Recent Calibrations of UTC(NIST) - UTC(USNO)

Victor Zhang[1], Thomas E. Parker[1], Russell Bumgarner[2], Jonathan Hirschauer[2], Angela McKinley[2], Stephen Mitchell[2], Ed Powers[2], Jim Skinner[2], and Demetrios Matsakis[2]

[1]Time and Frequency Division of the National Institute of Standards and Technology,
325 Broadway, Boulder, Colorado, U.S.A.

[2]Time Service Department of the United States Naval Observatory,
3450 Massachusetts Ave., NW, Washington, DC, U.S.A.

vzhang@boulder.nist.gov

Abstract—The National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO) use GPS common-view, carrier-phase time transfer and Two Way Satellite Time and Frequency Transfer (TWSTFT, also known as TWSTT) techniques in our time and frequency transfer applications and to compare our timescales. We have made five time transfer calibration measurements via TWSTFT since August 2010. In addition, one "hybrid" calibration was made via a cesium clock trip and TWSTFT, and another was made with a traveling GPS receiver. The TWSTFT calibrations agree with the TWSTFT differences within 1.6 ns peak to peak after the USNO TWSTFT station was rebuilt at the end of 2010. With the traveling GPS receiver, we used the carrier-phase Precise Point Positioning (PPP) technique to obtain the calibration result. If we use the TWSTFT calibration results to calibrate the operational PPP data, then the TWSTFT calibrations are also consistent with operational PPP to within 1.6 ns peak to peak. The calibration via PPP differs by 7 ns from that of the TWSTFT. The difference is most likely from the error in delay calibration of the PPP link. The hybrid calibration is consistent with the others, if its larger estimated uncertainties are taken into account. The possibility of reducing the uncertainties assigned by the BIPM is discussed.

I. INTRODUCTION

According to the America Competes Act of 2007, Coordinated Universal Time (UTC) is the official time for the United States and the responsibilities for its realization are shared by NIST and USNO. By mutual agreement, the difference between the two timescales, UTC(NIST) and UTC(USNO), should not exceed 100 ns.

NIST and USNO contribute their atomic clock data to the computation of UTC generated by the International Bureau of Weights and Measures (BIPM). The official time differences of UTC - UTC(NIST) and UTC - UTC(USNO) are reported in the BIPM's monthly *Circular T* publication. They are currently based on the time and frequency transfer through the Physikalisch-Technische Bundesanstalt (PTB) in Germany. The type B (systematic) uncertainty of UTC(NIST) to UTC currently assigned by the BIPM is 5.1 ns, because the NIST/PTB link was calibrated by code-based GPS common-view [1] time transfer about nine years ago. The current BIPM-assigned type B uncertainty of UTC(USNO) to UTC is 3.8 ns and the USNO/PTB link has been calibrated yearly, on average, with the USNO portable TWSTFT equipment, as well as one GPS experiment [2]. Therefore the total type B uncertainty of UTC(NIST) – UTC(USNO) from *Circular T* is 6.3 ns. We use GPS common-view, carrier-phase [3] time transfer and TWSTFT [4] methods in our time and frequency transfer applications. These methods are also used to compare and to monitor the UTC(NIST) and UTC(USNO) time difference on a daily basis. GPS time transfer and TWSTFT are two independent comparisons, and their relative system delay variations could be at the nanosecond-level over one year and longer.

In this paper, we study the time comparison of UTC(NIST) and UTC(USNO) starting from 2010. This paper therefore does not cover variations on order of 3 ns in the USNO and perhaps the PTB Ku-band TWSTFT systems from the fall of 2008 to the summer of 2009. We present, but ignore the 2010 USNO Ku-band operational TWSTFT data, because that system was rebuilt and recalibrated at the end of that year. Section II shows the UTC(NIST) – UTC(USNO) differences as obtained from the GPS common-view, the BIPM's PPP reductions of GPS carrier-phase (TAIPPP) [5], Ku-band TWSTFT and *Circular T* [6]. In Section III, we discuss the UTC(NIST) – UTC(USNO) calibration results from the USNO mobile TWSTFT equipment, a traveling GPS receiver and a hybrid clock trip plus TWSTFT measurement. We conclude our study in Section IV.

