SHORT TURN-AROUND INTERCONTINENTAL CLOCK SYNCHRONIZATION USING VERY-LONG-BASELINE INTERFEROMETRY--A PROGRESS REPORT*

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ABSTRACT

During the past year we have been working to bring into regular operation a new VLBI system for making intercontinental clock comparisons (as well as UT1 and polar motion measurements) with a turn-around of a few days from the time of data taking. Earlier R&D VLBI systems have required several weeks to produce results. The new system, which is not yet complete, incorporates a number of refinements not available to us in earlier systems, such as dual frequency ionospheric delay cancellation and wider synthesized bandwidths with instrumental phase calibration. In this paper we report on the state of the new system and give examples of its current performance.

INTRODUCTION

In order to meet the increasingly higher accuracy demands of spacecraft navigation to the outer planets, the Deep Space Network (DSN) is in the process of implementing a short turnaround clock synchronization technique utilizing Very Long Baseline Interferometry (VLBI) [1-5]. This technique has already been demonstrated to be an effective method of measuring relative clock offsets and offset rates at intercontinental distances [6, 7]. A review of the utility of VLBI for timekeeping and geodesy was presented by Fanselow in 1977 [8]. The system being developed at JPL for this purpose differs from those used in previous demonstrations in that it is designed as an "operational" system to provide clock offsets as well as earth rotation and polar motion measurements on a weekly basis from approximately three hours of observing. This paper reports our progress in implementing this system and gives typical results.

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OBJECTIVES

The development of a short turnaround clock monitoring system using VLBI has progressed from the prototype system reported in 1979 [9] to an early version of the operational system. This new system utilizes bandwidth synthesis [10], S- and X-band ionospheric delay cancellation, and instrumental phase calibration. The Deep Space Network intends to operate the three-station* interferometer on a weekly basis. Each week's observations will include an east-west and a north-south baseline to permit the estimation of earth rotation and polar motion as well as clock synchronization parameters.

An average of 20 extragalactic radio sources will be observed during three hours each week. Based on the precision expected from a VLBI system [8] we expect to determine:

- UT1 to ± 0.7 msec
- Polar Motion (X and Y) to ± 0.3 m
- Clock epoch offset to ± 10 nsec
- Clock frequency offset to ± 3 parts in 10^{13}

From the collected weekly observations we will be able to measure long-term clock stability to a few parts in 10^{14}. Although we are currently performing our processing on the general purpose computer facilities at Caltech, we are in the process of converting the post-correlation software to a JPL computer system which will be dedicated specifically to VLBI. Once all the elements of the new system are in place we expect to be able to produce results within 48 hours of receipt of data. A simplified diagram of the system is shown in figure 1.

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*DSS 14 at Goldstone, California; DSS 43 at Tidbinbilla, Australia, and DSS 63 at Madrid, Spain.

SYSTEM OVERVIEW

Our application is essentially a classical VLBI technique [10-13] wherein each pair of stations is independently scheduled to observe a specified set of extragalactic radio sources. The data from each observation are recorded at both S- and X-bands on eight time-multiplexed channels, each 250 KHz wide, spanning a 40 MHz receiver bandwidth. As soon as possible after the observing session the recorded data are transmitted over a 56K bit per second communication channel to JPL where they are recorded on magnetic tape for processing. In the final implementation, mass disk storage will be employed for recording.

In the present interim processing mode, prior to the activation of the new hardware correlator and dedicated processing computer, the magnetic tapes from both stations are read and correlated in software on an IBM 3032 computer. Then a Fast Fourier Transform (FFT) is performed on the correlation sums from each channel, with the resulting values of fringe frequency and amplitude inserted as a priori estimates to a more precise fringe-fitting processing which compensates more exactly for the troposphere and geometric delays. This produces estimates of fringe amplitude, frequency, phase and delay for each channel as well as synthesized delays for all channel pairs up to a spanned bandwidth of approximately 30 MHz. (The final system will have a 40 MHz spanned bandwidth.)

