N95-32320

P. 11

The 1994 International Transatlantic Two-Way Satellite Time and Frequency Transfer Experiment: Preliminary Results

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Abstract

The international transatlantic time and frequency transfer experiment was designed by participating laboratories and has been implemented during 1994 to test the international communications path involving a large number of transmitting stations. This paper will present empirically determined clock and time scale differences, time and frequency domain instabilities, and a representative power spectral density analysis. The experiments by the method of co–location which will allow absolute calibration of the participating laboratories have been performed. Absolute time differences and accuracy levels of this experiment will be assessed in the near future.

INTRODUCTION

The 1994 European/U.S. transatlantic two–way satellite time and frequency transfer (TWSTFT) experiment was designed to test the international communication path, the transfer of time and frequency between a large number of timing laboratories, the calibration accuracies, the non-reciprocal satellite delays, the estimates of time and frequency instabilities, and the exchange and

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processing of the data. The geostationary satellite INTELSAT–VA(F–13), located at longitude 307 degrees East, has been used for the communication link. The eight timing laboratories who participated in this experiment are: FTZ (Darmstadt, Germany), NIST (Boulder CO, USA), NPL (Teddington, United Kingdom), OCA (Grasse, France), PTB (Braunschweig, Germany), TUG (Graz, Austria), USNO (Washington DC, USA) and VSL (Delft, Netherlands). The first experiments were conducted on 1994 February 4 (MJD 49387.5).

Many papers exist in the literature covering the development of the formulae and methods currently used in producing time differences over the wide–band communication links used on commercial geostationary communication satellites and readers are referred to a selection of the many papers in the literature for specifics of how and why TWSTFT works[1,2,3,4,5,6]. At the 25th Annual PTTI meeting Gerrit de Jong of NMi Van Swinden Laboratorium gave an overview paper discussing recent developments, engineering aspects, data formats, and related details of the individual TWSTFT experiments specifically related to this international communication link[7].

Since PTTI is an "applications and planning meeting" an additional focus of this paper will be to present an example case where the empirically calibrated data are being used as an information source for management of real–time time and frequency resources.

INSTABILITIES AND NOISE PROCESSES

Figure 1 shows an example of raw uncalibrated time differences of the USNO(MC2)–VSL(HP5071A) time transfer of 1994 October 12 (MJD 49637). USNO(MC2) is the real–time realization of UTC(USNO) by the Sigma Tau hydrogen maser clock N3 which is steered by small daily frequency changes in its synthesizer. In general a white noise behavior is noticed. There is structure in the data so that even over 300 seconds (5 minutes) the TWSTFT process is not purely white. Depending on the experiment analyzed the structure is sometimes sinusoidal and other times possibly a step. This type of subtle structure manifests itself as flicker phase noise in the time domain instability estimates that will be shown later. The physical source generating this structure is not known but may originate from environmentally caused drift in the electronics, for example. The identification and physical understanding of the flicker phase noise sources and then the reduction or removal of the effects will improve the TWSTFT phase flicker floor instability and is an area where future effort should be placed.

The formulation used to generate the uncalibrated time differences is

$$
\begin{aligned}
UTC(USNO(MC2)) - UTC(LAB) = {} & 1/2[Ti(USNO) - Ti(LAB)] \\
& - [Tx(LAB) - Tx(USNO)] \\
& - [\delta 1pps(LAB) - \delta 1pps(USNO)] \\
& - [ic(USNO) - ic(LAB)] \\
& - Sagnac \\
& - RF
\end{aligned}
\tag{1}
$$