II. THE UTC(NIST) AND UTC(USNO) TIME TRANSFER RESULTS

NIST has used a dual-frequency, multi-channel (geodetic) GPS receiver as the primary timing receiver since July of 2006. For brevity, we shall refer to geodetic receivers, along with their antennas and associated electronics by their italicized International Global Navigation Satellite System (GNSS) Service (IGS) designations. The IGS designation of the NIST primary timing receiver is *NIST*. Data from the *NIST* receiver is used for both common-view and carrier-phase time and frequency comparisons. The *NIST* receiver has not been calibrated via a BIPM traveling receiver. Its internal delay on the L1 frequency is translated from the previous NIST primary timing receiver. The previous receiver is a single-channel GPS common-view receiver that was last calibrated by a BIPM traveling receiver in December of 2003. USNO used a single-frequency, multi-channel receiver for common-view comparisons from 2000 to 2011. The common-view data are now from a geodetic receiver (*USN3*). The *USN3* receiver has been used for carrier-phase comparison since the late 1990's. The GPS carrier-phase has been USNO's primary link to UTC since August 2010. Both of the USNO receivers have been calibrated by BIPM traveling receivers. The *USN3* receiver was also absolutely calibrated [7] in 2000; however, the calibration was not adjusted after certain system configuration changes and temperature-induced calibration jumps.

NIST and USNO have participated in the Ku-band transatlantic TWSTFT since the mid 1990's. Since 2002, the TWSTFT measurements with each European station have been made in a two-minute session, usually during the even hours of every day. The odd hours are used occasionally for link testing and experiments. The NIST/PTB TWSTFT link has been the NIST's primary link to UTC since 2002. The delay of the NIST/PTB TWSTFT link was initially estimated from the NIST/PTB GPS common-view comparison. The subsequent delay changes due to the changes of satellite, transponder, link frequency and equipment have been estimated with the bridging method utilizing both overlapping TWSTFT measurements and the GPS carrier-phase comparisons. USNO operated TWSTFT links on both Ku-band and X-band frequencies. The USNO/PTB X-band TWSTFT link was the USNO's primary link to UTC from May 2005 to July 2010. Both of the USNO/PTB Ku-band and X-band TWSTFT links have been, on average, calibrated yearly by use of the USNO portable TWSTFT equipment. Although NIST and USNO both participate in the Ku-band transatlantic TWSTFT, NIST and USNO have no direct TWSTFT link because NIST's only earth station is used for the transatlantic TWSTFT and we cannot receive each other's signal from the satellite used for the transatlantic TWSTFT. The NIST/USNO Ku-band TWSTFT comparison is obtained from the NIST/PTB and USNO/PTB Ku-band TWSTFT differences.

The UTC(NIST) – UTC(USNO) time differences as obtained from common-view, TAIPPP and TWSTFT are shown in Figure 1 for data period starting in 2010 (MJD from 55197). The differences from *Circular T* are also included as a reference. The common-view differences were corrected with the IGS measured ionospheric delay but not the IGS orbit corrections. Figure 1 shows the TWSTFT difference after the rebuild of USNO TWSTFT station at the end of 2010. We have corrected the excursions and offsets caused by the known equipment and reference signal changes in the TWSTFT differences. The TAIPPP differences are obtained from the BIPM monthly processing results with the delay corrections reported by both NIST and USNO. The UTC(NIST) – UTC(USNO) time difference is within ±16ns from 2010 to 2012. There are biases among the three time transfer results, and the biases vary over a few nanoseconds during the data period.

