# USING GPS & VLBI TECHNOLOGY TO MAINTAIN 14 DIGIT SYNTONIZATION

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## ABSTRACT

To facilitate the navigation of spacecraft to the outer planets, Jupiter and beyond, the JPL-NASA Deep Space Network (DSN) has implemented three ensembles of atomic clocks at widely separated locations (Goldstone, California/Canberra, Australia/Madrid, Spain). These clocks must be maintained, syntonized, to within a few parts in $10^{13}$ of each other and, the entire group must be maintained, to a lesser degree, in synchronism with UTC (NBS/USNO).

Over the last 1 1/2 years the DSN has been using Global Positioning Satellites (GPS) and Very Long Baseline Interferometry (VLBI) technology to perform these critical Frequency and Time (F&T) synchronization tasks. Both techniques are required because: 1) Though VLBI techniques permit direct F&T measurements on widely dispersed clocks, it is relatively insensitive to drift. Drift of the group away from UTC and second order drift of individual member clocks. 2) The present constellation of GPSs is quite sensitive to clock offset from UTC and to second order drift but simultaneous direct measurements on widely separated clocks (Australia to Spain) cannot be made.

This report covers a year of F&T synchronization data collected from the intercomparison of 3 sets of cesium and hydrogen maser driven clock ensembles through the use of GPS and VLBI techniques. Also covered, are some of the problems met and limitations of these two techniques at their present level of technology.

## INTRODUCTION

In order to meet the increasingly higher accuracy demands of spacecraft navigation to the outer planets (Uranus and Neptune), Deep Space Network (DSN) Operations is implementing and testing improved and more accurate frequency and time (F&T) technology. These F&T requirements are an order of magnitude more stringent* than they were for the Jovian planetary encounter. The three hydrogen maser (HMA)/cesium (CS) driven clock ensembles were syntonized to each other and to UTC (NBS) in late 1980 [1,2]. Employing a technique developed by the author that first transfers the $C_s133$ hyperfine line to the hydrogen line then, all subsequent syntonization is accomplished through the use of the hydrogen hyperfine line [3]. The syntonization, so established, is being maintained through the combined use of five techniques (GPS, LORAN, TV, Traveling Clocks and VLBI). This paper reports the results from one years GPS and VLBI F&T data use to maintain syntonization via direct frequency measurements and, by the integration of time domain measurements.

### The Larger Frequency and Time System

For the purposes of this report/study the Very Long Base Interferometer (VLBI) Time Sync System has been integrated into the Frequency and Time System. I refer the reader to Figure 1 which is an illustration of DSN's VLBI Time Sync Data System. At the present time, the Global Position Satelite (GPS) receivers are under an evaluation study as a high precision F&T data gathering system. Figure 2 illustrates how the GPS F&T sync hardware was configured during the period covered by this report. The design was to provide for regular and routine F&T data collection, provide communication pathways to data reduction centers, provide for the distribution of the reduced data, in the form of "quick look reports" via TWXs to the collection points, to the F&T Network Operations Analyst (NOA) and to the F&T System Cognizant Operations Engineer (SCOE).

### The 6 Month Test

Beginning early January, 1984, through mid-August a test was conducted for the purpose of: 1) Measuring the minimum level of effort required to meet the 1 sigma level of the four most critical F&T parameters (mutual syntonization between pairs of oscillators; syntonization of oscillators to the UTC rate; mutual synchronization between pairs of clocks; synchronization of clocks to the UTC epoch). These are listed in descending order of difficulty to meet and maintain. 2) Evaluating the comparative effectiveness of the GPS and VLBI techniques to measure these four F&T parameters.

First each of the three HMA were tuned (microwave cavity adjusted) in situ to the hydrogen line to bring the group into mutual syntonization. Next, each HMA synthesizer was adjusted to lower the output frequency to nullify the expected positive frequency pulling caused by accumulated cavity ageing. Last the master clock of each ensemble was reset to bring it within $\pm 1$ microsecond of the UTC (USNO) epoch.

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* The clock rates of the three globally distributed ensembles are to be maintained syntonized to the UTC rate within $\pm 1.7 \times 10^{-13}$. At Jupiter this requirement was implied to be within $\pm 1 \times 10^{-12}$.

Syntonization Tests

The mutual syntonization between the three pairs of oscillators was measured using both time domain and direct frequency domain measurements; employing both the GPS and VLBI instrumentation. The GPS time domain derivation of clock rate data (TABLE 1) were taken on multiple spacecraft in the pseudo simultaneous mutual view mode, and, is the 12 minute observation each sidereal day, averaged over the PERIOD indicated. The VLBI time domain derivation of clock rate (TABLE 1) is taken on multiple (6 to 20) Extra Galactic Radio Source (EGRS) observations taken every 6 to 10 days. The smaller values of STD DEV for the GPS data are more a reflection of the larger sample size than they are of instrumentation quality. The clock rate derived by the two techniques are always within less than 1 sigma variance over any common period.

If is significant to note that, since these are time domain data, they contain the noise of two clocks in addition to the noise of the two oscillators. The clock driven by oscillator #5 is significantly noisier than the others. This clock noise has adversely affected the VLBI data. But, since the GPS data on osc. #5 does not employ this clock (see Figure 2) there is no degradation from this cause. The data indicate we can meet the requirement within 2 sigma.

TABLE 2 contains oscillator vs oscillator syntonization data collected by direct frequency measurements of frequency (clock rate) by both the GPS and VLBI techniques. The GPS direct frequency data (TABLE 2) were taken only when one or more spacecraft were in true simultaneous mutual view. Note, that the measurement noise of the GPS data is more than an order of magnitude greater than that on the VLBI data.

TABLE 3 contains oscillator syntonization to UTC (NBS/USNO) data derived from time domain measurements. The VLBI time sync technique cannot measure this parameter therefore the table contains only GPS measurements. The data were derived from the relationship:
(UTC(NBS) - UTC(GPS) - (OSC/CLK - UTC(GPS)) = UTC(NBS) - OSC/CLK
The data were collected using the pseudo simultaneous mutual view technique. And so, the results still contain uncorrelated UTC(GPS) noise, uncalibrated path delays (Australia more noisy than Spain or USA) and, of course, the OSC/CLK noise. The largest contribution is that caused by OSC/CLK behavior. (i.e., unreported clock perturbations or resets and/or changes in the local magnetic or temperature environment* in which the oscillator is placed).

The 2ND ORDER DRIFT term data has not been filtered to remove the clock noise or, the affects of environmental changes. By use of eyeball integration upon the data presented in Figures 3, 4 and 5, the reader can easily detect non-linear oscillator performance. However, as the value of oscillator frequency offset decreases (becomes <10-13) it becomes progressively more difficult to determine the 2nd order term (frequency drift) because the GPS measurement noise (approximately 3x10-14) dominates the process.