Additional software takes the estimates for each source and produces a maximum likelihood estimate for clock offset and clock rate over the observing time span. These values and BIH UT1 and polar motion values are then used as the a priori for the final step where the data from both baselines are brought together for simultaneous estimation of clock, UT1 and Polar Motion parameters.

Calibration of the data for instrumentation delays [14, 15] and charged particles takes place prior to the final estimation step. It is performed only if phase calibration tones have been injected into the RF amplifier so that the instrumental delays can be determined. Dual frequency cancellation of charged particle effects cannot be properly performed if the instrumental delays have not been removed.

DEVELOPMENT PLAN

An exposition of the development steps involved is presented to demonstrate the progress that has been made to date. Figure 2 illustrates the development steps, where we were in that progression last year, and where we are now. The transition from the prototype system includes an interval where the level of precision on measured clock offsets drops from 50 ns to 150 ns. We are currently in this interval as is evident by the results reported.

The main reason for this loss of precision is that we have transferred from a 4 Mb/s system to a 500 Kb/s system. By the time of our report last year [9], the 4 Mb/s system had been upgraded from 64-26 meter antenna pairs to all 64 meter pairs and had been provided a more precise source catalog. Those measures were to help compensate for the signal to noise loss in going to 500 Kb/s this year.

To obtain 10 ns clock offset accuracy with the 500 Kb/s system we must use bandwidth synthesis to span the 40 MHz receiver bandpass. This capability cannot be realized until instrumental and charged particle effects can be calibrated. Thus figure 2 places the dual frequency and instrumental delay capabilities as steps that must be implemented prior to our being able to enter the 10 ns precision regime. At this time the dual frequency capability is functional but is not being used pending the installation of instrumental delay calibrators. Consequently clock offsets are now measured by averaging the bit stream alignment delays obtained on four 250 KHz channels, which results in the reduced precision of approximately 150 ns.

Once the instrumental delay calibration is available, further enhancements will refine the instrument's precision and improve turnaround. The transferral of data processing to a dedicated system will introduce a hardware correlator unit and a computer system which can receive the data directly from the communication lines without recourse to the intermediate magnetic tapes now being produced. This will permit us to achieve 48 hour turnaround, possibly in the summer of 1982. After this, installation of water vapor radiometers and modification of the software to utilize these measurements will conclude our development.

CURRENT RESULTS AND COMMENTS

Typical results from our weekly observing sessions are shown in figures 3 and 4; the results are tabulated in tables 1 and 2. No useful trend analysis of the data can be performed because of frequent clock resets and frequency standard changes producing epoch jumps. Individual results, however, are useful for the purpose of measuring the relative offsets and offset rates at particular points in time.

The results are sparse because of scheduling conflicts with Voyager Project operations and the usual problems of breaking in a new system. The variability of the reference standards as well as our operational readiness have improved considerably since the interval reported and problems in this area are expected to diminish measurably as we enter into the latter phase of development. Our objective for next year's report will be the presentation of preliminary results involving the use of dual frequency charged particle cancellation and instrumental delay calibrations.

ACKNOWLEDGEMENTS

We wish to express our gratitude to all the men and women of the Deep Space Network who contributed to the data acquisition, data processing and system engineering aspects of this development. We are especially thankful for the help and cooperation received from Marshall Eubanks, Rick Shaffer, John LuValle, Pam Wolkins, Dolly Gibbs, and Jeannyne Gunckel.

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TABLE 1

Block 1 Clock Offset Data for California-Australia Baseline
8 June 1980 - 23 October 1980

Date	Epoch	Measured Offset, μ sec	Residual to Fit, ns	Square Root Allan Variance, x 10^{-13}
24 June	15.20404	45.72	251	
15 July	16.99444	47.30	381	
31 July	18.374500	47.28*	-	
24 Aug.	20.43114	52.06	131	1.6
				(BREAK)
30 Sept.	23.61826	-5.30*	-	-
16 Oct.	24.9983888	-5.42*	-	-