The first term is the value of one half the of the sum of the differences of the recorded time interval counter readings recorded at each site. The second term is the transmit–to–receive delay differences of the MITREX modems also measured at each site. The third term is the delays from on time of the 1–pulse–per–second references as

measured at each site. The fourth term allows for any time difference introduced by intermediate clocks and allows adjustment to the true UTC(Lab) reference clock. The fifth term is the computed relativistic time delay, Sagnac delay, due to a rotating reference frame system. The sixth and final term is an unknown term for an uncalibrated timing link and is commonly called the "RF term." The RF term contains the sum of the unknown delays contributed from waveguides, RF

filters, and non–reciprocal satellite delays to name a few. This is the term that was adjusted empirically to put the time differences "on time" for this paper. Using an independent timing source, usually GPS or BIPM Circular T, we may then determine an empirical constant correction which is the sum of the unknown delays which may then applied to put the daily mean values computed from equation 1 "on time." The empirical calibrations then are only as good as the timing link used as the empirical reference plus any systematic deviations introduced by the TWSTFT method. Evidence from closure tests[8] indicate that TWSTFT will contribute less than 10 nanoseconds worth of error to the error budget where the error may is contributed from environmentally caused drift of electronics, nonidentical hardware at each laboratory, hardware problems, and hardware failures among others.

Figure 2 shows the empirically calibrated USNO(MC2)–FTZ(HP5070A) which was referenced to time differences published in the BIPM Circular T by the method given above. A clock change occurred at FTZ on MJD 49429.375 and the operational transition was smooth.

Time deviation (TDEV) instability estimates were generated from a C language program developed from pseudocode[9]. The TDEV instability estimate is ideal for visualizing time–domain noise processes, because the instability estimate resolves the two phase noise processes and the slopes are easily distinguished in a TDEV plot. The three main frequency–domain noise processes are also isolated when using TDEV, but the slope changes are a bit harder to distinguish because of the large slopes. Another pleasing aspect of using TDEV is that no preparation of the data is required or recommended other than making sure the data are equally spaced. Any data modification, such as first–differencing, acts as a digital filter removing some of the interesting signals in the data and is undesirable[1]0. The two–Allan Deviation (ADEV) was used in monitoring the FM noise processes at tau greater than one day.

Figure 3 shows a log sigma x (nanoseconds) versus log tau (seconds) plot of the time deviation (TDEV) instability estimate for USNO(MC2)–TUG(HP5071A). This plot contains instability estimates from 78 daily runs each made up of 300 seconds worth of 1–pulse–per–second comparisons. In addition, the plot contains the daily means which have been interpolated to daily values from unequally spaced data. White phase modulation noise, probably originating in the electronic equipment (MITREX modems) used to perform the experiments, dominates during tau (averaging time) 1 to 50 seconds and appears as a slope of tau$^{-frac12}$. After an inflection near tau$^{1.7}$ (50 seconds) a slope of tau^{0} is seen which is the characteristic slope of flicker phase modulation noise (the "structure" seen in Figure. 1). The physical source related to the flicker phase noise is not known with certainty. The average phase flicker floor as determined by the TDEV statistic is near 200 picoseconds which is close to but not exactly at the classical variance of the mean of a typical 300 second time transfer experiment, which is where the location of the inflection point should be if the noise were strictly white PM[9], which it is not. Near tau^5 seconds ($\approx$ 1 day) the slope is tau^1 which indicates flicker frequency modulation noise and is contributed by the TUG commercial cesium clock. The ADEV statistic at a sampling time of tau$^{6.1}$ seconds (15 days) gives an estimated instability level of 8 parts in 10^{15} as the flicker frequency floor. These results are similar to the results presented at the 25th Annual PTTI meeting in a paper on the calibrated TWSTFT link between the U.S. Naval Observatory in Washington, DC (USNO(MC2)) and the U.S. Naval Observatory Time Service Substation in Richmond, FL (NOTSS(HP5071A))[11]. The flicker phase floor determined from the TDEV instability statistic for TWSTFT, compared at an averaging time of 100 seconds, is more than an order of magnitude improved over that recently estimated from a new low–cost generation of GPS timing receivers[12].

Figure 4 shows a log sigma x (nanoseconds) versus log tau (seconds) plot of the time deviation (TDEV) instability for USNO(MC2)–NPL(H–maser). This plot contains instability estimates from 63 daily runs each made up of 300 seconds worth of 1–pulse–per–second comparisons with one run being of 1500 seconds duration. In addition, the plot contains the daily means which have been interpolated to daily values from the unequally spaced data. As expected there is little difference in the phase noise compared to that shown for TUG in Figure 3 so the phase instabilities are similar. The frequency performance of the maser–to–maser timing link shows improved FM instability estimates when compared to the Figure 3 maser–to–cesium comparison. The ADEV statistic at an sampling time tau$^{6.1}$ seconds (15–days) gives a value of 4 parts in 10^{15} as the flicker frequency floor.

