DETERMINATION OF UT1 AND POLAR MOTION BY THE DEEP SPACE NETWORK USING VERY LONG BASELINE INTERFEROMETRY

J. L. Fanselow
J. B. Thomas
E. J. Cohen
P. F. MacDoran
W. G. Melbourne
B. D. Mulhall
G. H. Purcell
D. H. Rogstad
L. J. Skjerve
D. J. Spitzmesser

California Institute of Technology
Jet Propulsion Laboratory, Pasadena, California

Jose Urech
Institute National De Technica Aerospacial
Madrid, Spain

George Nicholson
National Institute for Telecommunications Research
Johannesburg, Republic of South Africa

ABSTRACT

The Deep Space Network (DSN) [operated by JPL under contract to the National Aeronautics and Space Administration] is implementing a Very Long Baseline Interferometry (VLBI) capability at DSS 63 (Spain), DSS 14 (California, USA), and DSS 43 (Australia) to support the navigation requirements of planetary space missions. The early development work for this system has already demonstrated the capability of measuring UT1 with a formal accuracy as low as 0.6 msec with only 6 hours of data. Further, a radio astrometric catalog of approximately 45 sources whose positions are known to better than $0\overset{''}{.}05$ has been constructed. In addition to these measurements, this paper describes the characteristics and anticipated performance of the complete VLBI system being implemented within the DSN for operational use in mid-1979. In particular, one of the capabilities of this system will be the measurement of UT1 and polar motion at weekly intervals. Although the navigation accuracy requirement is only 50 cm for the Voyager mission, this system should be capable of delivering UT1 and polar motion determinations with decimeter accuracy if it is operated at maximum performance. An additional requirement of this operational system is that it have the capability of providing these results within 24 hours of the actual observations.

D. D. McCarthy and J. D. Pilkington (eds.), Time and the Earth's Rotation, 199–209.

INTRODUCTION

Independent station radio interferometry, more commonly known as VLBI (Very Long Baseline Interferometry), is a technique that was pioneered in 1967 by radio astronomers to study the structure of compact natural radio sources. Since then various groups throughout the world have expanded the applications of VLBI to geodesy, spacecraft navigation, astrometry, and to clock synchronization. In this paper we will discuss the work of only one such team, that of Caltech's Jet Propulsion Laboratory (JPL). Furthermore, we will discuss only the effort directly connected with the Deep Space Network (DSN).

DESCRIPTION OF THE EXPERIMENTS

Since 1971, the Jet Propulsion Laboratory of the California Institute of Technology has been developing VLBI for application to geodesy and spacecraft navigation under contract to the National Aeronautics and Space Administration. We will discuss only the work associated with the Deep Space Network. The Deep Space Network consists of a ground communications facility, a network operations control center at JPL, and three complexes of very low noise radio antenna systems. One complex is in Spain, near Madrid, another is at Goldstone in southern California, U.S.A. and the third complex is near Canberra, Australia. Intercomplex baselines of 8-10 thousand kilometers are thus available. At each complex there are at least two 26-meter diameter antennas, and one 64-meter diameter antenna. Typical system temperatures of 25-30°K at both S Band ($\lambda\sim13$ cm) and X Band ($\lambda\sim3.8$ cm) are available.

Table 1 summarizes the observations which have produced the results in this report. Up to this time, the emphasis of the program has been system development, including hardware and software. No attempt has been made to routinely collect data at times optimized to improve geophysical understanding of the Earth's rotation.

In the results to be presented, all of the data summarized in Table 1 were simulatneously fit in a least-squares type estimation process. Both delay and delay rate were fit when both were measured. This produced a total of about 1000 observables with which were associated approximately 270 estimated parameters. The delay observable was usually dominant where both delay and delay rate were included. We chose to adjust only those model parameters whose a priori determinations were less accurate than the sensitivity of our data to that parameter.

