Long-Term Uncertainty in Time Transfer Using GPS and TWSTFT Techniques

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***Abstract*—The techniques of GPS time and frequency transfer (code based and carrier phase) and TWSTFT are widely used in remote clock comparison and in the computation of TAI and UTC. Many timing laboratories in the world utilize both techniques (GPS and TWSTFT transfer links) to compare each other's clocks. A time link must be calibrated to assure the time transfer accuracy. In many cases, calibration campaigns have been very infrequent due to the expense and lack of suitable equipment. In lieu of repeated calibrations, some information regarding the long-term stability of these links can be obtained through comparisons between the two links (a so called double difference). Without frequent calibrations it is impossible to tell where the instabilities originate, but information regarding the magnitude of the instabilities can be obtained from double difference data. We have been investigating the combined variations of GPS and TWSTFT links for a number of laboratory pairs, including both long and short baselines. Our results show that the relative change between GPS and TWSTFT transfer links can be as large as 6 to 7 ns over a few years and that all of the laboratory pairs that have been investigated show similar magnitudes in the double difference data. Currently the longest set of good double difference data is about 7 years. The study results point out the need for frequent calibration campaigns if accuracies at the nanosecond level are required.**

Keywords—time and frequency transfer; GPS carrier-phase time and frequency transfer; Precise Point Positioning; Revived Rinex-Shift Algorithm; two-way satellite time and frequency transfer; time transfer link calibration; Type A and Type B time and frequency transfer uncertainty.

I. INTRODUCTION

Time and Frequency transfer is used to compare remote clocks or frequency standards. It is also an integral part of the generation of International Atomic Time (TAI) and Coordinate Universal Time (UTC). Timing laboratories around the world use time and frequency transfer to contribute data from their clocks and primary frequency standards to the computation. The International Bureau of Weights and Measures (BIPM) computes TAI and UTC. The monthly Circular T publication [1] reports TAI – TAI(*k*) and UTC – UTC(*k*), where TAI(*k*) and UTC(*k*) are a laboratory *k*'s real-time realization of TAI and UTC.

According to the Circular T 326 published on March 10, 2015, 69 of the 71 contributing laboratories used Global Positioning System (GPS) code and carrier-phase time and frequency transfer [2, 3, and 4] and two-way satellite time and frequency transfer (TWSTFT) [5] to transfer their clock data to the computation. Many laboratories in Asia, Europe and the United States employ both of the techniques or transfer links for remote clock comparisons and the TAI/UTC computation. The uncertainty of each link is a combination of the Type A and Type B uncertainties. The Type A uncertainty is mainly introduced by the stability of the time and frequency transfer technique used, and the Type B uncertainty is a measure of the time transfer accuracy, which is dominated by the uncertainty of link delay calibration. The typical Type A uncertainty for the GPS carrier-phase links ($Link_{GPSCP}$) and the TWSTFT links ($Link_{TW}$) is 0.3 ns. We will focus on the $Link_{GPSCP}$ for GPS time and frequency transfer in this paper. The Type B uncertainty of a link depends on several aspects, such as how the link was calibrated. In recent years, many successful link calibration campaigns have reported the calibration uncertainty at about 1 ns using traveling dual-frequency GPS receivers with the GPS carrier-phase solutions and using mobile TWSTFT stations [6, 7]. The Type B uncertainty for these recent calibrated links is from 1 to 1.2 ns in Circular T 326.

The Type B uncertainty of a time transfer link is also associated with effects other than calibration uncertainty. After a calibration, any change in the link, such as the delay change due to equipment aging or malfunction, will change the calibration result and therefore increase the uncertainty. Therefore, it is necessary to have frequent calibrations in order to keep the Type B uncertainty of a time transfer link as close to the calibration uncertainty as possible. However, some laboratories' link calibrations have been very infrequent (no calibration for two and more years) due to the expense and lack of suitable equipment. In lieu of repeated calibrations, some information regarding the long-term stability of $Link_{GPSCP}$ and $Link_{TW}$ between two laboratories can be obtained through comparisons between the two links (a so called double difference). Because the $Link_{GPSCP}$ and $Link_{TW}$ between two laboratories compares the same pair of remote clocks, the double difference removes the clock difference, and reveals the combined relative change between the two links. Although it is impossible to tell where the changes or instabilities originate, information regarding the magnitude of the instabilities can be obtained from double difference data.