CLOCK AND TIME SCALE MONITORING USING TWSTFT

Figure 5 shows time differences of commercial cesium clocks from FTZ, TUG and NOTSS against PTB(CS2) which is a laboratory cesium frequency standard operated as a clock. The USNO(MC2)–NOTSS(HP5071A) timing data are obtained by an independent and calibrated, by the method of co–located antennas, TWSTFT link using SBS–6[11].

Figure 6 shows USNO hydrogen maser clocks N4 and N5 and the USNO(A.1MEAN) time scale compared, by empirically calibrated TWSTFT, again against PTB(CS2). Individual linear rates have also been removed from each clock difference by the method of linear least squares. From inspection of Figure 5 and Figure 6 shows that the clocks stay together very well in time. The cesium clocks shown in figure 5 indicates a slightly higher amplitude of variation over the hydrogen maser clocks in this comparison. There is perhaps some common structure seen in both in Figure 5 and Figure 6 and best indicated by the "dip" near MJD 49565. This simple analysis using TWSTFT time comparison data might be useful because it will allow for detection, characterization, and isolation of correlated local environmental effects on clocks that might not otherwise be detected, and it can be done in near real time.

An extremely useful and elegant algorithm, given with pseudocode, has been recently reported that generates power spectral density (PSD) estimates, "a digital spectrum analyzer (DSA)." The DSA makes use of digital filters and by application of one or two stages of filtering to form an estimate of the PSD of the input data[13]. The DSA method, when added to Fourier, phase dispersion minimization and other methods of periodic signal detection, is a nice independent way to detect periodic signals in time and frequency data, since no single method is "best" for analysis of periodic signals in all data. Figure 7 shows a PSD estimate generated using the DSA method on TWSTFT frequency data where the original unequally spaced timing data was interpolated to daily intervals and then converted to frequencies in parts in $10^{6.1}$. The total data interval reflected in the PSD is 281 days. The low significance peaks at frequencies greater than 0.1 are related to the original unequally spaced sampling rates. The peak at 1 month is probably related to monthly steering of USNO(MC2) towards UTC(BIPM).

CONCLUSION

These preliminary results shown in this paper point out that much more work needs to be done in all areas of TWSTFT. Completion of the calibration data analysis, continued monitoring of the performance of TWSTFT over longer and longer averaging times, and the continued comparison and improvement of the performance of remote clocks and/or time scales are important. The new knowledge and information that TWSTFT supplies to decision makers is extremely useful. New hardware, especially the new generation modems, hopefully, will make TWSTFT more automated and make data analysis much easier and more automated. Data formats such as the newly proposed international format are improving and allow much more information to be passed about technical and environmental conditions related to the TWSTFT and can only improve accuracy and stability estimates.

ACKNOWLEDGEMENTS

J. DeYoung thanks Gernot M. R. Winkler (USNO) for coding up the C program that computes the TDEV instability estimates and for useful discussions.