* not included in fit

TABLE 2

Block 1 Clock Offset Data for California-Spain Baseline
8 June 1980 - 23 October 1980

Date	Epoch	Measured Offset μ sec	Residual to Fit, ns	Square Root Allan Variance, x 10^{-13}
7 June	13.68634	-3.82*	-	-
17 June	14.51530	-6.16	62	
14 July	16.90876	-7.84	-242	
19 July	17.35684	-7.78	74	
25 July	18.15724	-8.21	102	2.88
				(BREAK)
24 Aug.	20.41996	-4.88	25	
15 Sept.	22.32136	-4.45	-43	
17 Oct.	25.06342	-3.67	17	0.11
			RMS = 108 ns	

* not included in fit.

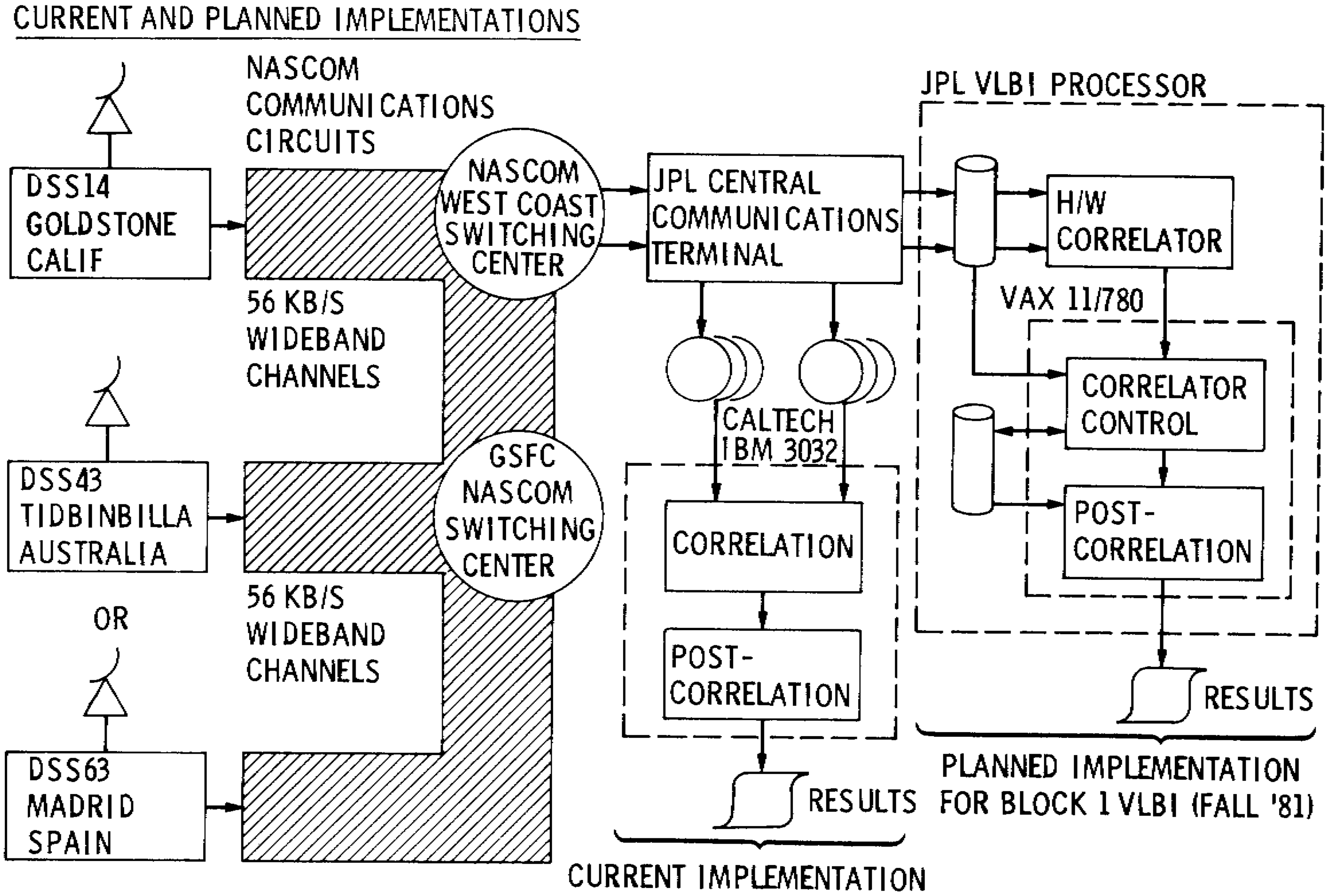

Figure 1. JPL-DSN Short Turnaround VLBI System Configuration Showing Current and Planned Implementations

