determinations showed similar trends (see Figure 1).

The accuracy of our UT1 results derive partly from the assumption that the pole position values we had used were accurate. We decided to test this assumption.

The histograms of Figure 2 illustrate the effects of nominal errors of 1 ms in UT0 and 0"015 in variation of latitude on the set of LLR observations through May 1978. The units of delta tau are nanoseconds. It had been felt for some time that the inability to accurately model pole position might be significantly degrading model fits to the LLR data. This feeling was dramatically confirmed by a simple test based on the histogram results. Using the full set of observations and a nominal model which included BIH values of pole position and a continuous piece-wise-linear correction to BIH values of UT1, we obtained postfit residuals which had a normalized RMS[1] of 1.79. Using

---

1. The normalized RMS is defined as

$$\left(\sum_{i=1}^{n} (e_i/\sigma_i)^2/n\right)^{1/2}$$

where n is the number of residuals, e_i is the value of the ith residual, and σ_i is the *a priori* estimated standard deviation of the ith observation.

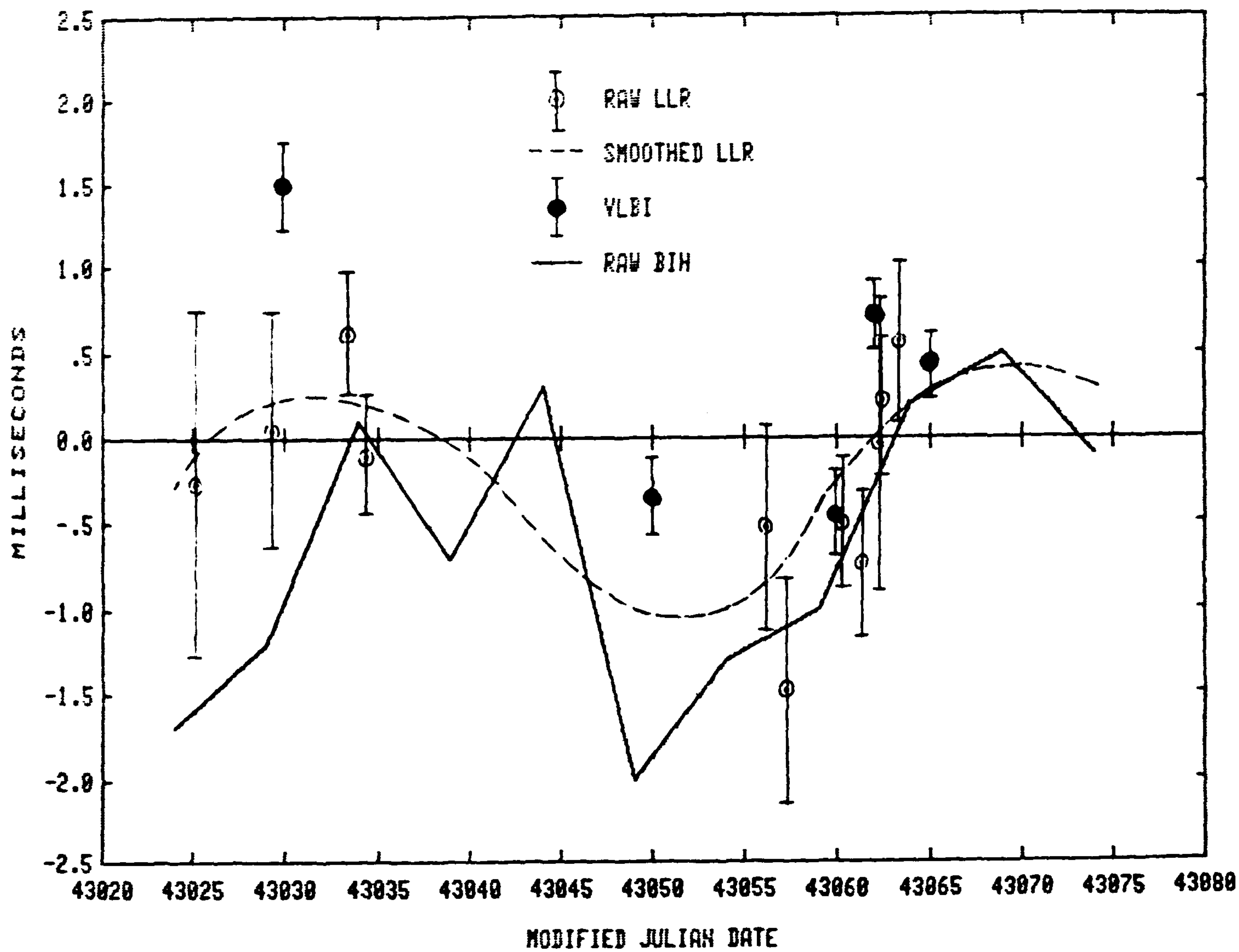


Fig. 1. DIFFERENCES BETWEEN 1) LUNAR LASER RANGING (LLR), 2) VERY LONG BASELINE INTERFEROMETRY (VLBI) AND 3) RAW BUREAU INTERNATIONAL DE L'HEURE (BIH) VALUES OF UT1 AND SMOOTHED BIH VALUES OF UT1 IN THE 1979 SYSTEM. MODIFIED JULIAN DATE 43020 IS 28 AUG. 1976.

```
                                                                        0    10   20   30   40   50   60   70%
                                                                        |____|____|____|____|____|____|____|
FOR DELTA UT0 = 1 MS:
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.0  AND LT 0.20 =  328  ********
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.20 AND LT 0.40 =  293  *******
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.40 AND LT 0.60 =  208  *****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.60 AND LT 0.80 =  160  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.80 AND LT 1.00 =  127  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.00 AND LT 1.20 =  146  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.20 AND LT 1.40 =  172  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.40 AND LT 1.60 =  291  *******
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.60 AND LT 1.80 =  323  ********
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.80             =  267  *******

FOR DELTA PHI = 0.015":
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.0  AND LT 0.20 =  180  *****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.20 AND LT 0.40 =  223  ******
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.40 AND LT 0.60 =  216  *****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.60 AND LT 0.80 =  207  *****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.80 AND LT 1.00 =  147  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.00 AND LT 1.20 =  161  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.20 AND LT 1.40 =  118  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.40 AND LT 1.60 =  147  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.60 AND LT 1.80 =  147  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.80             =  769  *****************

FOR DELTA UT0 = 1 MS AND DELTA PHI = 0.015":
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.0  AND LT 0.20 =    0  *
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.20 AND LT 0.40 =   19  *
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.40 AND LT 0.60 =   41  **
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.60 AND LT 0.80 =   65  **
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 0.80 AND LT 1.00 =   93  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.00 AND LT 1.20 =   94  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.20 AND LT 1.40 =  114  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.40 AND LT 1.60 =  105  ***
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.60 AND LT 1.80 =  158  ****
NUMBER OF OBSERVATIONS WITH DELTA TAU GE 1.80             = 1626  ***********************************
```

Fig. 2. THE SENSITIVITY OF TWO-WAY RANGE OBSERVATIONS TO ERRORS IN UT0 AND THE VARIATION IN LATITUDE DUE TO POLAR MOTION