The following describes the model in more detail. In the geometric portion of the delay model we estimated radio source positions, station locations, and UT1-UTC. We did not estimate polar motion, the parameters of the solid Earth tide model we used, nor the precession and nutation constants.

The model for delay was calculated employing special relativity to all

Table 1. Preliminary results for UT1 from 1971-77 VLBI data.

DATE	BASELINE°	NO. OF OBS	UT1 VLBI-BIH (msec)
8/20/71	14/62	72	2.9±2.3
9/1/71	14/62	24	1.1±2.2
9/1/71	51/62	22	
9/6/71	14/62	45	-2.4±2.0
9/10/71	14/62	45	-1.3±2.4
4/30/73	14/62	24	-3.1±2.8
9/8/73	14/62	17	5.1±3.5
11/20/73	51/63	12	21±10
2/15/74	14/62	20	1.6±2.7
4/21/74	14/62	22	3.4±3.0
6/21/74	14/62	17	4.2±4.5
8/6/74	14/62	7	3.6±4.4
1/12/77	11/43	12	1.1±2.3
1/21/77	14/43	28	-2.8±1.6
1/21/77	11/43	22	
1/31/77	14/63	27	REFERENCE
2/1/77	11/43	24	REFERENCE
2/13/77	14/43	40	-2.3±1.6
2/13/77	11/43	34	
2/20/77	14/43	64	-5.3±1.7
2/20/77	11/43	9	
4/13/77	14/63	48	-0.1±0.6

°DSS 11, 14 IN CALIF.; DSS 51 IN S. AFRICA; DSS 62, 63 IN SPAIN; DSS 43 IN AUSTRALIA

orders of v/c, and using the Earth's velocity about the center of mass of the solar system. Diurnal polar motion, the effects of a liquid core, and general relativity were not included. However, the effects of these deficiencies in our model are thought to be less than our data noise with the current data.

Our a priori model used the Bureau International de l'Heure (BIH) Circular D smoothed values for UT1-UTC, and polar motion. A priori station locations were those that have been obtained over the years by spacecraft tracking. If a radio source had an optical counterpart which could be placed on the FK-4 system, we used that position as a priori, and included its coordinates with the proper statistical weight (typically a few tenths of an arc second). Otherwise, we used positions obtained by single radio antenna measurements.

Although VLBI can determine source declination absolutely, a coordinate origin definition on the celestial sphere must be made for right ascension. Likewise, a baseline longitude (or alternatively, UT1) definition for the Earth must be made. In an effort to mesh our results with the conventional coordinate systems, we have made the following definitions.

1. The right ascension of the radio source NRAO 140 was fixed at a given value in the final fit. This particular right ascension value was determined by means of a preliminary fit in which the right ascensions of all the optical counterparts were statistically constrained by their a priori error. This defined the right ascension origin and produced an overall shift in the right ascensions of all the sources such

that the offset between the radio reference frame and the FK-4 system was approximately 0$''$.1 or less.

2. The Earth-fixed longitude origin for the baselines was established by adopting the BIH values for UT1-UTC on January 31, and February 1, 1977 as exact. (Since two main baselines were used, and the data on these baselines did not overlap, fixing the value of UT1-UTC on two days was required).

With regard to the clock contribution, the effect on the observed time delay of the different epochs and rates of the two independent oscillators for each station pair was modeled as a function linear in time. In the least-squares estimation process the parameters representing the differential epoch and rate were given independent status for each experiment. On several days, however, it was necessary to break the clock model into several time segments within the day, fitting a separate linear function within each of the segments.

We modeled the troposphere as a spherical shell with the thickness specified as a parameter to be estimated. For each experiment, a new estimate of this thickness was allowed for each station. For each station, and for each date, the a priori troposphere thickness was obtained from a table of monthly mean values developed for the DSN by C. Chao. The a priori error of these values, which was used to constrain the estimated troposphere parameter, turned out to be roughly equal to the error which the VLBI data alone would have produced in estimating the troposphere thickness.

