EARLY RESULTS FROM A PROTOTYPE VLBI CLOCK MONITORING SYSTEM

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ABSTRACT

Four sets of experiments were conducted to measure the relative epoch offsets between atomic clocks in California, Australia, and Spain by means of very-long-baseline interferometry (VLBI). The experiments were conducted using an incomplete R & D VLBI system with a number of inherent limitations. However, the results give us confidence that our measurement objective of epoch offset to 10 nanoseconds will be met using the carefully calibrated system to begin regular operation next year.

INTRODUCTION

With the increasing navigational precision demanded of future planetary missions comes the increasing need for precise monitoring of the atomic frequency standards at the deep space tracking stations in Goldstone, California, Canberra, Australia, and Madrid, Spain. To keep the clock contribution to range error at outer planet distances (beyond Mars) below 0.5 meters it will be necessary to know the relative frequency offsets to three parts in 10^{13}. In addition, the Deep Space Network (DSN), which is charged with operating and maintaining the stations, has a vigorous interest in monitoring the behavior of its clocks as precisely as possible. Consequently, a variety of methods for intercontinental clock comparison have been under evaluation at JPL for some time.

OBJECTIVES AND PLAN

In the Navigation Systems Section at JPL we plan soon to begin regular weekly monitoring of several clock and geophysical parameters by the technique of very-long-baseline interferometry (VLBI) [1-7]. Each weekly observing session will employ two baselines (sequentially), with eight to 10 observations of extra galactic radio sources on each, and will last approximately three hours. From the data gathered during one session we expect to determine:

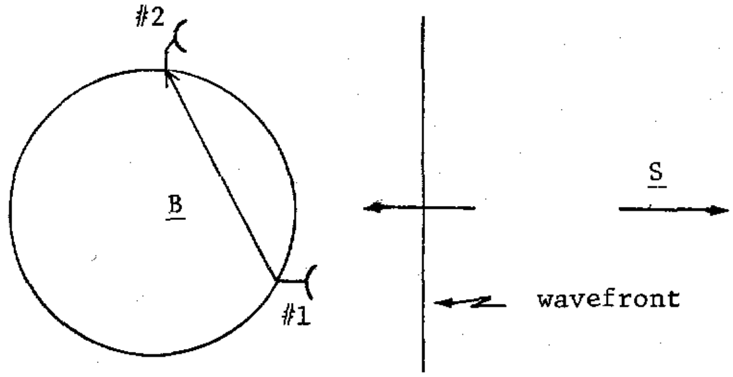
- UT1 to $\pm$ 0.7 msec
- Polar motion (X and Y) to $\pm$ 0.3 m

- Clock epoch offset to $\pm$ 10 nsec
- Clock frequency offset to $\pm$ 3 parts in 10^{13}

From the weekly epoch offsets we will be able to compute long-term clock stability to a few parts in 10^{14}. Within several years, when various pieces of dedicated hardware are in place, we will be able to produce those results within 24 hours of the onset of data taking.

THE VLBI SYSTEM

To obtain results of that quality we require both a very accurate prior knowledge of the VLBI geometry and the ability to remove a number of contaminating delays. The diagram below illustrates the VLBI geometry.



The signal arrives from a distant radio source and is received first at Station 1 and then, a time τ later, at Station 2. The received signals are sampled and recorded on magnetic tape with time-tags derived from the station clocks. The apparent delay can be very precisely measured by later cross-correlation of the two recorded signals. When all components of the true delay τ have been accurately modeled or otherwise calibrated and removed from the measured delay, what remains is the apparent delay due to clock synchronization error.

The components of the true delay include

- τ_G - the delay due to geometry
- τ_P - the delay due to atmospheric charged particles
- τ_N - the delay due to the neutral atmosphere
- τ_I - the delay due to instrumentation

Removing the geometric delay requires knowledge of baseline length to ~0.5 m and of source positions to ~0.01". Such accuracies are now being achieved with VLBI measurements being made at JPL and elsewhere. The VLBI clock monitoring system to begin operation next year will include enhancements to remove the other delay components. They include:

- S- and X-band recording for dual-frequency cancellation of charged particle delay.
- More accurate modeling of the neutral atmosphere based on surface weather measurements and (later) water vapor radiometer measurements.
- Continuous calibration of instrumental phase and group delay [8,9].

