

Long-term instability in UTC time links

Zhiheng Jiang¹, Demetrios Matsakis² and Victor Zhang³

1 BIPM, Bureau International des Poids et Mesures

2 USNO, United States Naval Observatory, 3450 Massachusetts Ave, NW, Washington DC 20392, US

3 NIST, National Institute of Standards and Technology, 325 Broadway, Boulder, CO80305, US

with contributions from

J. Achkar (OP), F. Arias (BIPM), P. Defraigne (ORB), E. Dierikx (VSL), H. Esteban (ROA), M. Fujieda (NICT), F. J. Galindo (ROA), T. Gotoh (NICT), K. Jaldehag (SP), P. Jarlemark (SP), K. Liang (NIM), C. Lin (TL), S. Mitchell (USNO), J. Nawrocki (AOS), T. Parker (NIST), G. Petit (BIPM), C. Rieck (SP), G. D. Rovera (OP), I. Sesia (IT), C. Schlunegger (METAS), P. Uhrich (OP), and W. WU (NTSC)

BIOGRAPHIES

Dr. Zhiheng JIANG obtained his PhD at Paris Observatory. He worked at the Research Institute of Surveying and Mapping, Beijing China; the French Geographical Institute, France and since 1998 at the International Bureau of Weights and Measures (BIPM) as a principal physicist. His main interest is in timing metrology and gravimetry, and he is deeply involved in the generation of the international time scale, Coordinated Universal Time (UTC). Email: zjiang@bipm.org ;

Dr. Demetrios MATSAKIS is Chief Scientist for Time Services at the US Naval Observatory (USNO). He received his undergraduate degree in Physics from MIT. His PhD was from U.C. Berkeley, and his thesis, under Charles Townes, involved building masers and using them for molecular radio astronomy and interferometry. Hired at the USNO in 1979, he measured Earth rotation and orientation using Connected Element Interferometry and Very Long Baseline Interferometry (VLBI). Beginning in the early 90's, he started working on atomic clocks and in 1997 was appointed Head of the USNO's Time Service Department. He has over 100 publications, has served on many international commissions, and for three years was President of the International Astronomical Union's Commission on Time. Email: demetrios.matsakis@usno.navy.mil;

Mr. Victor Shufang ZHANG has a MS degree from the Electrical and Computer Engineering Department of University of Colorado. He has been with the National Institute of Standards and Technology (NIST) Time and Frequency Div. since 1989, working on various time and frequency transfer projects using GPS and geostationary satellites. He also involves in the time transfer equipment and link calibrations. He co-chaired the timing subcommittee of the Civil GPS Service Interface Committee (CGSIC) from 2002 to 2015. Since September 2015, he has served as the chair of the Consultative Committee for Time and Frequency Working Group (CCTF) Working Group on Two-Way Satellite Time and Frequency Transfer. Email: victor.zhang@nist.gov.

ABSTRACT

Calibration and link stability are the key issues for UTC time transfer. This study is made in the framework of a joint task group of the CCTF Working Groups on TWSTFT and the Working Group on GNSS Time Transfer to investigate the long-term stability of the UTC time transfer links with our suggestions to monitor and limit the instabilities.

For a UTC time link, stability is as important as the calibration. We investigated the site-based and link-based instabilities of UTC time transfer. Using the zero-baseline common clock difference analysis, we compared co-located GPS receivers that use common reference signals from the same clock to directly investigate the long-term instability of the individual C/A, P3 and PPP techniques.

Using the double clock difference between separated UTC laboratories, we compared GNSS and TWSTFT time links to indirectly investigate the long-term instability of GPS C/A, P3, PPP, GLONASS L1C and TWSTFT over the period 2011-2016. Our study is interested in instabilities at the nanosecond level, since the combined (statistical and systematic) calibration uncertainty of a TW link (using mobile TW station or GPS calibrator) is 1-1.5 ns and that of the GPS equipment calibration is 1.7 ns, cf. Circular T 345 [1].

Keywords: Stability, Uncertainty, GNSS, TWSTT, TWOTT, CCD, DCD, UTC, Time link, and Time transfer

I. INTRODUCTION

At present, the UTC (Coordinated Universal Time) time transfers use the techniques of Two-Way Satellite Time and Frequency Transfer (TWSTFT, TWSTT, or TW) and Global Navigation Satellite Systems (GNSS), of which only GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) are discussed here. The first TW calibration guidelines were approved by the CCTF (Consultative Committee for Time and Frequency) Working Group on TWSTFT in Sept. 2015, and at almost the same time the BIPM (Bureau International des Poids et Mesures) approved the GNSS equipment calibration guidelines. The combined Type A (u_A , statistical) and Type B (u_B , systematic) uncertainty of a TW link calibration (using mobile TW station or GPS calibrator) is 1-1.5 ns, and the uncertainty is 1.7 ns for GPS equipment calibration. The combined calibration uncertainty determines the Type B uncertainty of the UTC links. The combined uncertainties for the comparisons of TW and GPS links are therefore 2~2.3 ns. Since 2014, the TW and GPS calibration campaigns have been organized for many laboratories worldwide that use both TW and GPS. Based on mutual agreements among the regional metrology organization, timing laboratories and the BIPM, eight widely-separated laboratories have been designated as Group One (G1) laboratories. These G1 laboratories operate and maintain both TW and GNSS UTC links. The BIPM calibrates the G1 UTC links on a regular basis. The remaining timing laboratories are referred to as Group Two (G2) laboratories. The UTC links of the G2 laboratories are calibrated by the G1 laboratories.

To monitor the link stabilities, the BIPM has for over 10 years computed double clock differences (DCD) between TW and GPS PPP (Precise Point Positioning) or P3 (ionosphere-free code) monthly, making them publicly available just after each Circular T computation. If the links have sufficient long-term stability, the DCD should remain within their combined uncertainty, typically 2 ns. Independent studies by Achkar, Fujieda, Jiang, Lin, Matsakis, Zhang, and others have found that large variations (in some cases as large as 7 ns) can occur in a DCD over a period of a few years or less. Figure 1.1 shows an example of the variation between NIST (National Institute of Standards and Technology, USA) and PTB (Physikalisch-Technische Bundesanstalt, Germany). In these cases, the calibration of the TW link, the GPS link, or both have changed. This suggests that, for some UTC time links, the calibration uncertainty for u_B of the UTC time link is only valid for a short period of time, such as one year.

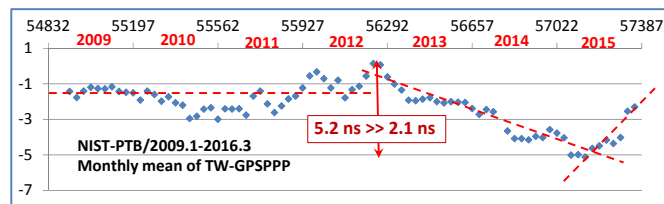


Figure 1.1 A 7- year comparison between the UTC time links of TW and GPSPPP over the NIST-PTB baseline. The variation of 5.2 ns is much more than the combined formal uncertainty of 2.1 ns, which itself is largely composed of systematic terms. The x-axis label is MJD/year and the y-axis label is time difference in ns. The same is in the following figures.

To better understand the problem, the CCTF Working Group on TWSTFT joined with the Working Group on GNSS Time Transfer created a task group to study the long-term instability of the UTC time transfer links. The task group's goal is to search for the causes of these variations in the UTC time links, and this paper is the first step of the study. The task group membership and contributors to this study are given after the author list on the first page.

Complementary to DCD data are the zero-baseline (<100 m) common clock differences (CCD), and we compare co-located GPS receivers that use reference signals from the same clock to directly investigate the long-term *relative* instability of the individual C/A (coarse/acquisition), P3 and PPP link techniques. From the CCD, we find the GNSS receivers of the current UTC pivot

laboratory PTB have been stable relative to each other over a 5-year period from 2011-2016, with an average linear drift of 0.1 ns/year. In contrast, from the long-baseline analysis, the long-term drifts of some links have reached up to 2 ns/year at times during this period. Unfortunately, we have no reason to believe any system will be immune from ns-level variations.

Our full data set includes CCD, DCD, repeated calibrations, environmental factors, and configuration changes. Aiming at improving the uncertainty of UTC-UTC(k), we have limited our investigations to mid- and long-term durations (from one month to five years), and the variations of more than 1 ns, which is the state-of-the-art of the present calibration uncertainty. Smaller variations also exist, and they are of concern when they accumulate to the ns level. Closure variations in TW data are not part of this study because their influences for any one baseline (out of the three in each closure sum) would probably be less than, though close to, the 1 ns criterion [2].

In all of these cases, we can only measure the changes in the relative calibration of different systems, which involves all elements from a laboratory's master clock onwards; it is well known that cables and reference signal distribution systems can make systems susceptible to common mode variations. One might also suspect different receivers to display common mode variations if they are made by the same manufacturer.

Throughout the paper, the standard uncertainty ($k = 1$ or $\sigma = 1$) is employed, as that is how uncertainties are expressed in the Circular T and in the calibration reports. For readability, we refer to the laboratories by their acronyms only; a full identification of the laboratories can be found in the BIPM web pages at <http://www.bipm.org/en/bipm/tai/annual-report.html>.

II. METHOD OF ANALYSIS AND DATA COLLECTION

II.1 Data used in the analysis

The TWSTFT, GPS C/A, P3, PPP and GLONASS (GLN) L1C are used.

The 5-year Europe and the US data from 1101-1603 (63 months from January 2011 to March 2016 which corresponds to the Modified Julian Date or MJD 55562-57474) are used for the analysis. This period and data set are selected because of the following considerations:

1. Calibration information over this period is more traceable and clear, such that it is easier to identify if a variation or jump comes from the equipment or from a calibration;
2. The data sets of TW, GPS and GLONASS are almost complete.