For the ionosphere we used a simple model of the total electron content as a function of local time. This model was only an approximation. However, more detailed models made little difference. Because we plan to remove the effects of the ionosphere by simultaneously observing at both S and X Band, no significant effort is being directed to improve this model.

RESULTS

With the models and constraints defined above, a simultaneous multiparameter fit was made to all experiments to obtain estimates of the parameters. Figure 1 plots the UT1 (VLBI) - UT1 (BIH) values given in Table 1. Notice the improvement that results from measuring delay in addition to delay rate. Note also that the most recent point has a formal uncertainty (1σ) of 0.6 msec with about 6 hours of data. This last observing session was on the nearly east-west Goldstone-Spain baseline. The geometry of that baseline lends itself very well to the determination of UT1 at the same time source positions are being estimated.

Baseline vectors are closely tied with UT1 measurements. Table 2 presents the various components of the baselines relevant to the

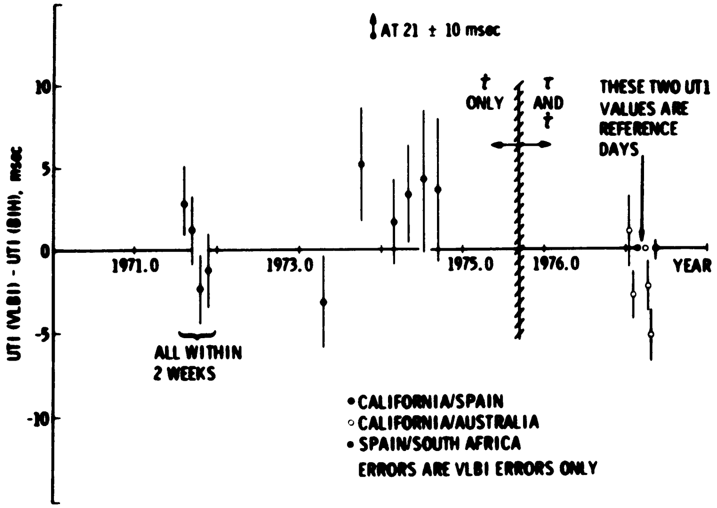

Figure 1. UT results for 1971-77 VLBI data.

Table 2. Preliminary results from intercontinental baselines from 1971-77 VLBI data.

BASELINE	CALIFORNIA/SPAIN (14/63)	CALIFORNIA/ AUSTRALIA (14/43)	SPAIN/SOUTH AFRICA (51/63)
EQUATORIAL LENGTH (m)	8378987.2 ± 0.3	7620842.95 ± 0.45	3037637.5 ± 0.9
"LONGITUDE"	$30^0.726453$ ± 1.5 msec (1 m)	$106^0.052285$ ± 2 msec (1.2 m)	$265^0.537323$ ± 6 msec (1.3m)
POLAR COMPONENT(m)	438056.1 ± 1.2	-7351802.3 ± 1.3	
TOTAL LENGTH (m)	8390430.23 ± 0.30	10588968.0 ± 1.0	

experiments we are reporting. The equatorial length and total length of the California-Spain baseline was determined with a formal uncertainty (1σ) of 30 cm, while the polar component uncertainty was 1.2m. The uncertainties on the components of the other two baselines ranged between 0.4 and 1.3m. Notice a typical problem with long baselines, the relative difficulty in measuring the polar component. This is because that parameter tends to correlate with other parameters. Also, note that because we did not have measurements of time delay on the Spain-South Africa baseline, we are unable to measure that baseline's polar component.

To eventually be able to measure Earth orientation with arbitrary blocks of antenna time, it is desirable to have the sky well covered with sources whose positions are well known. Figure 2 schematically displays the sky coverage of our current source position catalog. In the interest of clarity, we have plotted only those sources for which the error in right ascension or declination (or both) was ≤0"1. Note that the scale for the errors is different than the scale for positions.

