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COMMON-CLOCK TWO-WAY SATELLITE TIME TRANSFER EXPERIMENTS

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Abstract

We report the results of a series of measurements designed to determine the magnitudes and noise types of the various sources of instability in the two-way satellite time and frequency transfer (TWSTFT) process. We find that, for our equipment, the earth-station noise predominates at the 1 day time scale. We also report results from a maser-to-maser time transfer conducted between NIST-Boulder and USNO (Washington D.C), which show a stability at 1 day of about 1 ns.

KEY WORDS - Two-way satellite time and frequency transfer, two-way time transfer, time transfer, TWSTFT.

Introduction

Two-way satellite time and frequency transfer (TWSTFT) is used to measure the time difference between two geographically-separated clocks A and B. This is done using a transmitting/receiving earth station at each location as well as a geosynchronous communications satellite [1], [2]. If reciprocity in the atmospheric and satellite transponder delays is assumed [3], [4], one can compute the time difference between the two clocks as:

$$\begin{aligned}\text{time}(A) - \text{time}(B) = \tfrac{1}{2}\{&[\text{TIC}(A) - \text{TIC}(B)] \\ &+ [\text{Tx}(A) - \text{Rx}(A)] - [\text{Tx}(B) - \text{Rx}(B)]\} \\ &+ \text{Sagnac effect} \qquad (1)\end{aligned}$$

where

TIC(i) = time interval counter reading at station i
= time between transmit and receive 1 pulse per second (PPS) at station i
Tx(i) = transmit delay through equipment at i
Rx(i) = receive delay through equipment at i.

The first line of Eq. 1 contains the time interval counter (TIC) measurements taken at both sites. Line 2 is the difference between the transmit and receive delay at site A minus that difference at site B. Line 3, the Sagnac effect, depends on the geographic locations of the two earth station antennae and the satellite.

To obtain an accurate time difference (time(A)-time(B)) one needs to know the values of the quantities on the second and third lines of Eq. 1. For accurate frequency transfer it is necessary only that these quantities remain constant over time. This is often assumed in TWSTFT. In 1994, at the National Institute of Standards and Technology (NIST), several ongoing experiments to evaluate the stability of the quantity [Tx(A) - Rx(A)] - [Tx(B) - Rx(B)] (line 2), were begun. In this paper we report our findings on various aspects of the time and frequency stability of a co-located TWSTFT earth-station pair and also assess the performance of TWSTFT between two geographically-separated stations.

Method

Operationally, TWSTFT is used to determine time(A) - time(B) where clocks A and B and their respective earth stations are geographically separated. In our primary measurement, two separate earth stations have been set up at the NIST facility in Boulder, and UTC(NIST) serves as the clock for both earth stations. We then perform TWSTFT between our own two earth stations. In this case, Clock A = Clock B = UTC(NIST) so that time(A) - time(B) = 0. In addition, because the antennae are located atop the same building, the Sagnac effect goes to zero. Applying these facts to Eq. 1 yields:

$$\tfrac{1}{2}\{\text{TIC}(B) - \text{TIC}(A)\} = [\text{Tx}(A) - \text{Rx}(A)] - [\text{Tx}(B) - \text{Rx}(B)] \qquad (2)$$

By observing ½{TIC(B) - TIC(A)} over a period of time, the day-to-day stability of the earth-station pair can be evaluated. It should be noted, however, that common-mode environmental instabilities may not be observed.

One of the earth stations used in this measurement is that which is routinely used for time transfer between NIST and other laboratories in North America and in Europe. This earth station features a 3.7 m diameter antenna and its transmit/receive frequencies can be adjusted in steps of 120 Hz. The second earth station, a less-expensive "VSAT" earth station package, has an antenna 1.8 m in diameter. Its transmit/receive frequencies can be tuned in steps of 1 MHz. These earth stations are shown in Figs. 1 and 2. SBS-6, a geosynchronous communications satellite located at 95 degrees west longitude, was used as the transfer satellite.