In addition, the time transfer data over the BIPM's standard 5-day computations are used. These computation results are personally viewed by the BIPM physicist and the assistant on duty for the monthly Circular T computation and therefore their quality is guaranteed.

II.2 The figures

Most of this work is based upon simple subtraction of time transfer data. However we have often simplified the figures by removing overall constant biases and the effects of known configuration changes. The y-axis is always the CCD or DCD values in ns and when the x-axis in MJD covers a long period, the ticks are on the first day of a year. In many figures, such as Figure 3.1.3, a linear regression is made to $y = ax + b$, where a is the phase drift coefficient in ns/day and b the constant in ns.

II.3 Method of analysis

The long-term variation studied in this work can come from: (1) change of the *total delay* of a receiver system: the signal delay from the antenna phase center to the reference point UTC(k) and (2) instability of the local frequency and time distribution systems to which the receivers are connected. We note that what we are studying is the *relative* variation of two time links. Obviously, a zero variation between the two links would result if the absolute variation is zero, but it could also be that the two links changed at the same rate and in the same direction.

The GPS P3/PPP and C/A solutions for UTC generation use the same precise GPS time reference and precise orbit corrections, but different ionosphere corrections. The P3/PPP uses the receiver's measured ionosphere correction while the multi-channel (MC) C/A uses the corrections from the IGS (International GNSS Service) ionosphere map. The map is generated and based on the measured ionosphere data from nearby stations in the IGS global tracking network, often including the laboratory itself. Figure 2.1.1 shows one month's CCD of the GPS P3 and MC C/A at IT (Istituto Nazionale di Ricerca Metrologica (INRIM), Italy). Due to inconsistent calibrations of the receiver L1 and L2 biases, a constant but non-zero difference exists. The scatter of the CCD is consistent within the combined u_A uncertainty, although they show a bias that will not affect our main conclusion. In Figure 2.1.1 the mean value (the calibration difference plus the bias between the measured and the IGS mapping ionosphere corrections) is 10.89 ns with standard deviation $\sigma = \pm 0.78$ ns. Noting that, the u_A of MC C/A and P3 in the BIPM Circular T are respectively 1.5~2.0 ns and 0.7 ns. The combined u_A is 1.7~2.1 ns. We have the same observations for the CCDs at PTB and OP as well as from the long-term comparisons shown in Sections 3.1 and 3.2 where C/A code and P3 codes are compared. This calibration bias, the P1-C1 bias, and other constant mis-calibration biases, are not of concern for this study.

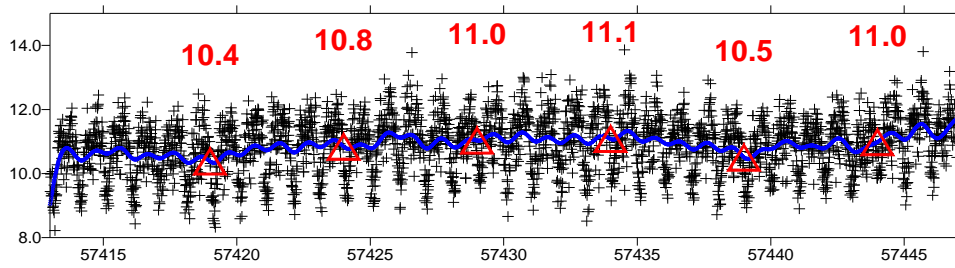


Figure 2.1.1 The Common Clock Differences (CCD) between the P3 and MC (C/A) at IT is 10.9 ± 0.8 ns. The red triangles denote the values on MJD's ending in 4 or 9.

III. ZERO-BASELINE COMMON CLOCK COMPARISONS (CCD) AT PTB, OP, AND USNO

In this section, we study the site-based instability through the zero-baseline common clock difference (CCD) analysis. We analyze the CCD of three laboratories: PTB, OP ((Laboratoire national de métrologie et d'essais – Systèmes de références space-temps, Observatoire de Paris (LNE-SYRTE), France) and USNO (US Naval Observatory). The three laboratories all have multiple time transfer facilities. A more complete set of CCD analyses can be found in TM263 [4].

As we know, in many laboratories, there is/are one or more backup GNSS time transfer receiver(s). Each receiver *system* is considered *independent* if it consists of a separate receiver, antenna, and cabling between the components and the UTC(k) reference or calibration point. The correlation of the CCD may be weaker when the receivers are from different manufacturers, observing different satellites (GPS or GLONASS) and producing different types of measurements: P3 or L1 C/A codes etc. The 5-year data from these three laboratories are relatively complete, in particular at PTB and OP, with relatively satisfactory quality.

We investigate the instability of the time transfer facility mainly by the two indicators:

- 1) The mean value and its standard deviation of the CCD between two measurements: Mean $\pm \sigma$, with $\sigma \leq 1.5$ ns to be acceptable if the C/A code measurements are used;
- 2) The tendency of the CCD to vary linearly, with drift ≤ 0.5 ns/year to be acceptable.

III.1 Zero baseline comparisons at PTB

PTB is the pivot laboratory used in UTC generation. We will study the long-term total delay variations of the three *independent* GNSS receiver systems:

- 1) PTBB/PT02 (AshTech Z12T receiver): pivot receiver of the GPS PPP and P3 measurements in the UTC computation, which was last calibrated in July, 2015;
- 2) PTBG/PT03 (AshTech Z12T receiver), backup of PTBB;

3) PTB_/PT05 (PikTime TTS3 receiver): pivot receiver of the GPS MC C/A and GLONASS L1C measurements in the UTC computation, which was last calibrated in 2008.

Each of the receivers has its own antenna mounted on a close-by position and uses its own antenna cable of different length. The dates given for calibration are when the receiver files were changed. A calibration is not reported in the RINEX (Receiver Independent Exchange) data files for GPS PPP computation and for generating the P3 data, but it is reported in the file header of the CGGTTS (Common GNSS Generic Time Transfer Standards) files for GPS P3, MC C/A, and GLONASS L1C data.

Figure 3.1.1 shows the structure of the reference signals for the PTB timing equipment. With the corrections of the equipment calibration and the reference signals delay, the GPS PPP solutions, P3, MC C/A and the GLONASS L1C measurements are the UTC(PTB)-GNSS system time. In the ideal situation, the CCD of these measurements should be zero because the UTC(PTB) and the GNSS system time are canceled.

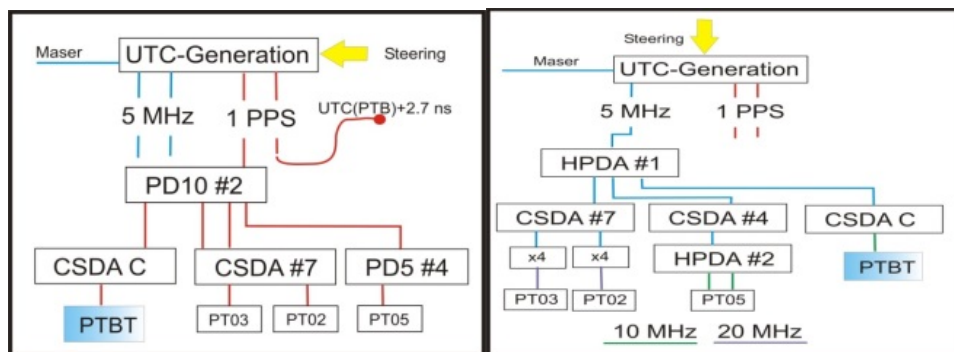


Figure 3.1.1 The structure of reference signals for the PTB timing equipment. CSDA is the Clock Signal Distribution Amplifier, 1 PPS in/ 5 signals out, 5 MHz in / 5 signals out / doubler 5 signals 10 MHz out. HPDA is the High-Performance Distribution Amplifier. Same board as in CSDA, but no 1 PPS signals. Frequency doubler may or may not be included, but color code tells the facts. PD5 / PD10 are pulse distribution amplifiers (1 PPS) with 5 or 10 outputs. All units are 19" 1 HE, produced by Spectra Dynamics, Louisville, CO (USA).

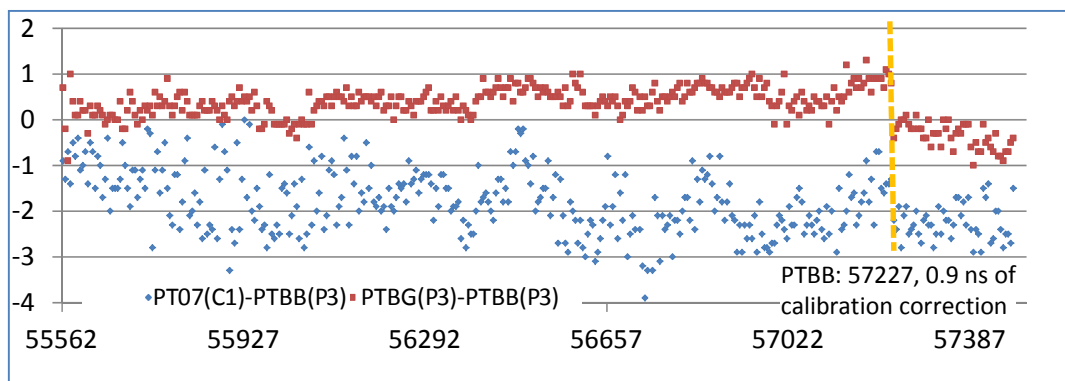


Figure 3.1.2 CCDs of PT05, PTBB and PTBG. The data are given on UTC Standard MJDs, i.e., one point over 5-day. (as seen, the PTBB was affected by the implementation of the BIPM G1 calibration correction 0.9 ns on 57227, July 24, 2015).