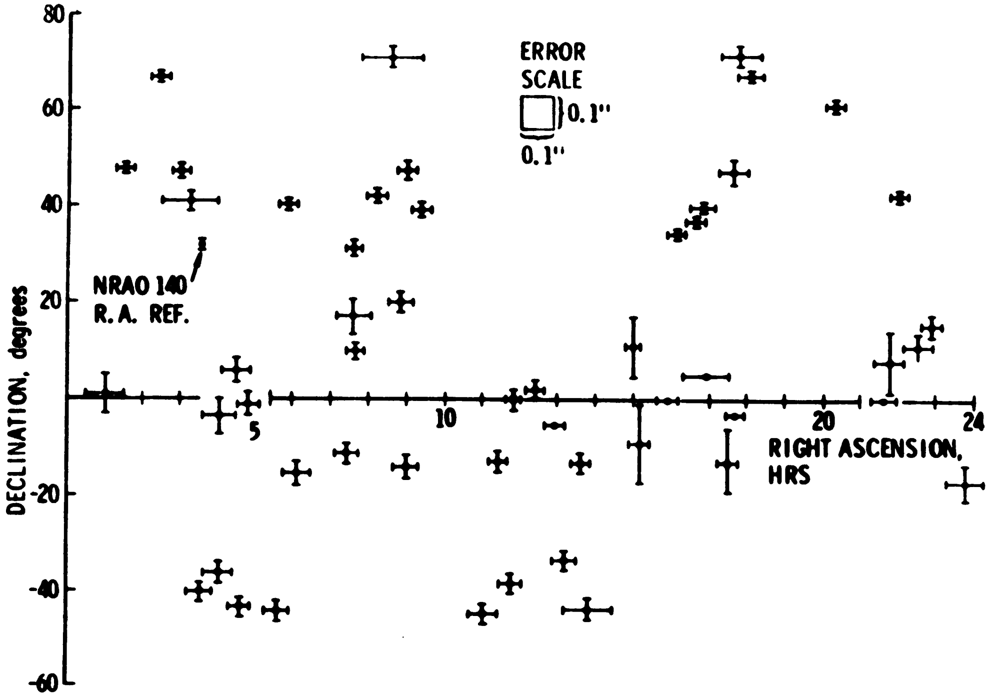

Figure 2. Distribution of sources from 1971-77 VLBI data. Only sources with an error ≤0"1 are included (S-band only).

Also the lack of an error bar implies that the error in that component was $\gtrsim$0".1. Only about one half of the sources in our eventual catalog have had their positions measured with an accuracy better than 0".1.

All these data are preliminary and are for S-band only. Inclusion of X-band data, and the solving for relevant components of polar motion must be performed before we consider the analysis of these data completed. However, even these preliminary results indicate a current capability of measuring source positions and Earth orientation with a formal accuracy of 0".01 - 0".04 and intercontinental baselines at a 0.3-1.5m level.

ANTICIPATED VLBI CAPABILITY OF THE DSN FOR EARTH ORIENTATION MEASUREMENTS

The current capability discussed above has been demonstrated during engineering development tests for an operational VLBI system. This system is being implemented within the Deep Space Network for the support of spacecraft navigation and will be operational by July, 1979. The remainder of this paper outlines the characteristics of this particular system, and the projected VLBI capabilities of the DSN into the early 1980's.

Table 3 summarizes the capabilities of the VLBI system being implemented. Its primary purpose is to monitor the hydrogen maser oscillators within the network and thereby determine if their stability meets the oscillator requirements of the Voyager mission to Saturn. In this role the system will be used on a weekly basis to determine clock offsets between the three DSN complexes. In the analysis of the weekly measurements, a priori radio source positions amd Earth fixed station locations will be provided by other longer, but less frequent, VLBI measurements. Data will be taken for approximately two hours on the California-Spain baseline, followed within 24 hours by another two hours of data on the California-Australia baseline. For each of the two sessions, the clock epoch offset and rate offset will be estimated. These clock parameters, along with UT1 and both components of polar motion, will be simultaneously estimated in a fit to the data from both observing sessions. Thus, each pair of 2-hour sessions will yield estimates of 7 parameters - three Earth orientation parameters and four clock parameters.