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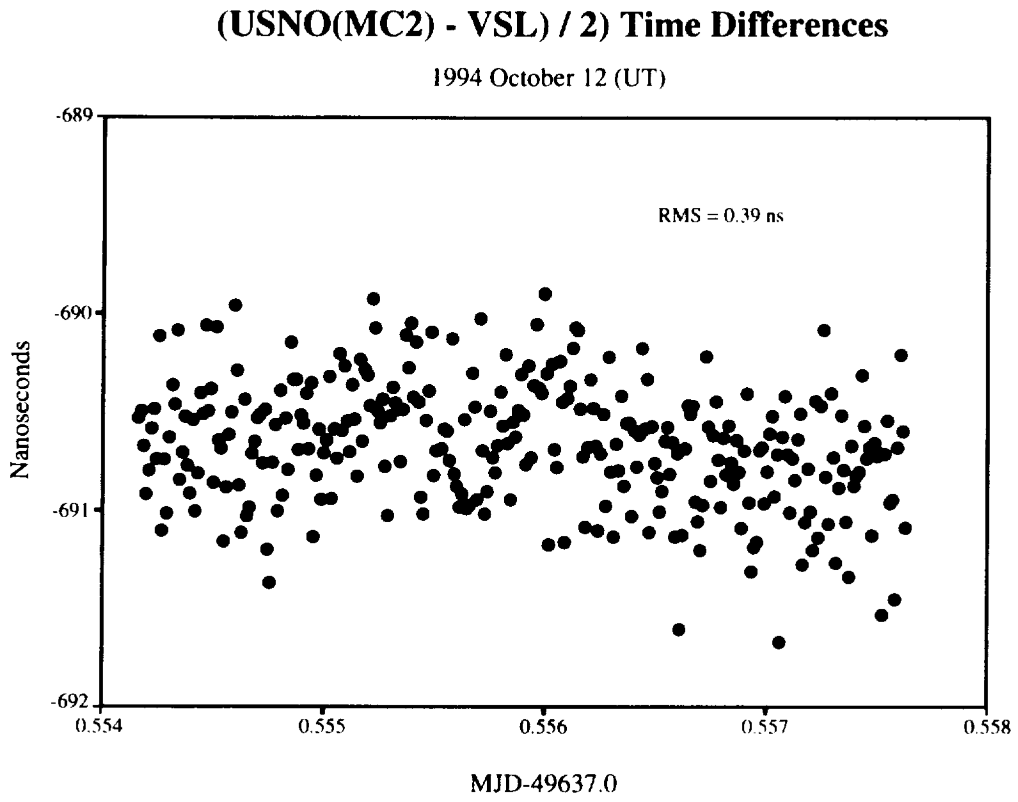