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* On 2 occasions (one in Spain April 1984 and one in USA March, 1984) local area environmental changes (magnetic and temperature) caused a step change in the oscillator frequency. These are visible in Figures 3 and 5.

TABLE 1

TIME DOMAIN MEASUREMENTS OSCILLATOR vs OSCILLATOR

| (1) OSCILLATORS | MEAS. TECHNIQUE | PERIOD | AV CLK RATE OFFSET $X10^{-13}$ | MEAN STD DEV $X10^{-13}$ | 2ND ORDER DRIFT $X10^{-15}$ |
|---|---|---|---|---|---|
| #14 - #5 | VLBI | 5559-5651 | 1.3 | 20 | 14.1 |
| #14 - #5 | GPS | 5544-5585 | 3.6 | 2.5 | - 1.55 |
| #14 - #5 | GPS | 5591-5645 | 5.89 | 3.0 | 21.5 |
| #6 - #5 | GPS | 5706-5714 | -0.299 | 2.9 | -30 |
| #6 - #5 | VLBI | 5712-5840 | 0.0952 | 14.6 | - 3.0 |
| #6 - #5 | GPS | 5732-5810 | -2.48 | 4.3 | - 7.1 |
| #6 - #5 | VLBI | 5840-5860 | NOT USEABLE | | |
| #6 - #5 | GPS | 5814-5861 | -6.1 | 8.5 | - 4.8 |
| #6 - #5 | VLBI | 5861-5914 | 2.79 | 3.7 | -57.5 |
| #6 - #5 | GPS | 5866-5896 | 0.9 | 8.7 | -25.2 |
| #7 - #5 | VLBI | 5511-5583 | -0.824 | 39 | -14.5 |
| #7 - #5 | VLBI | 5587-5691 | 1.82 | 30 | - 3.4 |
| #7 - #5 | GPS | 5587-5644 | 4.5 | 13 | 1.6 |
| #7 - #5 | GPS | 5654-5694 | 3.74 | 2.6 | 24.6 |
| #7 - #5 | GPS | 5706-5715 | -0.324 | 0.76 | - 9.5 |
| #7 - #5 | VLBI | 5721-5937 | 0.446 | 12.4 | - 0.26 |
| #7 - #5 | GPS | 5727-5865 | -1.20 | 12.8 | - 5.0 |
| #7 - #5 | GPS | 5867-5897 | -0.675 | 1.78 | - 7.4 |
| #7 - #6 | GPS | 5587-5645 | -3.06 | 3.0 | 3.9 |
| #7 - #6 | GPS | 5654-5691 | 3.96 | 4.6 | 42.2 |
| #7 - #6 | GPS | 5732-5897 | 0.944 | 6.06 | 8.5 |

TABLE 2

DIRECT FREQUENCY MEASUREMENT - OSCILLATOR vs OSCILLATOR

| (1) OSCILLATORS | MEAS. TECHNIQUE | PERIOD | FREQUENCY OFFSET $X10^{-13}$ | MEAN STD DEV $X10^{-13}$ |
|---|---|---|---|---|
| #14 - #5 | VLBI | 5533-5660 | 10.0 | 7 |
| #14 - #5 | GPS | 5533-5675 | 59 | 140 |
| #6 - #5 | GPS | 5721-5889 | -19.8 | 470 |
| #6 - #5 | VLBI | 5816-5861 | - 0.28 | 7.5 |
| #7 - #5 | VLBI | 5529-5679 | 6.5 | 7.9 |
| #7 - #5 | GPS | 5584-5631 | 287.5 | 19 |
| #7 - #5 | GPS | 5713-5895 | 64.5 | 104 |
| #7 - #5 | VLBI | 5822-5903 | - 6.6 | 7.5 |

Note: (1) All oscillators are Smithsonian Astrophysical Observatory hydrogen masers. Serial numbers 5, 6 and 7 are model VLG-10B and, #14 is model VLG-11. Serial #6 and 14 were located in Australia, serial #5 in California and, serial #7 in Spain.

TABLE 3
TIME DOMAIN MEASUREMENTS REF UTC (NBS/USNO)

| (1) OSCILLATOR | MEAS. TECHNIQUE | PERIOD | AV CLK RATE OFFSET $X10^{-13}$ | MEAN STD DEV $X10^{-13}$ | 2ND ORDER DRIFT $X10^{-15}$ |
|---|---|---|---|---|---|
| VLG-10B#5 | GPS | 5629-5659 | -2.95 | 3.6 | 45.7 |
| VLG-10B#5 | GPS | 5673-5710 | -2.4 | 4.8 | -10.7 |
| VLG-10B#5 | GPS | 5727-5813 | -1.14 | 2.3 | - 5.4 |
| VLG-10B#5 | GPS | 5814-5870 | -3.97 | 16.2 | 6.74 |
| VLG-10B#5 | GPS | 5889-5897 | -1.94 | 3.7 | 7.94 |
| VLG-11B#14 | GPS | 5622-5653 | 5.37 | 82.7 | -2.73 |
| VLG-11B#14 | GPS | 5654-5659 | NOT USEABLE | | |
| VLG-10B#6 | GPS | 5675-5694 | 0.35 | 2.77 | 9.69 |
| VLG-10B#6 | GPS | 5706-5714 | 0.50 | 2.94 | 46.7 |
| VLG-10B#6 | GPS | 5732-5870 | 0.49 | 8.68 | 3.15 |
| VLG-10B#7 | GPS | 5673-5694 | -5.22 | 2.25 | 12.7 |
| VLG-10B#7 | GPS | 5706-5715 | 0.084 | 1.04 | 4.1 |
| VLG-10B#7 | GPS | 5727-5870 | -0.568 | 9.5 | 0.34 |
| VLG-10B#7 | GPS | 5883-5897 | 0.054 | 2.6 | 0.534 |

Note: (1) All oscillators are Smithsonian Astrophysical Observatory hydrogen masers. Serial numbers 5, 6 and 7 are model VLG-10B and, #14 is model VLG-11. Serial #6 and 14 were located in Australia, serial #5 in California and, serial #7 in Spain.

Time Synchronization to UTC

Neither the National Bureau of Standards nor the U.S. Naval Observatory is presently equipped to provide traceability to the UTC (NBS/USNO) epoch via the VLBI technique. Therefor all UTC referenced time sync data was acquired through the use of the GPS technique. The algorithm used for the Australian Clock sync measurement was:

[(NBS-GPS)-(USA CLK-GPS)]-[(AUS CLK-GPS)-(USA-GPS)]=NBS-AUS

This algorithm differs from that used for Spain's clock sync measurement, in that the (USA CLK-GPS) measurements, in the first half of the equation is not made at the same time as the (USA-GPS) measurement in the second half. However, the same GPS spacecraft is used for both measurements. This scheme had to be adopted because the large angular separation between the N.B.S., @ Boulder, Colo. and the Australian clock @ Tidbinbilla, Australian Capitol Territory (A.C.T.) makes mutual view very unlikely.