In this paper, we use the double difference technique to study the long-term uncertainty in $Link_{GPSCP}$ and $Link_{TW}$ among the National Institute of Standards and Technology (NIST) in Boulder, Colorado, the LNE-SYRTE, Observatoire de Paris (OP) in France, the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the U.S. Naval Observatory (USNO) in Washington, DC. The four timing laboratories are chosen because all of them have had stable $Link_{GPSCP}$ and $Link_{TW}$ data for more than four years. The four laboratories also enable the study to cover the time transfer links between the timing laboratories in Europe and the USA as well as the links within both Europe and the USA. Section II shows how we prepared the $Link_{GPSCP}$ and $Link_{TW}$ data for the study. We then present the study results in Section III and summarize the study in Section IV.

II. THE GPS CARRIER-PHASE, TWSTFT AND DOUBLE DIFFERENCE DATA

We use the BIPM TAIPPP [8] solutions as the $Link_{GPSCP}$ in remote clock comparisons. The TAIPPP solution uses the precise point positioning (PPP) technique to obtain difference between a GPS receiver's reference clock (REF) and rapid product of the International GNSS Service Time (IGRT). The BIPM started the TAIPPP process in April 2008. The monthly TAIPPP solution for a laboratory contains the REF-IGRT difference over a 35-day or 40-day period. We can apply the delay correction involved in the GPS carrier-phase measurements to each of the TAIPPP solutions and then difference the two laboratories' delay-corrected TAIPPP solutions of the same time stamp to obtain the time difference of the $Link_{GPSCP}$ between the two laboratories. The TAIPPP solutions contain a data boundary discontinuity due to noise of the pseudo-range measurements. To study if the 35-day or 40-day data boundary discontinuity affects the long-term uncertainty of the $Link_{GPSCP}$, we compared the TAIPPP results to the Revised Rinex-Shift PPP (RRSPPP) results [9, 10]. The RRSPPP is an algorithm developed at NIST to minimize data boundary discontinuity and to handle data anomalies, which are achieved by continuously processing multi-day data batches with the successive data batch advanced to one day later, and producing a PPP carrier-phase solution at the mid-point of each multi-day data batch. Fig. 1 shows the double difference of TAIPPP - RRSPPP for comparing UTC(NIST) and UTC(PTB) over a period of more than six years. The TAIPPP agrees with RRSPPP to within ±0.5 ns most of the time, indicating that data boundary discontinuity from the TAIPPP solutions will not deviate for more than 1 ns in the long-term stability of $Link_{GPSCP}$ study.

NIST, OP, PTB and USNO all participate in the transatlantic TWSTFT. OP and PTB also take part in the Europe-to-Europe TWSTFT. We do not have a direct TWSTFT link between NIST and USNO. The TWSFT between NIST and USNO are obtained from the difference of [UTC(NIST) – UTC(PTB)] - [UTC(USNO) – UTC(PTB)]. The regular TWSTFT measurements are made during even hours, 12 times a day. Each laboratory's TWSTFT measurements are reported in a daily file in the format according to the International Telecommunication Union (ITU) recommendation, ITU-R TF.1153 [11]. In addition to the measurements, the file contains information of link calibrations, delays of the local reference signal and TWSTFT equipment. When we compute the TWSTFT difference of two remote clocks, we difference the two TWSTFT measurements with corrections of link calibration and delays of reference signal and equipment of each TWSTFT station.

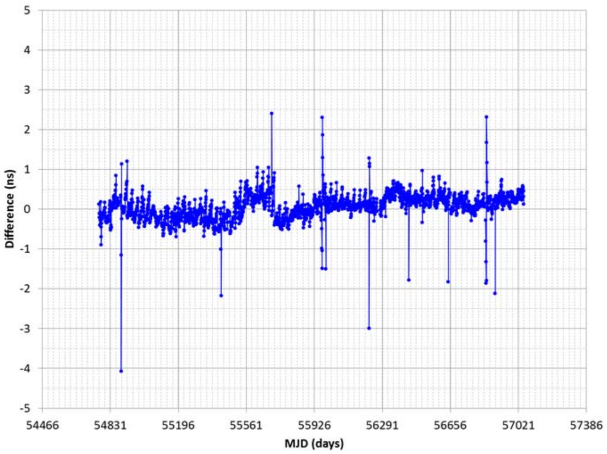

Fig. 1. Double difference of the daily averaged TAIPPP – RRSPPP for the UTC(NIST) – UTC(PTB) comparison. Data period is from November 2008 to January 2015.