only observations for which an error of 1 ms in UT0 would introduce an error of less than 0.2 ns in two way range with the same model as used for the full set of observations, we obtained postfit residuals with a normalized RMS of 1.61. 331 normal points were used. Using only observations for which an error of 0".015 in variation of latitude would introduce an error of less than 0.3 ns in two way range with again essentially the same model that we used for the full set of observations, we obtained postfit residuals with a normalized RMS of only 1.28. 313 normal points were used in this case. These results indicated that while we were adequately modeling the effects of variations in UT0 on the LLR observations, the variations in latitude were not adequately modeled. We concluded that since none of the readily available sets of pole position data (BIH, IPMS [International Polar Motion Service], DMAHTC [Defense Mapping Agency Hydrographic/Topographic Center]) are sufficiently accurate, we should estimate the variation in latitude at McDonald Observatory directly from the LLR observations themselves. To do so, we modeled the variation of latitude with a continuous, piece-wise-linear function of atomic time of the same form as that used to determine the long period trends in UT0. Again, the tabular points were estimated simultaneously with all other parameters.

The time intervals between successive tabular points were the same as those used for the function describing UT0. The number of tabular points was 96. By adding these parameters to our analysis, we reduced the RMS of the postfit residuals from 25.8 cm to 19.5 cm, a reduction of almost 25%!

We have compared our LLR estimates of variation of latitude with those derived from the pole position values reported by workers using other techniques. We have determined the variation of latitude at McDonald Observatory from (i) the smoothed 5-day Circular D values of the BIH, (ii) the smoothed 0.05-year values of the IPMS as reported in the Monthly Notes of the IPMS, (iii) the raw daily values from the Polar Motion Reports of the DMAHTC, (iv) the raw 5-day values produced by the Goddard Space Flight Center (GSFC) from laser ranging observations of the satellite LAGEOS and (v) the raw 5-day values produced by the Institute of Advanced Study in Orbital Mechanics (IASOM) of the University of Texas, also from laser ranging observations of LAGEOS.

The raw DMAHTC, GSFC and IASOM pole position values contain a significant amount of high frequency variation. Just how much of the high frequency component is noise and how much is true pole position is not yet known. In an attempt to study this problem we have smoothed the pole position data sets and produced smoothed values of variation of latitude at McDonald Observatory.

Two smoothing techniques have been investigated: convolution of the raw data with a Gaussian-shaped window and Whittaker's smoothing procedure [Whittaker and Robinson, 1940] as implemented by Vondrák [Vondrák, 1969; Vondrák, 1977]. For the most part the procedure of applying Gaussian smoothing to the pole position data follows that used for the LLR UT0 values. However for the smoothing of the pole position values an improvement in the Gaussian smoothing technique was made. The Gaussian smoothing technique suffers from an inability to provide reasonable values within data gaps if those gaps are much larger than the full-width-at-half-maximum (FWHM) of the smoothing filter. This is particularly true for data containing periodicities with large amplitudes. To improve the smoothing and interpolating ability of the Gaussian smoothing technique, we first removed from the data best-fitting sinusoids with periods of 432.1 days (Chandler), 365.24 days (annual) and 275.0 days (a periodicity to be discussed later). We then smoothed the resulting residuals and subsequently added back the sinusoidal terms.

The raw DMAHTC, GSFC and IASOM values were smoothed using Gaussian windows with FWHM of about 8.3, 16.7, 33.3, 50.0, 66.6 and 83.3 days. The variation of latitude at McDonald Observatory was determined from each set of smoothed values and compared to the estimates derived from the LLR observations. The RMS differences about the mean were calculated for each comparison and are shown in Table 1.

Table 1

RMS DIFFERENCES ABOUT THE MEAN BETWEEN LLR AND VARIOUS OTHER DETERMINATIONS OF THE VARIATION OF LATITUDE AT McDONALD OBSERVATORY

FWHM (days)	DMAHTC[1]	GSFC[1]	IASOM[1]	BIH68[1]	BIH79[1]	IPMS[1]
8.3	8.26	16.92	28.26			
16.7	6.85	14.51	22.16			
33.3	5.90	11.23	13.99			
				8.57[2]	6.36[2]	11.66[2]
50.0	5.46	9.49	11.39			
66.6	5.26					
83.3	5.18					

1. Organizations are defined in text. Units for each entry are milliarcseconds.
2. BIH and IPMS data used were smoothed by those organizations. The equivalent FWHM of a Gaussian filter is roughly one month.