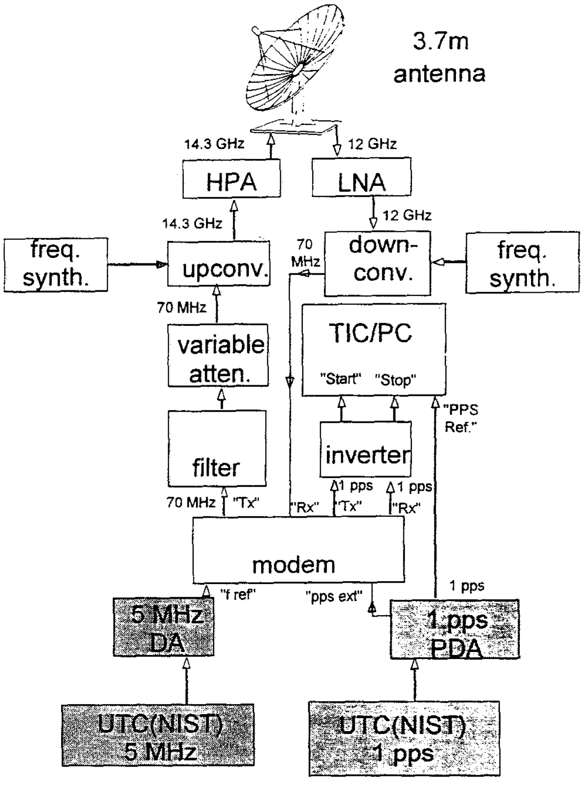

Figure 1. The NIST TWSTFT earth station used for time transfer with other metrology laboratories. The shaded rectangles represent equipment common to both this and the VSAT earth station. PDA is an abbreviation for pulse distribution amplifier, TIC/PC is the time-interval-counter and DA is a distribution amplifier.

Measurement 1

Here we evaluated the noise contributed by the measuring system, i.e., the time interval counters, spread spectrum modems, etc. [5]. These evaluations were made by measuring the time intervals between two 1 PPS signals for 5 minutes (300 measurements) once each day and then calculating an average value for each session. This process was repeated approximately three times per week (usually Monday, Wednesday and Friday) over a period of 116 days.

The data in these measurements, and some of the other measurements to be discussed later, were unevenly spaced. This complicates the process of calculating $\sigma_x(\tau)$ [6]. The $\sigma_x(\tau)$ values were computed by using the adjacent time values as if they were evenly spaced to compute $\sigma_x(\tau = 2.3, 4.6, 9.2, \text{etc. days})$, where $\tau = 2.3$ days is the average interval between data points. By

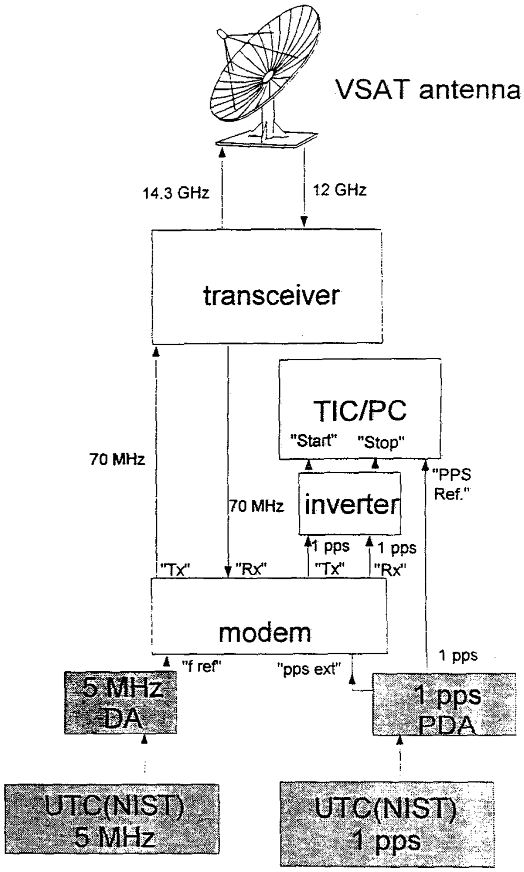

Figure 2. The NIST VSAT earth station used for test purposes.

