VLBI Solutions for the Time Variation of DSN Baselines: 1978 to 1983

R. N. Treuhaft, J. L. Fanselow, K. M. Liewer, A. E. Niell, O. J. Sovers, J. B. Thomas, and K. S. Wallace
Tracking Systems and Applications Section

Very Long Baseline Interferometry (VLBI) results are presented for the two baseline vectors between the Goldstone DSN antenna complex and the overseas sites at Canberra, Australia and Madrid, Spain. Results from solutions using data taken between 1978 September and 1983 May show an apparent California-Spain baseline length increase of 21 cm during this time span, while the California-Australia length has remained constant. Statistical investigations of the integrity of the data are discussed along with dominant systematic error sources and their effect on baseline length determination. Results and interpretation of the time behavior of the angle between DSN baselines are also described.

I. Introduction

Three principal concerns motivate the study of changes in intercontinental baseline vectors. Navigational demands, which require the location of the DSN stations in an inertial radio reference frame, necessitate modeling relative motion of points on the Earth. Secondly, because DSN baselines span the North American, Pacific, Indian, and Eurasian plates, detection of their motion will aid in the understanding of continental drift, which is of geophysical interest. Finally, since VLBI solutions entail the adjustment of hundreds of correlated parameters, the plausibility of any changes in the estimated baselines supports the integrity of the entire solution.

This article focuses on the two baseline lengths and the single angle (inner angle) between the baselines because, for any two vectors, these three quantities are invariant under rotations of the coordinate system in which they are presented. Rotational invariance is an important criterion for parameters studied in baseline time-behavior analyses because, in VLBI, the orientation of a baseline is determined with respect to an inertial reference frame defined by extragalactic radio sources (EGRS), and we wish to measure the baselines in an Earth-fixed reference frame. Since translations relative to the EGRS can be ignored, transforming a baseline from the EGRS frame to the Earth-fixed frame requires only a rotation. The necessary rotations are monitored regularly by services such as the Bureau International de l'Heure (BIH), TEMPO at the Jet Propulsion Laboratory, and POLARIS at the National Geodetic Survey (Ref. 1).

To study the baseline variations in an Earth-fixed frame, we could (1) use the Earth orientation measurements of the above services to transform the EGRS-referenced VLBI results to the Earth-fixed frame, and/or (2) consider the variations of baseline parameters which are unchanged in the transformation between the two reference frames. Since the errors in the Earth orientation measurements are often larger than the intrinsic VLBI errors for the data set considered[1] (Ref. 2), we choose

[1] Treuhaft, R. N., "The Time Variation of Intercontinental Baselines using VLBI," IOM 335.1-113, June 1983, private communication to Tracking Systems and Applications Section, Jet Propulsion Laboratory.

to study the rotationally invariant lengths and inner angle. The inner angle, as measured, is actually quasi-rotationally invariant as will be discussed later. Future studies of this type will also include rotationally sensitive quantities as the accuracy of Earth orientation measurements improves.

The parameter estimates which are discussed in this article were obtained from multiparameter adjustments using dual-frequency VLBI data. The data were taken between 1978 September and 1983 May on the California-Australia (C-A) and California-Spain (C-S) baselines. 3090 delay and delay rate observations of 132 extragalactic sources comprise the data set analyzed. A general description of the 1971 to 1980 VLBI observation and fitting procedure is given in Ref. 3. The baseline results in this article are estimated independently for each experiment, as opposed to estimating a single baseline for the entire span of data; in Ref. 3, results from both methods of estimation are reported. Three requirements placed on the data currently analyzed force the exclusion of experiments reported in Ref. 3 which were performed before 1978 September: (1) All experiments considered here contain delay and delay rate data (as opposed to delay rate only); (2) All the data were taken at S- and X-band simultaneously for charged-particle calibration; and (3) Hydrogen maser time standards were used at both stations of each baseline. Comparison of the estimated global parameters (e.g., source positions) of Ref. 3 with those derived here yields agreement within quoted errors. In addition to solving for baseline components and source positions, the fit to the VLBI data includes solutions for station clock parameters and total (dry + wet) zenith troposphere delays for each session.

In section II of this article, we present baseline length results and interpretation. Section III contains a discussion of dominant systematic errors affecting the length measurements; troposphere mismodeling is given special attention. Section IV contains inner angle results, and section V, the conclusions.