The time span used for all the comparisons was MJD = 42969 (10 July 1976) to MJD = 43809 (28 October 1978). In this time span each data set contains 169 5-day values. The overall results of this comparison had been anticipated. Since the LLR estimates are in effect the result of low-pass filtering with a cut-off of roughly one month, it is not surprising to see the agreement between the LLR estimates of variation of latitude and the values derived from the observations of other techniques improve as these values are more heavily smoothed. Clearly, the best agreement between the LLR values and those of the other techniques is that for the heavily smoothed satellite Doppler values. However, if the raw BIH or IPMS data were to be as heavily smoothed, they might also provide as good a comparison. We intend to do our own smoothing of BIH and IPMS data to confirm this prediction. One cannot judge from this comparison whether any of the high frequency variations seen in the data provided by the other techniques are real.

Another comparison of pole position values was performed which *is* sensitive to high frequency variations. Each of the data sets included in Table 1 (with the exception of BIH68 and IPMS) was used to provide *a priori* pole position values in separate analyses of the LLR data using PEP. Apart from the pole position values, the models used in these runs were identical. The postfit normalized RMS of the residuals resulting from the analyses are shown in Table 2.

Table 2

POSTFIT NORMALIZED RMS OF LLR RESIDUALS
OBTAINED USING VARIOUS SMOOTHED POLE POSITION DATA SETS

FWHM (days)	DMAHTC	GSFC	IASOM	BIH68	BIH79	IPMS
8.3	1.38	1.83	1.65			
16.7	1.30	1.72	1.56			
33.3	1.25	1.61	1.50			
					1.22	
50.0	1.22	1.57	1.49			
66.6	1.20					
83.3	1.19					

Again, the best result is that for the DMAHTC data smoothed with a filter with a FWHM of 83.3 days. The results presented in Table 2 seem to indicate that a lot of the high frequency structure present in various pole position data sets is noise, either due to observational error or reduction error.

The Gaussian smoothing was carried out after the best-fitting Chandler, annual and 275-day sinusoids had been removed from the raw data. We adopted this procedure in order to improve the signal-to-noise ratio of the smoothed data. We observed that when Gaussian smoothing was carried out after sinusoid removal and the resulting data sets used to provide *a priori* values, there was a drop in the postfit normalized RMS of the LLR residuals over that obtained when the pole position data were filtered without sinusoid removal. As expected, the drop was particularly significant for the more heavily smoothed data. For example, when the data were smoothed with a filter with a FWHM of 50.0 days *with* sinusoid removal, the postfit normalized RMS of the LLR residuals was 10% lower than the normalized RMS obtained using smoothed data *without* sinusoid removal.

All of the DMAHTC, GSFC and IASOM data sets used in the comparisons presented above were obtained by smoothing the raw data (with best-fitting sinusoids removed) with a Gaussian filter. The other smoothing technique which we have investigated is that of Whittaker. This work is being carried out under another contract and will be discussed elsewhere.

In the course of removing the sinusoids prior to smoothing the DMAHTC pole position values, a 275-day periodicity in the data was found. The approximate period of this term was determined from a visual inspection of the corresponding peak in the frequency spectrum of the DMAHTC data. The uncertainty in the estimated period has yet to be determined. In the X-component of pole position this 275-day term has an amplitude of 13.1 milliarcseconds (mas) and in the Y-component, 5.9 mas. The phase of the periodicity in the Y-component is 67° ahead of that in the X-component. This term has been observed in DMAHTC, BIH and IPMS data sets by other workers [Bowman and LeRoy, 1976; Graber, 1976; Rudnick, 1956] and is believed to be real although no explanation of its origin has yet been offered. We intend to investigate this term further.

II. Performance and Analysis of Intercontinental VLBI Experiments

We have conducted a number of intercontinental VLBI experiments involving the Onsala Space Observatory in Sweden, the Haystack Observatory in Massachusetts, and several other United States and European antennas. The results from experiments through 1978 were analyzed under the present contract and have been accepted for publication by the Journal of Geophysical Research (see Appendix A).

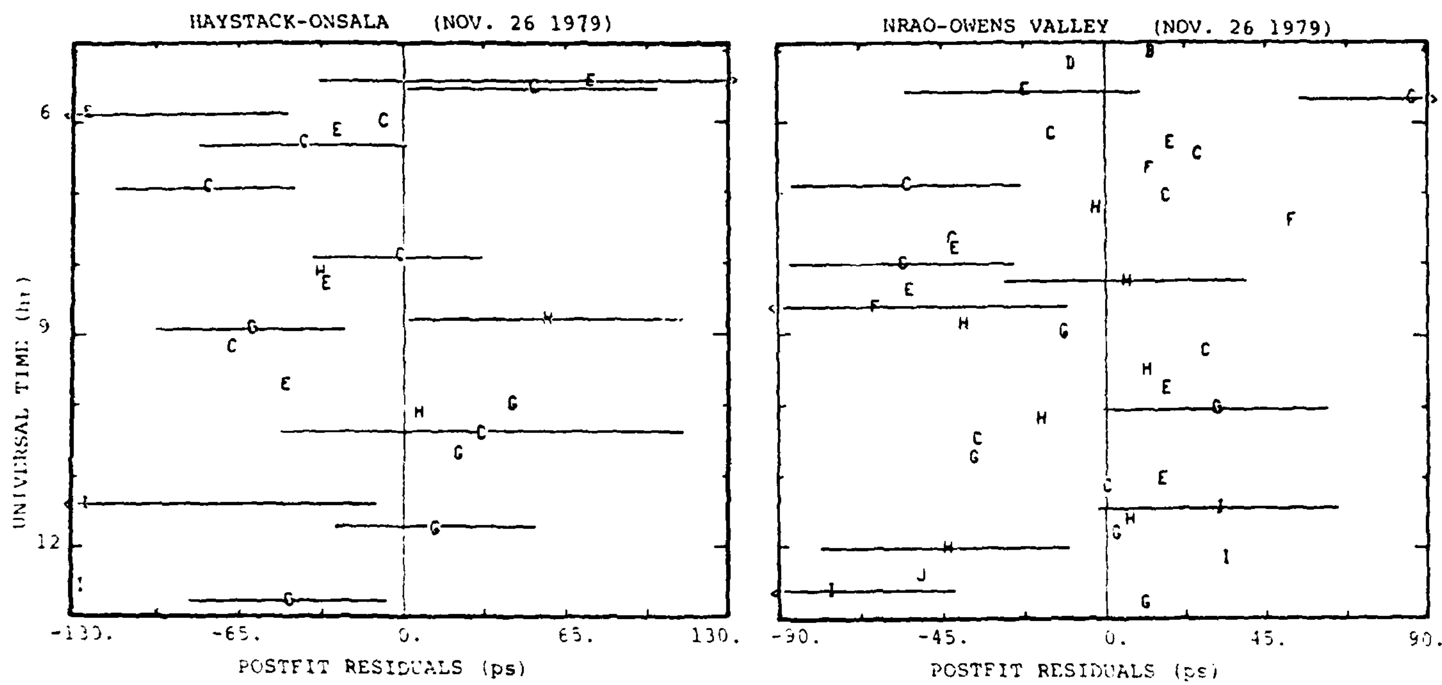
These experiments through 1978 were carried out with our Mark I VLBI System. Starting in November 1979, our intercontinental VLBI experiments have utilized our new Mark III System which is more than tenfold as sensitive as the Mark I System.