Figure 1

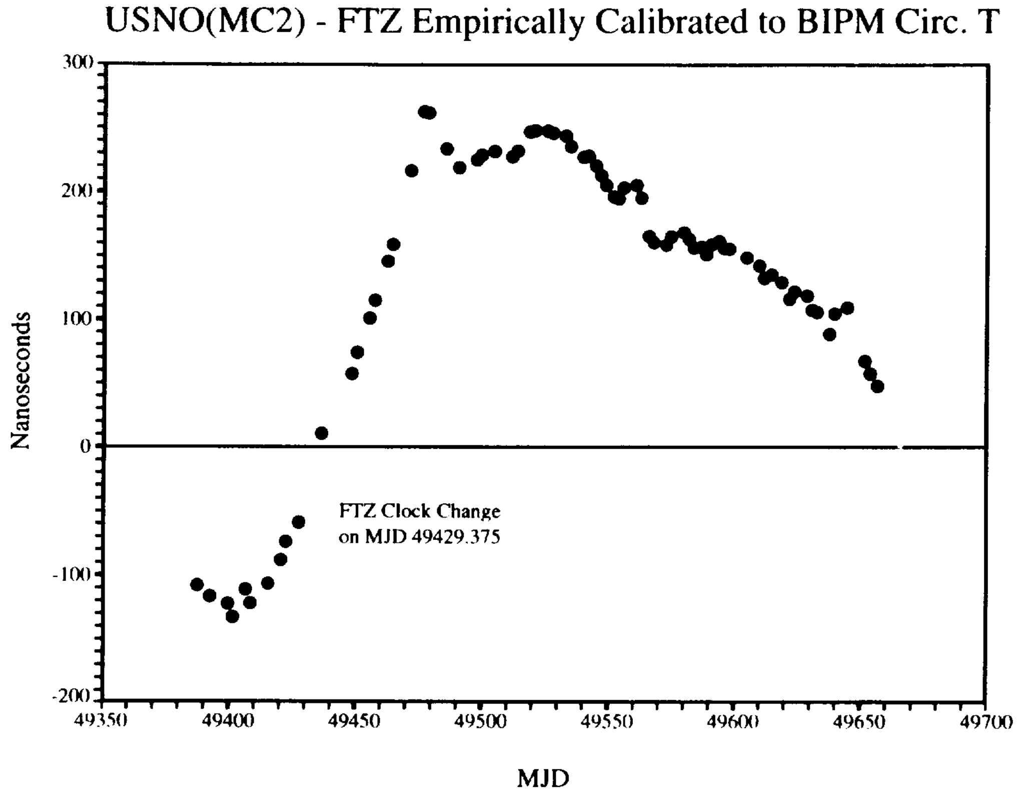
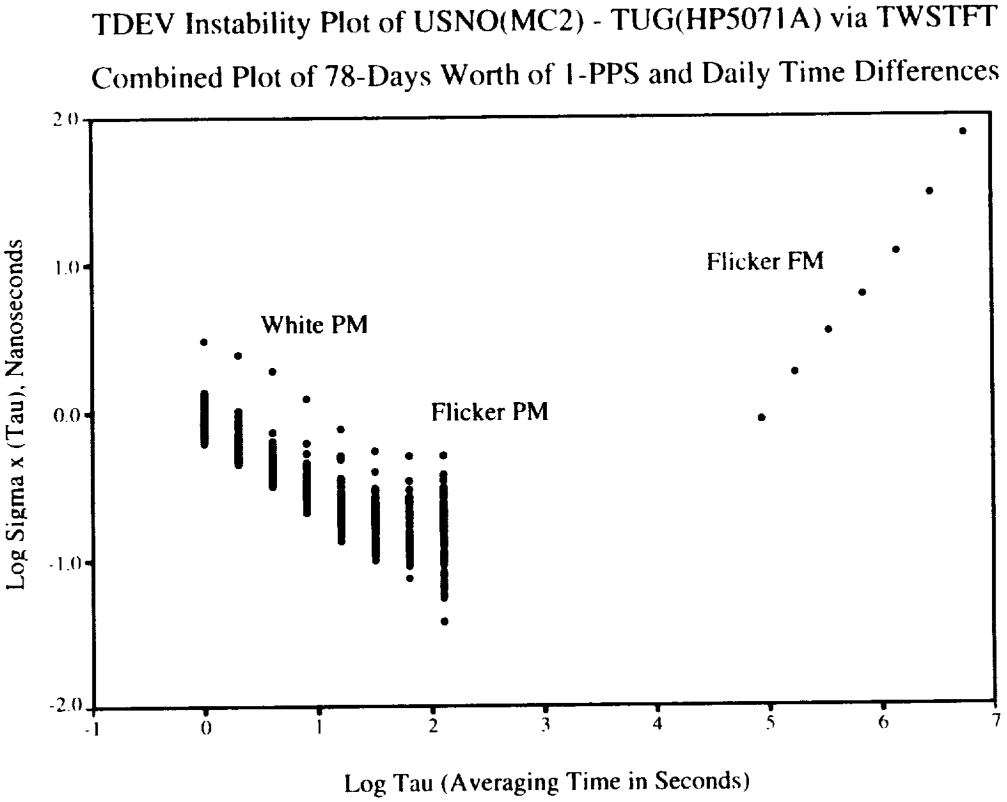