II. Baseline Length Results and Interpretation

The solutions for baseline components and lengths obtained from each experiment are given in Table 1. As mentioned above, for single-baseline VLBI solutions, Earth orientation transformations must be applied to the VLBI results. The BIH transformations were used for the components presented in Table 1. This Table also gives the DSS 13-DSS 14 short-baseline tie used to refer all measurements to the 64-meter antenna at Goldstone (DSS 14). The results for the baseline lengths plotted as a function of time are shown in Figs. 1(a) and (b) for C-A and C-S, respectively. The linear fit to the data was performed by including all the correlations between the baseline coordinate parameters in the global fit from which the lengths were derived. From Fig. 1, the baseline time rate of change for C-A is statistically insignificant and, from the chi-square per degree of freedom (χ^2/DF) of 0.97, the time variation of the C-A baseline is consistent with a linear fit, or indeed with no motion at all. For C-S, the baseline rate is six times its formal error, and is therefore significant with regard to that measure of error. However the large χ^2/DF means that there may be problems with the linear parameterization of the data. The probability of getting a χ^2/DF of 1.98 or greater with twelve degrees of freedom is about 2%, assuming that the measured length variation results from a pure linear drift degraded only by Gaussian noise. Below, we assess the validity of this assumption and interpret the result of the chi-square test.

A linear model for intercontinental baseline motion is potentially applicable because points in the interior of continental plates are not expected to respond to high frequency driving forces applied at the boundaries (Ref. 4). Of the DSN stations, the Goldstone complex is the only one very close to a known plate boundary – the San Andreas Fault. In addition to any tectonic motion, local, small-scale phenomena far from plate boundaries near either station of a baseline could produce abrupt changes in the long baseline results. Therefore, the quality of linear fits over the five-year data span may not be a good indicator of the integrity of the data, and we must explore the possibility of abrupt changes in baseline length. Table 2 shows the lengths of Fig. 1 averaged for the 1978 to 79, 1979 to 80, and 1982 to 83 observation clusters, or epochs. Note that the Table shows a statistically significant change in baseline length between the second and third epochs for C-S, while the C-A lengths are remarkably constant over the three epochs.

Concentrating on the more controversial C-S results, it is possible that abrupt motion near Goldstone or Madrid produced the 21-cm change in the C-S baseline length between the last two epochs in the Table. However, the Crustal Dynamics Project (CDP) regional VLBI data show no such significant motion on any of the baselines containing Goldstone over the same time span (Ref. 5). It should be noted that since the CDP data do not preclude large (20-cm) changes in the Goldstone vertical, and since the Goldstone vertical has a 66% projection onto the C-S length, the CDP data alone do not exclude the possibility that much of the 21-cm jump was due to Goldstone local vertical motion. However, the Goldstone vertical also has an 83% projection onto the C-A length, which is relatively constant over the same three-year span. Considering both the CDP and the C-A data, it is unlikely that Goldstone local motion could be responsible for the 21-cm shift observed in the C-S data. We do not have a firm case for excluding the local motion possibility at Madrid, since we do not have available any measurements to local reference points for the Spain complex. A geophysical phenomenon as large as a 21-cm change over three years would probably call attention to itself via ground survey techniques. The frequency of past measurements by survey as well as VLBI techniques must be investigated. The appropriateness of the linear model for the C-S baseline variation is therefore contingent upon evidence excluding the possibility of local, abrupt motion near the Madrid complex.

If such evidence finally does exclude the possibility of abrupt motion, the 2% probability quoted above for the chi-square test is an indication of a problem in the error analysis: namely that it is highly improbable that the actual length errors are Gaussian with standard deviations given by the error estimates of Table 1. The error estimates could be incorrect due to unmodeled systematic errors, or due to underestimation of the statistical errors. If the apparent change in the C-S baseline is due to faulty error analysis, the step-function pattern in Fig. 1(b) suggests that unmodeled systematic effects are part of the problem. Further, a comparison of Figs. 1(a) and 1(b) indicates systematic problems may affect different parameters in different ways; for example, in this case, the C-S linear fit is suspect, and the C-A fit is acceptable.

III. Systematic Errors in Baseline Length

The baseline length is principally derived from observations of the interferometric time delay, between two ends of a baseline, of the arrival of an electromagnetic signal from a distant radio source. Uncalibrated phenomena affecting the measured delay can cause errors in baseline length estimates. If, for a group of measurements, the observation-to-observation delay errors are correlated with the sequence of partial derivatives of time delay with respect to baseline length, the error in the estimated length may be large. Since the partial derivative of delay with respect to baseline length parameters will be largest for low elevation angle observations, and since unmodeled troposphere delay errors are also likely to be large at low elevation angles, the errors will track the partials for many observation strategies.