Data were obtained with the Mark III System in experiments involving Onsala and Haystack in November 1979, July 1980, and September 1980. The data are still being analyzed; many problems were encountered, as described in part in our Quarterly Reports. However, preliminary results are now available from the November 1979 experiment. Table 3 shows a comparison of our baseline estimates from these data with our earlier determinations (Appendix A). The agreement is reasonably good, the consistency being at the several-centimeter level, better than 6 parts in 10^9. Typical postfit residuals for the group-delay measurements are shown in Figure 3 for the November 1979 VLBI data; the RMS spread is only about 30 ps, equivalent to 1 cm in distance.

Table 3 PRELIMINARY MARK III RESULTS

BASELINES	DATA SETS MARK I FINAL VALUES (1650 obs) (m)	25th 02:20* - 16:50 NOV. '79 (233 obs) (m)	26th 04:40* - 13:30 NOV. '79 (152 obs) (m)	COMBINED* (385 obs) (m)	COMBINED* (source positions estimated) (385 obs) (m)
HAYSTACK-ONSALA	5,599,714.66 ±0.03	5,599,714.60 ±0.02	5,599,714.64 ±0.03	5,599,714.62 ±0.02	5,599,714.66 ±0.04
NRAO - ONSALA	6,319,317.75 ±0.03	6,319,317.69 ±0.03	6,319,317.78 ±0.04	6,319,317.73 ±0.02	6,319.317.77 ±0.05
OWENS VL-ONSALA	7,914,131.19 ±0.04	7,914,131.17 ±0.04	7,914,131.29 ±0.04	7,914,131.20 ±0.03	7,914,131.21 ±0.07

*SOURCE POSITIONS NOT ESTIMATED.



The horizontal bars placed on "typical" points represent $\pm$ one standard deviation. Each letter in the figure denotes a different radio source: B = 3C 454.3; C = NRAO 150; D = VRO 42.22.01; E = 0552 +398; F = 3C 120; G = 4C 39.25; H = OJ 287; I = 3C 273B; J = 1749 +701.

Fig. 3. TYPICAL POSTFIT RESIDUALS FOR BASELINES HAYSTACK-ONSALA AND NRAO-OWENS VALLEY

References

Bureau International de l'Heure, "Annual Report for 1978," Paris, 1979.

Bowman, B. R. and C. F. LeRoy, "DMATC Doppler Determination of Polar Motion," Proceedings of the International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, October 1976.

Graber, M. A., "Polar Motion Spectra Based upon Doppler, IPMS and BIH Data," Geophys. J. Roy. Astron. Soc., 46, 75-85, 1976.

Harris, A. W. and J. G. Williams, "Earth Rotation Study Using Lunar Laser Ranging Data" in Scientific Applications of Lunar Laser Ranging, ed. J. D. Mulholland, D. Reidel Publishing Company, Dordrecht, Holland, 1977.

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

Robertson, D. S., T. A. Clark, R. J. Coates, C. Ma, J. W. Ryan, B. E. Corey, C. C. Counselman, R. W. King, I. I. Shapiro, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, J. C. Pigg, B. R. Schupler, "Polar Motion and UT1: Comparison of VLBI, Lunar Laser, Satellite Laser, Satellite Doppler and Conventional Astrometric Determinations, Radio Interferometry Techniques for Geodesy (proceedings of a conference held at MIT, Cambridge, MA, 19-21 June 1979), NASA Conference Publication 2115, 71-87, 1980.

Rudnick, P., "The Spectrum of the Variation in Latitude," Trans., Am. Geophys, Un., 37, 137-142, 1956.

Stolz, A., P. L. Bender, J. E. Faller, E. C., Silverberg, J. D. Mulholland, P. J. Shelus, J. G. Williams, W. E. Carter, D. G. Currie and W. M. Kaula, "Earth Rotation Measured by Lunar Laser Ranging," Science, 193, 997-999, 1976.

Vondrák, J., "A Contribution to the Problem of Smoothing Observational Data," Bull. Astron. Inst. Czech., 20, 349-355, 1969.

Vondrák, J., "Problem of Smoothing Observational Data II," Bull. Astron. Inst. Czech., 28, 84-89, 1977.

Whittaker, E. T. and G. Robinson, The Calculus of Observations: A Treatise on Numerical Mathematics, 3rd. edition, Blackie and Son Ltd., London, 1940.