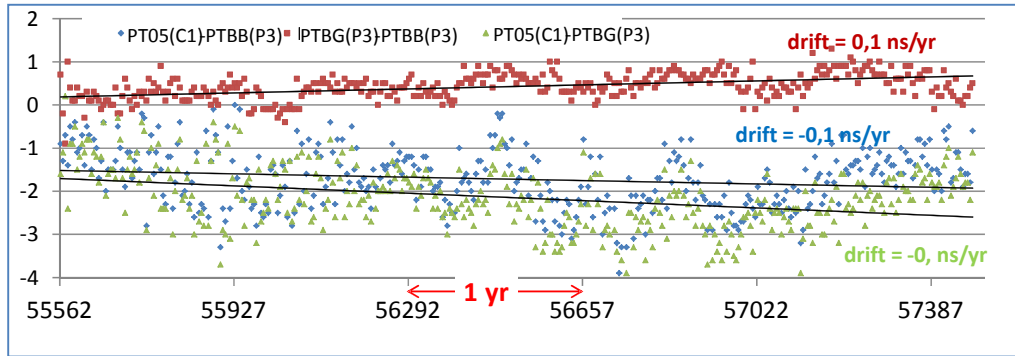


Figure 3.1.3 CCDs of PT05, PTBB, and PTBG (without the 0.9 ns of BIPM G1 calibration correction).

Figure 3.1.2 shows two CCDs, of GPS MC C/A (PTB_PT05) – GPS P3 ($PTBB/PT02$) and GPS P3 ($PTBG/PT03$) – GPS P3 ($PTBB/PT02$). A constant (500 ns) is used to align the $PTBG$ to $PTBB$ on MJD 55500 (October 30, 2010), and 555 ns were applied to $PTBG$ on MJD 55986.5. As can be seen, in the last five years, the only visible jump is on MJD 57227 in the measurements of the $PTBB$ when the BIPM GNSS G1 calibration correction of 0.9 ns was implemented while there was no calibration applied in the $PTBG$ or $PT05$ measurements. This 0.9 ns correction was therefore removed from this investigation. The same is for the other cases in the following, i.e. we try to maintain the continuity of the measurements. The CCDs, after removing the 0.9 ns calibration correction, are given in the Figure 3.1.3. The linear drifts of the CCD among the $PTBB/PT02$, $PTBG/PT03$ and PTB_PT05 measurements are shown in Figure 3.1.3 and Table 3.1.1.

Table 3.1.1 Statistics of the CCD among $PTBB$, $PTBG$ and $PT05$ measurements.

CCD	$PT05 - PTBB + 0.9$	$PTBG - PTBB + 0.9$	$PT05 - PTBG$
Mean $\pm \sigma$	-1.72 ± 0.71	0.43 ± 0.30	-2.15 ± 0.74
Linear Drift	-0.1 ns/year	0.1 ns/year	-0.2 ns/year

From Figure 3.1.3 and the Table 3.1.1, in the past 63 months, we see:

- the maximum variation of the two CCDs between C/A and P3 codes is 2 ns or a drift of 0.2ns/year;
- the mean of the P3 CCD of the $PTBB$ and its backup $PTBG$ receivers are 0.43 ± 0.30 ns, with a drift of 0.1 ns/year;
- the averaged drift of $PTBB$ P3 measurements (0.1 ns/year relative to the $PTBG$ P3 measurements and -0.1 ns/year relative to the $PT05$ measurements) is zero for the past five years, which stands in contrast to data from 2009-2011 (Figure 3.1.4);
- the standard deviations of the CCDs (0.30 ns for the P3 to P3 and 0.71 for the P3 to MC C/A) are within the 1- σ tolerances 1.0 ns (P3) and 1.7 ns (P3 and MC C/A combined);
- the three CCDs also display a possible annual variation probably due to the outside temperature effects on the antennas and the antenna cables.

Although it is not shown in Figure 3.1.3 and Table 3.1.1, the mean of the CCD between the GPS MC C/A and GLONASS L1C from the $PT05$ measurements is -0.22 ± 0.25 ns with a drift of 0.08 ns/year. However, Figure 3.1.4 indicates that at least one of the $PTBB$ or $PTBG$ receivers showed considerable drift previous to 2011 in the USNO PPP solution.

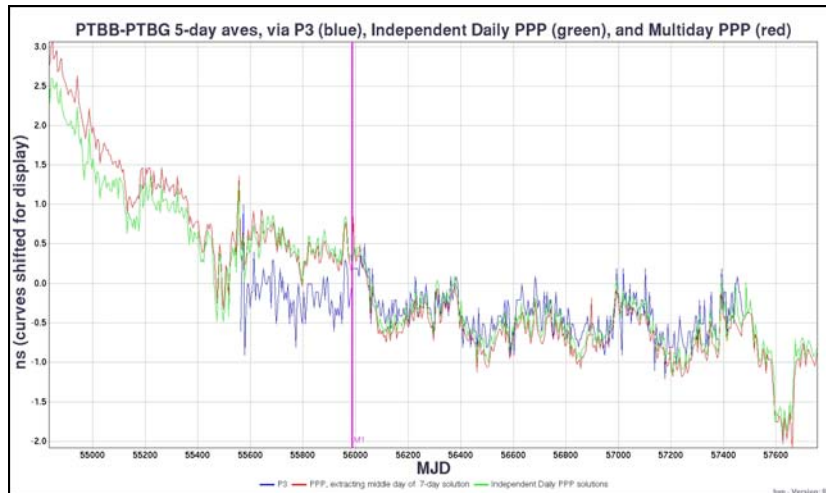


Figure 3.1.4 USNO reductions of PTBB - PTBG, showing variations before the period of this study, and BIPM reductions that cover a shorter time range but show no such variations. The BIPM reductions (blue) follow the P3 (code-only) procedure. The marker indicates the time when a 555 ns manual shift was applied to P3 reductions of PTBG (MJD 55986.5, February 29, 2012). USNO reductions are 5-day averages of PPP solutions. One curve is of independent daily solutions and the other extracts the middle day out of a sliding set of 7-day solutions; some large jumps were removed by a semi-automated procedure, but the closest one to 55986 was a 4 ns jump 30 days later, on 56016.

The differences between analyses that use the same or very similar data can be termed analysis noise. Analysis noise is not discussed further, except to note that short-term noise can become long-term noise if it is the basis of manual calibration adjustments.

We conclude that:

- the GPS PPP/P3 pivot receiver *PTBB* was stable *relative* to its backup *PTBG* receiver in the five years since January 2011;
- the GPS MC C/A pivot *PT05* receiver was stable *relative* to the PPP/P3 pivot *PTBB* receiver in the five years since January 2011;
- All PTB receivers did not show this same level of stability in the years previous to 2011 (the variation of 55986, if real, would be ascribed to PTBG).

III.2 Zero baseline comparisons at OP

OP operates two receivers, of which the calibrations were not changed over the period of this study. Although OP is not the pivot laboratory of the UTC time link, an OP receiver (*OPM5*) is used to compute UTC - GPS broadcast time in the Circular T. We use the same methods and indicators for the OP CCD analysis. The description of the receivers is given here:

- 1) *OP02* (also known as *OPMT*) is an AshTech Z12T, PPP/P3 receiver, with the reference signals came from HM 889 and that changed to HM809 in July 2013. A corresponding 1.2 ns jump is corrected in our analysis. The reference signals for *OP02* receiver was changed to UTC(OP) in August 2015;
- 2) *OPM5* is a TTS3, GPS/GLONASS MC C-code receiver, with the reference signals come from UTC(OP) and the source of UTC(USNO via GPS) that is reported in the Circular T.
- 3) *OPMT* and a receiver whose data are not shown here (*OPM2*) share a common temperature-stabilized antenna, which is suspected to show signs of failing.

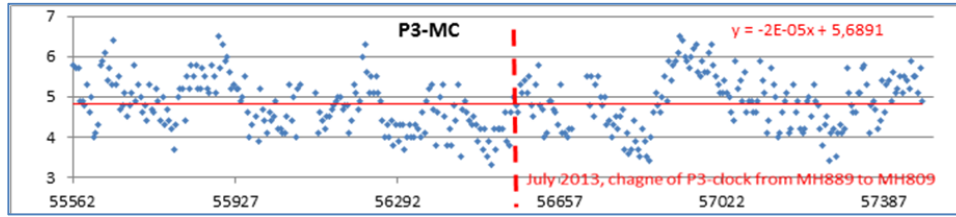


Figure 3.2.1 CCD of *OPMT* - *OPM5*. The reference clock for the GPS MC C/A measurements is UTC(OP) while the reference clocks for GPS P3/PPP measurements are HM 889/HM 809/UTC(OP). 1.2 ns is added before 56524 (July 2013) for the HM 899 to HM809 change.

Table 3.2.1 Statistics of the CCD between the *OP02* GPS PPP/P3 measurements and the *OPM5* GPS MC CA measurements.

CCD	GPS P3 – MC + 1.2 ns
Mean $\pm \sigma$	4.82 ± 0.67 ns
Linear Drift	-0.01 ns/year

From Figure 3.2.1 and Table 3.2.1, the mean of the CCD between *OP02* P3 and *OPM5* MC C/A measurements (two receivers with two different type of measurements of P3 and C/A codes) are 4.82 ns and 0.67 ns respectively. The standard deviation $\sigma = \pm 0.67$ ns is much smaller than the combined uncertainty of the CCD ($1\text{-}\sigma$), 2.0 ns. The linear drift is -0.01 ns per year and thus negligible. However, the CCD shows an annual variation of up to 3 ns. The mean offset is believed to reflect the calibration bias of *OPM5*.

