SOME OPERATIONAL ASPECTS OF THE INTERNATIONAL TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER (TWSTFT) EXPERIMENT USING INTELSAT SATELLITES AT 307 DEGREES EAST

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Abstract

Eight laboratories are participating in an international TWSTFT experiment. Regular time and frequency transfers have been performed over a period of almost two years, including both European and transatlantic time transfers. The performance of the regular TWSTFT sessions over an extended period has demonstrated conclusively the usefulness of the TWSTFT method for routine international time and frequency comparisons.

Regular measurements are performed three times per week resulting in a regular but unevenly spaced data set. A method is presented that allows an estimate of the values of $\sigma_y(\tau)$ to be formed from these data. In order to maximize efficient use of paid satellite time an investigation to determine the optimal length of a single TWSTFT session is presented. The optimal experiment length is determined by evaluating how long white PM instabilities are the dominant noise source during the typical 300-second sampling times currently used. A detailed investigation of the frequency transfers realized via the transatlantic TWSTFT links UTC(USNO)-UTC(NPL), UTC(USNO)-UTC(PTB), and UTC(PTB)-UTC(NPL) is presented. The investigation focuses on the frequency instabilities realized, a three-cornered-hat resolution of the $\sigma_y(\tau)$ values, and a comparison of the transatlantic and inter-European determination of UTC(PTB)-UTC(NPL). Future directions of this TWSTFT experiment are outlined.

INTRODUCTION

TWSTFT has developed into a useful method for regular and routine time and frequency transfer. During the INTELSAT field trial, several important details related to TWSTFT

operations were identified as areas that needed further study or confirmation. This paper will discuss and give solutions to several of those. In the future satellite time will have to be paid for; therefore, a logical question to consider is what is an optimal single experiment length. In a routine operational TWSTFT system, one of the goals is to reduce satellite costs while optimizing the timing precision considering the typical noise sources encountered in the TWSTFT measurement systems over the range of 1 to 300 seconds. A paper was presented previously which studied the time-domain parts of the INTELSAT field trial[1]. This paper will concentrate on the frequency-domain results by presenting a detailed analysis of the realized long-distance transatlantic frequency comparisons. The specific frequency differences studied are UTC(USNO(MC2)) - UTC(NPL(H maser)), UTC(USNO(MC2)) - UTC(PTB(CS2)), and UTC(PTB(CS2)) - UTC(NPL(H maser)). UTC(USNO(MC2)) is a Sigma Tau Corporation hydrogen maser steered once a day by small changes in its synthesizer settings, hereafter UTC(USNO). UTC(PTB(CS2)) is generated by a laboratory cesium-beam primary frequency standard operated as a clock, hereafter UTC(PTB). UTC(NPL(H maser) is generated by a steered Sigma Tau hydrogen maser where approximately every 100 days a rate change is manually applied, hereafter UTC(NPL).

UNEQUALLY SPACED $\sigma_y(\tau)$ ESTIMATES

The following formulation has been developed to allow estimates of $\sigma_y(\tau)$ to be obtained from unequally spaced time-domain data such as are encountered in TWSTFT. In the case of equally spaced data, it is equivalent to the classical two-sample deviation, which is the square root of the two-sample zero variance[2,3,4]. In the case of unequally spaced data, such as are encountered in TWSTFT, we apply a normalization to account for the unequal data spacing. The normalizing terms which have been added in the following equation are the multipliers $\sqrt{(\tau_2)}/\sqrt{(\tau_1)}$ and $\sqrt{(\tau_1)}/\sqrt{(\tau_2)}$. The rest of the equation is standard.

$$\sigma_y(\tau) = \frac{\frac{1}{n}\sum_{1}^{n}\left[\frac{\sqrt{(\tau_2)}}{\sqrt{(\tau_1)}}(x_{n-1}-x_n) - \frac{\sqrt{(\tau_1)}}{\sqrt{(\tau_2)}}(x_n - x_{n+1})\right]}{\frac{\sqrt{2}}{n}\sum_{1}^{n}(\sqrt{\tau_1}\sqrt{\tau_2})}$$

OPTIMUM EXPERIMENT LENGTH

Figure 1 shows TDEV, $\sigma_x(\tau)$, instability estimates formed from a large number of individual 300-second TWSTFT experiments obtained by USNO against nine other labs all using a mix of MITREX model 2500 and 2500A modems. Specifically, the TDEV instabilities were estimated from the differences of the time interval counter readings divided by two. The phase-instability floor for the average of these experiments is reached near an averaging time of 100 seconds. The 100-second optimal sampling was stated quite elegantly previously in [5]: "Averaging for about 100 seconds exceeds the performance specifications of the limiting components." The limiting components in this case are the measurement systems, which are dominated by thermally produced white PM noise out to 100-second averaging times.