Studies of the effect of troposphere mismodeling show that dry troposphere elevation mapping function fluctuations can cause 12-cm errors in C-S baseline and up to 25-cm errors in the C-A baseline. These mapping fluctuations are caused by changes in local meteorology at the two ends of the baseline and should be seasonally variable (Ref. 6). Wet troposphere fluctuations can also cause 5 to 10 cm of baseline length error and would be expected to vary from experiment to experiment (Ref. 7). Neither the wet nor the dry effect should exhibit the qualitative temporal behavior of the C-S baseline lengths shown in Table 2. The magnitude of these systematic effects is, however, within a factor of two of the C-S length changes observed, and, therefore, more extensive calibrations will be attempted before conclusions are drawn concerning the statistical significance of length changes. Acquiring surface meteorology and water vapor radiometer data should help to reduce the errors contributed by both of these tropospheric effects.

Another potentially important systematic effect which could contribute to baseline length errors can arise from instrumental effects which depend on time or elevation angle. Phase calibration of the data (Ref. 8) can help to remove such effects, but the results shown in Fig. 1 do not include phase calibration. For some experiments, phase calibration was impossible due to instrumentation failures, but calibration may be possible for a subset of the data. Preliminary tests show that instrumental miscalibration might also contribute as much as 10 cm to the baseline length error. The effects of changes in the data acquisition hardware between 1980 and 1982 have not been thoroughly investigated, and instrumental effects cannot be discounted.

IV. Inner Angle Results

Along with the baseline lengths, the inner angle between simultaneously measured C-A and C-S baseline vectors (approximately 82 degrees) is a rotational invariant, and its time behavior could be another good measure of station movement. In Fig. 2 the inner angle (θ) between the two baseline vectors is shown in the standard Earth-fixed coordinate system, with the x-axis passing near the Prime Meridian. Since the C-S and C-A baselines are not measured simultaneously, but are typically observed within one to three days of each other, the Earth's short-term orientation changes must be calibrated in order to avoid interpreting global rotations as relative station motion. Because the inner angle measurement is sensitive to short-term Earth rotations, but is insensitive to rotations with periods longer than the time between experiments, the inner angle is quasi-rotationally invariant and its time variation might yield information on continential motion in one direction perpendicular to the baseline vectors. Fig. 3 shows the inner angle as a function of time after applying corrections based on the BIH Earth orientation data. The large χ^2/DF for the linear fit is mostly due to the problematic second to last point on the plot. This point represents data taken on 23 January 1983 and 25 January 1983 for C-A and C-S, respectively.

To investigate whether that point's severe departure from the line could be due to high-frequency orientation errors, Fig. 4, reproduced from Ref. 9, shows the Kalman filtered BIH

Length of Day (LOD) data, which is a measure of the difference between the rate of change of the actual global rotation about the pole ($\dot{UT1}$) and a universally accepted standard rate used in VLBI analysis ($\dot{IAT}$). Predictable tidal changes in $\dot{UT1}$ were removed before estimating the LOD. The peak of this plot is near the dates of the experiments determining the inner angle for the questionable point in 1983 January. An arrow points to the date of the problematic inner angle measurement. The peak in Fig. 4 is believed to result from the El Niño phenomenon (Ref. 9). To see if better high-frequency ($\dot{UT1}$–$\dot{IAT}$) data would track this peak more faithfully, the inner angle was recalculated with Kalman filtered POLARIS data for 1982 to 83 and lunar laser ranging data for the rest of the time span by T. M. Eubanks (personal communication), and the results are plotted in Fig. 5(a). The decreased χ^2/DF suggests that the fit is improving, but the best fit by far is that in Fig. 5(b) where the 1983 January point is eliminated completely. It is possible that the actual angular rate peak of Fig. 4 was beyond the high-frequency detection capability of any external service, since the typical sampling interval of the external services, such as BIH or POLARIS, is one week. For the 1983 January point our two experiments were 2.3 days apart, and it is possible that our measurements were more sensitive to high-frequency global orientation changes than any others. To investigate this possibility, we are currently studying the apparent angular rate of the baselines within each experiment of the suspect inner-angle pair. If Earth orientation changes are large between the experiments, they may also be large within a single experiment. A complete explanation of the behavior of the 1983 January point will require further analysis, but for now, the data suggest that poor high-frequency Earth orientation determination may plague the use of the inner angle to measure real continental motion.