In conclusion, the *OPMT* receiver's P3/PPP measurements were stable relative to the *OPM5* receiver's MC C/A measurements in the 63 months.

III.3 Zero baseline comparisons at USNO

The USNO GNSS receivers are summarized in Table 3.3.1, where *USN6* is the USNO primary receiver for UTC. The receivers that use reference signals directly from UTC(USNO) share a common antenna and are maintained in the same room, whose environmental controls reduce temperature variations to the one-degree level. The Ashtech receivers *USN3* (later *USN7*) and *USNO* are particularly temperature-sensitive. During this period all receivers have had their calibrations adjusted due to system configuration changes, or to achieve better consistency with the other receivers. The time reference for the *USNO* receiver comes from a maser that is steered to UTC(USNO) via a hundred meters of largely underground cables.

Table 3.3.1 USNO receiver ensemble. The time references designated “MC3” are a maser steered to UTC(USNO). Those referenced to UTC(USNO) share a common antenna, which was moved at the time *USN3* was renamed *USN7*.

Informal Name	IGS Designation	Manufacturer	Time Reference	Steering Time Transfer
<i>NOV1</i>	<i>USN6</i>	NovAtel	UTC(USNO)	No
<i>NOV2</i>	<i>USN5/USN9</i>	NovAtel	UTC(USNO)	No
<i>USN3/7</i>	<i>USN3/7</i>	Ashtech Z12T	UTC(USNO)	No
<i>SPX2</i>	None	Septentrio PolaRx#	UTC(USNO)	No
<i>SPX3</i>	<i>USN8</i>	Septentrio PolaRx#	UTC(USNO)	No
<i>SPX6</i>	None	Septentrio PolaRx#	UTC(USNO)	No
<i>USNO</i>	<i>USNO</i>	Ashtech Z12T	MC3	Under-ground cables

With the exception of the highly temperature-sensitive Ashtechs, the total extent of the CCD variations has been < 1 ns after corrections are made for configuration changes and easily-detected jumps. One receiver (*USN9*) shows a linear trend that has accumulated 0.7 ns over 1000 days. A second (*SPX6*) has shown a somewhat parabolic trend ranging over almost 0.7 ns in the 18 months it has been in service. Figures 3.3.1-3.3.3 display the P3 CCDs of each USNO receiver against the *USN6* system. Since the Ashtech receivers are so temperature sensitive, their figures also display a relevant temperature. The markers denote times of data adjustment to correct for jumps, often due to recorded configuration changes. A progressive failure of the splitter common to

all the antennas listed as directly referenced to UTC(USNO) culminated on October 31, 2014 (MJD 56961); the new system reproduced the calibration to within an estimated 0.5 ns; data for MJDs 56955-56980 (October 25, 2014 – November 19, 2014) were deleted from this analysis.

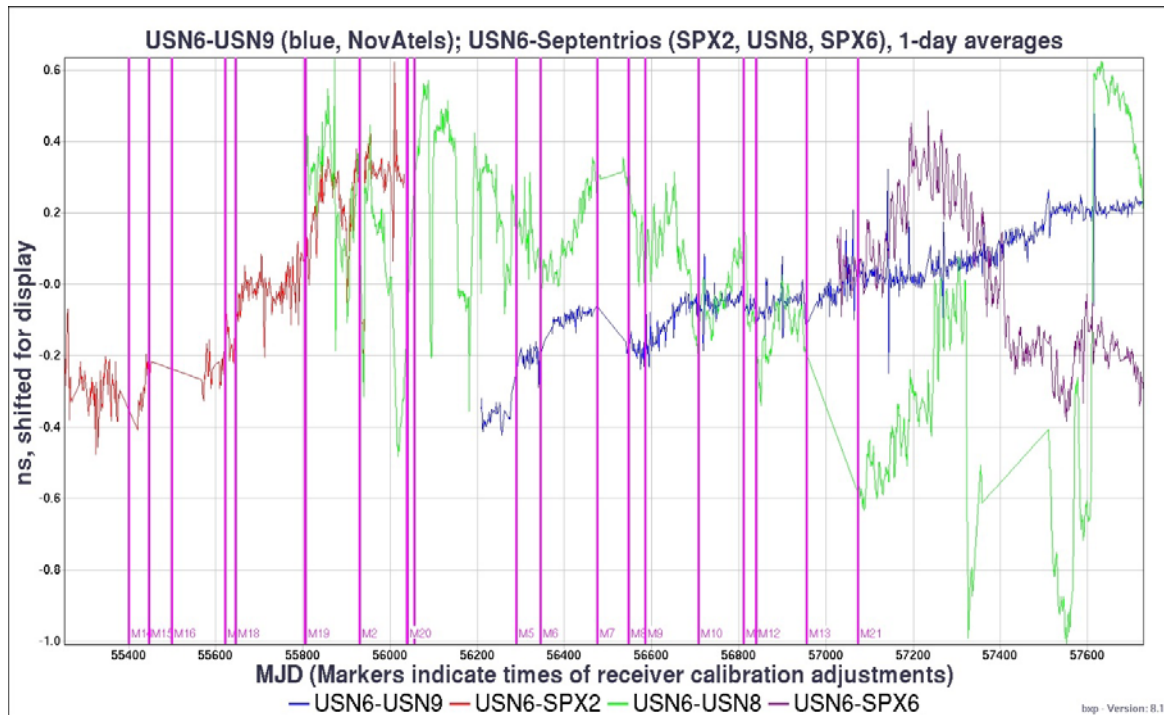


Figure 3.3.1 CCDs involving four GPS receivers with low temperature coefficients. The NovAtel *USN6* is the common receiver, and the blue curve shows the difference between it and *USN9*, which is also a NovAtel. The cyan curve for *USN6* - *SPX6*, which was placed in service on MJD 57026 (January 14, 2015) suggests a possible seasonal variation; however, all of these units are housed in the same chamber and share a common antenna. Markers indicate times when at least one receiver's data were shifted to take into account a jump, usually caused by a configuration change. The last shift of *USN6*'s data was on 56055. Full scale in this plot is 1.5 ns.

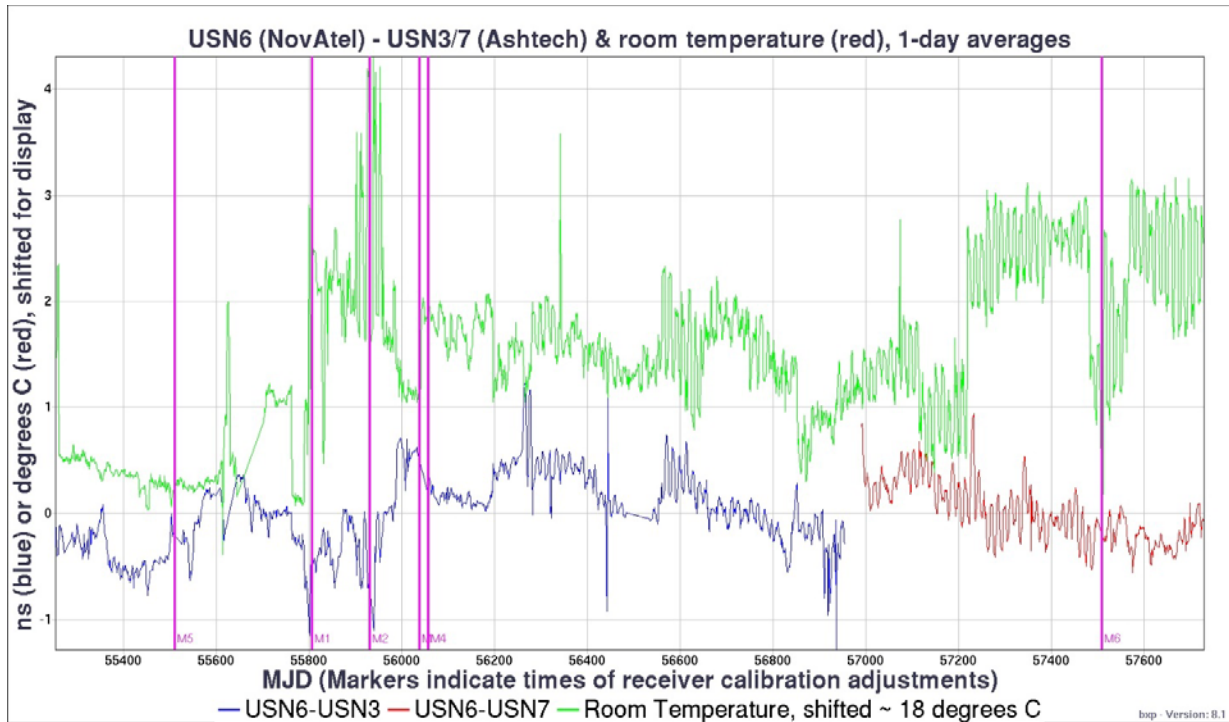


Figure 3.3.2 CCDs of *USN6* and the *USN3/7*. The short-term (few-day) temperature variations are strongly anti-correlated with the Ashtech's timing. The markers indicate when the data were jump-corrected.