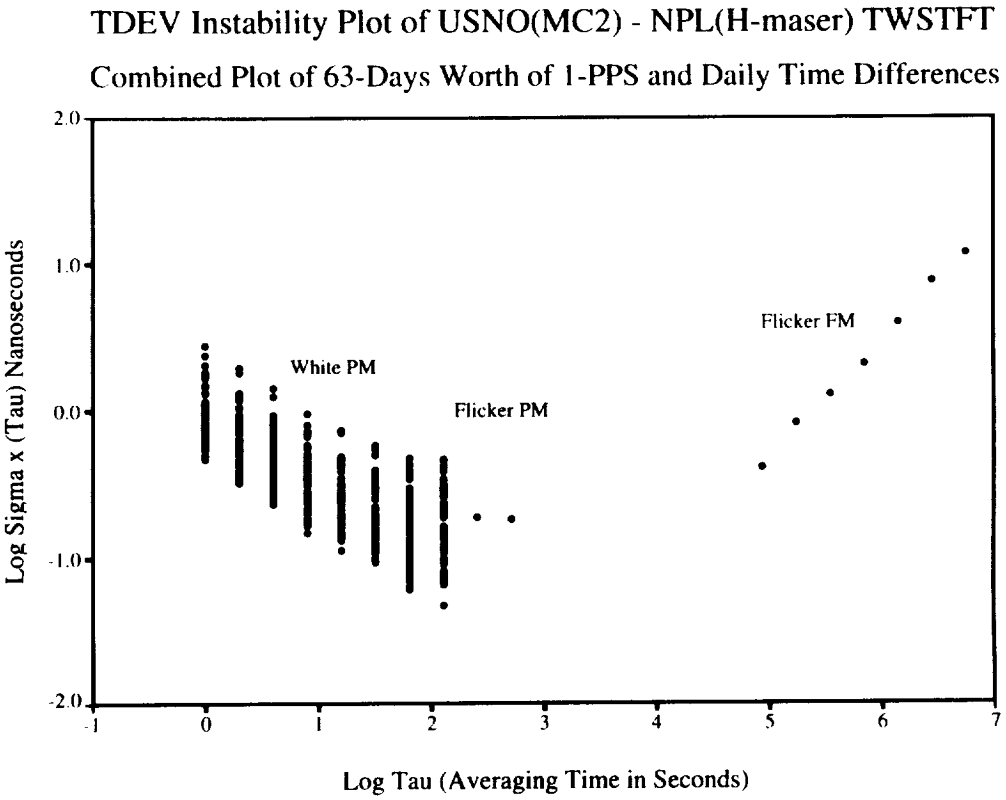
Figure 2



TDEV Instability Plot of USNO(MC2) - TUG(HP5071A) via TWSTFT

Combined Plot of 78-Days Worth of 1-PPS and Daily Time Differences

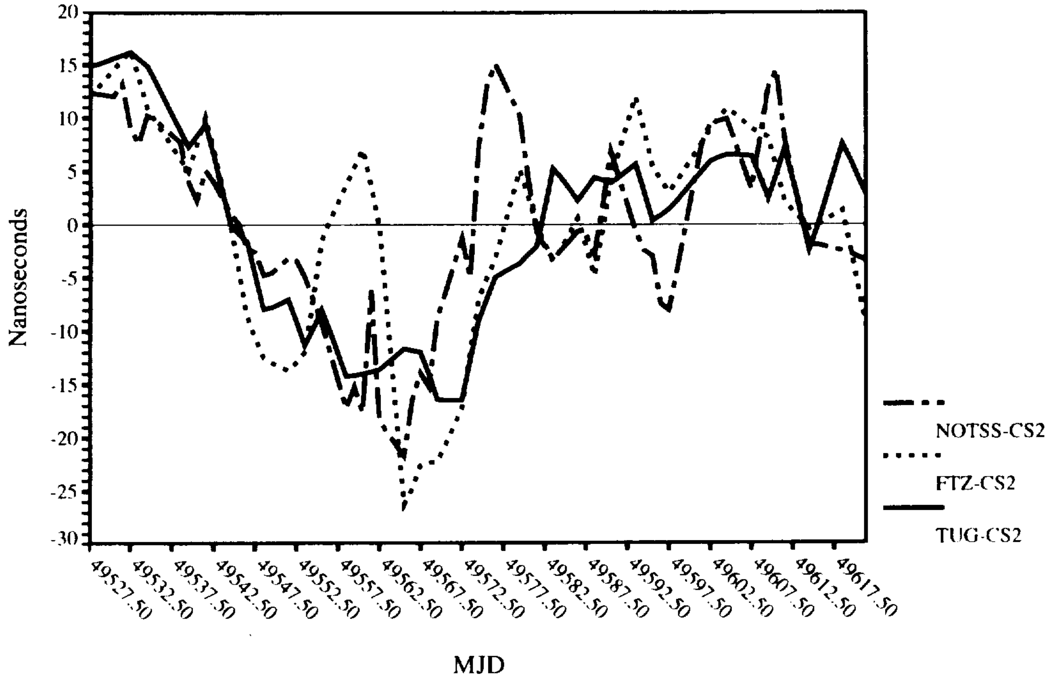
Figure 3



TDEV Instability Plot of USNO(MC2) - NPL(H-maser) TWSTFT