It should be pointed out that the inner angle errors as well as the linear fit parameters were calculated including all the relevant correlations among the baseline coordinates in the global fit from which the inner angles were extracted. If correlations are ignored, the parameter estimates and errors change only at the 10 to 20% level, but the χ^2/DF values change enough to substantially alter the conclusions of hypothesis tests. This comment applies to the baseline length analyses as well.

V. Conclusions and Discussion

The baseline length results can be summarized as follows: based on formal baseline errors, there is a statistically significant change in the **C-S** length over the time spanned by the data. The change in the baseline is only twice the possible contribution of either of our two biggest known systematic error sources, the troposphere and instrumental calibration. Although the time variation of troposphere errors is not expected to induce the sort of time variation observed on the **C-S** baseline, the magnitude of the possible length error is sufficiently close to the observed length change that skepticism about the significance of that change seems appropriate for now. Instrumental effects, on the other hand, could conceivably cause the step-function behavior of the observed **C-S** baseline length, although we know of no major changes in the instrumentation between 1980 and 1982. The large χ^2/DF of the linear fit indicates the presence of unmodeled error sources or the possibility that the actual motion is not linear. Verification of the possibility of a nonlinear length change would require external evidence of local motion near the Spain complex.

The **C-A** length results are in good statistical agreement with no motion. It should be noted that until the above-mentioned systematic problems are resolved, the **C-A** baseline length results should also be suspected. The formal errors of the **C-A** baseline are, however, on the average larger than those of the **C-S** baseline and may dwarf the relevant systematics, perhaps explaining why the χ^2/DF for the **C-A** length linear fit is so close to 1.

The next step in the analysis of the length results is to examine further the consequences of unmodeled effects in the data. Current efforts include estimating the effect of errors in spin-axis orientation (precession and nutation) on baseline length estimates. We have also investigated the possibility of allowing the VLBI data to determine new troposphere mapping function parameters, which include station-to-station variations. Results from such studies show that indeed there is enough strength in the data to determine statistically significant changes to both the standard Chao (Ref. 10) and the new Lanyi (Ref. 6) mapping functions, both developed at JPL. The details of the new mapping function parameters, as well as the results, will be reported in the near future. Also to be reported are the effects on baseline lengths and source positions of the time-varying wet component of the troposphere.

Length rate analyses will soon depend critically on our ability to determine short baseline intracomplex ties to 1 cm, because the availability of the DSN stations changes from year to year. For example, DSS 14, the 64-meter antenna at Goldstone used for most of the data of Fig. 1, has been unavailable from 1983 July to 1984 August. In the interim, we are using DSS 12. Also, when DSS 14 becomes operational again, it may be displaced by a few centimeters, and its position relative to the other antennas will have to be redetermined. That short-baseline ties may be a problem is evident from the fact that the first two points of the **C-S** 1982 to 83 epoch were measured with DSS 13 and a DSS 13-DSS 14 tie. They, as well as the single **C-A** DSS 13 point in 1982 July, are systematically above the line.

The local vertical at Goldstone, which is poorly determined by short baseline experiments without accurate dry and wet troposphere calibration, has large projections on both the **C-A** and **C-S** baseline vectors, as noted in section II. Consequently, improved troposphere calibration might be necessary. We have therefore performed experiments, currently being analyzed, involving long and short baselines simultaneously, to check our procedure for determining the intracomplex ties. To improve the precision of the short-baseline ties, phase-delay results, which are now being analyzed, will supplement the bandwidth-synthesis result shown in Table 1. In addition, ground survey results will be investigated. In the absence of accurate short-baseline ties, the baseline length time behavior could still be parameterized with one slope and several intercepts, one for each Goldstone antenna. This least desirable alternative would weaken the determination of slope by introducing more parameters, but is always available as a last resort.

From the inner angle results in the most plausible case of Fig. 5(b), there is a statistically insignificant slope over the time span of the data. Studying the individual baseline component time behavior may explain the problem with the inconsistent point of 1983 January. If we can explain this point's behavior without resorting to the inadequacy of external high-frequency Earth rotation measurements, then there is hope that inner-angle studies may be useful. There is only a remote possibility of making regular, nearly-simultaneous measurements of the **C-A** and **C-S** baselines, in order to exclude any contribution from the short-term Earth orientation error. One solution to this dilemma is to measure a third baseline to monitor rapid changes in earth orientation. The time behavior of the inner angle would then complement the station movement results obtained from the length measurements. The possibility of using facilities in Japan to form triangles with both **C-A** and **C-S** is being explored.