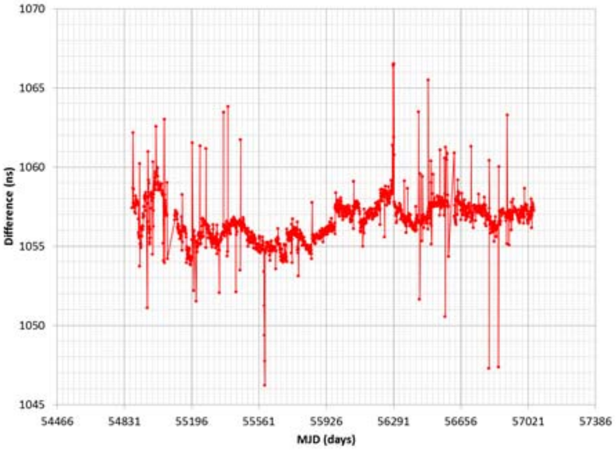

Fig. 2. Double difference of the daily averaged $Link_{TW}$ - $Link_{GPSCP}$ for the UTC(NIST) – OPH comparison. Data period is from February 2009 to January 2015

The reference signals for both $Link_{GPSCP}$ and $Link_{TW}$ at NIST, PTB and USNO are derived from UTC(NIST), UTC(PTB), and UTC(USNO), respectively. Each of the links' delay correction is available for comparisons between two laboratories. However, the reference signals for OP's GPS carrier-phase and TWSTFT links are directly from a hydrogen Maser clock, and sometimes from two different hydrogen Maser clocks. The delay corrections for converting the reference Maser clock to UTC(OP) are included in the TWSTFT data files, but we don't have the information for OP's TAIPPP data. To cancel the OP's reference clock (OPH) in the double difference, we first compute the daily averaged

TWSTFT and TAIPPP data, then difference the daily averaged TWSTFT and TAIPPP data when both used the same reference clock, and finally remove the estimated time steps due to the different delays in the TWSTFT and GPS carrier-phase measurements. Fig. 2 shows the UTC(NIST) and OPH comparison result obtained from the procedures described above. The result contains many larger than 5 ns outliers from unknown causes. The outliers do not obscure the long-term trend between the $Link_{GPSCP}$ and $Link_{TW}$. Thus, we will disregard the outliers and use the cleaned-up double difference in the analysis.

In the next section, we analyze the $Link_{TW}$ - $Link_{GPSCP}$ double difference for comparisons of NIST/OP, NIST/PTB, USNO/OP, and USNO/PTB over the transatlantic baseline and NIST/USNO and PTB/OP over the United States and Europe baselines. The double difference of the NIST/PTB comparison covers the period of MJDs from 54553 (March 28, 2008) to 57051 (January 29, 2015). The NIST/OP comparison has the second longest double difference stretch (MJDs 54874 – 57051, February 12, 2009 – January 29, 2015). The data used in the PTB/OP comparison is over MJDs 55104 – 57051 (September 30, 2009 – January 29, 2015). The USNO TWSTFT facility finished renovation at the end of 2010. The double differences involving USNO start on MJD 55562 (January 1, 2011) and end on MJD 57051 (January 29, 2015).

III. THE LONG-TERM STABILITY OF GPS CARRIER-PHASE AND TWSTFT LINKS

The double difference of comparisons among NIST, OP, PTB and USNO are grouped in Fig. 3 through Fig. 5. The figures show the $Link_{GPSCP}$ and $Link_{TW}$ can differ by more than 1 ns relative to each other over a one-year period. From MJD around 56261 (December 2012) to MJD 57051 (January 2015), the double differences for the UTC(NIST) – UTC(PTB) and UTC(NIST) – UTC(USNO) in Fig. 3 show about a 6 ns decrease, while the double differences for the UTC(USNO) – OPH and UTC(PTB) – OPH comparisons in Fig. 4 show about a 3 ns increase. On the other hand, the double differences for the UTC(NIST) – OPH and UTC(USNO) – UTC(PTB) comparisons do not have big changes except for the about 2 ns change around MJD 56291 in the UTC(NIST) – OPH comparison and the about 3 ns change after MJD 56940 (October 2014) in the UTC(USNO) – UTC(PTB) comparisons. There is no evidence that the relative changes between $Link_{GPSCP}$ and $Link_{TW}$ are baseline related.