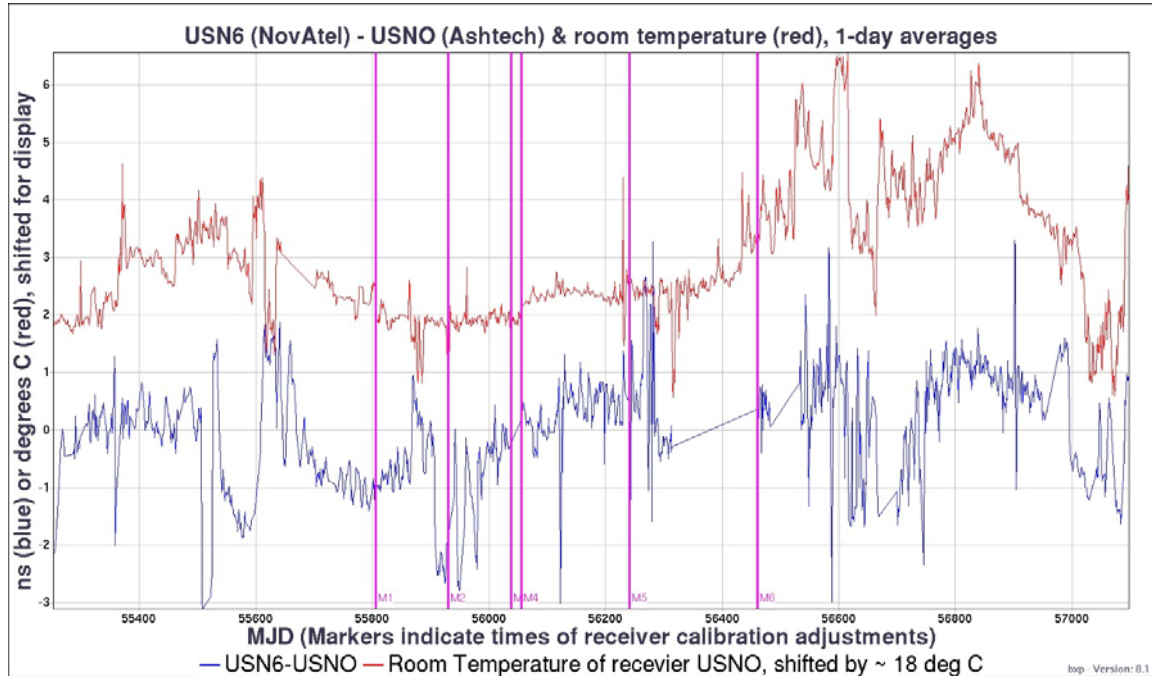


Figure 3.3.3 Almost-CCD differences of *USN6* vs *USNO*, which is maintained in a nearby building and referenced to a maser that is steered to UTC(USNO). The receiver *USNO* suffered numerous hardware issues over most of this time range. The markers indicate when the data were jump-corrected.

IV. DOUBLE CLOCK DIFFERENCES (DCD) OVER LONG BASELINES

In this section, we investigate the instability presented in the UTC time *links*. We analyze the double clock difference (DCD) of different link techniques, i.e. the comparisons of the time links using TW, GPS PPP, GPS P3, GPS MC C/A and GLONASS L1C.

Generally speaking, the DCDs among different GNSS links show less variation and drift than that of the DCDs between GNSS and TW links. The variations of the DCD of TW and GNSS seem very complex. On different baselines or even on the same baseline, this TW - GNSS DCD demonstrates different behaviors. This suggests there are multiple causes for the variations with one or more dominant at different times.

4.1 The baseline OP - PTB, and its unidirectional drift in TW - GNSS DCD

The UTC baseline OP - PTB may be the most interesting one in this analysis because we have all types of TW and GNSS time links: TW, GPS PPP, GPS P3, GPS MC C/A, and GLONASS L1C. The GPS PPP/P3 links are between two AshTech Z12T receivers, *OPMT* and *PTBB*. The GPS MC C/A and GLONASS L1C links are between the two TTS3 receivers, *OPM5* and *PT05*. The two recent TW link calibrations, one in 2014 [5] and one in July 2016 [6], agree to 0.26 ns. Figure 4.1.1 describe the UTC(OP) - UTC(PTB) time transfer results of the five types of link techniques during the past five years.

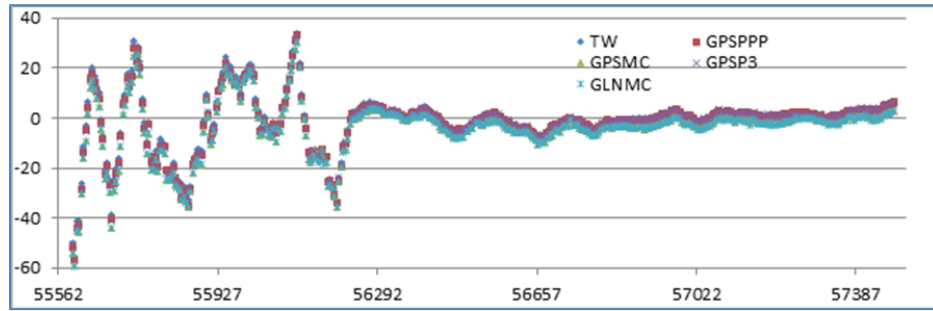


Figure 4.1.1 Time transfer results of the baseline OP - PTB using five different techniques from January 2011 to March 2016. The great improvement at the end of the second year is due to OP's introduction of an atomic fountain in its UTC-realization algorithm.

Table 4.1.1 Statistics of the DCD between different link techniques over the baseline OP-PTB between 1101-1603

DCD	TW - PPP	TW - GPSMC	TW - GPSP3	TW - GLNMC	PPP - MC	PPP - P3	PPP - GLN	GLN - GPS
Mean $\pm \sigma$	0.09 ± 1.36	2.31 ± 1.34	-0.04 ± 1.37	2.55 ± 1.23	2.21 ± 0.91	-0.13 ± 0.37	2.45 ± 0.94	-0.22 ± 0.25
Linear drift	-0.8 ns/year	-0.6 ns/year	-0.8 ns/year	-0.6 ns/year	0.2 ns/year	0.02 ns/year	0.18 ns/year	-0.08 ns/year

Table 4.1.1 shows the statistics of the DCDs between different types of links. The results are also shown in Figures 4.1.2-4.1.4. We still use the two indicators: the mean ($\pm \sigma$) and the drift for the discussion of the instability. The mean value of the DCDs gives the calibration differences and indicates the possible bias between the measured and IGS mapped ionosphere corrections for the GPS PPP/P3 - GPS MC DCD. The σ gives mainly the relative instability between the two link techniques. The drift shows the linear tendency of the DCDs. In the ideal case, the drift should be zero.

The two indicators should be considered together. For example, the mean = 0.09 ± 1.36 ns for the DCD of TW - PPP. The mean value is very small and negligible, but the drift is -0.8 ns/year moved the DCD by 4 ns over five years. Considering the combined uncertainty in the DCDs is $\sqrt{(1.7^2 + 1^2)} = 2.0$ ns, the *average* drift of -0.8 ns/year is large. From Figure 4.1.2, we observed the TW - PPP DCD's peak-to-peak variation during 2013-2014 was about 4 ns.

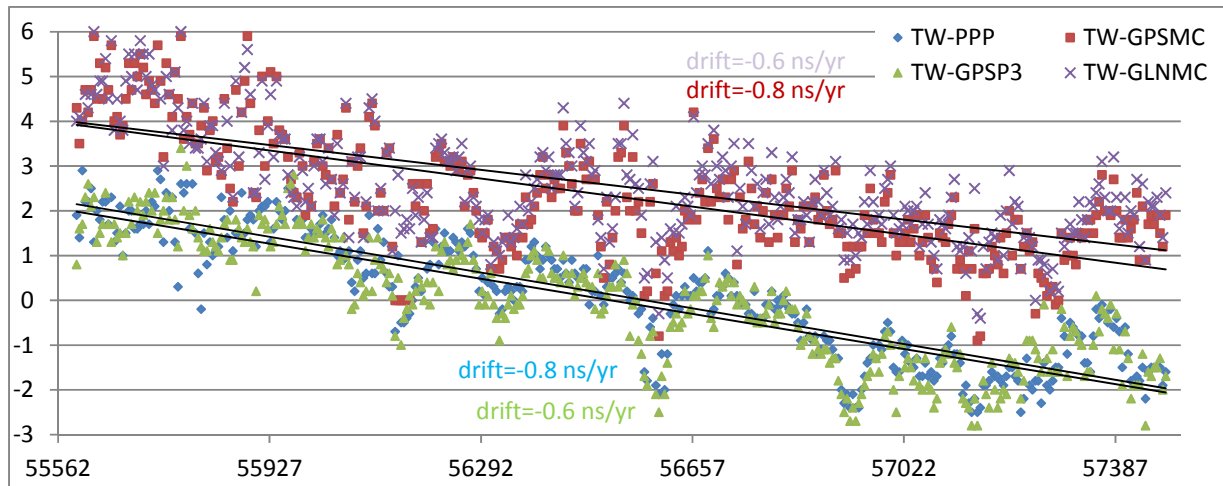


Figure 4.1.2 DCDs of the links between TW and GPS PPP, GPS P3, GPS MC C/A, GLONASS L1C for the baseline OP - PTB during 1101-1603.