Appendix A

GEODESY BY RADIO INTERFEROMETRY: INTERCONTINENTAL DISTANCE DETERMINATIONS WITH SUBDECIMETER PRECISION

T. A. Herring,[1] B. E. Corey,[1] C. C. Counselman III,[1]
I. I. Shapiro,[1 7] B. O. Rönnäng,[2] O. E. H. Rydbeck,[2]
T. A. Clark,[3] R. J. Coates,[3] C. Ma,[3] J. W. Ryan,[3]
N. R. Vandenberg,[3] H. F. Hinteregger,[4] C. A. Knight,[4]
A. E. E. Rogers,[4] A. R. Whitney,[4] D. S. Robertson,[5]
and B. R. Schupler[6]

---

[1]Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

[2]Onsala Space Observatory, S-439 00 Onsala, Sweden.

[3]Goddard Space Flight Center, Greenbelt, Maryland 20771.

[4]Northeast Radio Observatory Corporation, Haystack Observatory, Westford, Massachusetts 01886.

[5]U.S. National Geodetic Survey, Rockville, Maryland 20852.

[6]Computer Science Corporation, Silver Spring, Maryland 20910.

[7]Also at Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

Abstract. Analysis of very-long-baseline interferometer (VLBI) observations yielded estimates of the distances between three radio telescopes in the United States and one in Sweden, with formal standard errors of a few centimeters: Westford, Massachusetts-Onsala, Sweden: 5,599,714.66±0.03m; Green Bank, West Virginia-Onsala, Sweden: 6,319,317.75±0.03m; and Owens Valley, California-Onsala, Sweden: 7,914,131.19±0.04m, where the earth-fixed reference points are defined in each case with respect to the axes of the telescopes. The actual standard errors are difficult to estimate reliably but are probably not greater than twice the formal errors.

1. Introduction

Very long baseline interferometry (VLBI) has been used for the past decade to determine distances between radio telescopes and positions of radio sources. Improvement in the precision of baseline length determination in North America over this period has been substantial -- from a precision of about 1 m [Hinteregger et al., 1972] to a precision of under five centimeters [Robertson et al., 1979] for baselines from about 1000 km to just under 4000 km in length. Near the middle of the decade, distances between North America and Europe were determined with a precision of about half a meter [Robertson, 1975; see also Cannon et al., 1979]. In this paper we describe more recent VLBI determinations, with subdecimeter precision, of these intercontinental distances.

2. Data Analysis

The data analyzed consisted of interferometric group delays [Shapiro, 1976] which were obtained from three sessions of observations involving up to four antennas, as described in Table 1. All observations were made with the Mark I VLBI system with a center radio frequency of about 8 GHz. A multichannel bandwidth synthesis technique [Whitney et al., 1976] was used. Each recorded channel had the Mark I bandwidth of 360 kHz, whereas the synthesized bandwidth was $\sim$100 MHz in the first session of observations and $\sim$300 MHz in the last two sessions. A hydrogen maser frequency standard of modern, post-1970, design was used at each telescope for each session.

The Cartesian coordinate system used in the analysis was geocentric and earth-fixed with the Z axis parallel to the mean pole of rotation of 1900-1905, as defined by the International Latitude Service and maintained by the Bureau International de l'Heure (BIH). The X axis was defined to be perpendicular to the Z axis and in the direction of the Greenwich meridian. The Y axis completed the right-handed triad. Operationally, the origin of this system was defined by the coordinates for the intersection of the azimuth and elevation axes of the Haystack radio telescope, obtained from a combination of spacecraft-tracking and VLBI observations made at various sites. The orientation was defined by the BIH values for pole position and UT1 (1968 system), with the addition of fortnightly and monthly terms of small amplitude [Woolard, 1959], and by the models for diurnal polar motion [McClure, 1973] and earth tides (based on ephemeris positions of the moon and sun, on the Love numbers $h \approx 0.61$ and $\ell \approx 0.09$, and on the assumption of no dissipation). The small effects of antenna deformations [Carter et al., 1980], ocean loading, plate tectonics, and other errors in the model were ignored in view of the limited precision of the measurements being analyzed.

The orientation of this earth-fixed coordinate system in inertial space (with respect to the mean equinox and equator of 1950.0), was defined by the pole position, by UT1 and by the standard formulas for sidereal time, nutation, and precession, with certain small corrections: Woolard's [1953] theory as modified by Melchior [1971] was used for nutation; and $5{,}027\overset{''}{.}878$ per tropical century at 1950.0 was taken for the precession constant. The origin of right ascension was defined by the value 12 hr 26 min 33.246 sec for the radio source 3C 273B (elliptic aberration removed).

Using this framework and a theoretical model for the group delays [Robertson, 1975; Ma, 1978], we estimated by weighted least squares the baseline vectors, the source positions, and the other relevant parameters. Included in the last category are parameters that allow for the estimation of changes in pole position and variations in UT1 when data from two or more sessions of observations are combined [Shapiro et al., 1974, 1976; Robertson et al., 1979]. In addition to these purely geometric parameters there are parameters in the model that represent the effects on the group delays of the propagation medium and of the behavior of the clocks at the various radio telescopes. The representation of the propagation medium includes the zenith tropospheric delay as a parameter. Since the signal delay through the troposphere varies with time and with location, a number of such parameters are utilized with this model. The effects of the ionosphere, always under $\sim$1 ns in the zenith direction, but not separately modeled, are largely absorbed by these parameters because of the similarity in the signature in the group delays of the ionosphere and the troposphere. The representation of the behavior of the clock at one site relative to that at another consists of a polynomial in time of low order with the coefficients as parameters, the first two denoting the epoch and rate offsets. Since the clocks drift unpredictably with time, a number of such polynomials are usually employed.