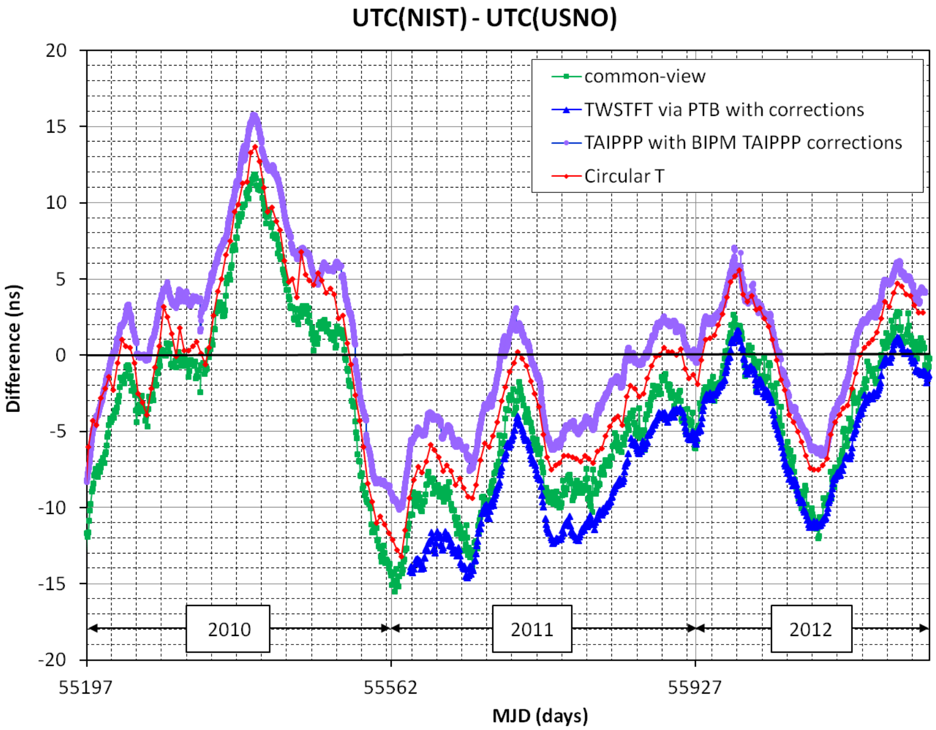

Figure 1. UTC(NIST) – UTC(USNO) time difference as obtained from GPS common-view, TAIPPP of GPS carrier-phase, TWSTFT and *Circular T* from 2010 to 2012.

Figure 2 shows the double-differences of the three time transfer results, by use of the data of Figure 1. Figures 3 and 4 display the analogous double differences for UTC(NIST) – UTC(PTB) and UTC(USNO) – UTC(PTB).

