THE ACCURACY OF TWO-WAY SATELLITE TIME TRANSFER CALIBRATIONS

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Abstract

Results from successive calibrations of Two-Way Satellite Time and Frequency Transfer (TWSTFT) operational equipment at USNO and five remote stations using portable TWSTFT equipment are analyzed for internal and external errors, finding an average random error of ±0.35 ns, an average type-B uncertainty of ±0.15 ns, and an average total error of ±0.38 ns for a single calibration measurement over time spans of up to 4.9 years. Closure discrepancies suggest that the operational apparatus is at least as good as the calibration equipment.

INTRODUCTION

The most accurate means of operational long-distance time transfer are Two-Way Satellite Time and Frequency Transfer (TWSTFT) and carrier-phase GPS, allowing clocks and timescales in widely separated laboratories to be compared with one another and with International Atomic Time (TAI) to within a few nanoseconds (ns). The U.S. Naval Observatory (USNO) performs TWSTFT measurements between its Washington, D.C. location and sites in five other states and 10 other countries. Up to twice a year, USNO performs on-site calibrations of several of these stations with portable equipment. USNO has been supporting the switch by the Bureau International des Poids et Mesures (BIPM) to TWSTFT as the primary means of time transfer for generation of TAI by BIPM and is collaborating in the regular calibration of the TWSTFT links connecting BIPM with the participating labs, including USNO.

Repeated calibrations of TWSTFT links are required to fully exploit the technique. Periodic evaluations of the equipment's internal time delays and delay changes are necessary to properly relate the stations involved, since these are the most significant error sources. While the repeatability of recent USNO calibration trips has generally been less than 1 ns, the stability of this error over time is of interest, especially in the presence of equipment changes. The objective of this study is to determine the internal and external statistical errors of USNO TWSTFT calibrations for five sites over the last 9 years.

CALIBRATION PROCEDURE

TWSTFT calibration is achieved using portable calibrated equipment to measure the timing delay between time ticks at USNO and at a remote site. The two locations must share a common satellite footprint; otherwise the time delay between satellite transponders will corrupt the data. Once the time ticks of the two stations have been calibrated, they can be used to set the relative calibration of any particular technique. This portable antenna is either one attached to a dedicated van (currently an SUV) in the continental U.S. or is part of a “fly-away” apparatus shipped to an overseas site. The SUV employs a 1.5-meter Vertex/RSI Ku-band antenna with a two-port (transmit/receive) linearly polarized feed (see Figure 1). The Fly-away uses a 2.4-meter Vertex/RSI X-band prime-focus, single-offset antenna (see Figure 2). Next, measurements are made at the remote site, using the time signal from the site’s master clock. In the final step, the measurements at USNO with both antennas are repeated to ensure closure.

Figure 1. The SUV calibration van at the Vandenberg AFB site.

The sites involved in this study are USNO’s Alternate Master Clock (AMC); Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany; Symmetricom, Inc. in Beverly, Massachusetts; Timing Solutions Corporation (TSC) of Boulder, Colorado; and Vandenberg AFB, California.

The 5 MHz signals at AMC, PTB, Symmetricom, and USNO are generated by hydrogen masers and those at TSC and VDB are cesium-beam frequency standards. These signals are referenced to those of each site’s master clock, converted to an intermediate radio (IF) frequency, and encoded for spread-spectrum transmission by a special time-transfer modem. Over the period of time covered by this study, we replaced our existing Mitrex and other modems with TimeTech SATRE modems. The data used in this study are modulated onto 2.5 megachip/second pseudorandom codes, which are transmitted at Ku-band frequencies and recorded once every second. The measurements are then averaged over 2-minute sessions.

Figure 2. The Fly-away calibration apparatus (left) and the PTB operational station.

During a two-way time transfer, each signal is delayed by the transmitting equipment, the receiving equipment, and the time for signal transit. The signal will also have an apparent delay introduced by the Sagnac effect as a result of the Earth's rotation during the transit period. The signal transit path is usually assumed to have total reciprocity, and, therefore, the transit time cancels to within a few hundred ps at most **[1].** Tables and standard formulae are available to determine the Sagnac value **[2]**. This leaves to be determined only the equipment delays involved. If these delays are unknown prior to TWSFT operations, a third two-way station may be employed, which is this is the calibration technique used at USNO and explained below.