Figure 3 is a 150 day history of the time offset of the designated DSN Master Clock located @ Goldstone, Caifornia, USA. The permanent change in clock rate was induced by a permanent change in the local frequency standards room environment. The change in the magnetic environment appears to have also caused a change in the secondary drift term. The three steps in clock offset were all operator induced and, were not caused by mechanical failures.

Figure 4 is a plot of the performance of the DSN's Tidbinbilla Clock, located in the Australian Capitol Territory (A.C.T). There are no microsecond level clock steps. There appears to be no secondary drift and, the random wandering of the clock rate is due to lack of tight environmental* control.

Figure 5 is a plot of the performance of the DSN's Robledo Clock, located near Madrid, Spain. There were two "unrecovered" submicrosecond** level steps. Both were caused by FTS hardware failures. There were the occasions when the clockrate changed. The first change was caused by a failure of the HMA. The second and third were induced by changes*** in the magnetic environment. It appears that the secondary drift term is the same, in magnitude and sign, as that visible in Figure 3.

The data presented (Figures 3, 4 and 5) clearly shows that the three clocks (DSN Master Clock, Tidbinbilla Clock and Robledo Clock) maintained synchronization to the UTC (NBS/USNO) epoch within less than 6 microseconds over the test period.

Clock to Clock Synchronization

Both GPS and VLBI techniques were used to measure and maintain the synchronism between DSN clocks. Since there was but a single VLBI measurement

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* A special frequency standards room, with very precise environment controls, has been constructed. But, the frequency standards cannot be moved until mid 1985.

** The design of the DSN's clocks is such that they can only be set to the nearest cycle of phase @ 1 MHz.

*** Hardware was removed from the frequency standards room then, later on, hardware was added.

on the Robledo/Tidbinbilla pair, all the data presented in Figure 8 was derived from the GPS technique. The VLBI and GPS time sync data points are from instrumentation connected directly to the DSN station Reference Clock, except @ Goldstone, California. Here the GPS time offset is taken from a phantom DSN Master Clock located in a building approximately 200 meters away (Figure 2), that is driven at the same rate as the DSN Master Clock, and, is synchronized to it through use of coaxial cables and a portable cesium clock.

Figure 6 is a plot of a 200 day history of the synchronism between the Tidbinbilla Clock and the DSN Master Clock as measured by both techniques (GPS and VLBI). The convention used is: Tidbinbilla minus the DSN Master. The large offset* between the two sets of data prior to Julian Day 5820 resulted from the lack of a convenient** means to synchronize the phantom clock in real-time.

Figure 7 is a plot of a 200 day history of the synchronism between the Robledo Clock and the DSN Master Clock as measured by both techniques (VLBI and GPS). The causes of the time offset prior to Julian Day 5820 are the same as for the Tidbinbilla vs DSN Master sync offset. The convention used is: Robledo Clock minus the DSN Master Clock.

Figure 8 is a plot of a 200 day history of the synchronism betwen the three pairs (Tidbinbilla vs DSN Master, Robledo vs DSN Master and Robledo vs Tidbinbilla) of DSN clocks. All three data sets were collected using the GPS time sync technique. The conventions used were: Robledo minus Tidbinbilla, Robledo minus DSN Master and Tidbinbilla minus DSN Master.

The data indicate that mutual time synchronization betwen all possible pairs of clocks has been maintained within less than 6 microseconds over the 200 day test period.

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* The GPS time sync data reports are distributed within 14 days of the oldest measurement point date. The VLBI Time Sync System was in the process of a major block upgrade and the reporting lag sometimes approached 90 days. Therefore the offset was discovered long after the test began. The phantom clock was adjusted but, the problem of maintaining sync in real-time remained.

** The DSN Master Clock is "operationally" maintained 24 hours/day, every day. The phantom clock was maintained 8 hours/day, 5 days/week.

## SUMMARY

Using GPS technology the frequency offset of four SAO VLG series hydrogen masers were measured to be within a part in 10 to the 12th of the UTC(NBS) rate, and, remained so for the entire test period of 200 days.

Using both GPS and VLBI technology the mutual syntonization between the 3 pairs of hydrogen masers was measured to be within 2 parts in 10 to the 12th, and remained so over the entire test period.

Using GPS technology the time offset of three globally separated clocks were maintained within less than 10 microseconds of the UTC(NBS/USNO) epoch over the 200 day test period.

Using both GPS and VLBI technology the three pairs of globally separated clocks were maintained in mutual synchronization within 6 microseconds over the entire test period.

The tests revealed 3 problems: 1) The need to continually synchronize the phantom clock 2) The need for prompt reporting 3) The need for more stringent control of the frequency standards room environment. Problem #1 will go away when the GPS system is transferred from "experimental" to "operational" status. Problem #2 has at present lessened considerably (VLBI data turn around time is now 48 hours).

## ACKNOWLEDGEMENT

My thanks to Mark Manning, Allied-Bendix Field Engineering, who programmed an H-P 85 computer to perform the data reduction and produced the plots.

REFERENCES

1. Ward, S, "The Operational Performance of Hydrogen Masers in the DSN", Proceedings of the Twelfth Annual Precision Time & Time Interval Applications Planning Meeting, pp 616-617, December 2-4, 1980 Goddard Spaceflight Center, Greenbelt, Md.

2. Ward, S, "A Two Year History of Atomic Frequency Standards Syntonization in the Deep Space Network", DSN Progress Report, 42-72, pp 118-127, October-December 1982.