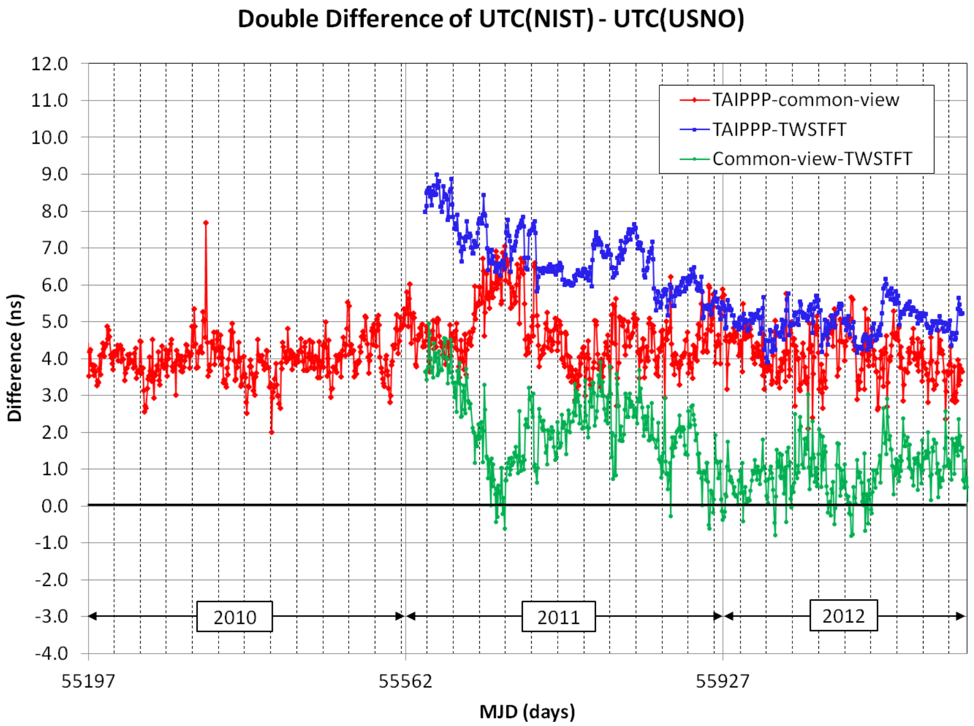

Figure 2. Double difference of UTC(NIST) – UTC(USNO) between three time transfer results. The double differences are computed with the data shown in Figure 1.

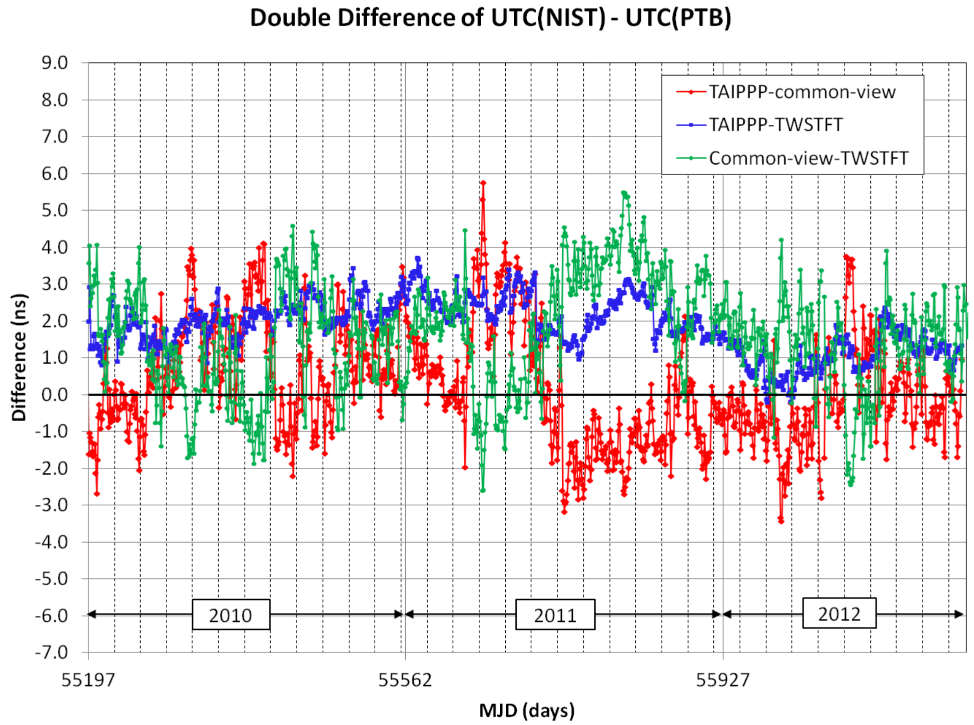

Figure 3. Double difference of UTC(NIST) – UTC(PTB) between three time transfer results.