The required accuracy is: 10 nsec for clock epoch offset, 3 x 10^{-13} for fractional frequency offset, and 50 cm for Earth orientation. Furthermore, there must be the capability to have these results within 24 hours of the time the data is taken. These specifications refer to a "worst-case" performance of the system. It is a capability that must exist for arbitrary assignments of 2-hour antenna time blocks. In actual practice the system performance can be somewhat better. Specifically, we expect to determine true clock epoch offsets to 2-4 nanosec (limited by calibrations of cable lengths). Furthermore, since uncertainty in a priori source positions will initially be a dominant error source, the expected steady improvement of the source position catalog wil lead to increasingly better Earth orientation values. Since improved positions can be applied to earlier data at any time, significant revisions of earlier real time results should be possible as new position data are incorporated a year or two later.

Table 3. Characteristics of DSN operational VLBI system.

Antenna Diameters	64 meters
Antenna Locations	Spain (DSS 63) USA (DSS 14) Australia (DSS 43)
Observing Frequency	S-band - 2.3×10^9 Hz X-band - 8.4×10^9 Hz simultaneous
Record Rate	500 Kbs (4 Mbs if not in near real time mode)
Spanned Bandwidth	40 MHz, S-band 50 MHz, X-band
Frequency Standards	Hydrogen Masers ($\Delta f/f \lesssim 10^{-14}$)
Nominal Interval between Observation Pairs (DSS 14/63, DSS 14/43	1 Week
Nominal Observation Time on each Baseline	2 Hours
Nominal Accuracy	
UT1, Polar Motion	30 cm
Fractional Frequency Offset	10^{-13}
Clock Epoch Offset	<10 nsec
Lag between Data Acquisition and Results	<24 hours

Special observing strategies also are feasible where increased accuracy of the variations in Earth orientation are desired. Longer, and more frequent, observing sessions, along with observing sessions chosen to utilize a particular portion of the source catalog, would greatly improve the accuracy with which variations in UT1 and polar motion could be measured. Use of the operational system to obtain short term variation measurements of accuracy $\sim 0\overset{\prime\prime}{.}003$ on a daily, or twice daily basis, is possible by late 1979, or early 1980. However, with the anticipated resource allocations, routine weekly measurements of ∼0″.01 accuracy are expected.

In support of this operational VLBI system, more advanced VLBI systems will be employed within the DSN on a development basis. These systems will be used to refine the radio source catalog and the relative Earth fixed station locations, as well as to improve the modeling capability of the software, and to test new hardware. Consequently, not only will there be a steady improvement in the accuracy of the operational system, but there will also be a "best efforts" capability in the advanced VLBI system far superior to that of the operational system.

Figure 3 schematically illustrates the anticipated accuracy of this development effort as a function of time. The solid line shows the purely instrumental errors as new hardware becomes available, while the dotted line is the overall accuracy for measuring Earth orientation. Note, the delivered performance always lags well behind the instrument capability. Such a lag results from software development with Earth modeling capability always lagging the instrument development. However, as Figure 3 indicates, we anticipate a 0″.002-0″.003 capability in the early 1980's with 12 hours of data on each of the two baselines, California/Spain, and California/Australia. This accuracy would not be limited to short term variation measurements, but would apply to all uses of the system for Earth orientation determination.

Certain assumptions, of course, have been made. One is that the positions of natural radio sources are time invariant. Some experiments by other groups have already indicated that this is a valid assumption. Experiments are now underway which will test this assumption more thoroughly. Another assumption is that integrating the Earth's motion for 12 hours is meaningful at the 0″.002 level. Again, that will have to be determined experimentally.