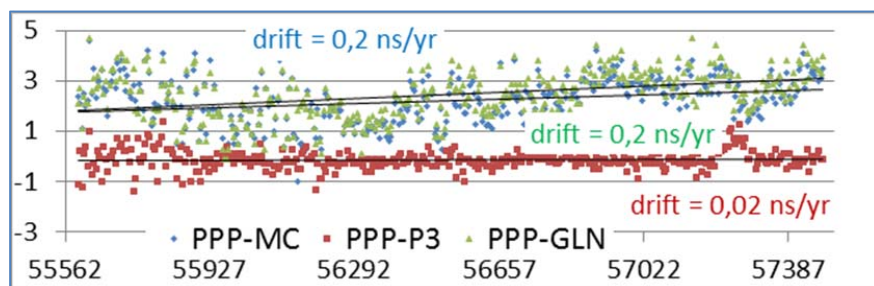


Figure 4.1.3 DCDs of the GNSS links among GPS PPP, GPS P3, GPS MC C/A and GLONASS L1C for the baseline OP - PTB during 1101-1603.

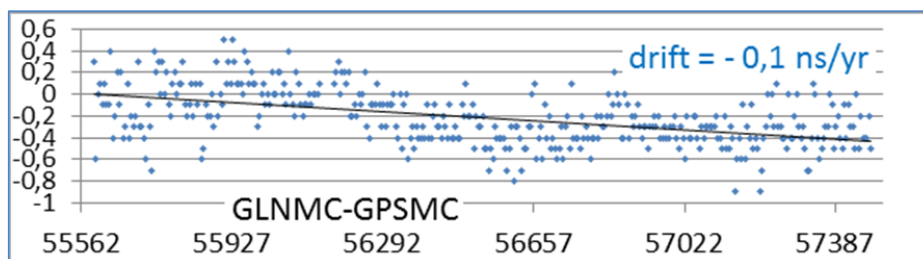


Figure 4.1.4 DCD of the GPS MC C/A and GLONASS L1C links for the baseline OP - PTB during 1101-1603.

On the other side, from the same Table and the Figures 4.1.3 and 4.1.4, we see the drift rates are on the order of 0.2 ns/year for the DCDs of GPS PPP/P3/MC CA and GLONASS L1C, i.e., 1 ns in total over five years, which is less than the combined uncertainty of $\sqrt{(1.7^2 + 1.7^2)} = 2.4$ ns. This is acceptable in view of the UTC time link calibrations.

To summarize the analysis:

- The GNSS DCDs show less variation and drift than the DCDs of TW-GNSS;
- There is an obvious unidirectional drift between TW and GNSS. The difference of the DCD at the beginning and the end of the data set is ~ 4 ns;

- However, the two TW link calibrations showed the OP-PTB TW link only changed 0.26 ns between 2014-2016. The first calibration trip visited OP on June 30, 2014 and PTB on July 16 (average MJD about 56845). The second calibration trip visited OP and PTB effectively in June 2016 on 57542; the DCDs varied by approximately 2 ns between those two dates.

IV.2 The baseline NIST - PTB, and its highly variable TW - GNSS DCD

Here we study the instability of TW, GPS PPP and GPS MC C/A link techniques for the NIST-PTB baseline. From Figure 4.2.1 and Table 4.2.1, we can make the following observations:

- TW and GPS links drift away from each other in three periods: the drift during 2011-2012 is zero on average; the DCD during 2013-2014 dramatically decreases by 5 ns and the drift rate is -2.5 ns/year; starting in March 2015, the DCD increases dramatically and reaches 3-4 ns at the end of March 2016;
- GPS PPP and GPS MC C/A agree in general within the combined uncertainty but with a visible linear drift of 0.3 ns per year. Part of the drift is contributed by the CCD of *PT05* - *PTBB* (see Figure 3.1.3 and Table 3.1.2). The NIST GPS PPP and GPS MC C/A measurements are from the same Novatel OEM-4 receiver, but the PTB GPS PPP and GPS MC C/A measurements are from the *PTBB* and *PT05* receivers;
- Noting that, the TW link NIST - PTB may be composed by the triangle relation: NIST - PTB = (NIST - USNO) - (PTB - USNO). Figure 6.1 and Table 6.2 show that the UTC TW links USNO - PTB and USNO - NIST agree perfectly with the TW MS calibrations with an average difference 0.14 ± 0.55 ns. This suggests the GPS link variation would be responsible for the DCD variation.

Table 4.2.1 Statistics of the DCD between the different link techniques over the baseline NIST - PTB during 1101-1603

Data	TW - PPP	TW - GPSMC	MC - PPP
All	-2.35 ± 1.47	-2.12 ± 1.74	-0.23 ± 1.24
Cleaned*	-2.34 ± 1.51	-2.22 ± 1.73	-0.11 ± 1.16
Linear drift	-	-	0.3 ns/year

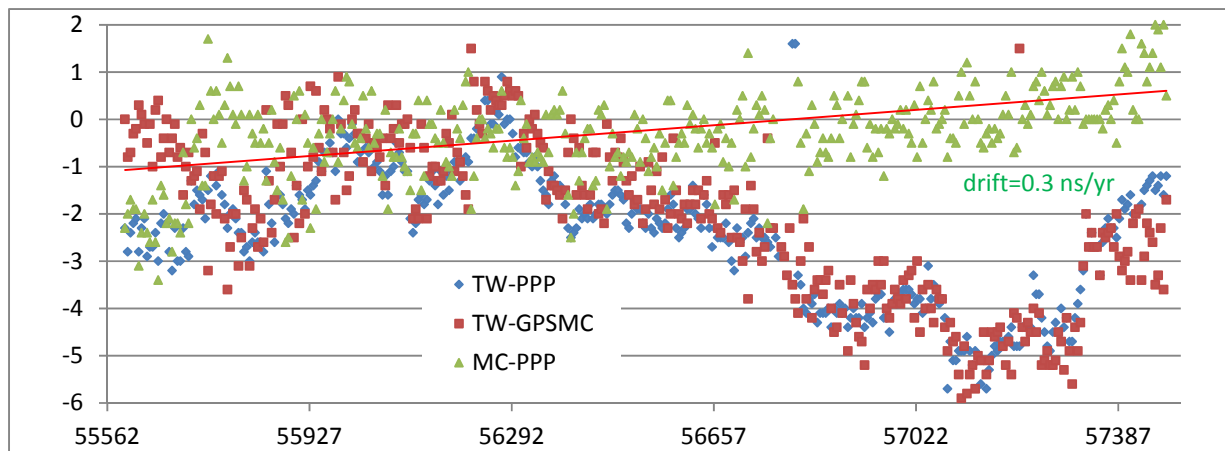


Figure 4.2.1 DCDs of TW vs. GPSPPP and C/A links of NIST - PTB from January 2011 to March 2016.

IV.3 The baseline VSL-PTB and its unusually strong annual variation in TW - GPS DCD

Figure 4.3.1 reveals a strong annual variation in the DCDs of the TW - GPSPPP and TW - GPS P3 for baseline VSL-PTB, although the longer-term drift is < 0.1 ns/year. Here the P3 and PPP DCD has an offset of 2.6 ns with the drift = 0. The annual variation is about 4 ns over a 40°C in temperature range, or about 0.1 ns/°C [7]. Such variations have also been reported on the baselines of TL-PTB and NICT-PTB. While sub-nanosecond annual variations are seen in Figure 3.1.3 for the CCD between the GNSS receivers of the PTB, Figure 3.2.1 shows 1-2 ns OP CCD variations.

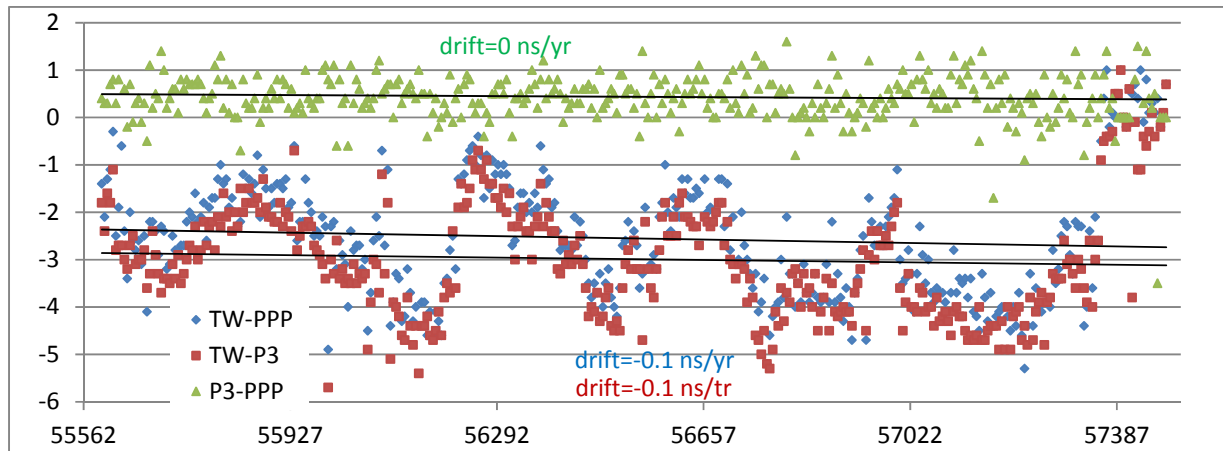


Figure 4.3.1 DCD of the TW, GPS PPP and P3 links for the baseline VSL-PTB during 1101-1603.

For the VSL-PTB baseline, depending on the temperature-sensitivity of the calibration equipment and the signals provided for calibration by the laboratories, TW or GNSS calibrations carried out in different seasons of a year may have up to 4 ns discrepancy due to this variation.

V. MITIGATING THE CONSEQUENCES OF LONG-TERM VARIATIONS

Although the CCD and DCD analyses do not tell us where the long-term variations come from and how to prevent the variations in the UTC time transfer facilities, there are some factors that need to be taken into account.