Regarding the SATRE modems at USNO, there is one delay that is not included in this discussion. It may be thought of as a reference delay, as opposed to an equipment delay, because it can be attributed to equipment design and calibration issues rather than two-way theory. The SATRE modem phase-locks the master clock's 5 MHz source to the modem's internal oscillator. The output of the internal oscillator is then used to generate a coherent 1 PPS signal. It is this replicated 1 PPS signal that is used as a basis for two-way operations. The master clock's external 1 PPS signal supplied to the modem is precisely timed and is, therefore, representative of the site's time. However, because the signal delay through the cable that supplies the external 5 MHz source is arbitrary, the internally replicated 1 PPS signal is not generally in phase with the externally supplied 1 PPS. For this reason, our latest SATRE modems include an internal time-interval counter (TIC), which measures the phase delay between the two 1 PPS signals (but other systems measure the difference with an external counter). This correction is automatically applied by the software.

Consider the setup shown in Figure 3. For the sake of illustration, assume that Station A is the two-way station at the USNO, Station B is the client two-way station, and Station C is the portable station. The portable station is depicted twice in the figure: once as C1, when it is collocated with the USNO station; and once as C2, when it is collocated with the client station. With this design, derivation of the two-way equations is a simple matter of summing all the signal delays. For example, if T_{AB} is the total time delay for the transmitted signal from Station A (USNO) to Station B (the client station), then

$$T_{AB} = EDel_{TA} + \tau_A + \tau_B + EDel_{RB} + Sagnac + (\Delta B - \Delta A) + (RD_B - RD_A)\,, \tag{1}$$

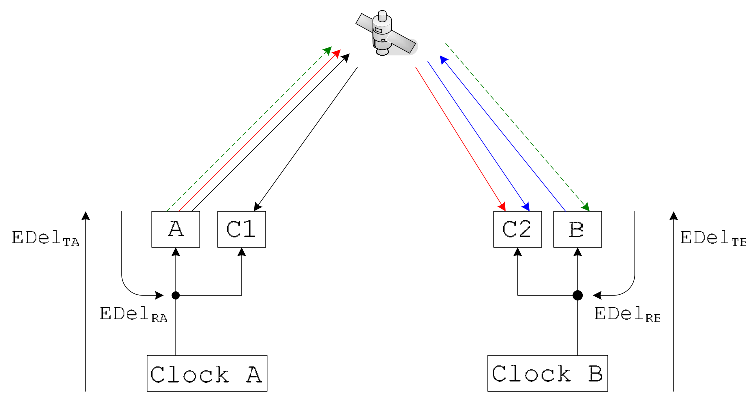

Figure 3. Common delays and signals of the two-way system. The portable system is moved from C1 to C2 and back.

where $EDel_{TS}$ is the transmitting equipment delay at site S, $EDel_{RS}$ is the receiving equipment delay at site S, τ_S is the transit time on path S (the path from Station S to the satellite), ΔA is the clock offset of Station A from UTC, ΔB is the clock offset of Station B from UTC, RD_A is the reference delay of the 1 PPS signal generated within the modem at Station A, and RD_B is the reference delay of the 1 PPS signal generated within the modem at Station B. Note that the arithmetic sign of the operations $(\Delta B - \Delta A)$ and $(RD_B - RD_A)$ is chosen in consideration of the fact that the value of T_{AB} is reported by the receiving modem (as opposed to the transmitting modem) and, as such, this value is determined through the use of a TIC, which starts counting at its 1 PPS tick and stops counting at the moment of demodulation of the received signal (and similarly for the receiver's and the transmitted signals).

Like Equation (1), an equation for the time delay of a signal transmitted from the client station to the USNO can be constructed as

$$T_{BA} = EDel_{TB} + \tau_A + \tau_B + EDel_{RA} - Sagnac + (\Delta A - \Delta B) + (RD_A - RD_B)\,. \tag{2}$$

The difference between Equation (1) and Equation (2) is

$$\Delta T_{AB} = (EDel_{TA} - EDel_{RA}) + (EDel_{RB} - EDel_{TB}) + 2(RD_B - RD_A) + 2Sagnac + 2\Delta t_{AB}\,, \tag{3}$$

where Δt_{AB} is the clock offset of Station A from Station B (see Figure 4 below).