In addition, the near-simultaneous observations on two baselines will permit solution for UT1 and polar motion, thereby improving the geometric model.

While this system has been under development, we have been conducting experiments with an earlier R & D system employing none of those enhancements. Consequently, the results presented here are substantially degraded by errors from the corresponding sources. Perhaps the most serious of these errors -- occasionally producing large apparent changes in epoch offset from one experiment to the next -- are a) changes in instrumental delays resulting from minor configuration changes, and b) spurious epoch jumps at the temporary clock reference point used for these experiments. Those effects would be removed by the instrumental calibration system.

In addition, the absence of instrumental calibration prevented our using the "bandwidth synthesis" technique to achieve large bandwidths and hence very precise delay measurements [10,11]. The delay measurements reported here were obtained with one comparatively narrow 1.8 MHz channel at S-band.

We must therefore be careful in defining the delay measurement error. The precision of the measurements -- that is, the random error due to such usual sources as ionosphere, neutral atmosphere, geometric modeling error, and system noise -- is estimated at 40 nanoseconds. However, because of the occasional changes in instrumental delay, the offset variation from one experiment to the next can be as much as several hundred nanoseconds. Finally, the large, uncorrected, but constant instrumental delay introduces a bias in delay measurements of up to one microsecond.

RESULTS

We have obtained epoch offset measurements between the California - Australia and California - Spain clock pairs for two experimentation periods lasting several months each. Figure 1 shows a set of 10 epoch offsets measured between California and Australia over the period 30 Sep 78 to 13 Jan 79. Both stations were using hydrogen masers as primary standards. The cause of the rate change, apparently in early December, is unknown. Because of the sparseness of points, exact placement in time of the rate change is impossible. There is a clearly anomalous point in early November, indicating either a large (~430 ns) temporary instrumental glitch or a much earlier rate change not well-determined by the data. We interpreted it as the former and excluded it from the linear fit. Residuals to the two fitted lines are shown in Figure 2. The rms residual, excluding the anomalous point, is 39 ns. The irregular spacing of samples in Figure 1 and subsequent plots precludes the meaningful computation of the two-sample variance. However, as an item of information we have computed it and included it with the numerical data from those plots. The data for Figures 1 and 2 are given in Table 1.

Figure 3 shows a set of eight offsets measured between California and Spain over the period 23 Oct 78 to 24 Dec 78. Clearly evident is the onset of apparently aberrant clock behavior at the sixth point. The jump at that point is believed to be due to instrumentation local to our VLBI system, probably the sync mechanism of the temporary clock, as it did not appear in data taken simultaneously with another experimental JPL VLBI system, the "Wideband Data Acquisition System" (WBDAS) [12]. The smaller rise in the last two points has apparently other causes since it does appear in the WBDAS data. Note the switch at Spain from a cesium standard to a hydrogen maser before the last point.

To more clearly illustrate the changes at the later points, the line in Figure 3 was fitted to the first four points only. Figure 4 is a plot of the residuals to that fit. Table 2 gives the values from those plots as well as the residuals to a line fitted to all eight points.

Figure 5 is a plot of 13 offsets measured between California and Australia over the period 19 May 79 to 25 Sep 79. Note that Australia was operating with a cesium primary standard until the last point and that two different Australia antennas were used. Those antennas use a common frequency standard; however, there is a small unknown instrumental delay difference between them which is uncorrected in the data.

The outstanding feature of Figure 5 is the abrupt, temporary rate change in early August. As it happens, those responsible for maintaining the frequency standards had the rate at California adjusted on 1 August and then had it reset on 16 August. The two anomalous points fall on 6 and 11 August. Separate lines were fitted to the points before and after the disruption. Note that the reset did not restore the rate to precisely its original value. The residuals to the fit are plotted in Figure 6 and the numerical values given in Table 3.

Finally, Figure 7 shows a set of eight offsets measured between California and Spain over the period 23 Jun 79 to 25 Sep 79. Both stations employed H-masers as primary standards, however, again two different overseas antennas with a common clock were used. For a number of reasons, including station configuration changes and scarce antenna time at Spain, there is a large gap in the data from the begining of August to early September.