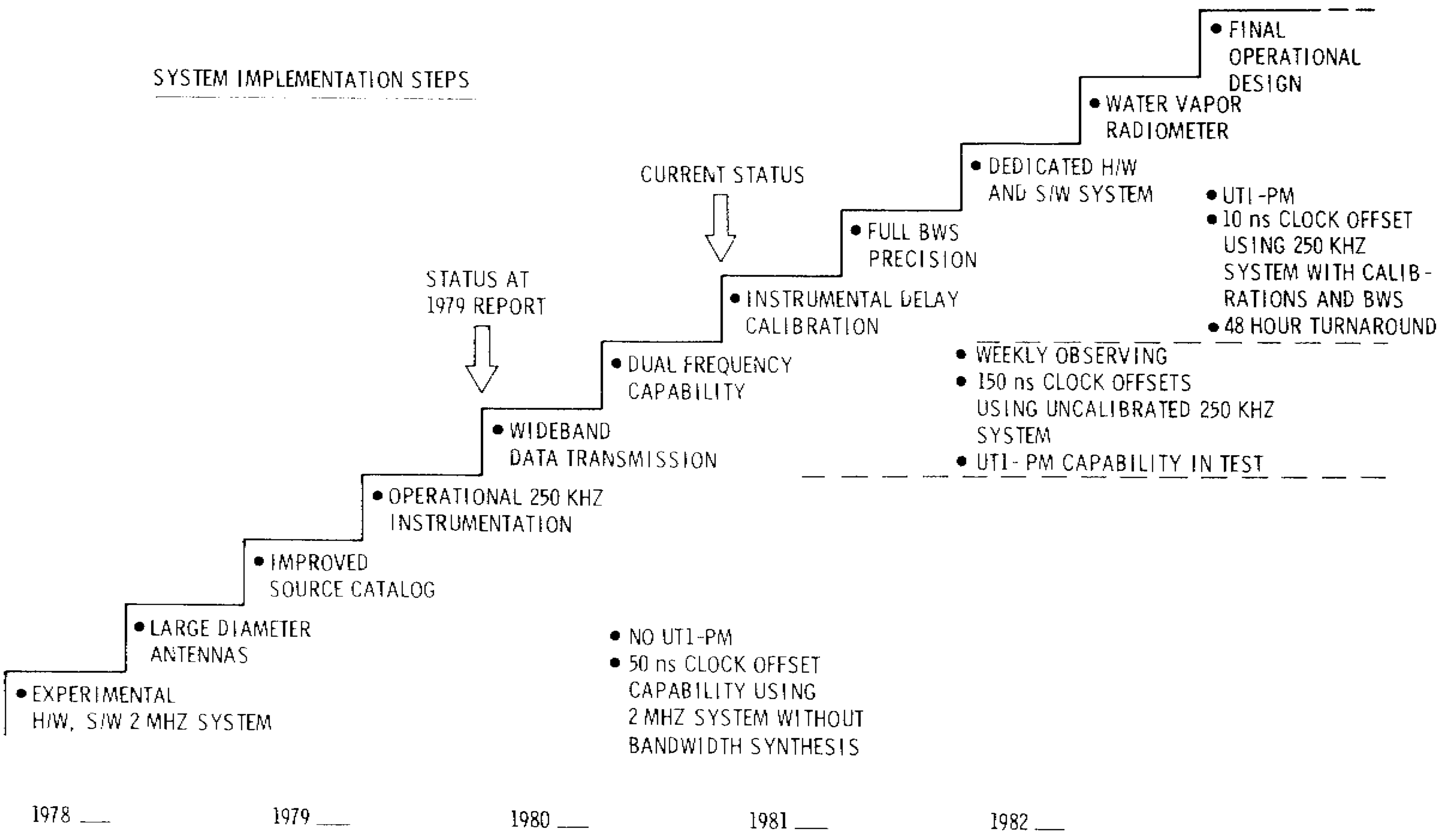

Figure 2. JPL-DSN Short Turnaround VLBI System Implementation Steps

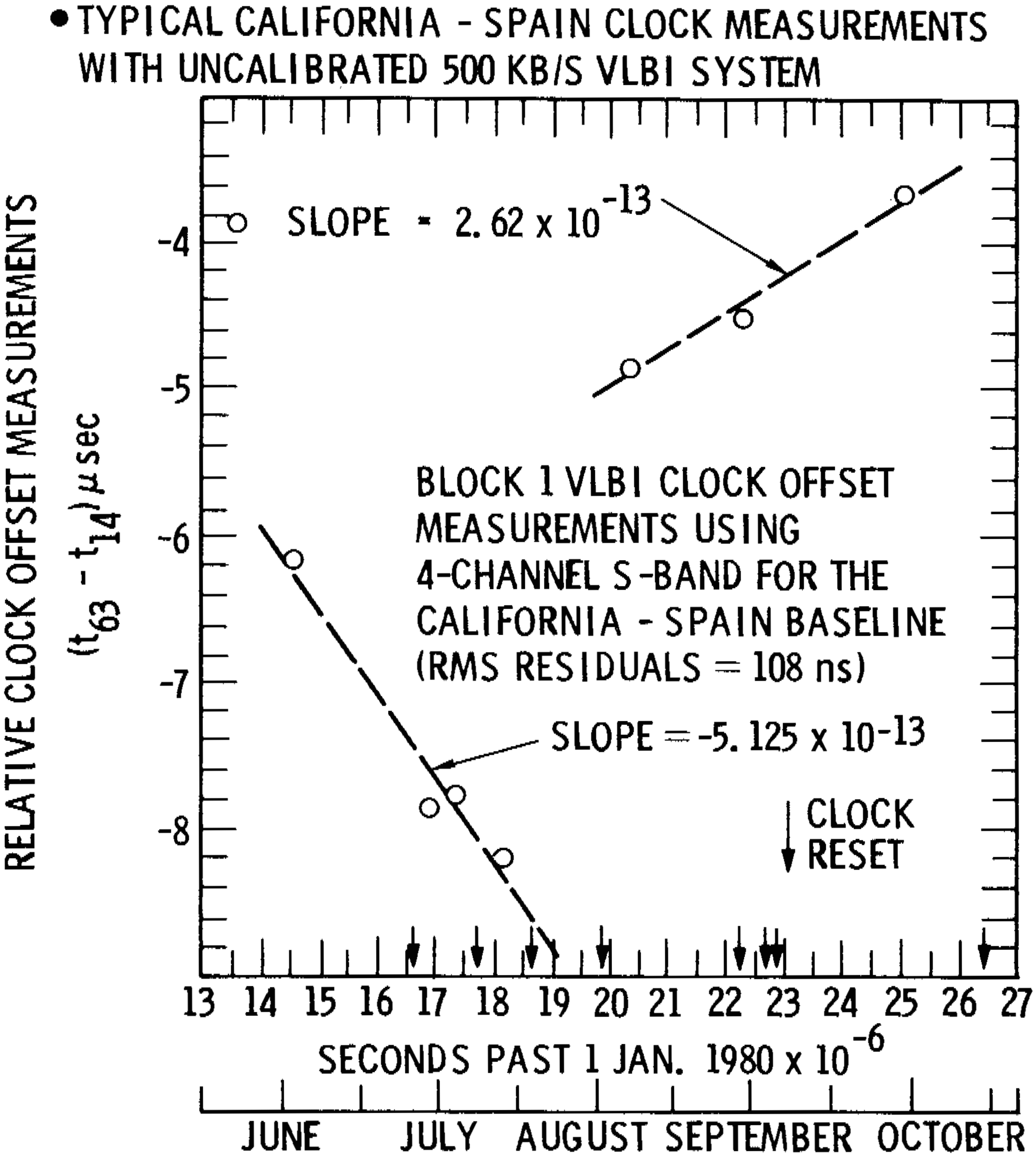

Figure 3. Typical VLBI Relative Clock Offset Results for the California-Spain Baseline Using the Uncalibrated 500 KB/s System