The changes in Fig. 3 could come from a decrease in the NIST $Link_{TW}$ - $Link_{GPSCP}$. It is also possible the downward change is caused by an increase of $Link_{TW}$ - $Link_{GPSCP}$ from USNO and PTB and that both laboratories change in the same direction by similar amount. This possibility can be seen in Fig. 4 for the upward change in the double differences for the UTC(USNO) – OPH and the UTC(PTB) – OPH comparisons. However, we can also argue the upward changes are caused by a decrease in OP's $Link_{TW}$ - $Link_{GPSCP}$. There is no obvious upward or downward change in Fig. 5 for the double differences of UTC(NIST) – OPH and UTC(USNO) -

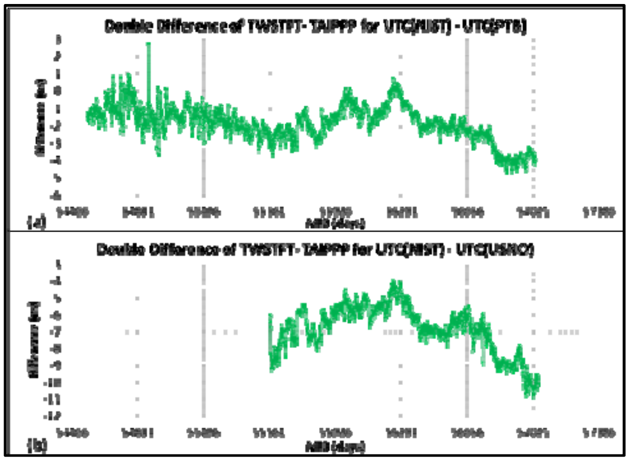

Fig. 3. Double differences of the daily averaged $Link_{TW}$ - $Link_{GPSCP}$ for the UTC(NIST) – UTC(PTB) and UTC(NIST) – UTC(USNO) comparisons. Each division in the horizontal axis is about one year, starting in 2008

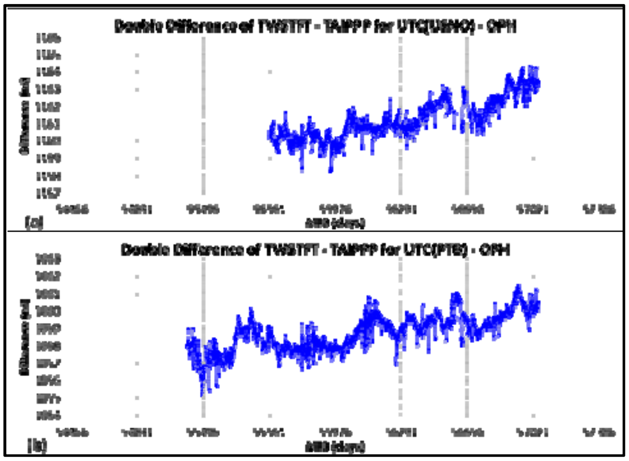

Fig. 4. Double differences of the daily averaged $Link_{TW}$ - $Link_{GPSCP}$ for the UTC(USNO) – OPH and UTC(PTB) OPH comparisons. Each division in the horizontal axis is about one year, starting in 2008.

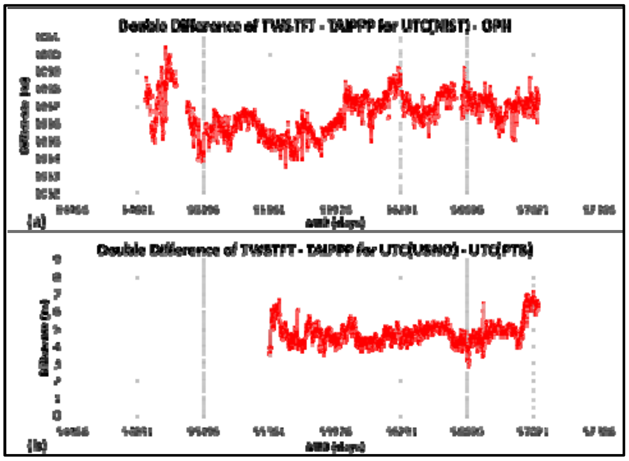

Fig. 5. Double differences of the daily averaged $Link_{TW}$ - $Link_{GPSCP}$ for the UTC(NIST) – OPH and UTC(USNO) – UTC(PTB) comparisons. Each division in the horizontal axis is about one year, starting in 2008.

TABLE I. USNO mobile TWSTFT calibration record. The TWSTFT Diff and TAIPPP Diff are UTC(NIST) – UTC(USNO).