Currently TWSTFT experiments are 300 seconds long (5 minutes). The 300 time interval counter readings from each laboratory or timing center are then differenced and divided by two to form a mean time difference for the experiment. Numerical experiments were performed to evaluate how an intermediate mean formed from 1 to (300-1) points deviated from the final mean formed from the full 300 points of a run. Figure 2 shows the results of the averaging of the

deviations from 1,492 experiments for UTC(USNO)-UTC(PTB) and UTC(USNO)-UTC(NPL). Generally, the subset means drop exponentially $(1/\sqrt{(N)})$ for the first 100 seconds, which is the white PM instability region. After 100 seconds, the convergence is a linear monotonic slope $(1/(1-N/300)$ behavior). TWSTFT is so good that on average a clock difference formed from a single 1-pulse-per-second (1pps) comparison is within approximately 500 picoseconds of the final value determined from the average of 300 1pps comparisons. A reasonable trade-off between length of the runs, cost of the satellite time, and measurement noise (averaging over the entire white PM regime of the measurement system being the ideal) seems to indicate that 120-second (2-minute) runs are optimal.

FREQUENCY TRANSFER ANALYSIS

In an effort to determine the quality of the transatlantic frequency measurements, the following clock differences, which were directly measured or formed indirectly as indicated below, were used.

UTC(USNO)-UTC(NPL) directly measured via transatlantic,
nominal experiment centers 14:12.5 U.T.,

UTC(USNO)-UTC(PTB) directly measured via transatlantic,
nominal experiment centers 14:36.5 U.T.,

UTC(PTB)-UTC(NPL) = [UTC(PTB)-UTC(USNO)] + [UTC(USNO)-UTC(NPL)]
indirectly formed via transatlantic, nominal experiment centers 14:24.5 U.T.,

and

UTC(PTB)-UTC(NPL) directly measured inter-European,
nominal experiment centers 10:20.5 U.T.

TRANSATLANTIC

The fractional frequency performance of the three transatlantic combinations as realized by TWSTFT is investigated first. These data were filtered so that only days where all three laboratories made TWSTFT sessions on the same day were used (MJD 49387 to 49952 with 141 days with common points). The resulting average τ was 4.0 days. The clock difference UTC(PTB)-UTC(NPL) was formed indirectly via transatlantic TWSTFT sessions with UTC(USNO) in this section. It is important to note that there is a difference of measurement times of 24 minutes between the two directly measured experiments. In order to interpret these results correctly, we must remember that UTC(PTB) is a primary frequency standard used in the formation of UTC(BIPM) and is neither steered nor stepped either in frequency or in time. It is also important to stress again that both UTC(USNO) and UTC(NPL) are hydrogen masers and that both are steered towards an extrapolated UTC(BIPM). UTC(USNO) is steered once daily by very small changes in the masers' frequency synthesizer, while UTC(NPL) is steered by introduction of a rate change approximately once every 100 days.

Figure 3 shows UTC(USNO)-UTC(PTB) with an rms of 1.7×10^{-14} and a very slight drift of -2.2×10^{-17} (7.8×10^{-18}) per day between UTC(PTB) and UTC(USNO). Figure 4 shows

UTC(USNO)-UTC(NPL) and has an rms of 1.1×10^{-14} and an estimated maximum frequency drift of 6.6×10^{-17} ($\pm 1.1 \times 10^{-17}$) per day. Figure 5 shows UTC(PTB)-UTC(NPL), which was formed via transatlantic TWSTFT with UTC(USNO). The rms for UTC(PTB)-UTC(NPL) is 1.9×10^{-14} and an estimated maximum frequency drift of 1.2×10^{-16} ($\pm 3.1 \times 10^{-17}$) per day. If one were to base decisions upon only the frequency-domain data presented in this paper, one might assume that a frequency drift is manifested in the UTC(USNO)-UTC(PTB) frequencies, for example. A drift interpretation would be an incorrect assumption. In reality, two very small discrete rate changes (frequency steps) are apparent in the time-domain UTC(USNO)-UTC(PTB) data and only appear unambiguously in the time-domain data.