V.1 The calibration correction in the pivot GNSS receivers

It is evident that any calibration correction will introduce a step in a time link. However, some corrections affect only one link, while other corrections may affect the entire UTC network. The latter case happens when a correction is applied to the pivot GNSS receiver(s) at PTB. Because the correction is applied to a pivot receiver, it results in a change in all its associated UTC GNSS links. For example, as shown in Figure 3.1.2 and Figure 5.1.1, the time step on MJD 57227 in the CCDs of *PT05-PTBB* and *PTBG-PTBB* and in the DCDs between PTB and OP, ROA (Real Instituto y Observatorio de la Armada, Spain), SP (Swedish National Testing and Research Institute, Sweden), and USNO is due to implementation of the 0.9 ns BIPM G1 calibration correction for *PTBB*. In consequence, all the GPSPPP and P3 links (a total of 50 P3 links and 52 PPP links in Sept 2016) jumped by the same amount. This in turn affected UTC generation, since each clock's contribution, and weight, is determined by its predictability. In this case all the clocks involved in those links, except for those also linked to the PTB via TW, contributed a correlated frequency shift to UTC, and were subsequently somewhat down weighted. If such jumps were compensated for in the clock predictions, the frequency stability of UTC would not be affected (because it depends upon the difference between a clock reading and its predictions). If the jump corresponds to a real change in the pivot receiver's calibration, such a jump could be justified as replacing an old measurement with a better one. As an extreme example, the first BIPM calibration of the USNO GPS receivers required a 29 ns adjustment, which was introduced to UTC-UTC(USNO) in steps of 3 ns per month in 1997 so as to minimize the immediate impact. Since the correction was not compensated in the PTB clock reference, all the G1 and the non-G1 laboratory's *link* calibrations and time/frequency transfers were affected, this is equivalent to adjusting the absolute calibration of the grid. As we know that, theoretically, a UTC laboratory contributes to UTC the rates of its clock ensemble so if the GNSS calibration correction would be implemented in a time *link*, as the TW links do, it affects only the *link* on question not globally all the links in the UTC network. In the case of the BIPM 2014 G1 calibrations, less than 10 laboratories would have been affected instead of 50 or so when the correction is applied referring to *PTBB*, the pivot.

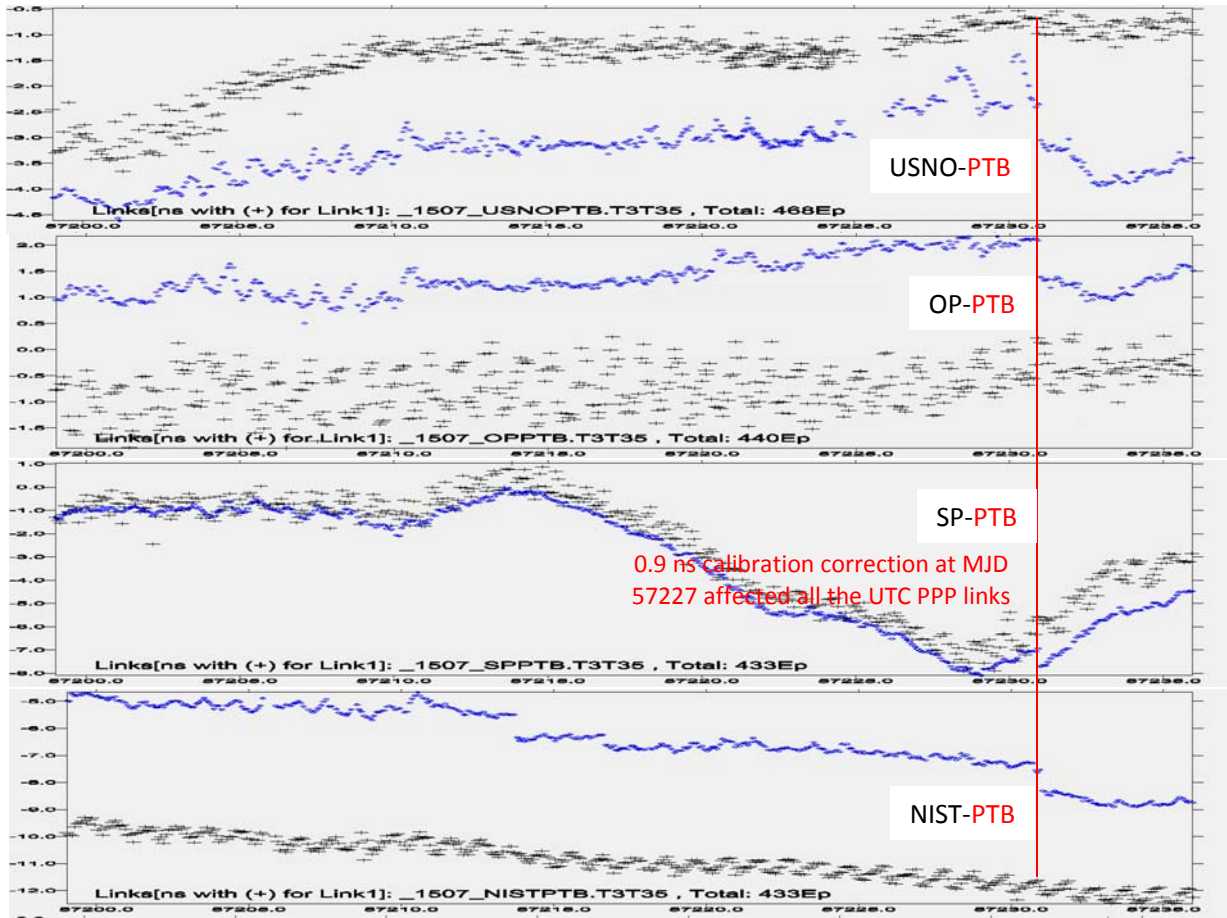


Figure. 5.1. Time step in TW - GPSPPP DCDs for the PTB-USNO, PTB-OP, PTB-SP and PTB-NIST, baselines.

V.2 Temperature effects on GNSS receiver systems

Many studies have shown a strong correlation between the temperature variations and the variation of GNSS receivers. We provide two examples where the temperature influenced a whole receiver system composing a receiver, an antenna and the cables.

Figure 5.2.1 demonstrates that a 10°C temperature change ($24^{\circ} \nearrow 34^{\circ} \searrow 24^{\circ}$) due to the failure of a room air-conditioner at TL (Telecommunication Laboratories, Chung-Li, Chinese Taipei) resulted in a 1.5 ns CCDs excursion. The CCDs are between measurements of a Septentrio PolarX3 receiver (*BP1C*) and of a GTR50 receiver (*BP0U*). The latter has a self-air conditioning system and was probably only weakly affected by the laboratory temperature changes, but we do not know the relative temperature-dependence of the amplifiers and their ports supplying the reference signals to the receivers.

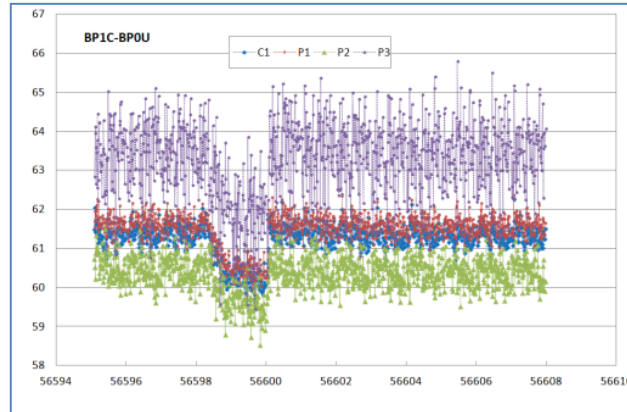


Figure 5.2.1 Impact of temperature change on GPS receiver measurements

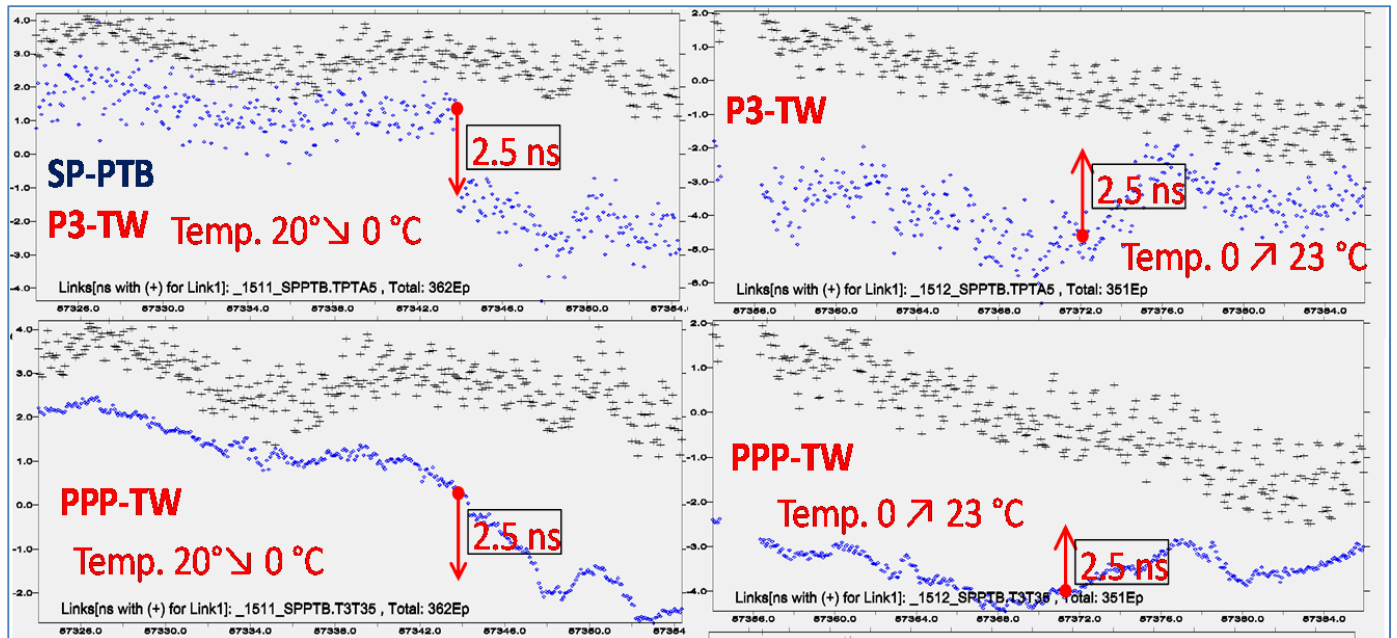


Figure. 5.2.2 Temperature effect on GPS P3 and PPP measurements due to the failure of heating system for antenna and cable on the SP-PTB baseline. The black curves are GPS and the red curves are TW. The antenna's pre-amplifier was found to have a large temperature sensitivity, and it was subsequently replaced.