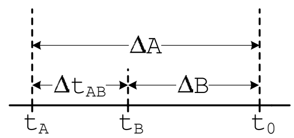

Figure 4. Timeline.

The system delays (i.e. the equipment delays plus the reference delays) can be extracted from Equation (3) and lumped together as

$$SDel = (EDel_{TA} - EDel_{RA}) + (EDel_{RB} - EDel_{TB}) + 2(RD_B - RD_A)\ . \tag{4}$$

Solving for $SDel$ begins by employing the portable station for a collocated two-way session at USNO, which produces the following equation:

$$\Delta T_{AC1} = (EDel_{TA} - EDel_{RA}) + (EDel_{RC1} - EDel_{TC1}) + 2(RD_{C1} - RD_A) + 2Sagnac + 2\Delta t_{AC1} \tag{5}$$

In a collocated two-way session, the Sagnac value is assumed to be zero. And, because the portable station uses the same time reference as the participating station, the value Δt_{AC1} is also zero. Equation (5) thus reduces to:

$$\Delta T_{AC1} = (EDel_{TA} - EDel_{RA}) + (EDel_{RC1} - EDel_{TC1}) + 2(RD_{C1} - RD_A) \tag{6}$$

From this point, the value $SDel$, given by Equation (4), can be solved by two different methods: (1) conduct a single collocated run involving the portable station and Station B, or (2) do two two-way sessions between Station A and the portable station, and Station A and Station B.

The simplest method for a direct realization of $SDel$ is the first method, which involves a single collocated run with the portable station and Station B, but requires Station B to have an antenna operating at the same frequency as the portable one. This collocated run yields the following equation:

$$\Delta T_{BC2} = (EDel_{TB} - EDel_{RB}) + (EDel_{RC2} - EDel_{TC2}) + 2(RD_{C2} - RD_B)\ , \tag{7}$$

where, as before, the portable station shares its 5 MHz clock reference with the cooperating collocated station, Station B.

Now, if none of the equipment of the portable station is changed between the time it is used at Station A and the time it is used at Station B, the equipment delays $EDel_{RC1}$ and $EDel_{RC2}$ will be equal, as will $EDel_{TC1}$ and $EDel_{TC2}$. Consequently, the value of $SDel$ is found simply by subtracting Equation (7) from Equation (6), and substituting Equation (4):

$$\boxed{SDel = \Delta T_{AC1} - \Delta T_{BC2} - 2(RD_{C1} - RD_{C2})} \tag{8}$$

Substitution of Equation (8) into Equation (3) produces the previously unknown value Δt_{AB}, which is the clock offset of Station A from Station B. Note, however, that Equation (3) is not necessary for the determination of $SDel$.

As previously mentioned, $SDel$ may also be found by conducting two two-way sessions, one between Station A and the Fly-Away (modeled below in Equation (9)), and one between Station A and Station B (which is modeled by Equation (3); it and Equation (6), for convenience, are repeated below).

$$\Delta T_{AB} = (EDel_{TA} - EDel_{RA}) + (EDel_{RB} - EDel_{TB}) + 2(RD_B - RD_A) + 2Sagnac + 2\Delta t_{AB} \tag{3R}$$
$$\Delta T_{AC2} = (EDel_{TA} - EDel_{RA}) + (EDel_{RC2} - EDel_{TC2}) + 2(RD_{C2} - RD_A) + 2Sagnac + 2\Delta t_{AC2} \tag{9}$$
$$\Delta T_{AC1} = (EDel_{TA} - EDel_{RA}) + (EDel_{RC1} - EDel_{TC1}) + 2(RD_{C1} - RD_A) \tag{6R}$$

The three equations shown above may be used to determine $SDel$. Note that, because Station C2 (i.e. the portable station, when located at Station B) and Station B share the same 5 MHz clock reference, ideally $\Delta t_{AB} = \Delta t_{AC2}$, as will be the case when both two-way sessions of Equations (3) and (9) are conducted simultaneously. However, under limitations of our hardware we are often unable to perform these two sessions simultaneously and, instead, we must conduct the sessions back-to-back. If we assume that we are making comparisons between two highly stable clocks, or clock conglomerates, this may not introduce noticeable error (as the clock at Station A will have a negligible drift, with respect to the clock at Station B, during the time that the two-way session of Equation (3) ends and the two-way session of Equation (9) begins). However, this may become a problem if one or both of the stations is using a clock with poor short-term stability. On the other hand, this method corrects for baseline-closure violations that afflict the results of the first method up to the ns level, and probably relate to bandwidth-gain mismatches.