plotting $\sigma_x(\tau)$ against τ, we could see that the noise type was generally either white phase modulation (PM) or near white PM. This was fortunate since the impact of non-periodic data on white PM noise is easily understood and the dependence on τ is preserved. For a white PM process, where all of the data points are independent, the calculated noise from our data set for $\tau = 2.3$ days would be the same as that for $\tau = 1$ day for a data set taken at a 1 day interval, assuming that the same white PM noise process was present at a 1 day time interval. We don't know this for a fact with the TICs or the modems, but for comparison purposes we will use estimated values for $\sigma_x(\tau = 1 \text{ day})$ since data were actually taken at 1 day intervals in measurements 2 and 3. Analyzing non-periodic data for other noise types (flicker PM or white frequency modulation (FM)) is considerably more complicated [6] and will be the subject of a future paper concerning typical TWSTFT data intervals [7].

The noise levels of both individual time-interval counters were estimated to be approximately 50 ps for $\tau = 1$ day, with three sigma confidence limits of approximately +32% and -20%. Note that the noise of both TICs combined in the manner of Eq. 2 gives $\sigma_x(\tau = 1 \text{ day}) = \frac{1}{2}(50^2 + 50^2)^{\frac{1}{2}} = 35$ ps (assuming the noise processes in the two TICs are independent). To evaluate the combined noise of the modems and TICs a two-way time transfer was performed by using a direct cable link between the two modems as shown in Figure 3. The individual TIC readings were used in Eq. 2 the same as they would in real TWSTFT. In this case, we obtain a $\sigma_x(\tau = 1 \text{ day})$ of 63 ps, again with the noise at larger averaging times decreasing as white PM. The confidence limits are approximately the same as for the TIC results. Clearly, the modems are contributing a significant amount of additional noise to the measurement process.

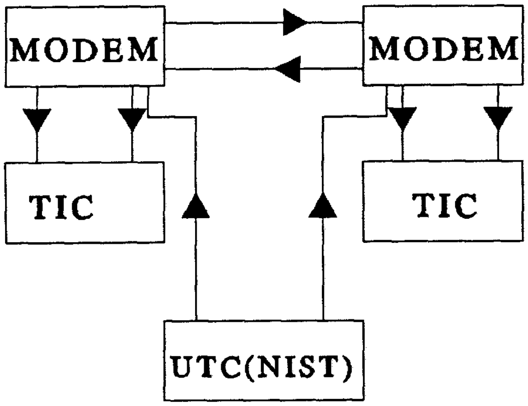

Figure 3. The experimental set-up used to evaluate the stability of a pair of measurement systems.

Measurement 2

Here we again evaluate the noise of the measurement system, but in this case rather than cabling the modems directly together as in Fig. 3, we send the signals up through the satellite using a single earth station. By using this configuration we force the parts of the transmit and receive delays associated with the earth stations in Eqs. 1 and 2 to cancel. The method of doing this is shown in Fig. 4. The 70 MHz outputs of the two modems are fed into a power combiner. The combined 70 MHz signal is then either sent up through the upconversion/transmission equipment of the 3.7 m earth