The two sets of points show markedly different slopes of -6.6×10^{-14} and 5.1×10^{-13}. Since there is no comparable rate change over the same period in the California - Australia data, we conclude that the change in slope is due to a rate change in the H-maser at Spain. However, we are unaware of any deliberate resetting of that clock. Residuals to the fits are shown in Figure 8 and the numerical values given in Table 4.

CONCLUSIONS

In view of the spurious clock and instrumental delay jumps inherent in the data, the fitting residuals from Tables 1-4 of 39 ns, 56 ns (8-point fit), 50 ns, and 43 ns are consistent with the quoted precision of 40 ns in delay measurements. Recent experience with operational phase calibrators and wide bandwidth delay measurements [13] suggests that the observed variability will be much reduced when those features are incorporated into the operational system. When, in addition, the planned enhancements to correct for propagation media and geodynamic effects become operational in 1980, we should have little trouble achieving the delay measurement accuracy required.

ACKNOWLEDGEMENTS

We are grateful to E. Cohen, R. Henderson, R. Shaffer, D. Spitzmesser, and the Deep Space Station personnel for their assistance in scheduling, configuring, and operating the stations, and processing the data.

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Table 1

Clock Offset Data for California-Australia Baseline
30 Sep 78 - 13 Jan 79

Date	Epoch	Measured* offset, μs	Residual to Fit, ns	Square Root Allan Variance, x 10^{-13}
30 Sep	23.629294	4.844	-29	----
14 Oct	24.844771	6.910	33	----
23 Oct	25.618483	8.156	3	0.63
27 Oct	25.975236	8.744	3	0.49
4 Nov†	26.670332	10.317	430	2.54
29 Nov	28.806020	13.397	-11	3.64
13 Dec	29.981315	14.776	17	3.37
20 Dec	30.671408	15.361	48	3.21
31 Dec	31.543594	15.955	-58	3.01
13 Jan	32.662017	16.984	73	2.88
			RMS 39	

*Approximate sigma for all offsets is 40 ns
†Not included in fit or in RMS residual

Table 2

Clock Offset Data for California - Australia Baseline
23 Oct 78 - 24 Dec 78

Date	Epoch	Measured* Offset, μs	Residual to 4-point Fit, ns	Residual to 8-point Fit, ns	Square Root Allan Variance, x 10^{-13}
23 Oct	25.655368	-3.965	3	31	----
30 Oct	26.180608	-3.828	-2	8	----
5 Nov	26.754849	-3.672	-2	-11	0.08
20 Nov	28.005401	-3.329	2	-49	0.06
27 Nov	28.611230	-3.184	-18	-88	0.15
3 Dec	29.202867	-2.800	206	116	1.45
16 Dec	30.249901	-2.604	118	-7	1.96
24 Dec	30.942036	-2.385	149	1	1.82
			RMS 99	RMS 56	

Table 3

Clock Offset Data for California-Australia Baseline
19 May 79 - 25 Sep 79

Date	Epoch	Measured Offset, μs	Residual to Fit, ns	Square Root Allan Variance, x10^{-13}
19 May	43.492585	26.438	71	----
1 June	44.611414	27.692	-64	----
8 June	45.214741	28.432	-75	0.75
15 June	45.823228	29.324	60	1.31
24 June	46.599963	30.205	-26	1.73
3 July	47.375655	31.205	8	1.59
16 July	48.512931	32.634	22	1.43
6 Aug	50.317639	33.487	---	----
11 Aug	50.743254	33.166	---	----
2 Sep	52.565956	38.348	-46	----
10 Sep	53.255908	39.158	54	----
18 Sep	53.945952	39.851	38	1.20
25 Sep	54.549574	40.391	-44	1.01
			RMS 50	

Table 4

Clock Offset Data for California-Spain Baseline
24 June 79 - 24 Sep 79

Date	Epoch	Measured Offset, μs	Residual to Fit, ns	Square Root Allan Variance x10^{-13}
24 June	46.594296	7.641	7	----
3 July	47.370614	7.593	11	----
10 July	47.973634	7.562	20	0.07
16 July	48.484081	7.414	-95	1.19
23 July	49.089347	7.526	58	2.17
10 Sep	53.222916	8.645	-17	----
17 Sep	53.839622	9.010	32	----
24 Sep	54.518217	9.312	-15	1.04
			RMS 43	