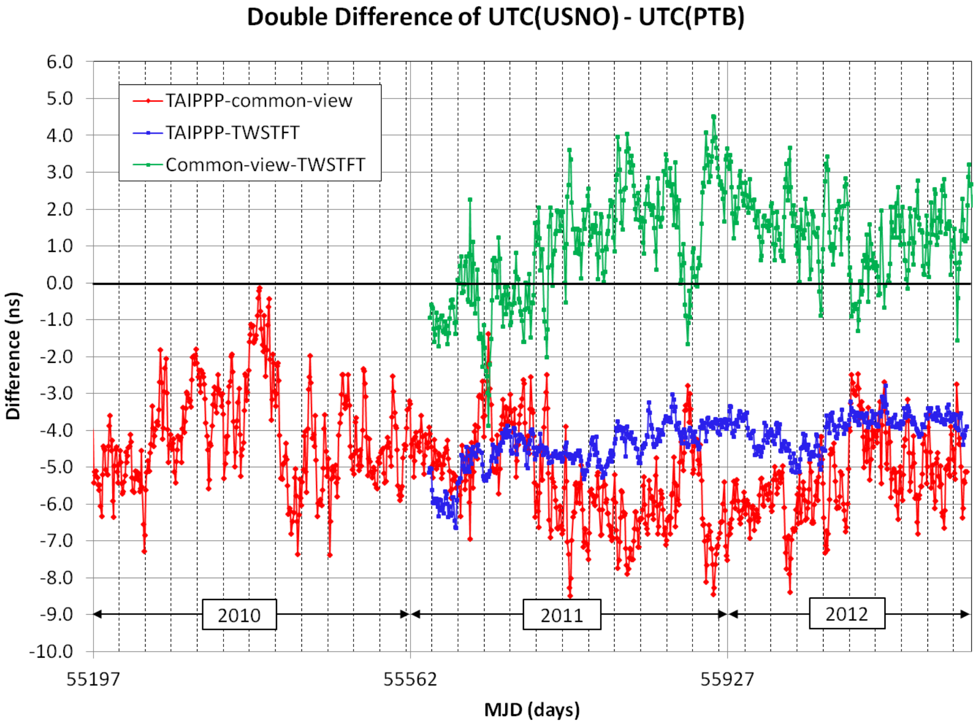

Figure 4. Double difference of UTC(USNO) – UTC(PTB) between three time transfer results.

The calibration offsets evident in the figures are due to lack of calibration, lack of recent calibration, and/or a decision not to change the calibration of non-operational links. In addition, the changes made to the USNO's TWSTFT configuration in early 2011 result in a 3 to 4 ns variation in all of its associated links. Although not obvious in the figures, the BIPM's PPP reductions show a 1 ns time step beginning at a day boundary for the receiver *NIST* on MJD 55712 (May 31, 2011) that is not observed in the USNO reductions of the same data. The USNO reductions are used in Table 1 of Section III; however, use of the BIPM's would not significantly alter the conclusions.

III. THE UTC(NIST) - UTC(USNO) CALIBRATIONS

The type B uncertainty of a time transfer link is a measure of how well we know the time transfer link delay, and this ideally depends on the precision of the calibration measurement, the ability to eliminate or measure systematic effects, and the amount of unpredictable systematic variation expected between calibrations. The delay varies over time due to environment change and equipment aging. The delay can be changed because of the change of equipment and reference signals for time transfer operations. The TWSTFT link delay can also be changed by the changes of satellite, transponder on the satellite and uplink/downlink frequencies. In recent years, several successful calibrations of the UTC(NIST) - UTC(USNO) time difference have been made by the USNO's mobile TWSTFT station and a traveling GPS receiver. One portable clock trip was also made between NIST and USNO Alternate Master Clock (AMC), which is calibrated against the USNO's Washington facility via TWSTFT.

The mobile station is calibrated with respect to the USNO master station using UTC(USNO) as the reference signal to determine the delay of the mobile station relative to the master station. At a remote location, the mobile station can directly use the remote clock as a TWSTFT reference, or it can use its portable cesium clock as a TWSTFT reference and transfer means to the remote site's clock. When visiting NIST, the measurements of a TWSTFT calibration usually last 2 to 3 hours. The measurement is therefore sensitive to diurnal variations, which could be at nanosecond-level and peak at roughly the same time of day. A traveling GPS receiver calibration is done in a similar way. The traveling receiver is calibrated with respect to the USNO primary receiver to determine its relative delay. The traveling receiver is then set up in a remote location and measures the difference between the remote clock and the GPS timing information. When we difference the measurements made by the traveling receiver at a remote location and the measurements made by the USNO primary receiver at the same time, we obtain the time difference of the remote clock and UTC(USNO). A traveling GPS receiver calibration usually lasts from 3 to 7 days. The NIST/USNO GPS calibration was done with the carrier-phase PPP comparison. The mobile TWSTFT station and traveling GPS receiver are calibrated again after they return to USNO to make sure the delay change is within the error budget. The closure measurements of the TWSTFT and PPP calibrations made in 2012 were less than 1 ns. For the portable clock calibration, a cesium clock was measured against the AMC timescale before the trip. The cesium clock was then transported to NIST and measured against UTC(NIST). After the clock returned to AMC a few hours later, it was again measured against the AMC timescale. The time difference between AMC and UTC(NIST) was obtained from the interpolation of the measurements of the portable clock and AMC timescale before and after the trip. The AMC timescale is synchronized to UTC(USNO) via TWSTFT, and would therefore be subject to any variations of the AMC-USNO TWSTFT calibration. We obtained UTC(NIST) - UTC(USNO) from the portable clock calibration by differencing the AMC – UTC(USNO) and AMC - UTC(NIST).