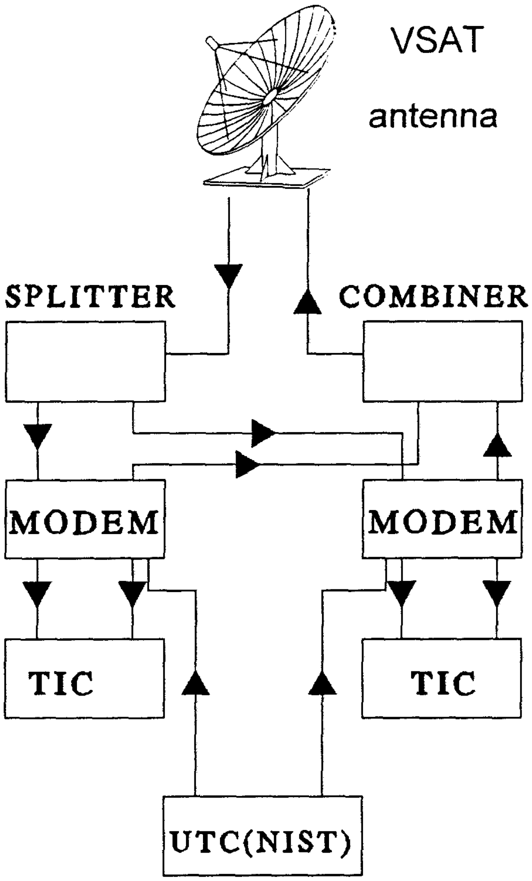

Figure 4. The single-dish common-clock experiment as used with the VSAT earth station. This experiment was also carried out using the 3.7 m earth station.

station or that of the VSAT earth station. The resulting 14.3 GHz signal is transmitted to the satellite, retransmitted by the satellite at 12 GHz, and then received back at the same antenna. This combined signal is then down converted, sent through a power splitter, and then back into the two modems.

Since we are only using one earth station, Tx(A) = Tx(B) and Rx(A) = Rx(B). Therefore, the quantity [Tx(A) - Rx(A)] - [Tx(B) - Rx(B)] will go to zero, and we are once again measuring only the noise contributed by the measurement system. However, in this case, we actually do send the signal up through the satellite. This series of measurements is referred to as "the single-dish common-clock experiment". These measurements were taken with both earth stations three times per week, 300 s at a time, over the course of about 220 days. In addition, measurements were also taken once per day using the 3.7 m earth station over a period of 3 weeks. Since the results were similar on both the 3.7 m and VSAT earth stations, only the results from the former will be discussed.

Figure 5 shows the time difference results obtained from the 3.7 m earth station. Figure 6 shows the $\sigma_x(\tau)$ values derived from the data in Fig. 5. The solid circles in Fig. 6 come from the three weeks of daily data and the x's represent the three-times-per-week data. The calculation of $\sigma_x(\tau)$ for the daily data is straightforward since the data are periodic, while the three-times-per-week data were analyzed using the technique discussed earlier. Note that the daily data and the three-times-per-week data are in good agreement at $\tau = 2$ days. The error bars in Fig. 6 represent three-sigma confidence limits.

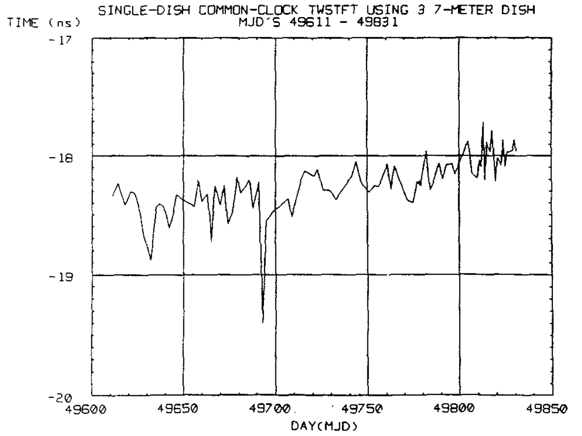

Figure 5. The time difference results obtained from the single-dish common-clock experiment. These results were obtained with the 3.7 m earth station.