Figure 6 gives a $\sigma_y(\tau)$ plot showing the instabilities of the frequency comparisons. UTC(USNO)-UTC(PTB) TWSTFT frequencies show a constant lowering of the instabilities, with an approximate $\tau^{-1/2}$ slope (white FM noise) from 4- to 250-day averaging times. This is astonishing even when considering the fact that UTC(PTB) is one of the primary inputs into the realization of frequency of UTC(BIPM) with respect to the SI second and towards which UTC(USNO) is steered. UTC(USNO)-UTC(NPL) exhibits a complex structure which is typical of the instability behavior of the UTC(USNO) and UTC(NPL), with the increased instabilities at the longer averaging times coming from the periodic component of the steering towards UTC(BIPM). The estimated minimum frequency instability for UTC(USNO)-UTC(NPL) is 3.5×10^{-15}, reached at an averaging time of 30 days.

Transatlantic TWSTFT-measured UTC(PTB)-UTC(NPL), using UTC(USNO) as an intermediary, exhibits a complex structure in the frequency instabilities which is typical of the instability behavior of the NPL hydrogen maser as steered towards UTC(BIPM). The estimated minimum frequency instability is 6.3×10^{-15}, reached at an averaging time of 60 days, and the rise at the longest averaging times comes from the periodic component of the steering.

These results indicate that the single 5-minute-long transatlantic TWSTFT instabilities are comparable to the short-baseline Vondrak smoothed GPS common-view experiments realized in Europe[6,7]

Using the $\sigma_y(\tau)$ results for UTC(USNO)-UTC(PTB), UTC(PTB)-UTC(NPL), and UTC(NPL)-UTC(USNO), we may now resolve the instabilities for each clock system using a three-cornered-hat analysis at three selected averaging times and using the indicated number of points to form the instability estimate (see Table I).

TRANSATLANTIC COMPARED TO INTER-EUROPEAN

We now difference the inter-European direct-measured values of UTC(PTB)-UTC(NPL) with the transatlantic (European-U.S.-European) formed determination of UTC(PTB)-UTC(NPL) to evaluate any degradation contributed by the transatlantic paths over the inter-European path. We should remember that there are 24 minutes between the transatlantic measurement of UTC(PTB) and UTC(NPL) against the intermediary UTC(USNO). There are also a total of 4 hours and 5 minutes between the inter-European and the transatlantic experiments. We have only compared TWSTFT data on days when both inter-European and transatlantic schedules have both had successful experiments. A total of 119 common points were matched over the interval MJD 49387 to 49943 and an average τ of 4.63 days was determined. No further adjustments such as interpolation, filtering, etc. were made to the data.

In Figure 7 we present the frequency differences between UTC(PTB)-UTC(NPL), measured inter-European, and UTC(PTB)-UTC(NPL), measured by transatlantic determinations using UTC(USNO), which were determined approximately 4 hours apart. In an ideal case where

the clock comparisons were made simultaneously via TWSTFT, we would expect almost all of the noise sources to cancel out. However, this is not the case because of the approximately four hours between the comparisons of the transatlantic UTC(PTB)-UTC(NPL) and the inter-European UTC(PTB)-UTC(NPL) measurements. The standard deviation of the frequency differences is 9.0×10^{-15} and the scatter is presumably due to the non-simultaneous clock comparisons. In order to get a feeling for what was contributing to this frequency noise, we generated a frequency instability plot (see Figure 8).