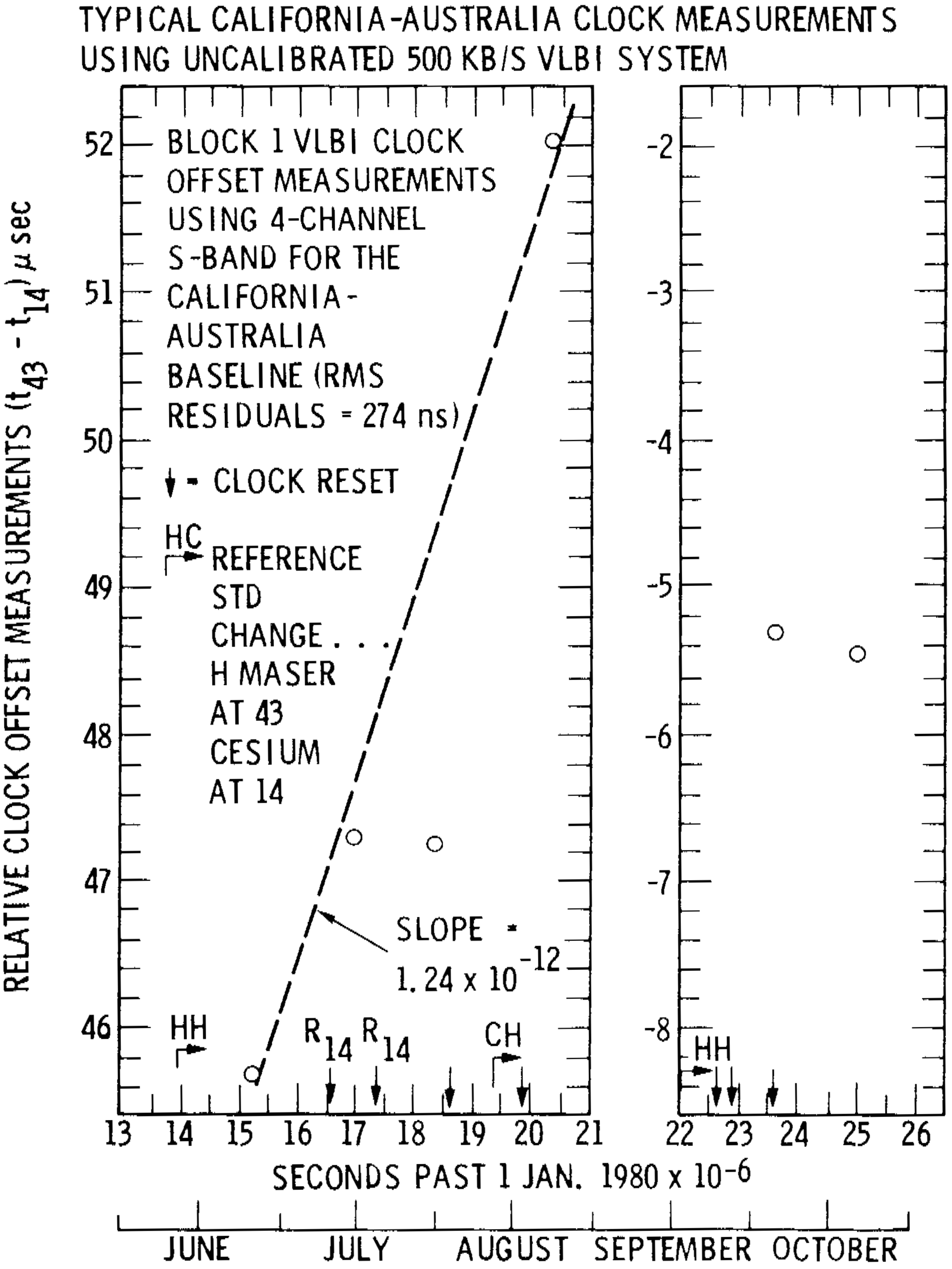

Figure 4. Typical VLBI Relative Clock Offset Results for the California-Australia Baseline Using the Uncalibrated 500 KB/s System

QUESTIONS AND ANSWERS

DR. WILLIAM WOODEN, DMA

Do you have any preliminary results for the polar motion studies that you talked about. You said that you had done some studies but you didn't give any numbers, how well do your results seem to compare with say the Naval Observatory results?

MR. MADRID:

Well, we do have some preliminary results but we haven't issued them because we have not fully understood their significance yet. We have compared them with BIH polar motion results and there seems to be a bias in our results which we cannot fully explain at this time. We are undergoing an analysis of our software and our modeling to understand what the nature of the problem is.

We do feel that it is probably due to a modeling problem which can, once we understand what the situation is, there is no reason to feel that we will not be in line with the BIH results.

MR. PAT FELL, Naval Surface Weapons Center

You use a bias to correct the linear model to model the clock synchronization between your two stations.

MR. MADRID:

Yes.

MR. FELL:

What are you observing? What time interval? What length of time do you apply that model load with?

MR. MADRID:

That was over a two month period at the longest.

MR. FELL:

Do you use one linear model over two months?

MR. MADRID:

That is right, essentially we have hydrogen masers most of the time, except for one case where we had a cesium at one station, and we expected that most of our drifts would be of that order, although I think our reason for using a linear model is this; that we fit initially to a linear case and we find that if the linear does not produce the right residuals than we would consider using non-linear models to try to determine the functioning of the standards.

MR. DAVID ALLEN, National Bureau of Standards

In regard to the driving force during this experiment, do you have a stronger need to determine UT-1 than you do the clock synchronization? For example, if you could obtain synchronization via GPS an alternate route, perhaps, would you still need to do it to get UT-1, or could you obtain adequate accuracy in the results from the BIH for the UT-1 values for deep space tracking?