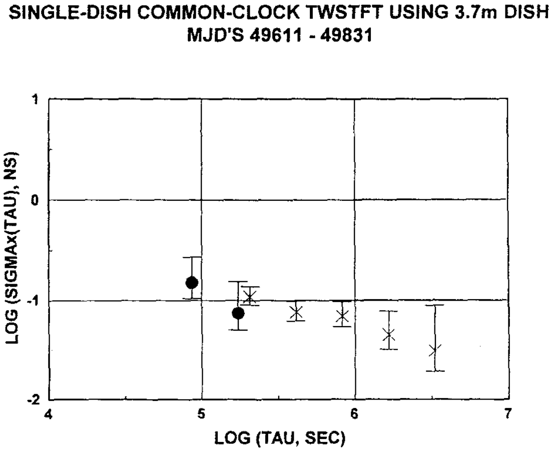

Figure 6. The time stability, $\sigma_x(\tau)$, of the data shown in Fig. 5. The black dots indicate results obtained from performing this experiment every day for 21 days. The x's indicate results obtained from taking data 3 times per week over the course of approximately 220 days. The error bars indicate three-sigma confidence levels.

As Fig. 6 shows, $\sigma_x(\tau = 1 \text{ day})$ is about 150 ps with a noise type between white PM and flicker PM. One might expect to get approximately 60 ps as observed in the experiment of Figure 3 since the earth station delays in the present experiment should cancel. However, there is an important difference. For this measurement, the time it takes for the signal to leave one modem and arrive at the other modem is on the order of 0.25 s, because the signal travels to and from the satellite. In the measurement of Fig. 3, it only takes a few tens of ns for a signal to travel from one modem to another. Flicker noise in the measurement system (most likely the modems) could be the reason that increased signal delay is associated with increased noise.

Another difference between the experimental set-ups shown in Figs. 3 and 4 is the signal-to-noise ratios as received by the modems at 70 MHz. However, measurements were made with the cable connected modems of Fig. 3 in which white noise was injected to create the same signal to noise ratio at 70 MHz as that present in the Fig. 4 configuration. The observed value for $\sigma_x(\tau = 1 \text{ day})$ was the same as that present without the injected noise. Finally, fluctuations in the delays up to and back from the satellite are not likely to cause the higher noise level since the propagation paths are virtually identical. Also, the same satellite transponder is used for both signals.

Figure 7 shows the frequency stability, $\sigma_y(\tau)$, derived

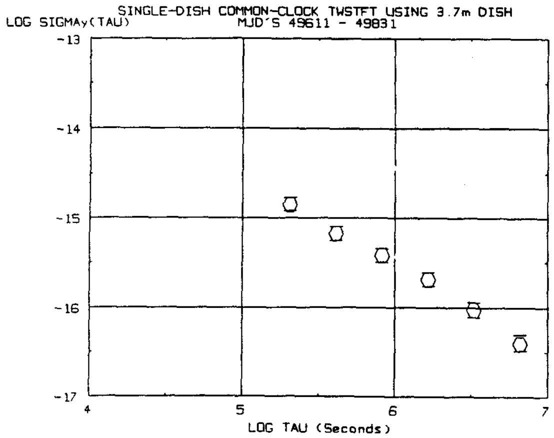

Figure 7. The frequency stability, $\sigma_y(\tau)$, of the results shown in Fig. 5.

from the data in Fig. 5. It is interesting to note that we reach a frequency stability of 10^{-15} at τ between 2.4 and 4.8 days.

To summarize, Figs. 5 through 7 represent the best possible TWSTFT results that could be obtained with the present modems and counters if all the noise from the earth stations, propagation paths and satellite were eliminated.

Measurement 3

In this experiment, we do two-dish common-clock TWSTFT. In other words, we have the two earth stations shown in Figs. 1 and 2 performing TWSTFT with each other. As in measurement 2, we have data from a 21-day set of once-per-day measurements, and a longer data set consisting of data taken 3 times per week over the course of roughly 230 days. By comparing the results of this series of measurements with those obtained from the single-dish common-clock experiment, we can determine what type of noise the transmitter/antenna/receiver packages contribute to the noise of TWSTFT. However, we cannot determine the magnitude of the noise as we are unable to separate the noise due to one earth station from that due to the other. Furthermore, there may be some noise cancellation or enhancement due to common environmental effects.