3. Ward, S, "Hydrogen Masers As Time and Frequency Standards", NASA Tech Brief NPO-15858.

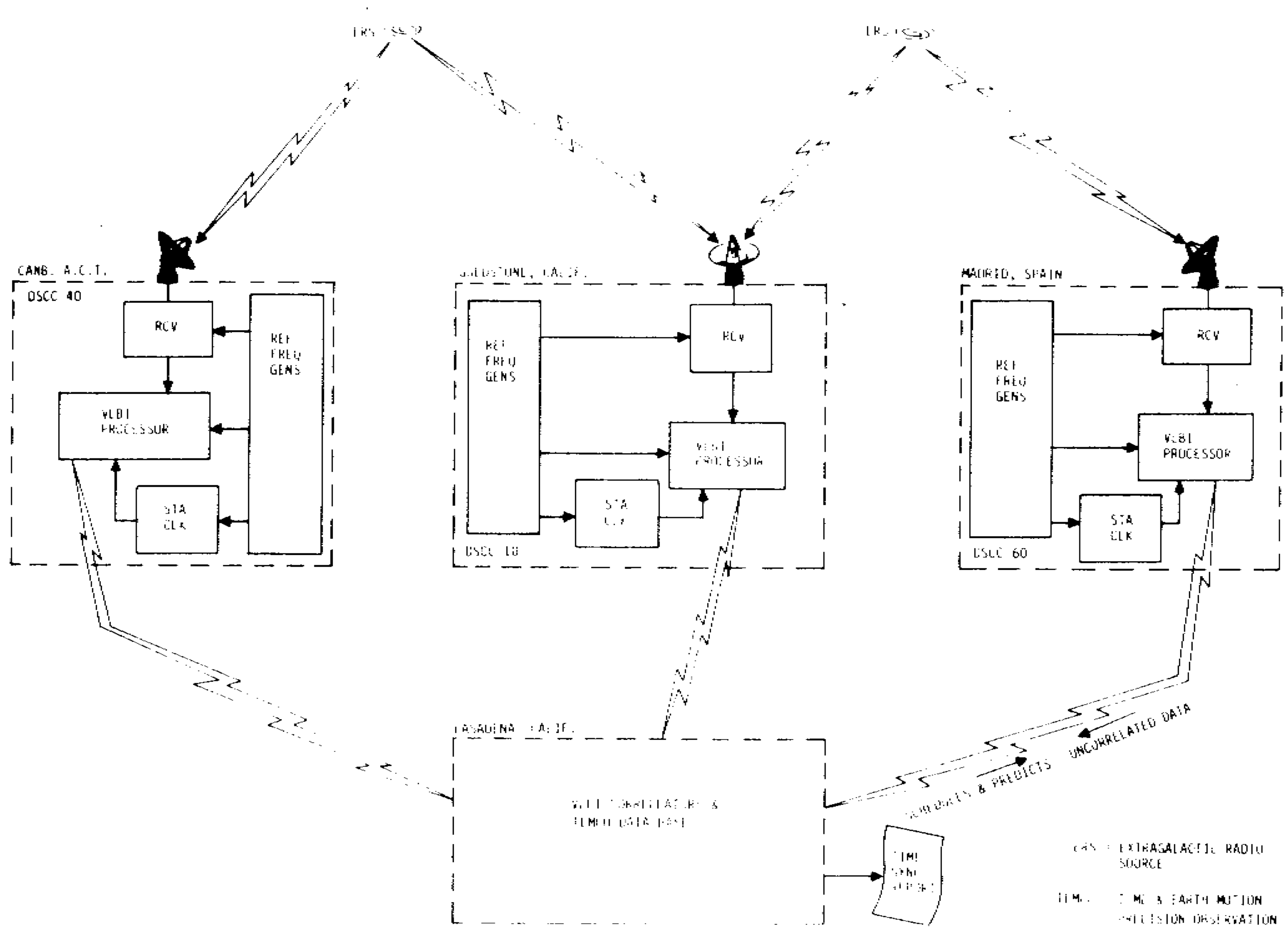


Figure 1. DSN VLBI Time Synchronization System

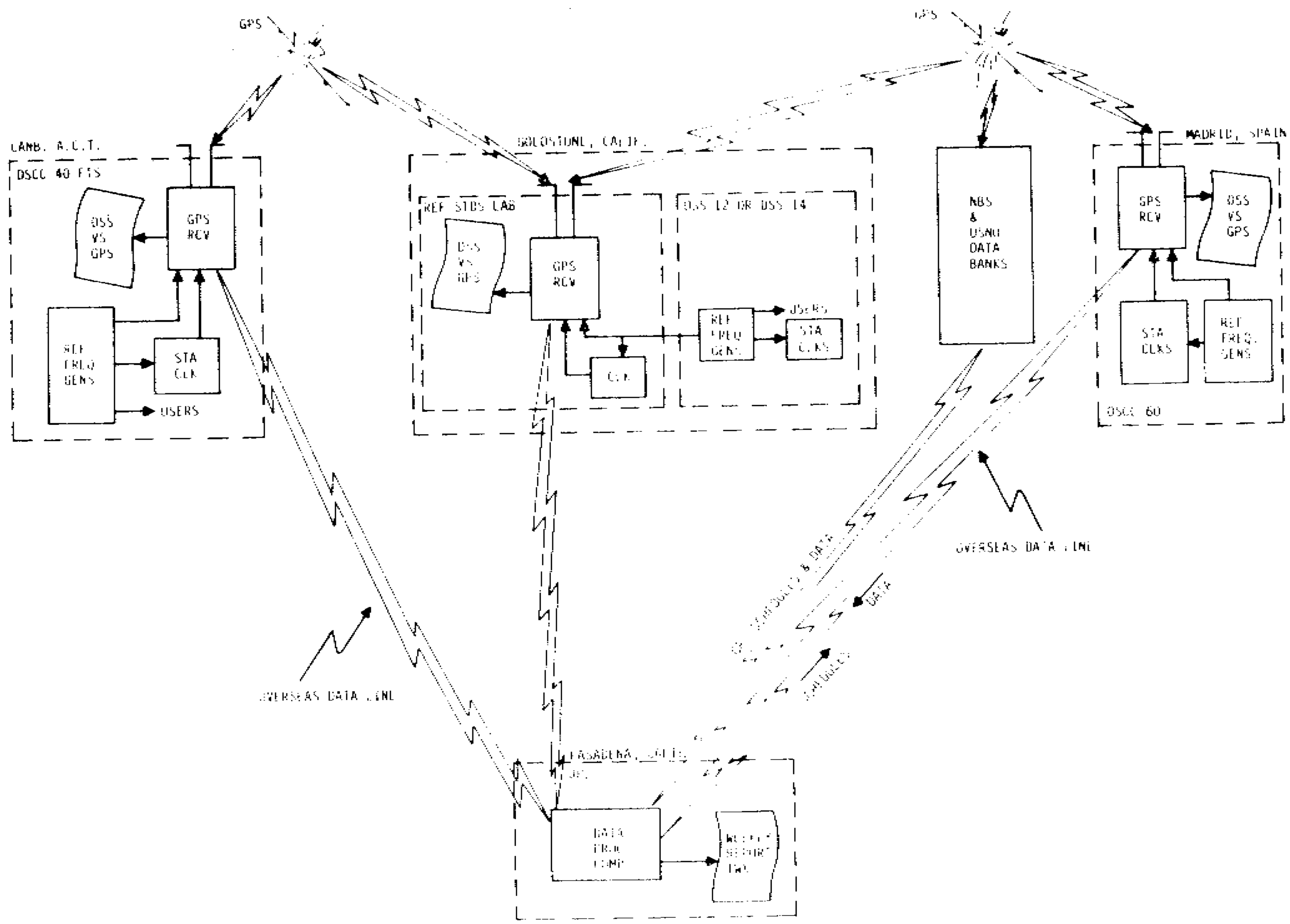


Figure 2. DSN GPS Experimental Time Sync System