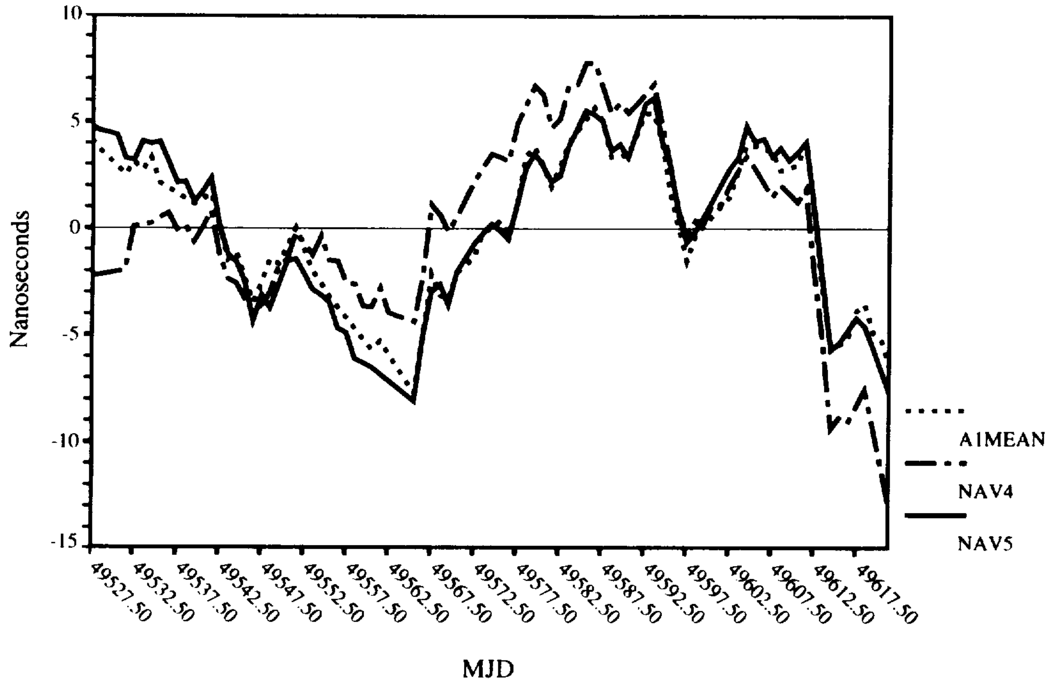
Combined Plot of 63-Days Worth of 1-PPS and Daily Time Differences

Figure 4


TWSTFT Cesium Clock comparisons against PTB(CS2)

Known Steps and Linear Rates Removed

Figure 5


TWSTFT H-Maser and Time Scale comparisons against PTB(CS2)

Two Unsteered Hydrogen masers and USNO(A1Mean)