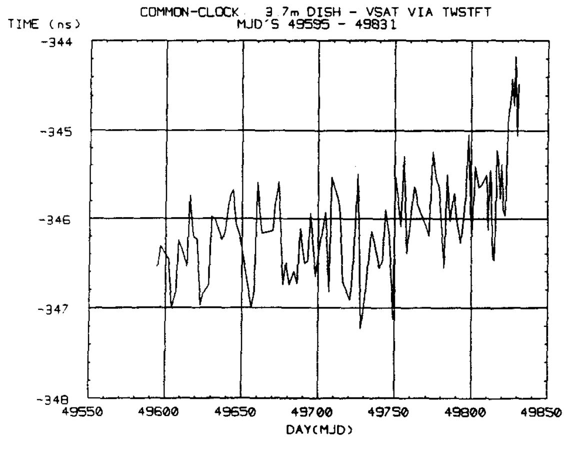

Figure 8. The time difference results obtained from the two-dish common-clock experiment.

Figure 8 shows the results from the two-dish common-clock experiment and Fig. 9 shows the time stability of the data in Fig. 8. Figure 9 shows that $\sigma_x(\tau = 1 \text{ day})$ is about 330 ps, and that the noise type is between white and flicker PM. Because the time stability of this experiment is considerably worse than the time stability obtained from the single-dish common-clock experiment (Fig. 6), we conclude that the earth stations are a significant additional source of noise with a noise type somewhere between white PM and flicker PM.

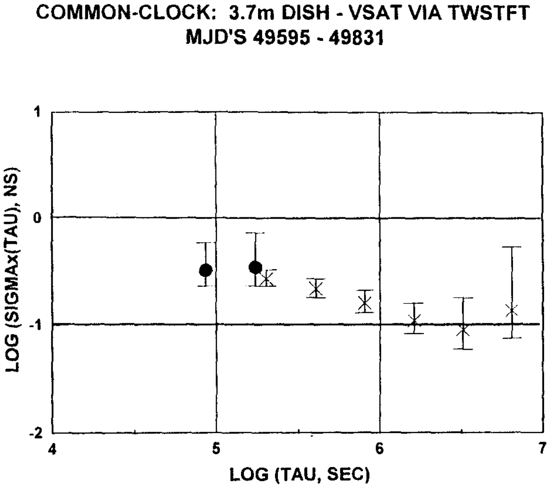

Figure 9. The time stability, $\sigma_x(\tau)$, of the results shown in Fig. 8. The interpretation of the symbols is the same as that in Fig. 6.

Measurement 4

We now report results obtained by doing TWSTFT between maser-based clocks at NIST and USNO. Note that this is no longer common-clock TWSTFT - the earth

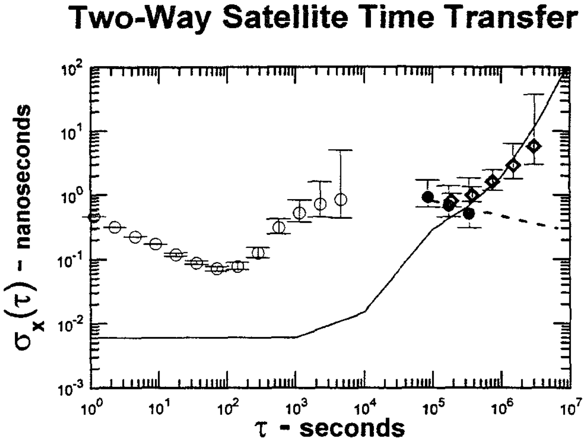

Figure 10. Time stability, $\sigma_X(\tau)$, of TWSTFT performed between NIST(Boulder) and the United States Naval Observatory (Washington D.C.). The open circles were obtained from performing a six-hour time transfer. The closed circles were obtained by performing a 5-minute time transfer once per day, every day, for 21 days. The open diamonds were obtained by performing a 5-minute transfer three times per week over the course of about 129 days. The solid line indicates the approximate level of the combined clock noise which we are attempting to measure.

stations at NIST and USNO are entirely independent and driven by separate clocks.