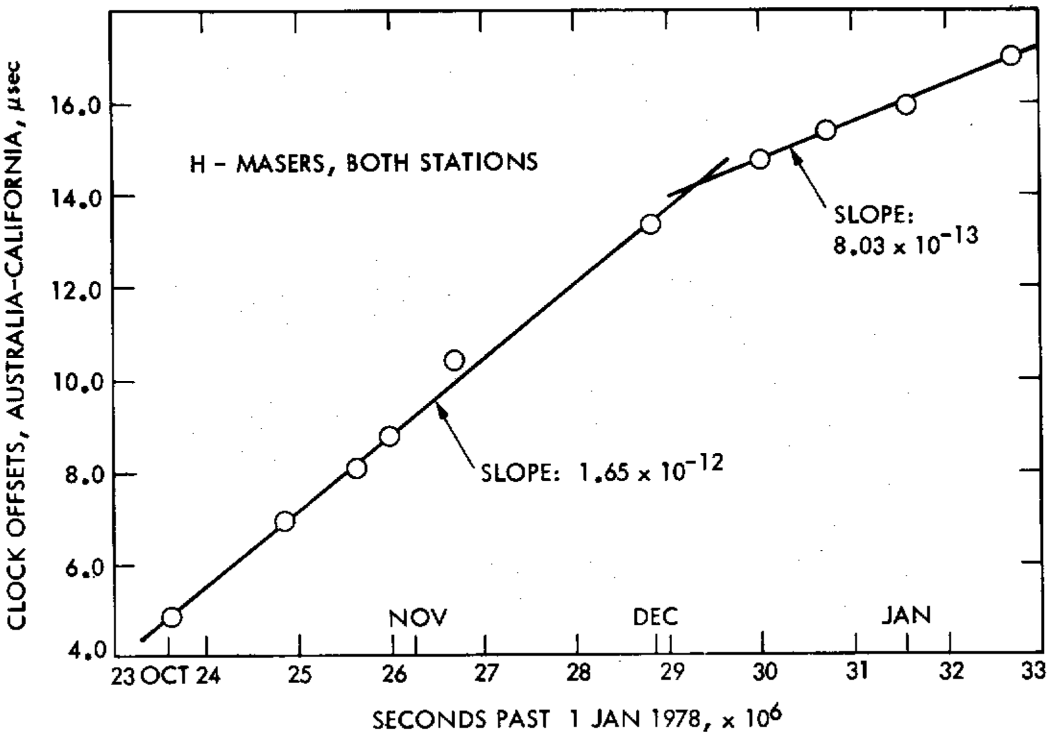

Figure 1. Clock Offsets, Australia Minus California, 30 Sep 79 - 13 Jan 79

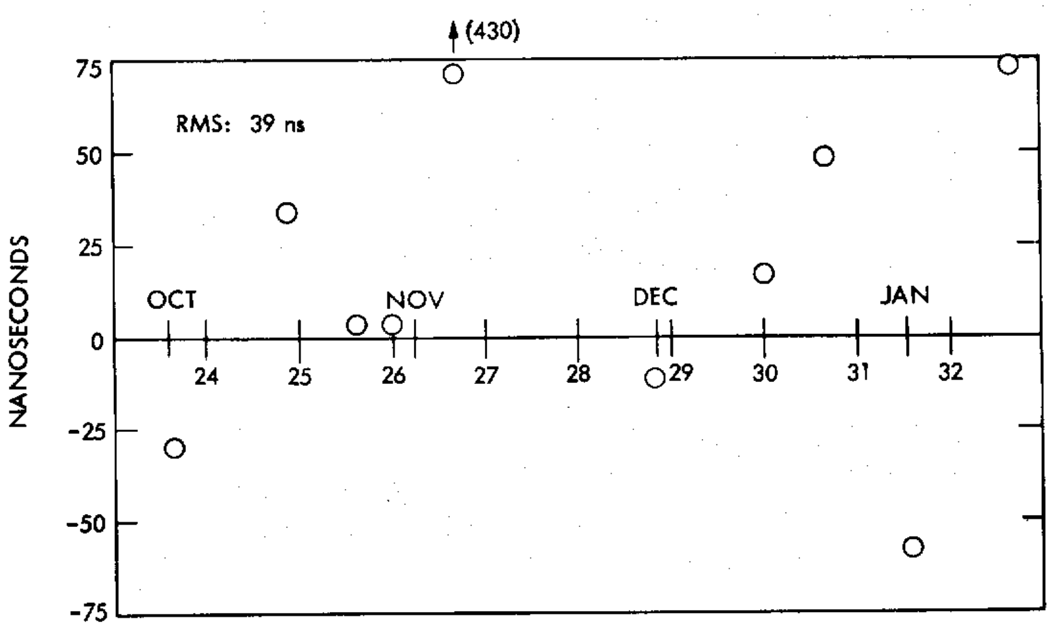

Figure 2. Residuals to Fits, Australia - California, 30 Sep 79 - 13 Jan 79

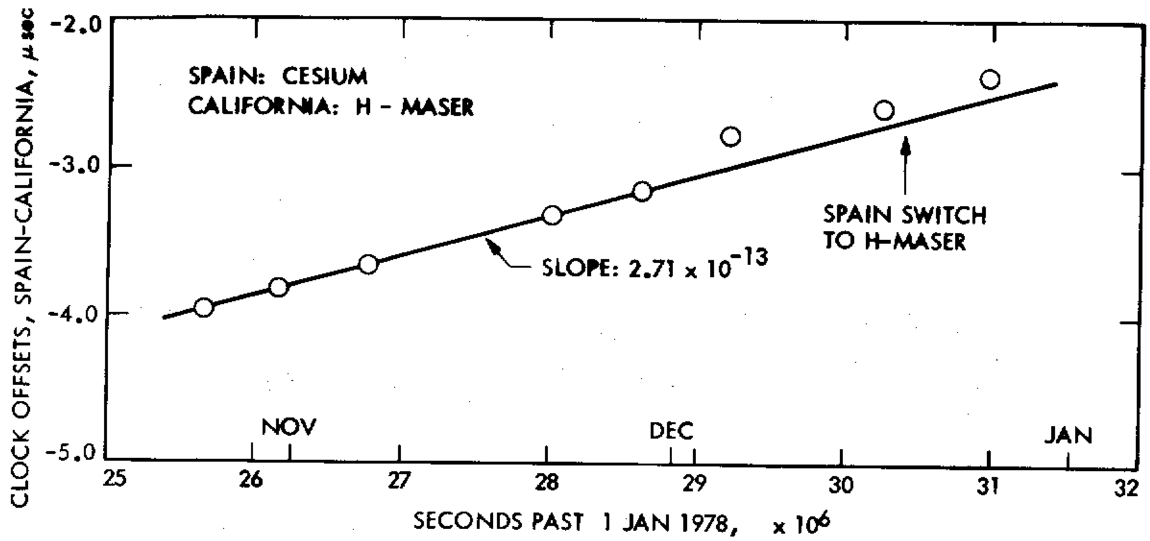

Figure 3. Clock Offsets, Spain Minus California, 23 Oct 78 - 24 Dec 78