A slope of τ^{-1} is evident over the entire interval and must be either white or flicker PM noise. At averaging times greater than about 100 seconds, we are at the phase instability floor of the time-domain TWSTFT measurement systems (see Figure 1). This TWSTFT measurement system phase noise must be contributing to the frequency instabilities seen in Figure 7. It also appears that the phase-instability floor from the four hours between measurements is relatively constant over the entire interval from 100 seconds to 75 days. At the longest sampling time of approximately 75 days, the phase-instability floor from the four hours between measurements would introduce only an 8×10^{-16} uncertainty in the determinations of the UTC(PTB)-UTC(NPL) frequencies. The most important fact is that there is apparently no deterioration in the resulting time differences when measuring UTC(PTB)-UTC(NPL) via this transatlantic link using an intermediate timing center compared to the directly measured European time transfers when estimated for the ideal case of simultaneous measures.

CONCLUSIONS AND FUTURE DIRECTIONS

It has been proven that, for the Mitrex modems currently being used for these TWSTFT experiments, averaging over 120 seconds (2 minutes) is optimal due to this being the region of white PM instabilities. Another important result presented shows that TWSTFT works very well even over very long distances and when using multi-hop experiments, with very little or no added noise.

TWSTFT has been proven to be very useful when applied to transfer of time and frequency between the best frequency standards and over long distances. TWSTFT will begin to be integrated as a routine time and frequency transfer method by the BIPM in the formation of International Atomic Time (TAI) beginning in 1996. Additional TWSTFT stations will be coming on-line in the future with the advent of new PN-code modems. A new TWSTFT-compatible modem, the AOA TWT-100 (USA), is available. A potentially new TWSTFT-compatible modem, TimeTECH$_{gmbh}$ SATRE (German) modem—currently used only for ranging—may soon be available. These new modems will allow more stations to come on-line for TWSTFT comparisons.

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Table I. Three-cornered-hat resolution of $\sigma_y(\tau)$s at three averaging times (units in 10^{-15}).

	COMBINATIONS		
$\tau = 4d$ (log 0.6) N=139	USNO-PTB 14.48	PTB-NPL 15.09	NPL-USNO 7.96
	RESOLVED		
	USNO 4.76	PTB 13.68	NPL 6.38

	COMBINATIONS		
$\tau = 33d$ (log 1.5) N=17	USNO-PTB 6.70	PTB-NPL 6.74	NPL-USNO 3.60
	RESOLVED		
	USNO 2.49	PTB 6.22	NPL 2.60

	COMBINATIONS		
$\tau = 64d$ (log 1.8) N=8	USNO-PTB 4.47	PTB-NPL 5.96	NPL-USNO 4.33
	RESOLVED		
	USNO 1.27	PTB 4.29	NPL 4.14

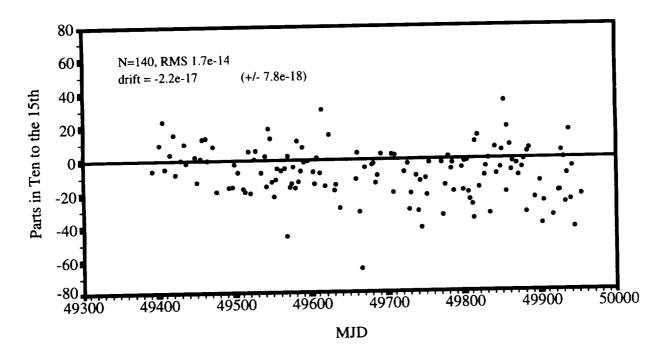**Figure 1.** Time-domain instabilty estimates of 1,492 MITREX modem experiments.

Figure 2. Convergence of intermediate means towards a 300-point mean.

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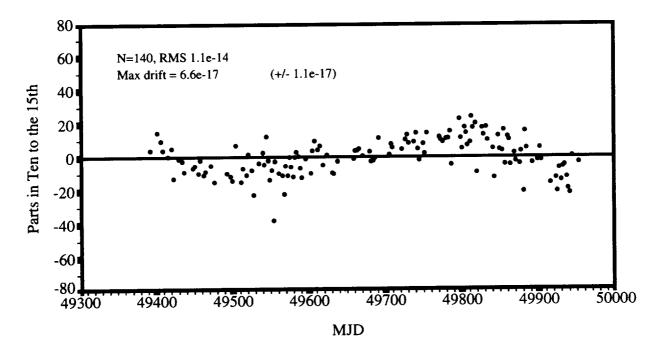Figure 3. UTC(USNO)-UTC(PTB) via transatlantic TWSTFT.