The choice of the number of parameters to represent the combined effects of the troposphere and the ionosphere and the behavior of the clocks as well as the choice of the time interval of applicability of each parameter are to a certain extent subjective. We therefore investigated the effects on the results of a variety of such choices. As extremes for the representation of the troposphere and the ionosphere, we considered for each telescope the use of one parameter for the zenith delay for each session of observations and one such parameter for each 12-hour period of observations. For the clock behavior we chose the clock at Haystack as the reference and considered for each other telescope for each session the use of one parameter each for the relative offsets in epoch, rate, and (in several instances) rate of change of rate. The intervals of applicability of such 'clock polynomials' ranged from 7.5 to 24 hours; only for this latter case was a parameter included for the rate of change of rate. The variations in the estimates of baseline lengths resulting from these different parameterizations were up to 1.8 and 1.2 times the corresponding standard deviation obtained for the adopted parameterization for the data from each of the first two sessions and from the third session, respectively. In view of this stability, we deem it unlikely that either the propagation medium or the behavior of the clocks has introduced errors in baseline length much in excess of the formal standard deviations. The adopted choice of epochs and intervals of applicability for these parameters (see section 4) was based primarily on examination of the postfit residuals, especially those from observations at low elevation angles for the parameters representing the behavior of the propagation medium.

The inverse of the weight for each group delay was obtained from the sum of the variance found from a signal-to-noise analysis [Whitney, 1974] and an ad hoc term included to account for error sources that were not a function of signal strength. The inclusion of this term was motivated by the desire to (1) allow for the effects of systematic errors, and, relatedly, (2) weight the observations of the different sources more evenly, since for some strong sources the signal-to-noise analysis yielded uncertainties that were well below the suspected contributions of other errors. The magnitude of this ad hoc term was assumed constant for the data for a given baseline for a given session of observations. Its value was obtained from the constraint that chi-square per degree of freedom be unity, and its square root ranged from 0.10 to 0.25 ns. Omitting this ad hoc term from the variances changed the estimates of baseline length by up to 1.2 times the standard deviations obtained with this term included.

3. Results

Table 2 gives our estimates of the distances between the radio telescope in Sweden and the three in the United States. The reference point for each telescope is the intersection of the azimuth and elevation axes, except for the NRAO telescope where the reference is the point on the polar axis closest to the (nonintersecting) equatorial axis [Hinteregger et al., 1972].

Typical postfit residuals from the simultaneous analysis of the data from all sessions are shown in Figure 1. The root mean square of these residuals ranged from 0.13 ns for the Haystack-NRAO data from the last session to 0.49 ns for the Onsala-NRAO data from the first session, the ratio being approximately as expected in view of (1) the threefold smaller synthesized bandwidth used in the first session of observations, (2) the generally larger correlated flux densities obtained from observations involving the shorter baselines, and (3) the slightly higher sensitivity of the Haystack-NRAO system compared to the Onsala-NRAO system.

The repeatability of the estimates of the baseline lengths shown in Table 2 indicates that the formal standard errors may not be much smaller than the actual errors. However, one fact detracts from the importance of this indication: The uncertainties of the estimates of baseline lengths from the third session of observations were much smaller than those from the second which, in turn, were smaller than those from the first. The disparity between the uncertainties from the first and second sessions was due primarily to the contrast in synthesized bandwidths. The further discrepancy between the uncertainties from the first two sessions and those from the third was due mainly to geometry; the schedule of observations for the first two sessions was controlled by requirements of other experiments involving only the U.S. antennas and therefore did not properly provide for Onsala's participation.

The estimates for the propagation delay through the atmosphere and ionosphere in the zenith direction ranged from 6.7 ns (NRAO) to 8.2 ns (Onsala); the estimates for the clock parameters were also each in approximate accord with expectations, ranging up to 23 μs for epoch offsets and from $\sim 3\times10^{-14}$ to $\sim 2\times10^{-12}$ for rate offsets.

The estimates for the source positions, the distances between the radio telescopes in the United States, and the pole position and UT1 variations will be given elsewhere and discussed there along with a much larger collection of VLBI observations that involved only the telescopes in the United States.

4. Conclusions

Combination of data from three sessions of VLBI observations involving sites in Sweden and the United States yielded results of subdecimeter precision in the determination of the intercontinental distances. Since sufficiently accurate and well-distributed observations to determine baselines to Sweden with subdecimeter precision were available for only one session, the data are not useful for the establishment of subdecimeter repeatability. Neither are the earlier VLBI determinations [Robertson, 1975] useful since they were less precise, and, in addition, involved a different telescope at Onsala which has yet to be located accurately with respect to the one we utilized (Table 1). Further, to assess inherent accuracy, comparisons would best be made with results from a more accurate technique. None now exists. The most accurate alternate technique currently available for the determination of these particular intercontinental baselines is based on observations of the Doppler shift of radio signals transmitted from satellites, plus standard ground surveys to tie the reference points for the Doppler measurements to those for the VLBI determinations. Such Doppler data exist (W. E. Carter, private communication, 1979), but the analysis and the ground surveys have not been completed and so no comparisons can yet be made.

Periodic repetitions of these intercontinental VLBI measurements are also planned with more radio telescopes in the interferometer array and with use of our new, more powerful, Mark III VLBI system. This system, among other attributes records data simultaneously from two well separated radio frequency bands, thus allowing ionospheric effects to be virtually eliminated as a source of error. The purpose of these further VLBI measurements will not only be to check on the repeatability of the present baseline determinations but, more importantly, to improve the precision to the level at which the expected [Minster and Jordan, 1978] $\sim$1.7 cm/yr spreading rate between Europe and the United States could be detected reliably within a decade.

Acknowledgements. We thank Reuben Epstein and Lucien Froidevaux for their contribution to the early stages of the analysis of the data, the staffs of the participating observatories for their indispensable assistance during the observations, and Robert Cady for drafting the figure. The Haystack Observatory is operated with support from the National Science Foundation (NSF), grant GP 25865; the NRAO is operated by the Associated Universities, Inc. under contract with the NSF; the Onsala Space Observatory is supported by a grant from the Swedish Natural Science Research Council; and the Owens Valley Radio Observatory is sustained by a grant from the NSF. The MIT experimenters were supported in part by the U.S. Air Force, contract F19628-79-C-0064, the National Aeronautics and Space Administration, grant NGR22-009-839, and the NSF, grant EAR76-22615.