For this work we are taking the PPP delay calibrations as unknown, to be determined by zeroing the average difference between the GPS data and the calibration via TWSTFT. This is because the *USN3* receiver's absolute calibrations were made long before the period in question, and adjustments were not always made for configuration changes, particularly before the receivers became operational. Also, the *NIST* receiver's internal receiver delay on the L1 frequency was translated from the single channel receiver calibrated about nine years ago, and the delay on the L2 frequency used in the PPP time transfer has never been calibrated.

The uncertainties from the hybrid calibration can be estimated as the Root Sum Square (rss) of the uncertainty of the TWSTFT calibration of AMC-USNO and the uncertainty of the cesium clock trip between the AMC and NIST. With a 0.4 ns type A uncertainty for the portable clock's stochastic variations, an additional 1 ns of uncertainty for the calibration of the AMC-USNO link, and 300 ps for the cesium measurements at AMC and NIST, the combined rss uncertainty is 1.3 ns. Recognizing that the automobile ride subjects the cesium to a different and more variable environment and electric power source, we estimate the uncertainty to be 2 ns.

The calibration results are shown in Figure 5 and summarized in Table 1. In Table 1, the TWSTFT data of 2010 are shown with an asterisk (*), since they predate the significant upgrade at the USNO site in early 2011. USNO's common-view receiver was switched to *USN3* in January 2012; data prior to that are shown with a double-asterisk (**). The calibration types of TW, Cs +TW and PPP stand for the calibrations with mobile TWSTFT station, portable cesium clock with TWSTFT, and traveling GPS receiver carrier-phase PPP techniques. The CirT, PPP, TW and CV are the UTC(NIST) – UTC(USNO) time difference as obtained from *Circular T*, PPP, TWSTFT and GPS common-view time transfer results. From these results, we see

1. The calibration of the operational TWSTFT and PPP systems has stayed constant to sub-nanosecond levels RMS over the period in question, as judged by TWSTFT-only calibrations and if we exclude the changes made to the USNO TWSTFT system in 2010.
2. The calibration of the hybrid TWSTFT and traveling cesium clock systems was not as good; however, it was consistent with the larger expected uncertainties of the traveling clock trip.
3. The calibrations via PPP and TWSTFT carried out on July 12, 2012 (MJD 56121) show a 7.1 ns difference. We suspect the offset between the two is most likely from the GPS measurement, because this particular traveling GPS system has differed semi-randomly with TWSTFT calibrations of other sites that also have a consistent calibration history with TWSTFT.