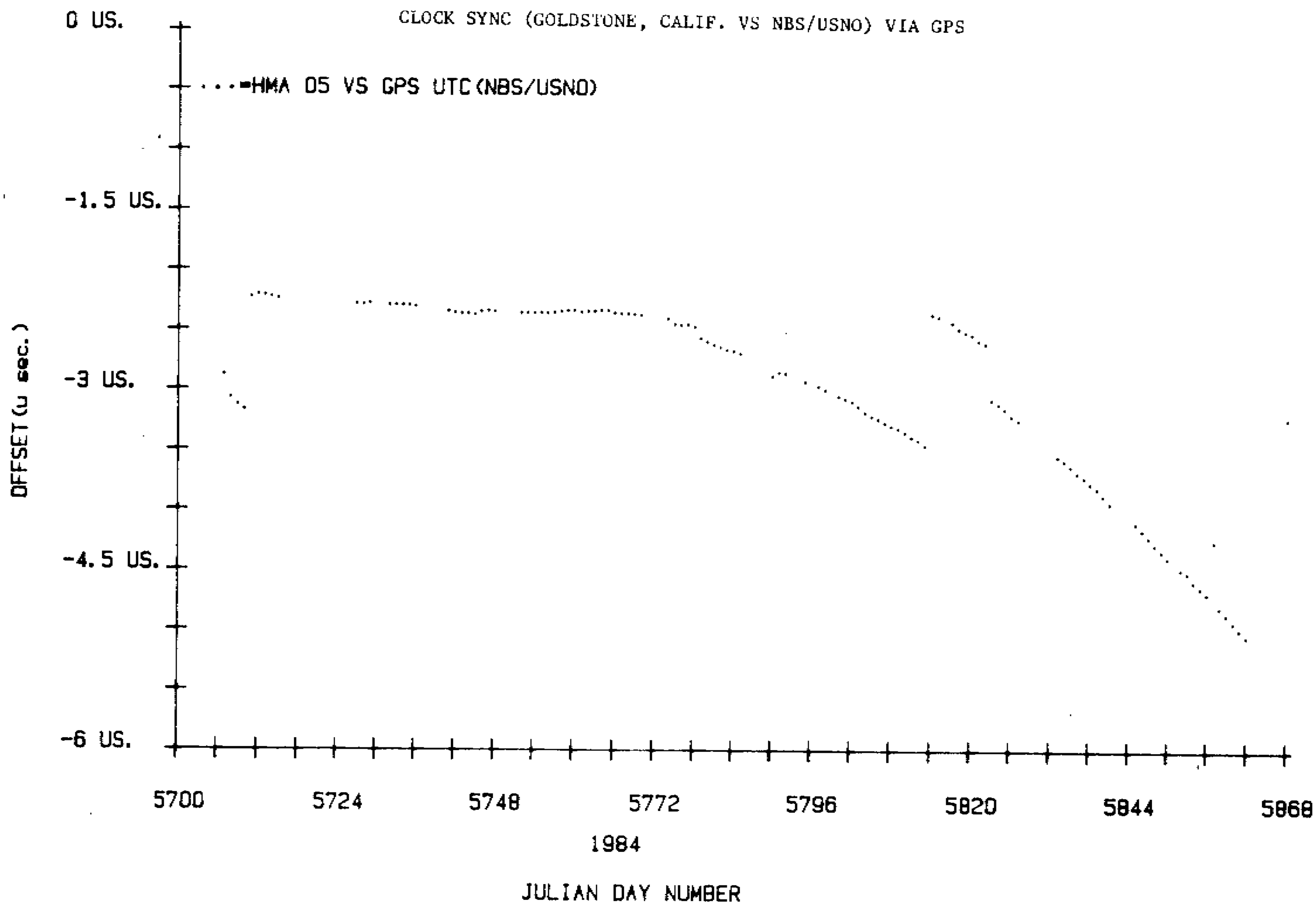


Figure 3. GPS Measurement of the Goldstone, Calif. DSN Master Clock Offset from UTC (NBS/USNO)

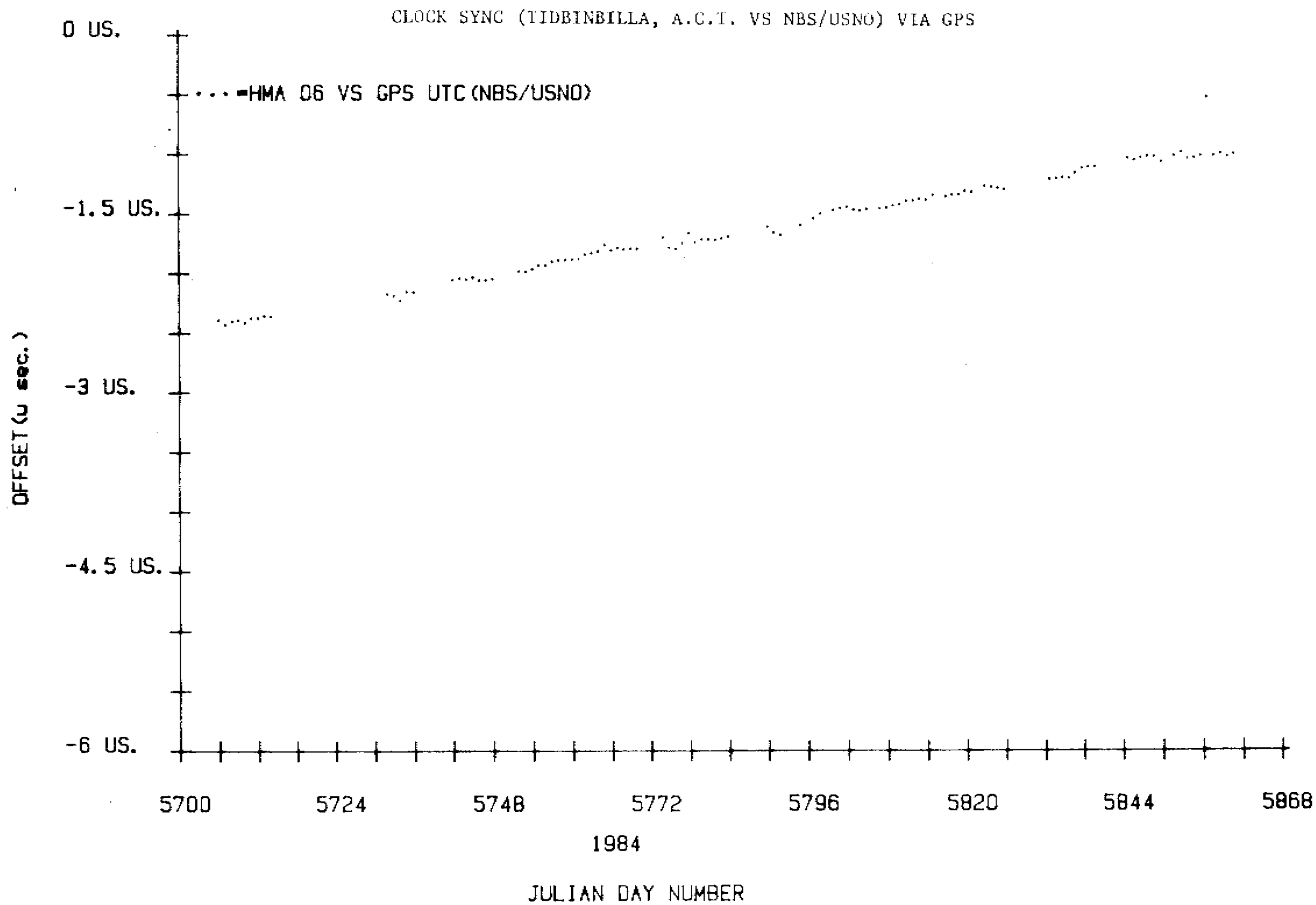


Figure 4. GPS Measurement of Tidbinbilla, A.C.T. Clock Offset from UTC (NBS/USNO)