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Table 1. DSS 14-DSS 43 (California–Australia)

Date yr/mo/day	x +2107200, m	Error	y −7323700, m	Error	z +7351800, m	Error	L −10588900, m	Error
78/9/3	−72.23	0.26	3.35	0.24	−1.56	0.27	66.58	0.35
78/10/28	−72.98	0.11	3.41	0.08	−1.14	0.12	66.48	0.12
78/11/4	−73.27	0.11	3.31	0.10	−0.99	0.14	66.37	0.15
78/12/31	−73.87	0.10	2.39	0.07	−1.70	0.12	66.34	0.12
79/11/23	−73.78	0.27	3.06	0.23	−1.14	0.24	66.39	0.31
79/12/20	−73.07	0.10	2.93	0.07	−1.44	0.11	66.37	0.11
79/12/29	−73.50	0.14	2.56	0.10	−1.30	0.13	66.10	0.14
80/1/12	−73.58	0.10	2.68	0.09	−1.60	0.13	66.41	0.13
80/1/27	−72.90	0.15	2.94	0.12	−1.79	0.14	66.59	0.16
80/2/14	−75.05	0.12	2.51	0.11	−1.60	0.14	66.59	0.16
80/2/23	−74.12	0.10	2.73	0.08	−1.50	0.12	66.48	0.12
82/7/1[a]	−71.31	0.09	3.76	0.06	−1.26	0.11	66.47	0.10
82/11/30	−72.79	0.14	3.30	0.10	−1.24	0.14	66.44	0.15
83/1/23	−71.84	0.10	3.66	0.06	−1.19	0.10	66.46	0.10
83/5/20	−73.69	0.08	3.29	0.04	−0.91	0.09	66.38	0.07

[a]Experiment was performed with DSS 13 referred to DSS 14 with the tie given below.

DSS 14-DSS 63 (California–Spain)

Date yr/mo/day	x −7202700, m	Error	y −4281100, m	Error	z −438000, m	Error	L −8390400, m	Error
78/10/30	13.73	0.22	60.24	0.32	57.05	0.32	29.79	0.20
78/11/6	13.65	0.18	60.62	0.19	56.89	0.25	29.91	0.19
79/11/26	13.00	0.08	61.81	0.10	56.57	0.11	29.94	0.06
79/12/21	13.46	0.16	60.71	0.29	57.12	0.25	29.80	0.13
79/12/27	13.02	0.09	61.66	0.15	56.83	0.17	29.89	0.09
80/1/26	13.32	0.16	61.22	0.17	57.06	0.22	29.93	0.14
80/2/14	12.30	0.07	62.86	0.08	56.58	0.11	29.87	0.05
80/2/24	12.98	0.08	61.60	0.14	56.46	0.15	29.80	0.08
82/7/4[b]	14.87	0.11	59.10	0.11	56.51	0.13	30.16	0.09
82/8/17[b]	14.42	0.10	59.98	0.11	56.40	0.13	30.22	0.08
82/11/28	13.50	0.05	61.06	0.06	56.96	0.08	30.01	0.03
83/1/25	14.85	0.05	59.05	0.06	56.89	0.08	30.14	0.04
83/4/8	13.81	0.05	60.83	0.06	56.66	0.08	30.14	0.04
83/5/22	13.27	0.04	61.55	0.06	56.99	0.08	30.06	0.03

[b]Experiment was performed with DSS 13 referred to DSS 14 with the tie given below.

DSS 14-DSS 13

Date yr/mo/day	x(m)	Error	y(m)	Error	z(m)	Error	L(m)	Error
79/8/15	2492.10	0.01	−14135.49	0.02	−16095.48	0.02	21565.88	0.01

Table 2. Baseline lengths per epoch.