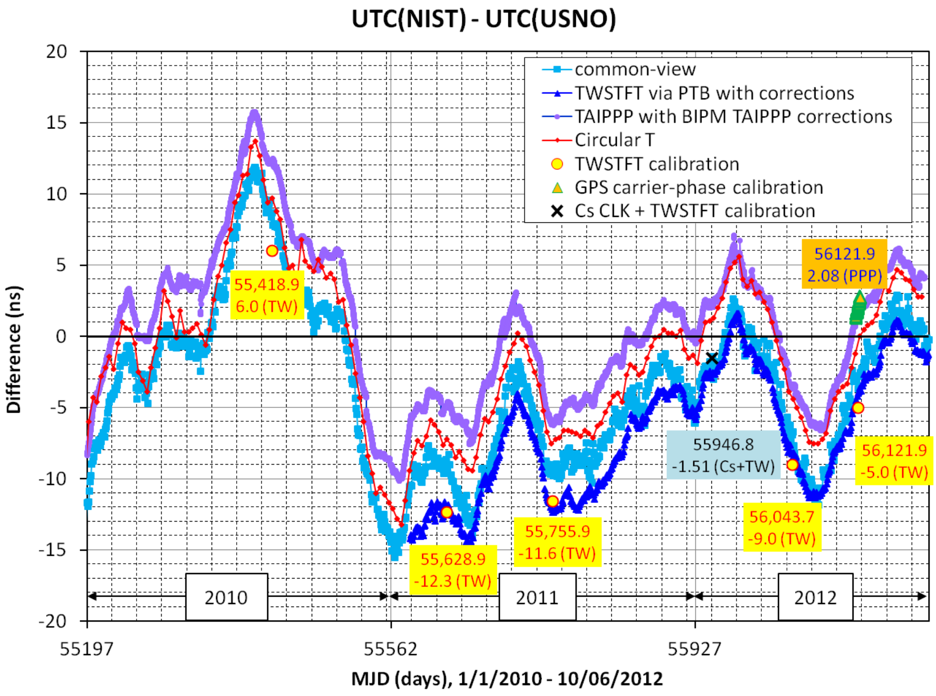

Figure 5. The UTC(NIST) – UTC(USNO) Time Differences and Calibrations.

Table 1. Summary of Calibrations.

Date/MJD	Calibration		CirT (ns)	CAL-CirT (ns)	CV (ns)	CAL-CV (ns)	PPP Shifted -93.7 (ns)	CAL-PPP shifted (ns)	TW (ns)	CAL-TW (ns)
	Type	NIST-USNO (ns)								
2010-08-10 55418	TW	6.0	9.6	-3.6	8.5	-2.5**	6.2	-0.2	12.8*	-6.8*
2011-03-08 55628	TW	-12.3	-7.3	-5.0	-9.0	-3.3**	-11.4	-0.9	-11.9	-0.4
2011-07-13 55755	TW	-11.5	-7.4	-4.1	-7.9	-3.6**	-11.4	-0.1	-12.3	0.8
2012-01-20 55946	Cs+TW	-1.5	1.3	-2.8	-2.1	0.6	-3.7	2.2	-2.9	1.4
2012-04-26 56043	TW	-9.0	-4.4	-4.6	-6.8	-2.2	-9.7	0.7	-8.6	-0.4
2012-07-12 56121	TW	-5.0	-0.8	-4.2	-3.4	-1.6	-4.3	-0.7	-4.2	-0.8
	PPP	2.1		2.9		5.5		6.4		6.3

IV. CONCLUSIONS

NIST and USNO use GPS common-view, TAIPPP of GPS carrier-phase time transfer, and TWSTFT techniques to compare UTC(NIST) and UTC(USNO) on a daily basis. The UTC(NIST) and UTC(USNO) have been kept within ±16ns since 2010. The *Circular T* results differ from the calibration results by 5 ns or less which is consistent with the 6.3 ns type B uncertainty from the *Circular T* publication.

The TWSTFT calibrations and the TWSTFT differences via PTB are within 1.6 ns peak to peak after the USNO Ku-band TWSTFT station was rebuilt at the end of 2010. If we use the TWSTFT calibration results to calibrate the operational PPP data, then the TWSTFT calibrations are also consistent with operational

PPP to within 1.6 ns peak to peak. The traveling GPS receiver's PPP calibration and the TAIPPP results are also within 0.5 ns. However, there is a 7.1 ns offset between the TWSTFT and GPS PPP calibrations performed on the same date. The offset is most likely from the error in calibration of the NIST/USNO GPS PPP link.

The ability to hold relative calibration to the sub-nanosecond level indicates that the type B uncertainties for the NIST/USNO link assigned by the BIPM could in principle be significantly decreased. In order to justify this, it will be important to have multiple systems at all relevant sites (include the pivot site that is currently the PTB) to ensure that calibration variations do not occur. We note that USNO, NIST, and PTB are in the process of upgrading their GNSS capability, and this will be a crucial step. Another step is to achieve routine consistency between calibrations via TWSTFT and via GNSS.

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