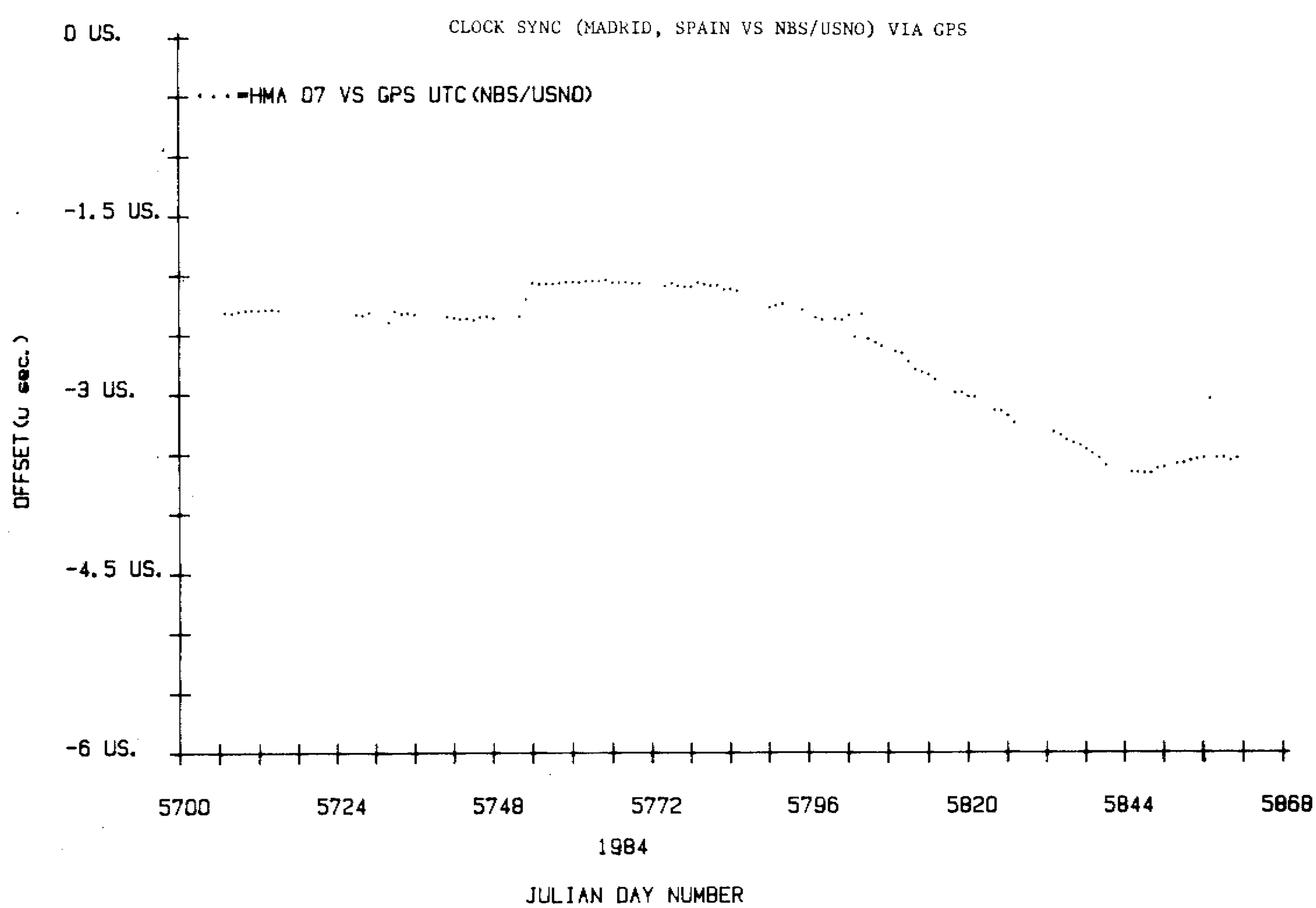


Figure 5. GPS Measurement of Robledo, Spain Clock Offset from UTC (NBS/USNO)