Epoch (year)	C-A (m)	C-S (m)
78.84	66.40 ± 0.07	29.85 ± 0.14
80.03	66.41 ± 0.05	29.88 ± 0.03
82.97	66.42 ± 0.05	30.09 ± 0.02

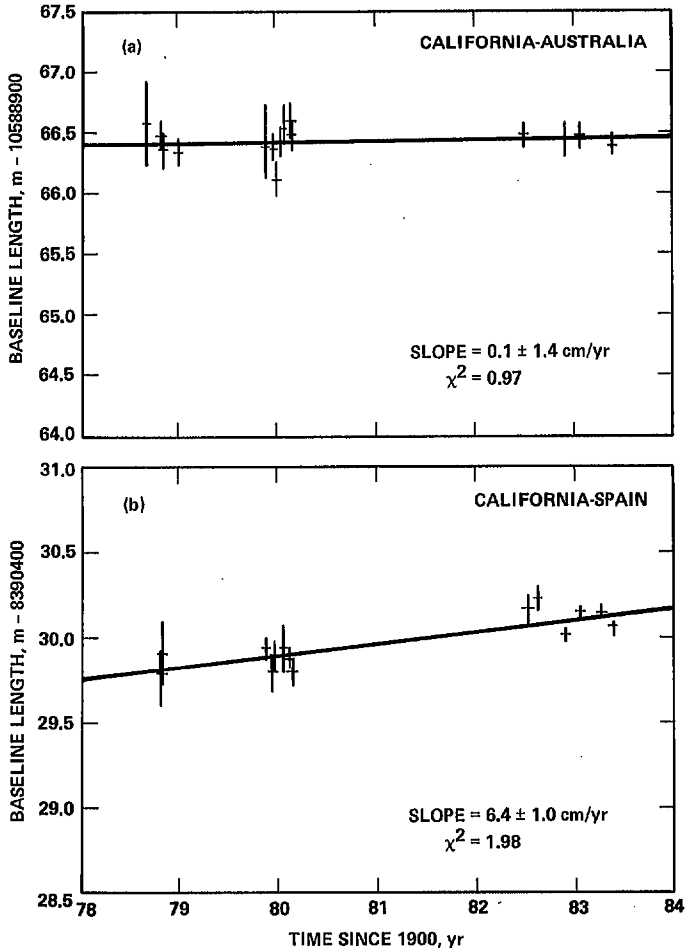

Fig. 1. The baseline length as a function of time: (a) California–Australia; (b) California–Spain

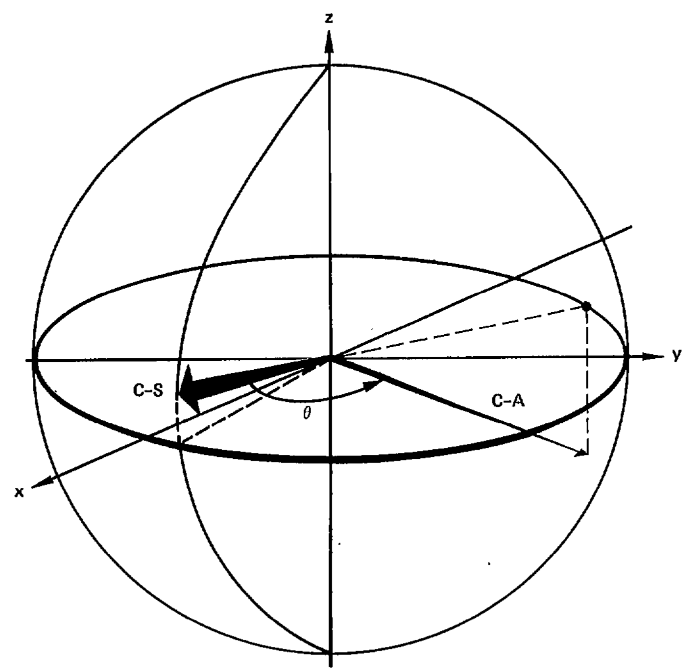

Fig. 2. The California–Australia and California–Spain vectors shown in the standard, Earth-fixed frame. θ is the angle between the two vectors, called the "inner angle" in the text