Figure 6

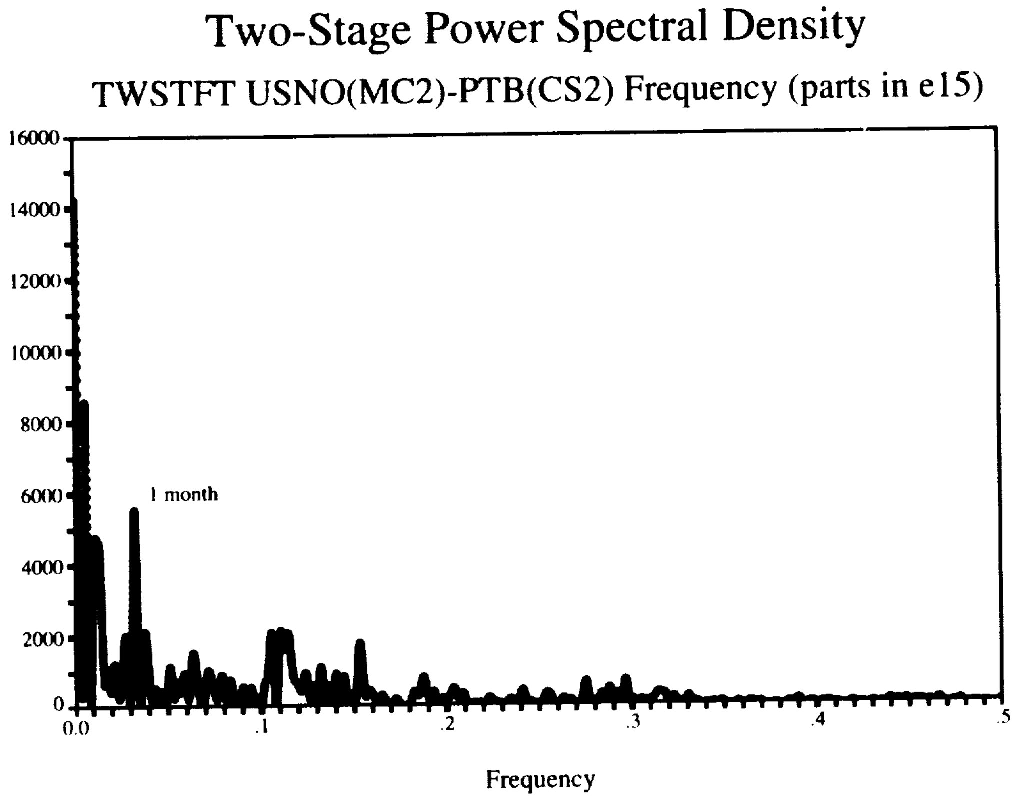

Two-Stage Power Spectral Density
TWSTFT USNO(MC2)-PTB(CS2) Frequency (parts in e15)
16000
14000
12000
10000
8000
6000
4000
2000
0
1 month
0.0
.1
.2
.3
.4
.5
Frequency

Figure 7

QUESTIONS AND ANSWERS

MARC A. WEISS (NIST): For the one–day estimate of TDEV, you said the data were not evenly spaced. I'm wondering how you got a one–day estimate.

J.A. DeYOUNG (USNO): Right. What I did was, the data is taken three times a week; so we have Monday, Wednesday and Friday. I simply interpolated linearly interpolated values to fill in in–between the actual measured values. I mean, that's the best we can do.

Well, I see a few heads shaking out there. There are lots of ways we can do something like that. I mean, you just have to pick one, and that's the one I picked to do. There was another one somewhere up here I believe.

FRED WALLS (NIST, BOULDER): The seven–day, 14–day, and 31–day peaks are what you would expect from environmental things in laboratories where people come and go. I'm pleased actually to see it show up in your data, because I think it means that if you would make your sampling coincident with a one–week period, that a lot of those fluctuations would be diminished.

J.A. DeYOUNG (USNO): Yes, that's quite possible. PSDs are very inherently difficult to interpret as to the source of where those peaks are coming from. That's one possibility that it's coming from that source. I just assumed it was coming from my interpolating the data that was at two–day intervals. Because if you look at all the combinations of the sampling, from Monday, Wednesday to Friday, that's two–day gaps. Then over the weekend, you have a three–day gap; and then over the week you have the five–day sampling Monday to Friday; and then you have the week again. Almost all of those peaks are almost exactly right where you expect those to be from that. It's possible it's from the source that you're mentioning.

TOM PARKER (NIST): By doing a linear interpolation on data with typically Monday–Wednesday–Friday–type analysis, you're going to underestimate TDEV at one day by about a factor of somewhere between two and three. So the data is overly optimistic at one day.

J.A. DeYOUNG (USNO): Do you have a suggestion as to how to –- I mean, if we're dealing with unequally–spaced data, what's the better way then? Do have a suggestion for that?

TOM PARKER (NIST): Well, I'll tell you what I did. I took some comparable GPS data that I had on one–day intervals and edited out all the points that didn't correspond to the two–way. So with the GPS data, I could get both ways with the two–way density and with the full one–day density and just made a comparison. That's where the two–to–three comes from.