Figure 10 shows the time stability analysis of three experiments. In one experiment (open circles), a six-hour-long time transfer was performed between NIST and USNO with time interval counter measurements made every second. Note that this experiment has only been performed once and we do not know whether the results obtained are typical. In the second experiment (solid circles), a 5-minute time transfer was performed once per day every day for 21 days. In the third experiment (open diamonds), we did our normal NIST-USNO time transfer routine, i.e., one 5-minute transfer 3 times per week, over the course of 129 days. Figure 10 also shows the approximate stability of the clocks involved (solid line). What the line shows is the stability of the NIST clock, a maser-driven micro-stepper, as compared to a second hydrogen maser. We believe that the NIST clock is comparable in stability to the USNO clock (MC2) for τ less than about 1 day. At τ greater than 1 day maser drift and some steering corrections to the micro-stepper have increased $\sigma_X(\tau)$ for the NIST clock. Therefore, the solid line is a reasonable approximation of the combined stability of the two clocks being measured.

As Fig. 10 shows, at $\tau = 1$ s, the time stability of TWSTFT is 470 ps. The stability of the transfer improves out to $\tau \approx 64$ s ($\sigma_X(\tau \approx 64$ s$) = 70$ ps). However, the transfer stability then becomes worse out to $\tau = 1.25$ hours, at which point $\sigma_X(\tau) = 840$ ps. From the every-day experiment, we find that the time stability of TWSTFT is about 915 ps at $\tau = 1$ day and that it continues to decrease in a white PM to flicker PM fashion out to $\tau = 4$ days. We have drawn in a dashed line to indicate that the transfer noise very likely continues to go down as the averaging time increases, based on our analysis of the two-dish common-clock experiment. Finally, the long-term transfer results indicate that for $\tau \geq 4$ days, the combined noise of the two clocks under study is larger than the noise of the transfer process.

The transfer noise of TWSTFT is clearly made up of more than one noise process, as is shown in Fig. 10. The white PM noise process at $\tau = 1$ s comes from the modems and counters. However, at least one other process sets in at about 100 s which causes $\sigma_X(\tau)$ to increase again to nearly 1 ns at 10^4 s. As mentioned earlier, the six hour run has been performed only once, and it is thus not known if the rise at 100 s is typical. More measurements are planned to determine the source of this noise process. It is clear, however, from the one day and normal three-times-per-week measurements that the noise consistently increases to near 1 ns by $\tau = 1$ day. The common-clock experiments indicate that at least part of this noise comes from the earth stations. Beyond about four days, clock noise dominates and the transfer noise could not be measured directly. However the common-clock experiments suggest that the transfer noise decreases for increasing τ as in a manner between that of white and flicker PM noise.

Conclusions

The noise contributed to TWSTFT by the two measurement systems (counters, modems, etc.) is about 150 ps at $\tau = 1$ day with a noise type between white and flicker PM. Most of this noise is from the modems. The two-earth station common clock measurements show that the earth stations are a significant source of noise with an observed value of $\sigma_X(\tau = 1$ day$) = 330$ ps. The precise magnitude of an individual earth station's noise could not be determined. However, the noise type of the earth station pair's contribution was observed to fall between white and flicker PM for τ greater than 1 day. Finally, a preliminary evaluation of actual TWSTFT between NIST and USNO shows that the transfer noise is rather complicated. At $\tau = 1$ day it is just slightly smaller than 1 ns and appears to decrease for larger τ at a rate between white and flicker PM. Future experiments are planned to further investigate the characteristics and sources of TWSTFT noise and to achieve improved performance.

Acknowledgments

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