Nevertheless, if we make the assumption that $\Delta t_{AB} = \Delta t_{AC2}$, the clock offset Δt_{AB} may be found by subtracting Equation (6) from Equation (9) as follows:

$$\Delta t_{AB} = \frac{\Delta T_{AC2}}{2} - \frac{\Delta T_{AC1}}{2} - (RD_{C2} - RD_{C1}) - Sagnac\ , \tag{10}$$

where the quantity $\frac{\Delta T_{XY}}{2}$ is the clock offset value reported directly by modem X, while in a two-way session with Station Y.

And substitution of Δt_{AB} and Equation (4) into Equation (3) produces the desired value:

$$\boxed{SDel = \Delta T_{AB} - \Delta T_{AC2} + \Delta T_{AC1} - 2(RD_{C1} - RD_{C2})} \tag{11}$$

In fact, we can further simplify the client's task by dividing Equation (11) by two and adding the Sagnac correction. Doing so reports a figure that may be subtracted from future modem clock readings to directly find the actual clock offset. This may be shown mathematically as follows:

$$\begin{aligned} CalibrationValue &= \frac{\Delta T_{AB}}{2} - \frac{\Delta T_{AC2}}{2} + \frac{\Delta T_{AC1}}{2} - (RD_{C1} - RD_{C2}) + Sagnac \\ FutureClockOffset &= \frac{\Delta T'_{AB}}{2} - CalibrationValue \end{aligned} \tag{12}$$

where $\frac{\Delta T'_{AB}}{2}$ is a future clock delay, reported directly by modem A. This is the method that is currently practiced at USNO.

Similar to Equation set (12), the first method may also be consolidated:

$$
\begin{aligned}
&CalibrationValue = \frac{\Delta T_{AC1}}{2} - \frac{\Delta T_{BC2}}{2} - (RD_{C1} - RD_{C2}) + Sagnac \\
&FutureClockOffset = \frac{\Delta T'_{AB}}{2} - CalibrationValue
\end{aligned}
\tag{13}
$$

Whichever method is chosen, the client is ultimately provided with a figure that permits him to conduct future two-way sessions for the tracking of his local clock time relative to USNO.

RESULTS

Calibration trips to client sites produce corrections which, if judged reliable, are applied to the operational time differences measured thereafter at USNO and the client site, at least until the next calibration trip or a significant change in the operational equipment occurs at either site or in the linking satellite. Such a change may involve equipment repair or replacement or may be simply a significant systematic fluctuation whose cause may or may not be understood. Often such a change is detected during regular operations, and a preliminary or "empirical" correction is applied until a site calibration can be performed. Such a correction is determined either from the stability of the underlying clocks or by comparison with the results of another time transfer method.

In order to assess the errors associated with the calibration corrections as independently of the operational equipment as possible, we looked at the differences between successive calibrations, assuming no significant uncorrected change occurred in both the operational and the calibration equipment. This assumption was verified through investigation of equipment records and testing of any change in calibration against its expected error of the average of two successive calibration corrections, assuming unchanged equipment. This error is the quadratic sum of the errors of the individual calibrations, which were assumed to be equal for a given site and are given in Table 1 for the five sites, where each pair of successive calibrations is denoted "x" and "y." The calculation of this error follows the test for equipment constancy, so some iteration was involved. The table also gives, for each site, the rms over all the pairs of calibrations.

The rms over the five sites in Table 1, weighting by the number of calibrations, is ±0.54 ns for time spans of up to 1805 days (summing continuous spans when the equipment is unchanged), depending on the site. There is no correlation between error (with or without sign) and time span. This error applies to a difference between two similar measurements, so presumably the total error of a single calibration is $\sqrt{2}$ times smaller, or ±0.38 ns. The internal errors in Table 1 apply to a single measurement; counting entries only once for each calibration, they average ±0.35 ns over the five sites.