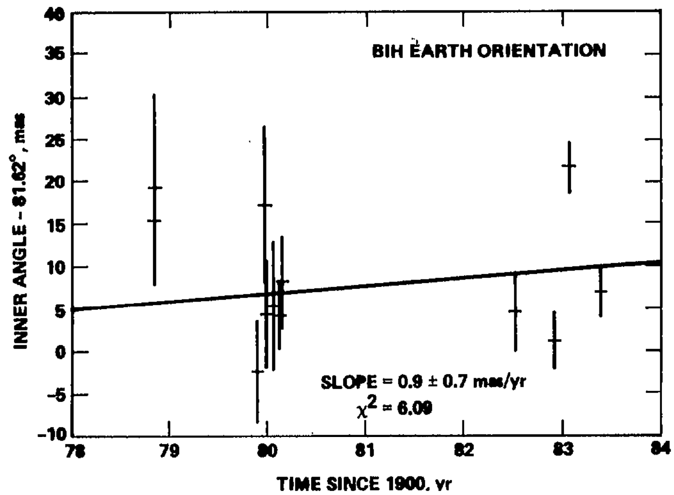

Fig. 3. The inner angle as a function of time using BIH Earth orientation values

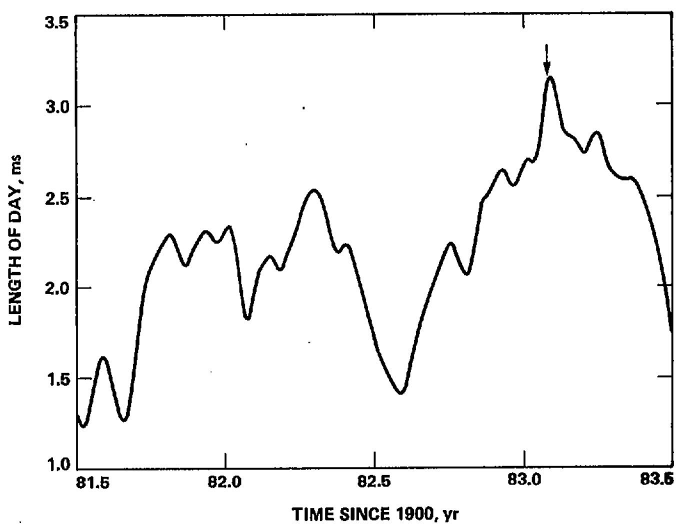

Fig. 4. The length of day, which is *d(UT1−IAT)/dt* in milliseconds per day, versus time. The arrow points to the time of the second to last experiment pair, corresponding to the second to last inner angle of Fig. 3.

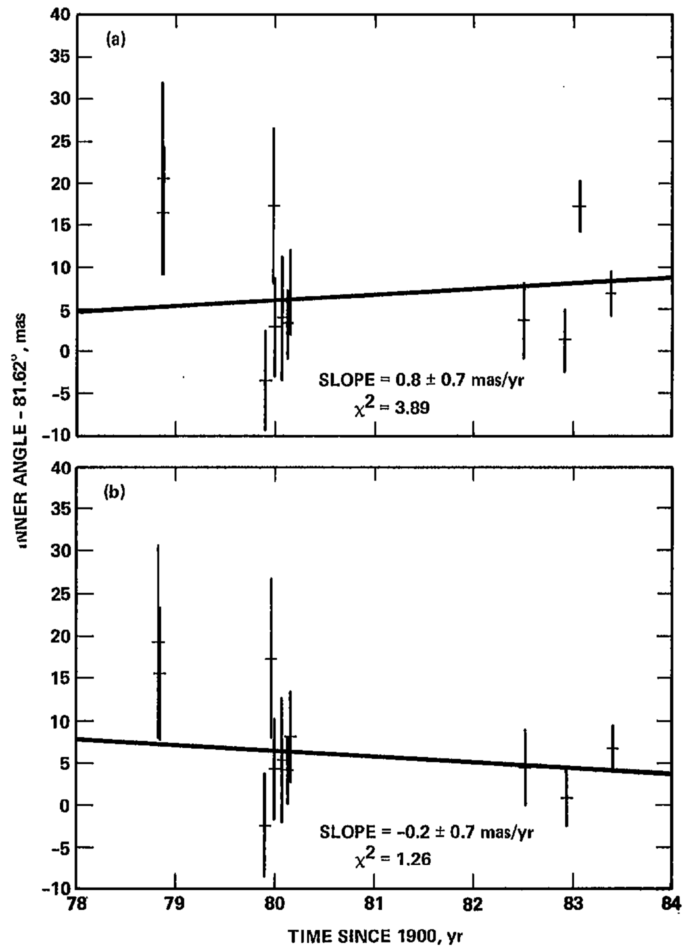

Fig. 5. The inner angle as a function of time using: (a) a combination of Kalman filtered POLARIS and lunar laser ranging Earth orientation values; (b) BIH Earth orientation values, excluding the second to last point