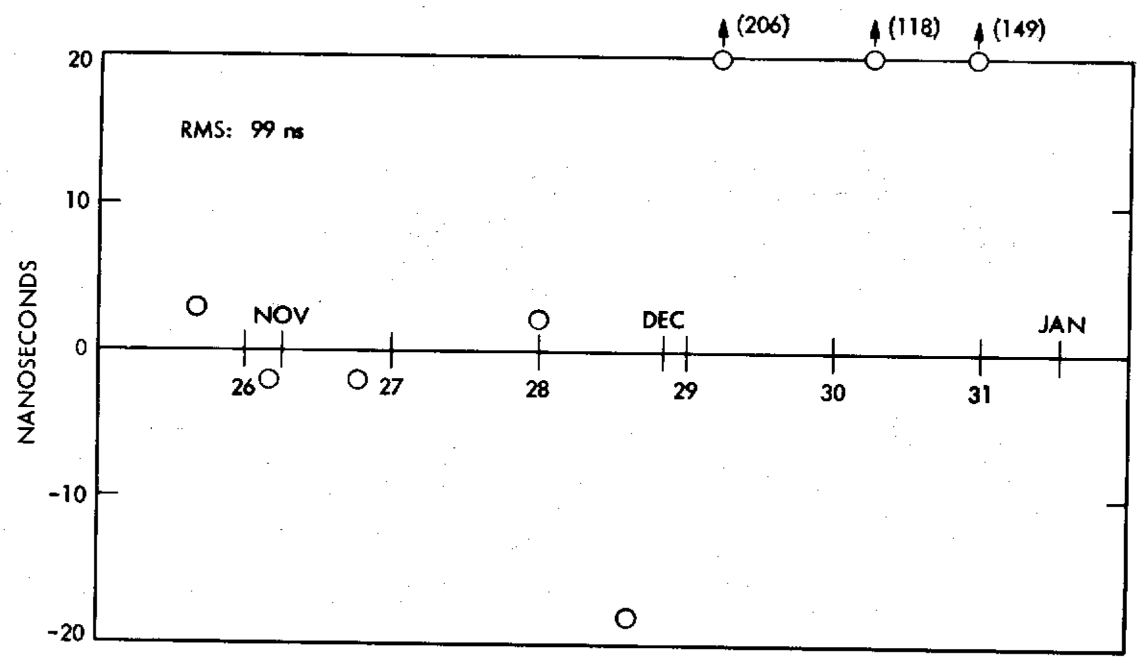

Figure 4. Residuals to 4-point Fit, Spain - California, 23 Oct 78 - 24 Dec 78

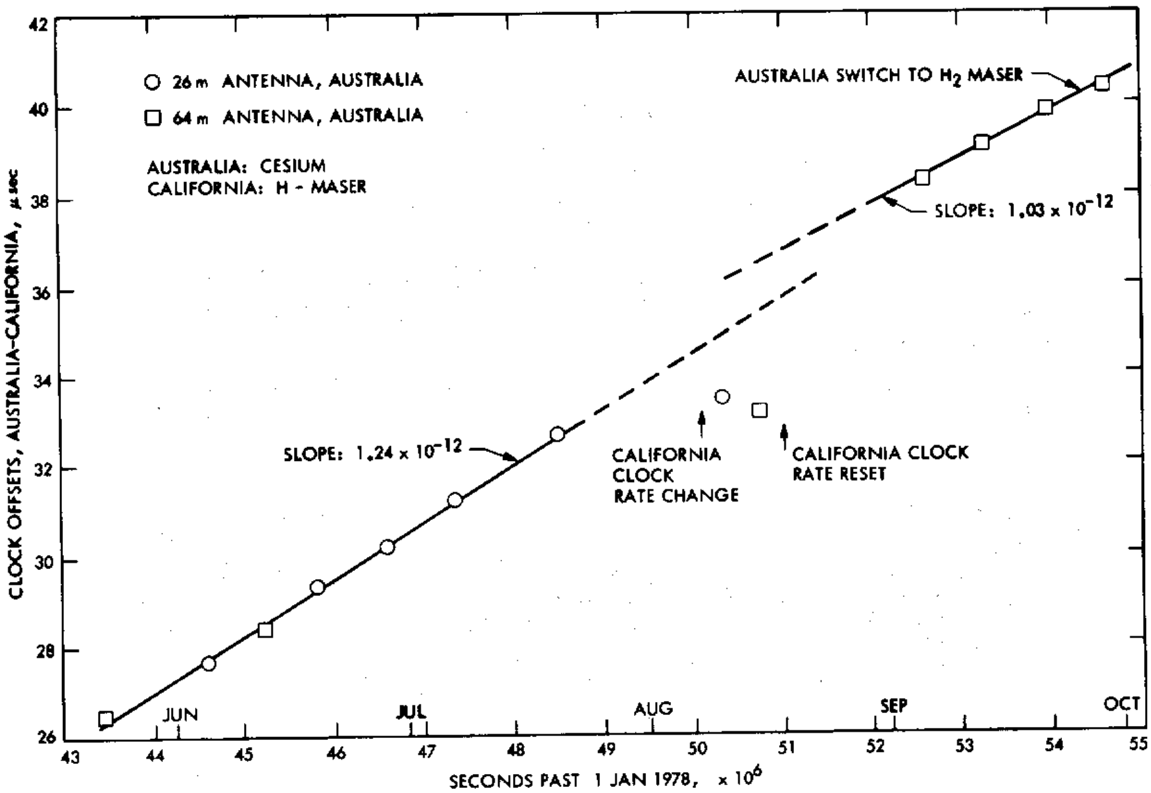

Figure 5. Clock Offsets, Australia Minus California, 19 May 79 - 25 Sep 79

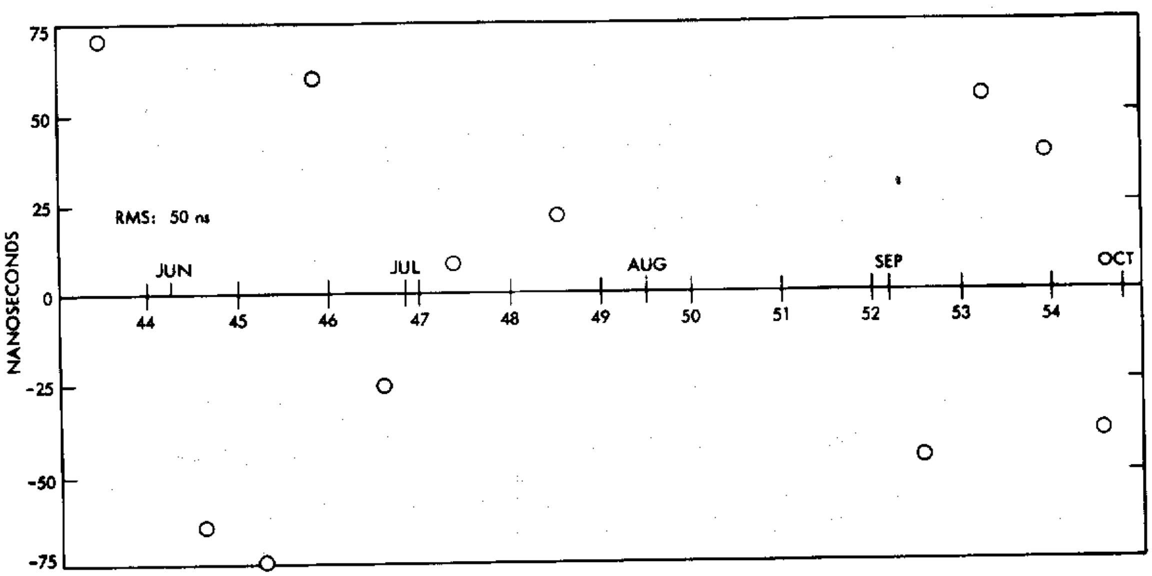