References

Carter, W. E., A. E. E. Rogers, C. C. Counselman, and I. I. Shapiro, Comparison of geodetic and radio interferometric measurements of the Haystack-Westford baseline vector, J. Geophys. Res., 85, 2685-2687, 1980.

Cannon, W. H., R. B. Langley, W. T.Petrachenko, and J. Kouba, Geodesy and astrometry by transatlantic long baseline interferometry, J. Geophys. Res., 84, 229-236, 1979.

Clark, T. A., L. K. Hutton, G. E. Marandino, C. C. Counselman, D. S. Roberston, I. I Shapiro, J. J. Wittels, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, A. E. Niell, B. O. Rönnäng, and O. E. H. Rydbeck, Radio source positions from very-long-baseline interferometry observations, Astron. J., 81, 599-603, 1976.

Hinteregger, H. F., I. I. Shapiro, D. S. Robertson, C. A. Knight, R. A. Ergas, A. R. Whitney, A. E. E. Rogers, J. M. Moran, T. A. Clark, and B. F. Burke, Precision geodesy via radio interferometry, Science, 178, 396-398, 1972.

Ma, C., Very long baseline interferometry applied to polar motion, relativity and geodesy, Ph.D. thesis, Univ. of Md., College Park, 1978.

McClure, P., Diurnal polar motion, Rep. X-592-73-259, NASA/ Goddard Space Flight Cent., Greenbelt, Md., 1973.

Melchior, P., Precession-nutations and tidal parameters, Celestial Mech., 4, 190-212, 1971.

Minster, J. B., and T. H. Jordan, Present-day plate motions, J. Geophys. Res., 83, 5331-5354, 1978.

Robertson, D. S., Geodetic and astrometric measurements with very-long-baseline interferometry, Ph.D. thesis, Mass. Inst. of Technol., Cambridge, 1975.

Robertson, D. S., W. E. Carter, B. E. Corey, W. D. Cotton, C. C. Counselman, I. I. Shapiro, J. J. Wittels, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, J. W. Ryan, T. A. Clark, R. J. Coates, C. Ma, and J. M. Moran, Recent results of radio interferometric determinations of a transcontinental baseline, polar motion, and Earth rotation, in Time and the Earth's Rotation, edited by D. D. McCarthy and J. D. Pilkington, pp. 217-224, D. Reidel, Dordrecht, Netherlands, 1979.

Shapiro, I. I., Estimation of astrometric and geodetic parameters from VLBI observations, in Methods of Experimental Physics, edited by M. L. Meeks, pp. 261-276, Academic, New York, 1976.

Shapiro, I. I., D. S. Robertson, C. A. Knight, C. C. Counselman III, A. E. E. Rogers, H. F. Hinteregger, S. Lippincott, A. R. Whitney, T. A. Clark, A. E. Niell, and D. J. Spitzmesser, Transcontinental baselines and the rotation of the earth measured by radio interferometry, Science, 186, 920-922, 1974.

Shapiro, I. I., D. S. Robertson, C. A. Knight, C. C. Counselman III, A. E. E. Rogers, H. F. Hinteregger, S. Lippincott, A. R. Whitney, T. A. Clark, A. E. Niell, and D. J. Spitzmesser, Transcontinental baselines and the rotation of the earth measured by radio interferometry, Science, 191, 451, 1976.

Whitney, A. R., Precision geodesy and astrometry via very long baseline interferometry, Ph.D. thesis, Mass. Inst. of Technol., Cambridge, 1974.

Whitney, A. R., A. E. E. Rogers, H. F. Hinteregger, C. A. Knight, J. I. Levine, S. Lippincott, T. A. Clark, I. I. Shapiro, and D. S. Robertson, A very-long-baseline interferometer system for geodetic applications, Radio Sci., 11, 421-432, 1976.

Woolard, E. W., Theory of the rotation of the earth around its center of mass, _Astron. Pap. Am. Ephemeris Nautical Alm._, _XV_ (I), 1953.

Woolard, E. W., Inequalities in mean solar time from tidal variations in the rotation of the earth, _Astron. J._, _64_, 140-142, 1959.

(Received July 10, 1980;
revised October 14, 1980;
accepted November 12, 1980.)

Table 1

Summary of VLBI Observations

Observation Session	Dates (day month year)	Duration (hr)	Antennas*	Number of Sources†	Declination Range of Sources (deg)	Number of Group-Delay Observations**
1	21-25 September 1977	88††	H,N,O	10(6)	-5.5 to 50.8	529 (151)
2	24-26 February 1978	50	H,O,V	8(4)	0.5 to 50.8	291 (77)
3	17-19 May 1978	45	H,O,N,V	10(10)	-5.5 to 50.8	830 (258)

* H ≡ 37-m diameter telescope of the Haystack Observatory, Westford, MA; N ≡ 43-m diameter telescope of the National Radio Astronomy Observatory (NRAO), Green Bank, WV; O ≡ 20-m diameter telescope of the Onsala Space Observatory, Onsala, Sweden: and V ≡ 40-m diameter telescope of the Owens Valley Radio Observatory, Big Pine, CA.

† The sources observed are listed in the caption to Figure 1. The numbers of sources observed at Onsala are given in parentheses.

** The numbers of observations involving Onsala are given in parentheses.

†† Onsala participated for the last 62 hr.