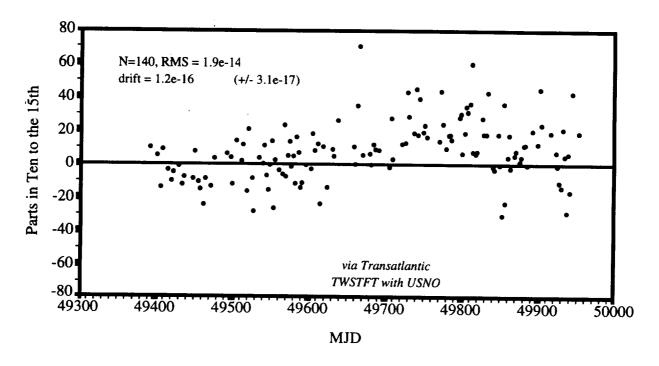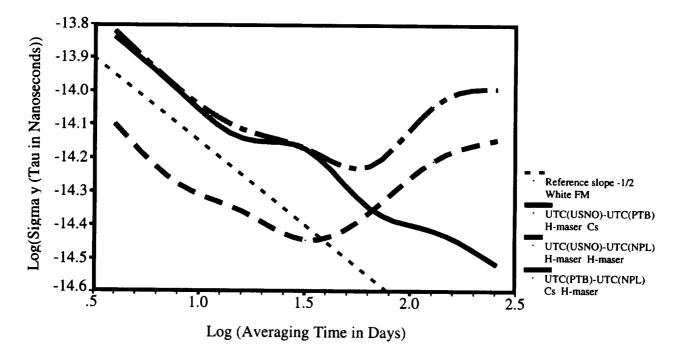Figure 4. UTC(USNO)-UTC(NPL) via transatlantic TWSTFT.

Figure 5. UTC(PTB)-UTC(NPL) via transatlantic TWSTFT with USNO.

Figure 6. Frequency instabilities via transatlantic TWSTFT.
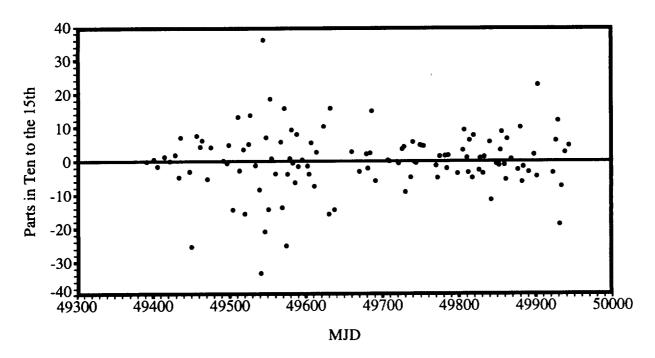
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Figure 7. Frequency differences of UTC(PTB)-UTC(NPL) [inter-European] minus UTC(PTB)-UTC(NPL) [via tranatlantic]. Four hours elapsed between the inter-European and transatlantic measurements.
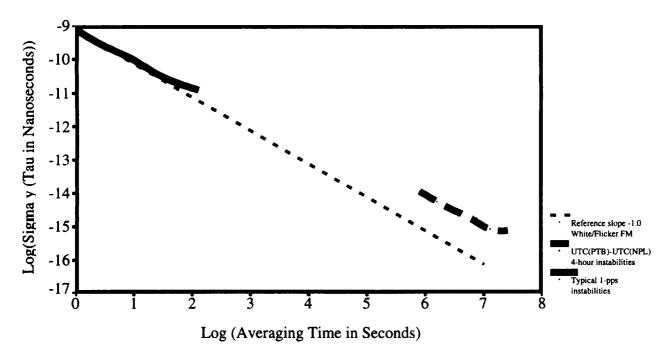

Figure 8. Frequency instabilities of UTC(PTB)-UTC(NPL) [inter-European] minus UTC(PTB)-UTC(NPL) [via transatlantic]. Four hours elapsed between the inter-European and transatlantic measurements. At the longest averaging times we are evaluating the τ = 4 hour instabilities of the time-domain measurement systems.

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