TWSTFT Diff		TAIPPP Diff		TW CAL		TW CAL-TW	TW CAL-PPP
Date/Time	Diff (ns)	Date/Time	Diff (ns)	Date/Time	Diff (ns)	(ns)	(ns)
55628.49	-11.9	55628.90	-4.9	55628.90 (03/08/2011)	-12.3	-0.4	-7.5
55755.50	-12.3	55755.90	-6.2	55755.87 (07/13/2011)	-11.6	0.8	-5.4
56043.74	-8.6	56043.69	-3.5	56043.67 (04/26/2012)	-9.0	-0.5	-5.5
56121.49	-4.2	56121.90	1.6	56121.89 (07/13/2012)	-5.0	-0.8	-6.6
56365.49	11.6	56365.10	17.3	56365.09 (03/14/2013)	12.0	0.4	-5.2
56604.53	-4.5	56604.90	1.4	56604.88 (11/09/2013)	-4.6	-0.1	-6.0
56730.49	-8.5	56730.73	-2.5	56730.72 (03/14/2014)	-7.6	0.9	-5.1
56953.49	-15.8	56953.83	-7.5	56953.83 (10/23/2014)	-15.7	0.1	-8.2

UTC(PTB) comparisons. The result does not necessarily mean there is no relative change in the $Link_{TW}$ and $Link_{GPSCP}$ between NIST and OP or between USNO and PTB. The $Link_{TW}$ - $Link_{GPSCP}$ changes for comparisons between NIST and OP or between USNO and PTB can be canceled if the changes are in the same direction and at about the same magnitude.

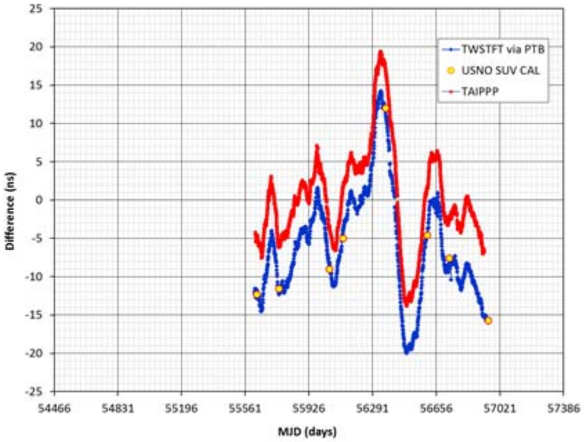

Fig. 6. UTC(NIST) – UTC(USNO) time transfer and mobile TWSTFT calibrations.

With the double differences, we are able to see that $Link_{TW}$ and $Link_{GPSCP}$ are changing relative to each other over the period of study, but unable to answer the question of which of the links of a remote clock comparison is the main source of the change. A calibration is needed to identify which link has changed. Fig. 6 and Table I show the record of the USNO mobile TWSTFT calibration of UTC(NIST) – UTC(USNO) [12]. USNO has been doing the calibration twice per year since 2011 to keep the two time standards in the United States as close as possible. For the calibrations in the past four years, the NIST/USNO TWSTFT via PTB agreed with the calibrations within ±1 ns, but the NIST/USNO TAIPPP is off the calibrations by 6.2 ±2 ns at these calibration points. In Fig. 3b the 3 ns drop in the last year of data appears to be mostly from the GPS carrier-phase link.

IV. CONCLUSIONS

We used the double difference to study the long-term time transfer uncertainty using GPS carrier-phase and TWSTFT techniques for comparisons among NIST, OP, PTB and USNO. The GPS carrier-phase link and TWSTFT link for each pair of the six comparisons (NIST/OP, NIST/PTB, NIST/USNO, PTB/OP, USNO/OP and USNO/PTB) all show changes relative to each other over time. There is no evidence the changes are related to the baseline of the comparisons. The changes can be more than 1 ns over a one-year period and reach about 6 ns over a longer period of time. The change contributed by individual laboratory could be canceled or added in the double difference if the changes were in the same direction with similar magnitude, or in the opposite direction. Only link calibrations can check if a time transfer link, either using GPS carrier-phase or using TWSTFT, has changed with respect to the last calibration result. Although calibrations using traveling GPS receivers and mobile TWSTFT can achieve calibration uncertainty of 1 ns, time transfer uncertainty is equal to the calibration uncertainty only at the time of calibration and it increases as time goes by. For time transfer using GPS carrier-phase and TWSTFT, we need a link calibration at least once a year in order to achieve time transfer uncertainty at the 1 or 2 ns level.

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