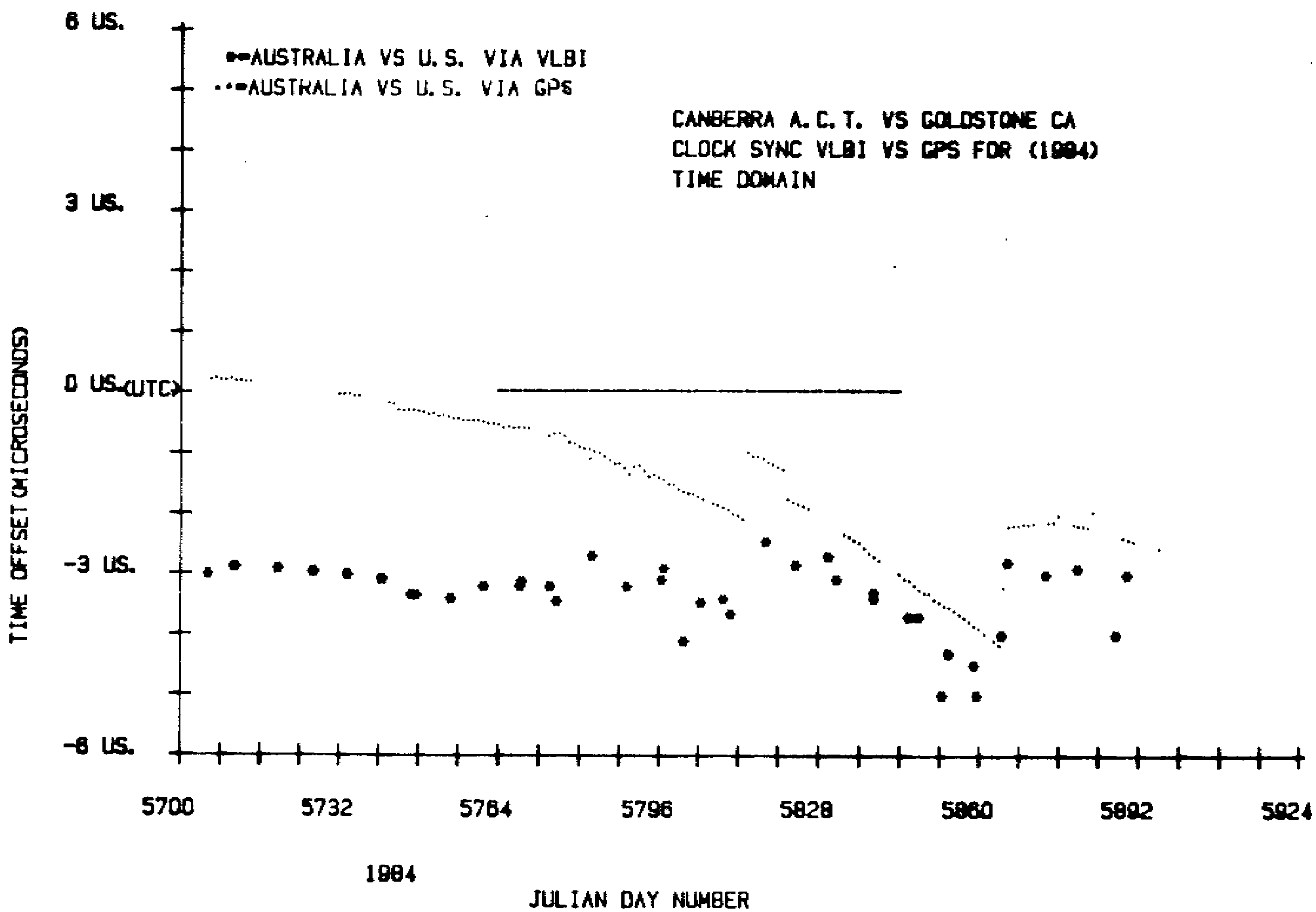


Figure 6. GPS & VLBI Measurement of the Tidbinbilla Clock Offset from the DSN Master Clock

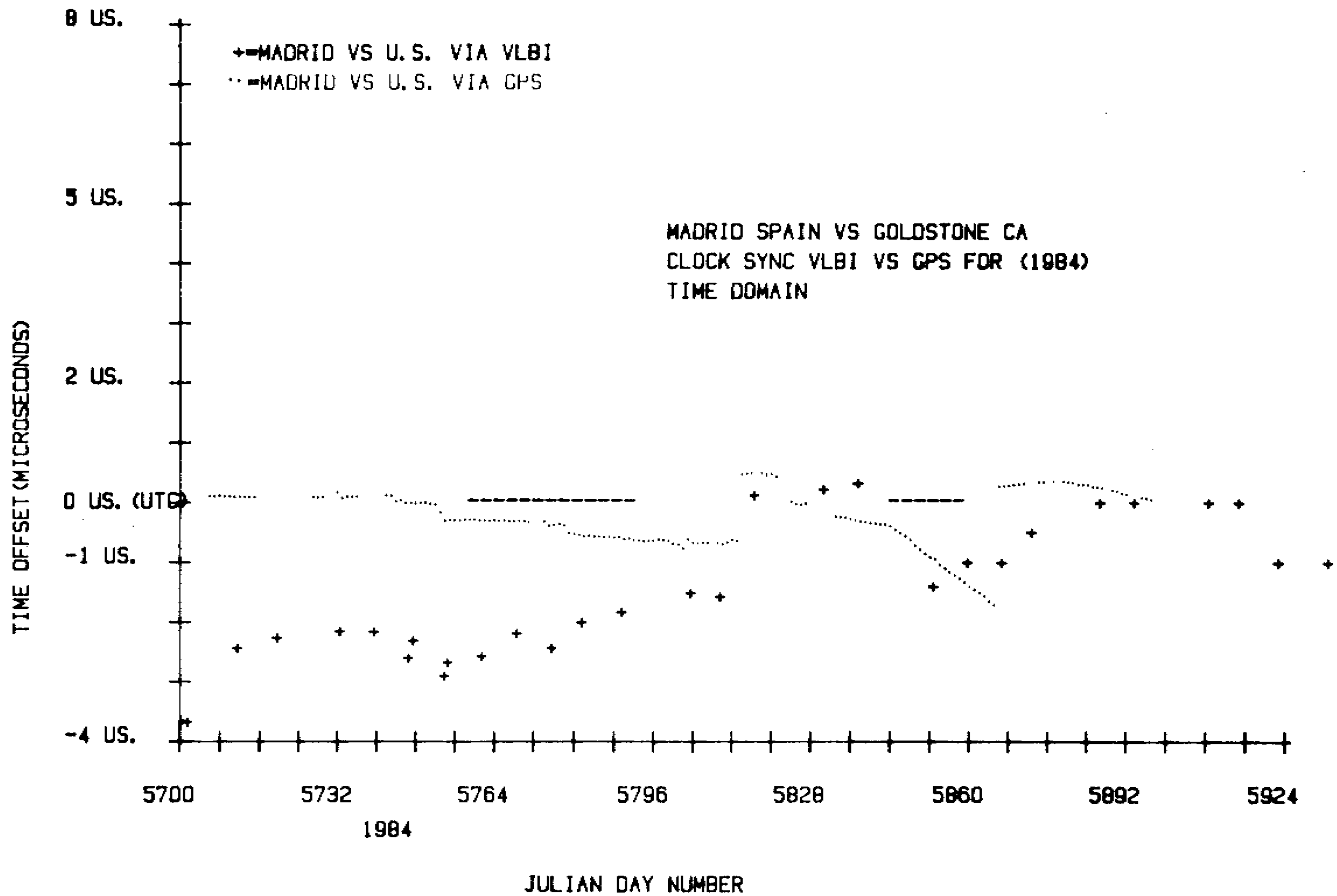


Figure 7. GPS & VLBI Measurement of the Robledo Clock Offset from the DSN Master Clock