Table 2

Baseline Length Estimates

Observation Session(s)*	HAYSTACK - ONSALA Length (m)	HAYSTACK - ONSALA Formal Standard Error (m)	HAYSTACK - ONSALA Difference† (m)	NRAO - ONSALA Length (m)	NRAO - ONSALA Formal Standard Error (m)	NRAO - ONSALA Difference† (m)	OWENS VALLEY - ONSALA Length (m)	OWENS VALLEY - ONSALA Formal Standard Error (m)	OWENS VALLEY - ONSALA Difference† (m)
1	5,599,714.948	0.301	0.288	6,319,318.156	0.354	0.404	---	---	---
2	.516	0.123	-0.144	---	---	---	7,914,131.372	0.169	0.180
3	.686	0.028	0.026	7.776	0.036	0.024	.173	0.043	-0.019
1 + 2 + 3**	5,599,714.660	0.027	---	6,319,317.752	0.034	---	7,914,131.192	0.040	---

* See Table 1 for definitions and text for discussion. The number of parameters estimated in each solution, in order of listing, was 47, 41, 56, and 102. The speed of light used to convert light seconds to meters was 299,792,458 m s^{-1}.

† Differences from adopted solution.

** Adopted solution.

Figure Caption

Figure 1. Postfit residuals from the adopted solution (see Table 2) for the Haystack-Onsala group-delay measurements from Session 3 (see Table 1). The root-mean-square of these residuals is 0.25 nsec. The vertical bars represent ± one standard deviation. Each letter in the figure denotes a different radio source: A ≡ NRAO 150; B ≡ 3C 84; C ≡ 4C 39.25; D ≡ 3C 273B; E ≡ 3C 345; F ≡ VRO 42.22.01; G ≡ 2134+00; H ≡ 3C 454.3; and I ≡ OJ 287. One other source, observed on some baselines in Session 3, was 3C 279. See Clark et al. (1976) for approximate values of the coordinates for each source.

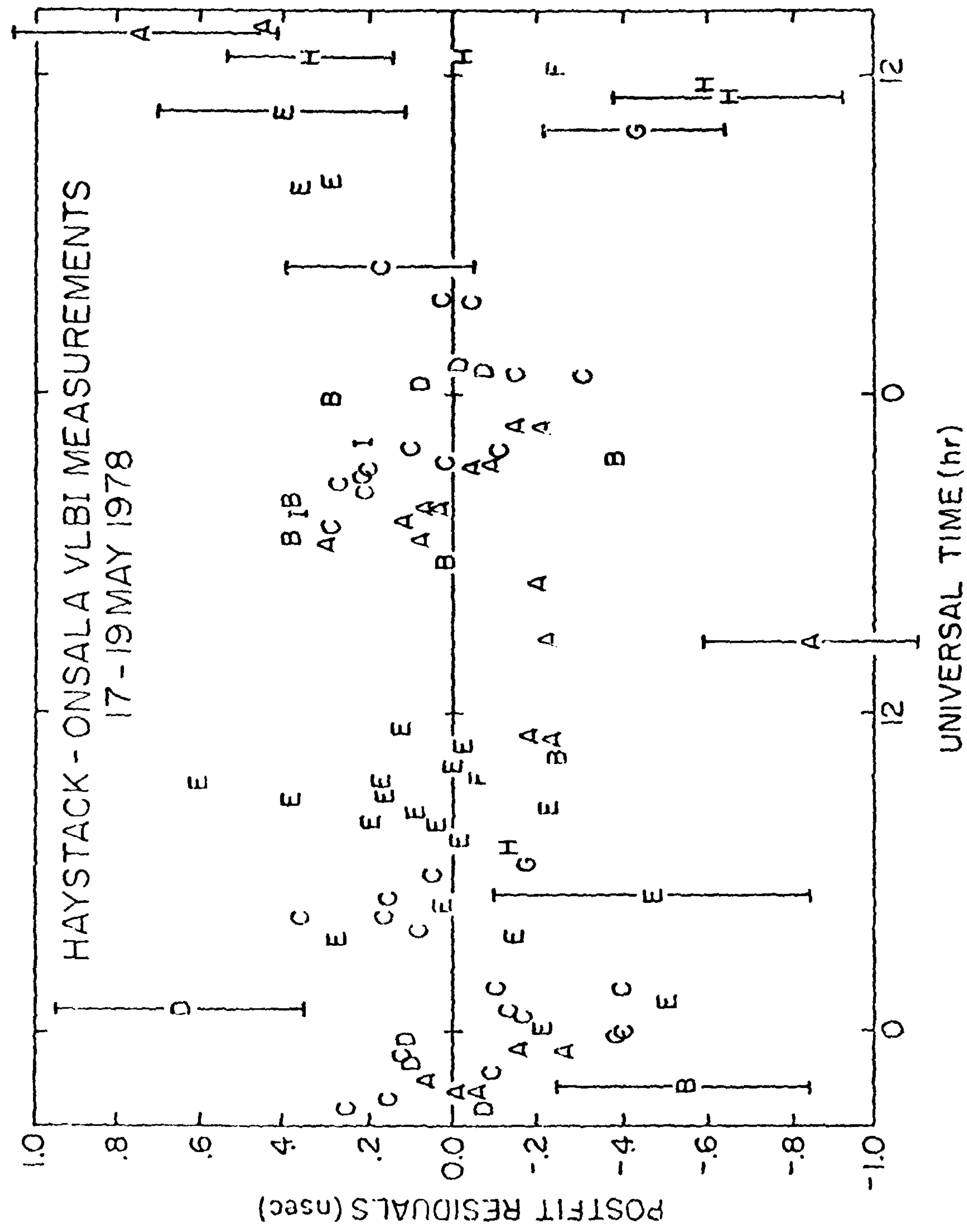

HAYSTACK - ONSALA VLBI MEASUREMENTS
17 - 19 MAY 1978
POSTFIT RESIDUALS (nsec)
UNIVERSAL TIME (hr)
1.0
.8
.6
.4
.2
0.0
-.2
-.4
-.6
-.8
-1.0
0
12
0
12

Figure 1