There are also other problems which must be considered before measurements at this accuracy are useful. For example, the current definitions of UT1 and polar motion are not strictly correct once measurement accuracy reaches levels comparable to the yearly movement of the crustal plates of the Earth. Another problem concerns the best definition of a right ascension origin for the radio source catalogue at the 0″.001 level. Practical considerations are going to force us into making working definitions for our use of VLBI by 1981. There is clearly a growing need for the consultation and cooperation of the international community in defining coordinate systems suitable for milliarcsecond measurements of Earth dynamics and source catalogues.

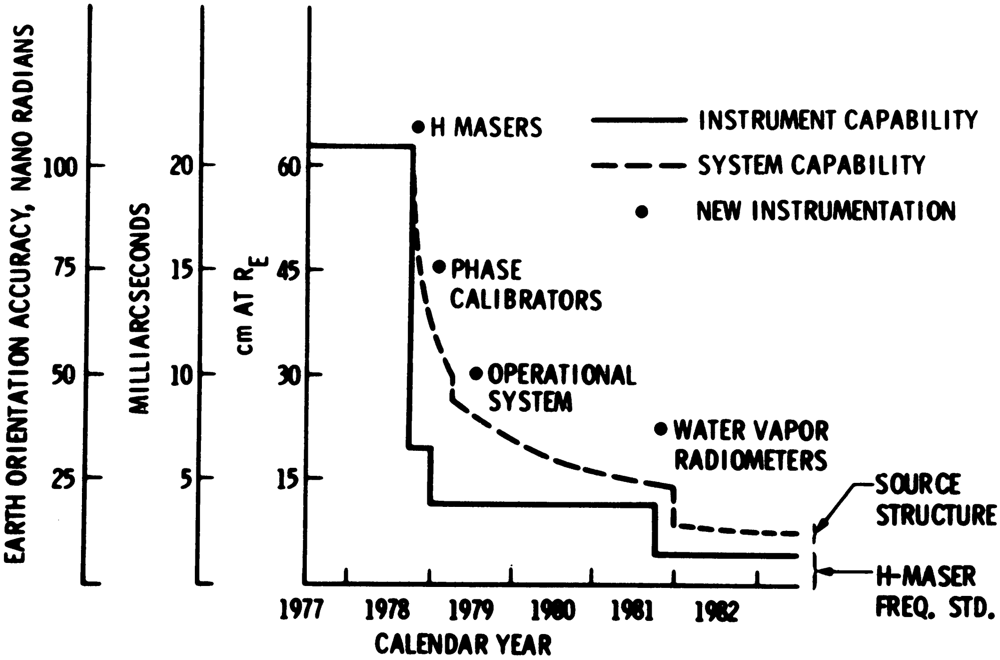

Figure 3. "Best efforts" capability for determining Earth orientation with 12 hours of VLBI data on each of 2 baselines: DSS 14/43 and DDS 14/63.

ACKNOWLEDGMENT

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

DISCUSSION

J. D. Mulholland: The need for the source to be visible at both sites means that 12-hour integrations are not possible on a single source. The predictions assume that more than one source will be observed during a run.

J. L. Fanselow: We do not necessarily use a single source. Many different sources are observed during a single experiment. We generally try to observe a given source at least three times during its passage through the common visibility pattern of the interferometer. This takes about four hours, almost independent of declination, for the Goldstone-Australia baseline; for Goldstone-Spain it varies from a few minutes for declination -20° to 24 hours for polar sources. We observe the polar sources many times during an experiment. The

Goldstone-Australia baseline is not good by itself but is very good in combination with Goldstone-Spain.

K. Johnston: The declination measurements are not absolute but are relative to the instantaneous spin axis of the Earth.
What is the error from a six-hour measurement of UT1?

J. L. Fanselow: I agree with your comment.
The formal 1σ error of our most recent UT1-UTC value was 0.6 ms from six hours of data. The Goldstone-Spain baseline is very suitable for the simultaneous determination of source positions and UT1-UTC.