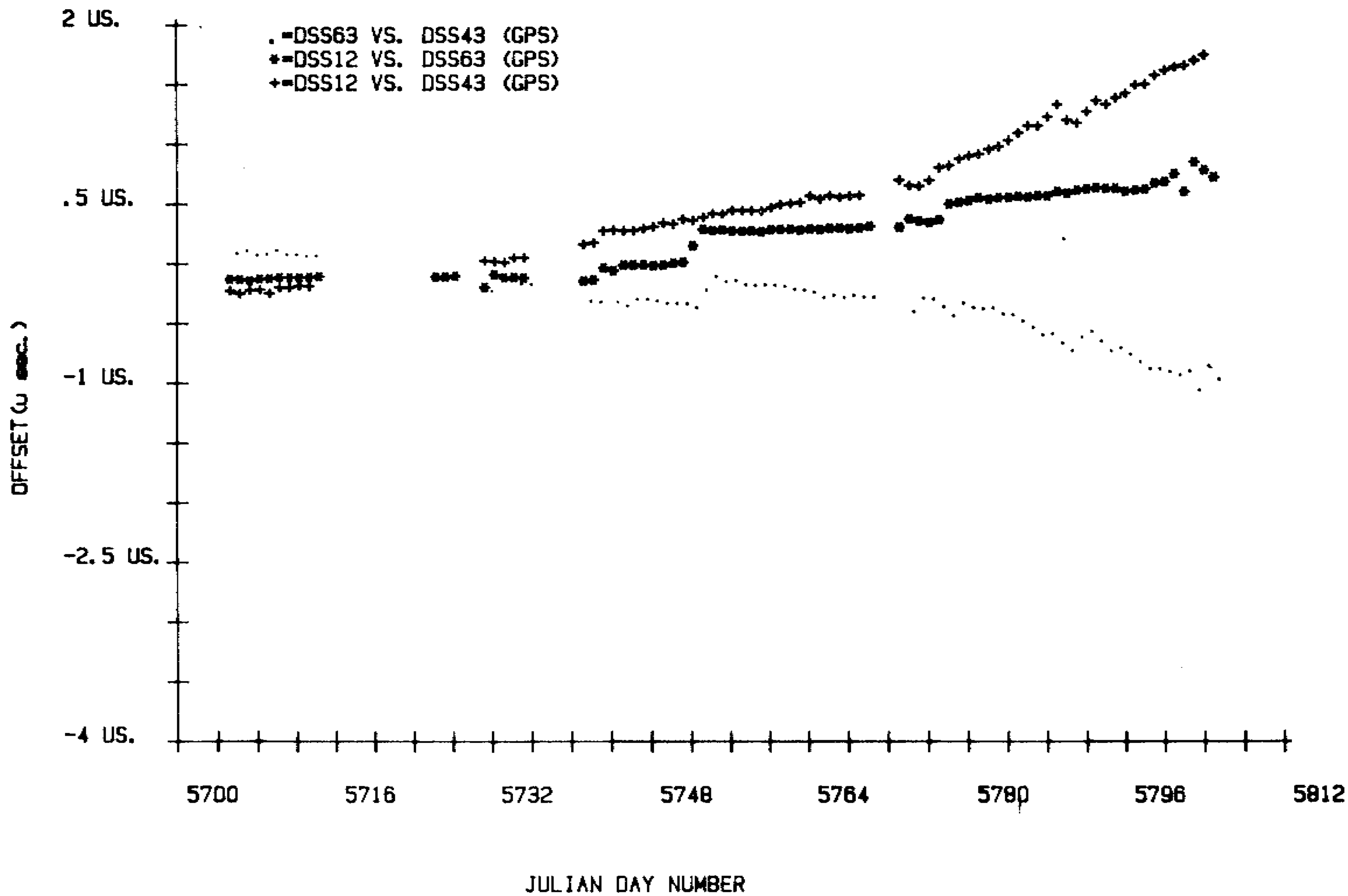


**Figure 8.** GPS Measurement of the Mutual Time Sync Between 3 Pairs of DSN Clocks

## QUESTIONS AND ANSWERS

DAVID SHAFFER, INTERFEROMETRICS: what VLBI system are you using, and what frequency? Was it S band or X band at Goldstone and did you try to remove the ionosphere by using both frequencies?

MR. WARD: We haven't removed the ionosphere nor the cable drift problems since we don't have our calibrator yet.

We are using both X band and S band. The VLBI system that we are using is about a Mark 2, or 1.5. During most of these observations we are using our Block Zero, which collects the data on wideband video tape. The rest of it used our Block One, which sends the data in digital form on wideband data lines back to the correlator in Pasadena.

GERNOT WINKLER, U.S.N.O.: Why these long delays in getting the VLBI data when you have transmitted the data back on wide band links?

MR. WARD: There is a big gap between doing things in the laboratory , and routinely doing it in the field. There is this business of getting procedures approved, and signed off, and getting software released.

MR. WINKLER: It is not a technical problem then, but an administrative one?

MR. WARD: Correct.

MR. WINKLER: The next question is: You show consistently that the GPS obtained values are very small in precision and, conversely, the VLBI's scatter about ten times more. Yet, when you show the rates, that is reversed. That is, the VLBI rates are much smoother from day to day than the GPS rates. I think that this is inconsistent.

MR. WARD: That again is part of the operations problem. There have been two occasions when the two systems were running on different clocks.

MR. ALLAN: I think that the reason for the difference is that if you average GPS over 12 minutes, as Klobuchar has shown in some work that he has done, you can be affected by multi-path. It's an excellent time point, but it's not a very good frequency measure over a few minutes. The scatter can be quite high. The frequency should be determined from day to day not over that short sample.

MR. WINKLER: I can't understand that, because GPS time values, day after day, are smooth. If you derive, from the time values, the rates -- or do you derive the rates directly from GPS?

MR. ALLAN: That's right.

MR. WINKLER: That's crazy!

MR. WARD: This is an evaluation period for us with GPS, and I just tried this to see which data type produced the greatest precision and accuracy. For instance VLBI has the greater precision, but it doesn't have the accuracy. Also, before you can use the VLBI, you have to use some other method to make sure that the two stations are within ten microseconds of each other to cut down the processing time at the correlator. It requires a priori synchronization and syntonization.

MR. REINHARDT: There is a very good reason for the big difference in VLBI between the rate data and the time data. There are two separate outputs in the VLBI processing. One is the fringe rate output, and one is the fringe output. They go through very different processing. I suspect the time data is highly contaminated by the fact that they don't have a cable calibrator.

My question is: Can you comment on the source of the large scatter in the time data? What do you think is causing it in the system, and do you expect that to be cleaned up?

MR. WARD: That is mostly an operational problem. That's strictly a matter of maintaining the clocks.

MR. REINHARDT: The scatter that I saw was a good fraction of a microsecond, and that is many orders of magnitude larger than you would expect from VLBI. You say that's not from the VLBI system?

MR. WARD: What you saw from the VLBI system is what the clocks were really doing. and the location of the equipment at Goldstone at Station 12 was an interim location while they were doing the antenna repair and upgrading the equipment at the 64 meter site.

MR. KLEPCZYNSKI: To calibrate the VLBI process, there are two areas you have to calibrate. One is cable delays in the system and the other is equipment delays. In addition, there is a very important delay with regard to the formater. That's the device that takes the tome from your local clock and puts it on the tape, so that you can tell when each bit of data was taken.

If the Block One or Block Zero system is similar to the Mark II system that is used elsewhere, it is an undetermined delay, which is very difficult to calibrate according to the clock time on the magnetic tape. Every time you start and stop your equipment, or turn it on from scratch, this delay changes. Unless you can calibrate every single time when you start you experiment, you can easily get delays of several microseconds.