MR. MADRID:

Yes, I believe that there are alternate systems that we could use. In fact, we have been using BIH for our space navigation up to now. And, there are two driving factors here.

One of the reasons that we are in the UT-1 polar motion business is that we have seen at the laboratory that there is going to be a need for a change in the next 10 years. That BIH is still operating with optical instruments essentially, and that there is going to be a period of change and a need to review all of the instruments that are being used to obtain UT-1 polar motion and we want to cooperate and be part of that cooperative effort to determine if laser ranging or VLBI or what other technique is available. The best way to do this is to be producers of UT-1 polar motion and have an inter-comparison of different techniques that will be useful to the scientific community to determine what instruments, in the future, can be used for UT-1 polar motion determination.

Now, as far as clock sync, there are alternative systems and we have considered GPS as an alternative. However, the fact that we have the REA telescopes operable there and they are busy and there are crews there, makes it sort of a natural thing for us to try to achieve clock sync using these REA telescopes at times when they are not occupied in supporting a mission.

MR. ALLEN:

I understood that the demands on the telescope were such that if you wouldn't have to use them then that would be a definite advantage.

MR. MADRID:

Well, that all depends on the load. I think right around Saturn encounter and Jupiter encounter, that was the case, however, our loading in the future is going to be rather different, and I think we are looking toward the future in that regard in the sense that we are not going to be supporting as many space missions within the next few years and we are trying to use the equipment and the facilities that we have for other cooperative ventures including time sync in UT-1 polar motion.