The total uncertainty u_C, for a 1-sigma confidence level (68%), is given by:

$$u_C = \sqrt{u_A^2 + u_B^2}$$

where u_A is the type-A (internal random) uncertainty and u_B is the type-B (systematic) uncertainty **[3]**. Substituting u_C = ±0.38 ns and u_A = ±0.35 ns yields ±0.15 ns for the u_B of a single calibration measurement. Rms errors rather than Gaussian standard errors were computed in order to be conservative, but the data are still too limited to be sure of their error distribution, and precision is not tantamount to accuracy. Still, our results are consistent will previously published error claims of ≤ 1 ns.

Both the operational sites and the portable calibration equipment contribute to these errors. A measure of those errors contributed by the calibration equipment alone can be obtained by comparing the phase differences measured at USNO before and after each trip. These roundtrip-closure discrepancies are listed in Table 2 for six trips. The mean discrepancy for the Fly-away apparatus is 0.48 ± 0.36 ns and that of the SUV is 0.03 ± 0.23 ns, suggesting that the operational apparatus is at least as good as the calibration equipment.

CONCLUSION

We estimate a random error of ±0.35 ns, a type-B uncertainty of ±0.15 ns, and a total error of ±0.38 ns for a single calibration measurement with our portable TWSTT equipment over time spans of up to 4.9 years. For comparison, one-time calibrations of European timing labs with portable clocks have produced estimated random errors of ±0.7 ns and systematic errors of ±1.9 ns **[4]**. Closure discrepancies suggest that the operational apparatus is at least as good as the calibration equipment.

DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, USNO does not endorse any commercial product nor does USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

ACKNOWLEDGMENTS

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Table 1. Differences, errors, and Modified Julian Dates for successive calibration measurements at five USNO TWSTFT sites.

SITE	Calibration x - y (ns)	MJD of x	MJD of y	Difference (days)	Internal Errors (ns)	
					of x	of y
AMC	-0.281	50728.960	51338.712	609.752	±0.41	±0.29
	-0.440	51359.620	51631.770	272.150		0.84
	-0.565	51631.770	51966.674	334.904	0.84	0.83
	0.651	52350.037	52381.674	31.637	0.42	0.22
	-0.191	52381.674	52576.769	195.095	0.22	
	-0.467	52708.807	52957.867	249.060	0.28	0.32
	-0.357	52957.867	53177.833	219.966	0.32	0.17
	0.087	53177.833	53261.688	83.855	0.17	0.18
	rms: ±0.42					
PTB	0.646	51682.530	52436.621	754.091	0.40	0.14
	-0.517	52436.621	52667.525	230.904	0.14	0.38
	rms: ±0.59					
Sym-metri-com	-0.084	51863.065	52990.955	1127.890	0.08	0.06
	-0.184	52990.955	53248.644	257.689	0.06	0.16
	rms:±0.14					
TSC	1.608	51723.706	51963.303	239.597		0.34
	-0.552	51963.303	52149.735	186.432	0.34	
	0.687	52368.700	52709.915	341.215	0.49	0.41
	0.110	52709.915	53181.872	471.957	0.41	0.56
	rms: ±0.92					
VDB	0.176	51367.684	51639.795	272.111		0.67
	-0.610	51639.795	51940.692	300.897	0.67	0.33
	0.290	51940.692	52715.013	774.321	0.33	0.45
	-0.037	52715.013	52978.862	263.849	0.45	0.20
	-0.297	52978.862	53172.753	193.891	0.20	0.18
	rms: ±0.34					

Table 2. Closure discrepancies for six different calibration trips.

MJD OF START	MJD OF CLOSE	TIME SPAN (days)	CLOSURE DIFFERENCE (ns)	EQUIPMENT
51321.463	51344.068	22.605	0.120	Fly-away
52697.496	52802.664	105.168	0.293	SUV
52947.065	52984.058	36.993	0.364	SUV
53048.197	53194.866	146.669	0.839	Fly-away
53164.043	53194.019	29.976	-0.635	SUV
53230.797	53289.701	58.904	0.089	SUV