Figure 6. Residuals to Fits, Australia - California, 19 May 79 - 25 Sep 79

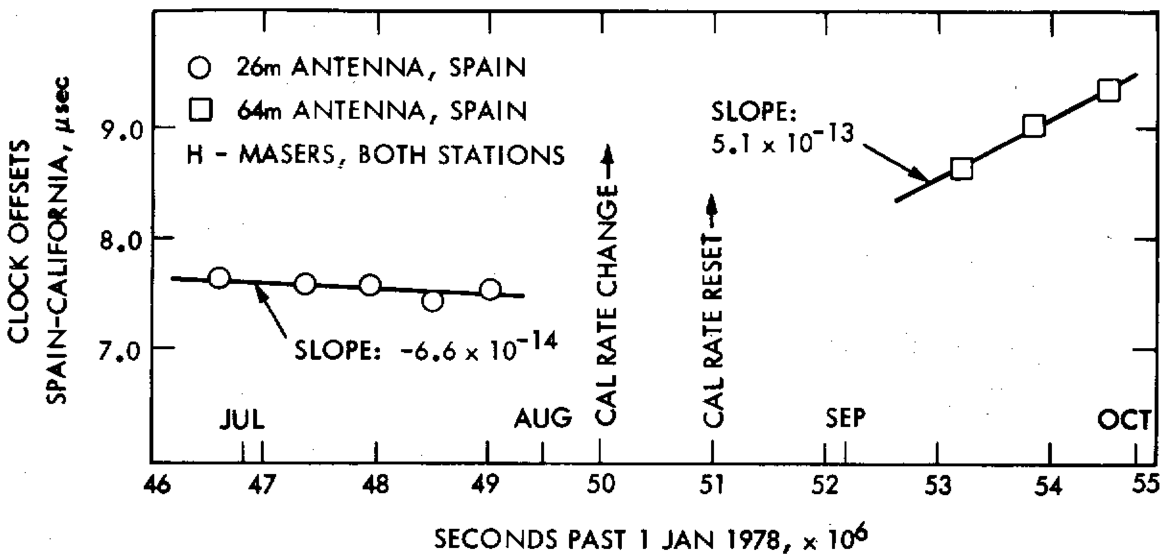

Figure 7. Clock Offsets, Spain Minus California,
24 Jun 79 - 25 Sep 79

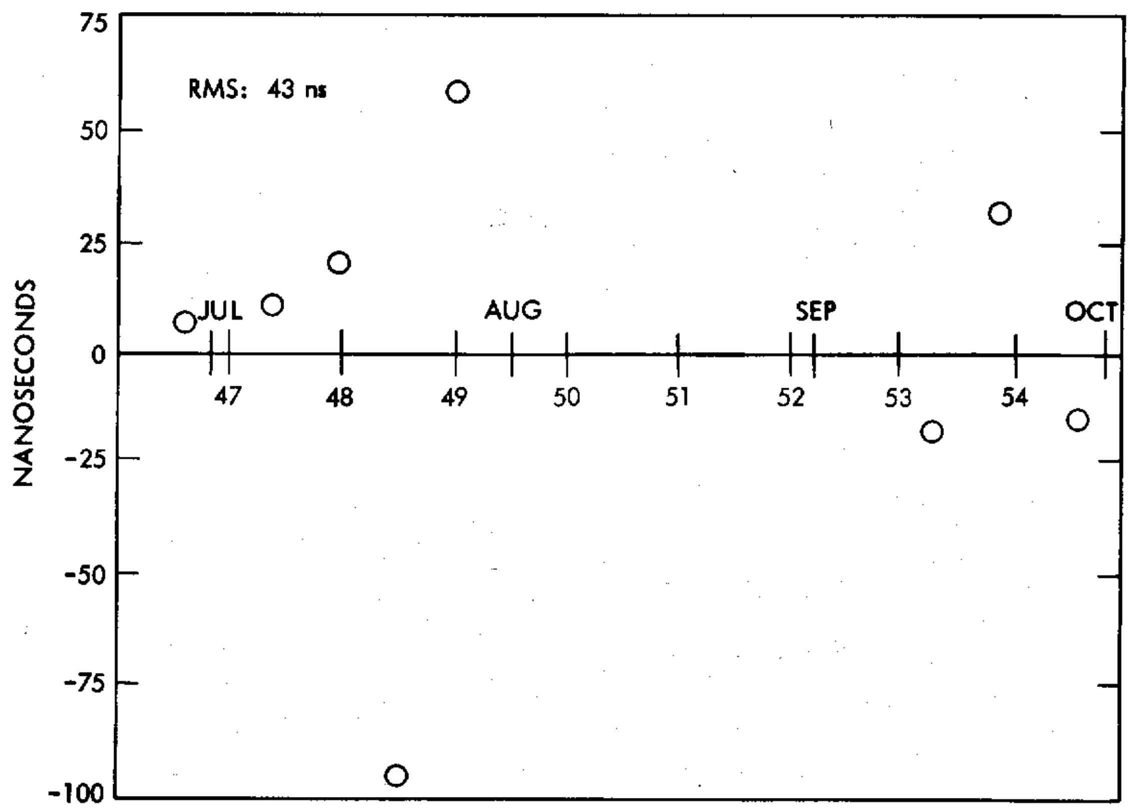

Figure 8. Residuals to Fits, Spain - California,
24 Jun 79 - 25 Sep 79

QUESTIONS AND ANSWERS

DR. CHI:

Are there any other questions? Yes. Would you please use the microphone and identify yourself?

DR. STEVE KNOWLES, Naval Research Laboratory

I would be interested in a few more of the specific details on bandwidth synthesis scheme being used or that you intend to use and how it fits this into the rather narrow bandwidth of your masers?

DR. YUNCK:

The bandwidth synthesis? Well, our receiver/amplifier will admit only a maximum of about 40 megahertz. The channels that we were using for this were 1.8 megahertz and that was purely a signal alignment measurement for delay. So when we use bandwidth synthesis we will go out to 40 megahertz and that is it.