Figure 5.2.2 shows the correlation between the outside temperature variations of the GPS P3 and PPP measurements at SP when the antenna/cable heating system in their radome was nonfunctional for one month. When the temperature changed 23°C, the measurements changed by 2.5 ns.

V.3 Configuration changes and aging

Some setup changes may cause variations without being observed by the operators. Figure 5.3.1 shows an example [12,14], where due to the reference signals change, the TL Ashtech Z12T's internal reference point (and its calibration) changed 5 ns without being immediately noticed. Reference signal change may produce a jump in the frequency depending GPS receiver.

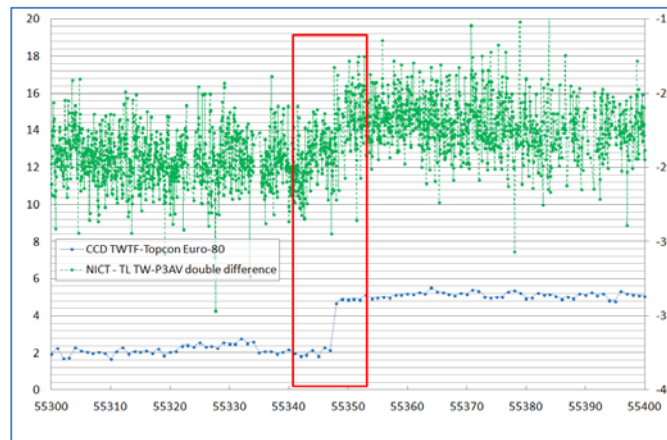


Figure 5.3.1 Changing TL’s master clock produced a jump of 5 ns in a Ashtech Z12T GPS receiver

A similar variation was noted when SP changed an antenna that was connected to two different receivers via an antenna power splitter. In this case, the change in the P1 difference was not the same as the change in the P2 difference (Figure 5.3.2). Impedance mismatching is one possible explanation.

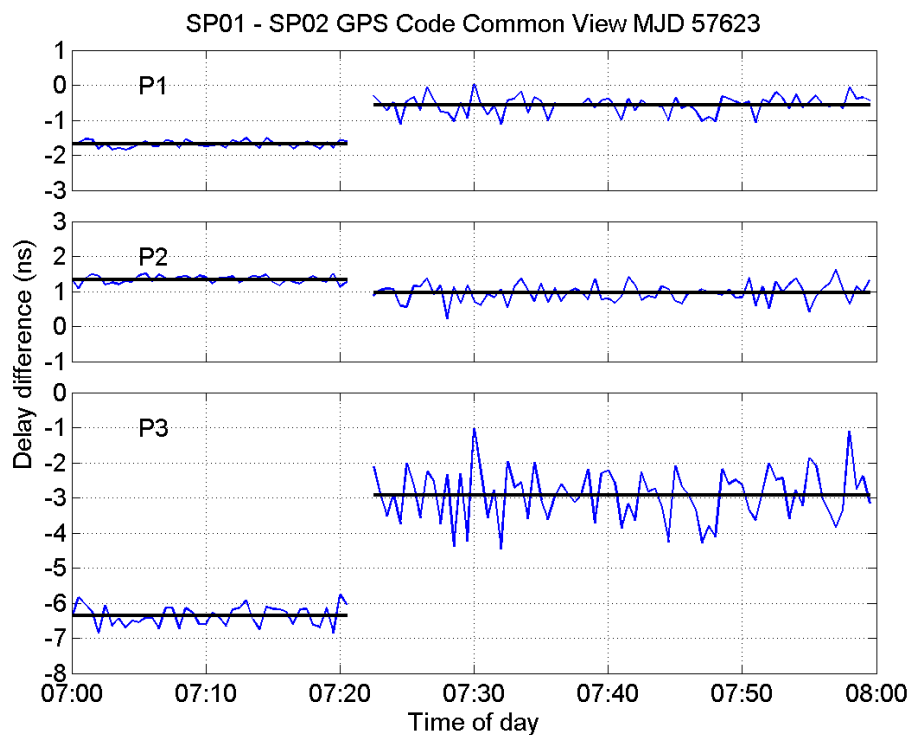


Figure 5.3.2 The change of an antenna feeding two GPS receivers has different effects on their P1 and P2 signals, also impacting their linear combination P3. Along with a change of calibration, note the increase in code noise.

The DCD of TW – GPS PPP (Figure 5.3.3) contains several time steps and a noticeable drift of 1.3 ns/year between the end of 2011 and the beginning of 2015. As reported by ROA [6], the drift disappeared when a Novatel NOV702 antenna and a low-loss H155 cable were replaced by a Leica AR25 choke ring antenna and a LMR400 cable. The drift was diagnosed as aging (sulfated oxidation) of the cable interior, due to humidity and the use of unprotected connectors.

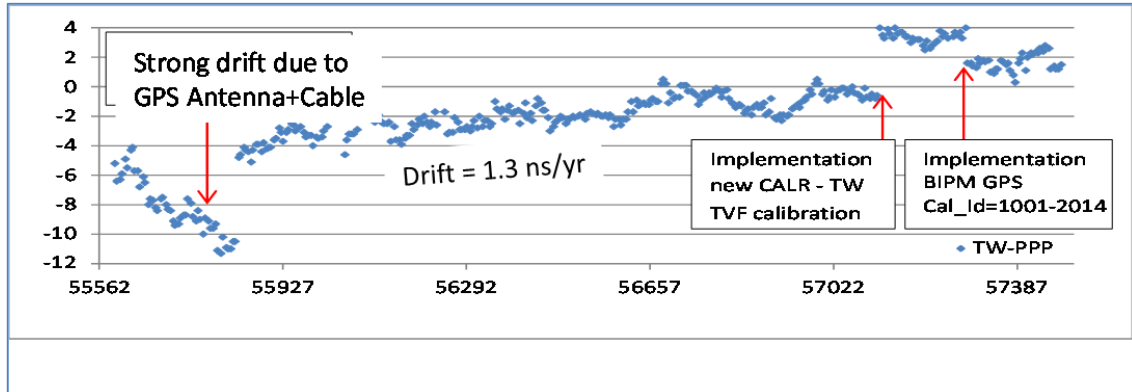


Figure 5.3.3 DCD of TW - GPSPPP for the baseline ROA-PTB during 1101-1603.

PTB has also reported that the TW signal-to-noise ratio increased considerably and the delay jumped by 1.8 ns after a connector to the antenna was cleaned. We also remind the readers that the erroneous reporting of faster-than-light neutrino time of flight was largely due to a poor connector leading to a GPS receiver [8].

VI. TWSTFT AND GNSS TIME TRANSFER STABILITY INVESTIGATED BY REPEATED CALIBRATION

We now review the TW and GPS repeated calibrations performed during the period of this study.

BIPM carried out two G1-laboratory calibrations. During the first calibration tour of 2013-2014, the BIPM GPS calibrator visited the OP, PTB, TL, NICT (National Institute of Information and Communications Technology, Japan), NIM (National Institute of Metrology, China), ROA, NIST and USNO. The second tour started in February 2016, and has visited TL, NICT, NIM and PTB. The differences of the repeated visits have so far been within or about 1 ns, consistent with the calibration uncertainty of ~ 1.7 ns.

The European TW link calibrations were performed in 2014 and 2016, when the TimeTech mobile station (MS) visited the 5 UTC laboratories IT, PTB, OP, ROA and SP. The changes of the calibrations are given in Table 6.1. With the conventional Circular T uncertainty $u_B=1.0$ ns and $u_A=0.5$ ns, the combined uncertainty of the TW links is 1.6 ns. From Table 6.1, except for the links with IT, all the differences (blue) are within 1.6 ns.

Table 6.1 Changes in TW link delay between the 2014 and 2016 European calibration campaigns

Changes	IT	OP	PTB	ROA	SP
IT	0				
OP	-2.88	0			
PTB	-2.63	+0.26	0		
ROA	-2.15	+0.73	+0.48	0	
SP	-3.74	-0.86	-1.12	-1.59	0

Currently, there is no direct TW link between NIST and USNO. An analytical indirect NIST-USNO TW link can be constructed via a European TW station, for example, $(\text{NIST} - \text{USNO})^{\text{PTB}} = (\text{NIST} - \text{PTB}) - (\text{USNO} - \text{PTB})$. A USNO Ku-band TW MS has been used to calibrate the NIST-USNO analytical TW link one or two times a year for more than five years. Figure 6.1 and Table 6.2 give the results of the calibration corrections with respect to the USNO-NIST TW and GPSPPP links.

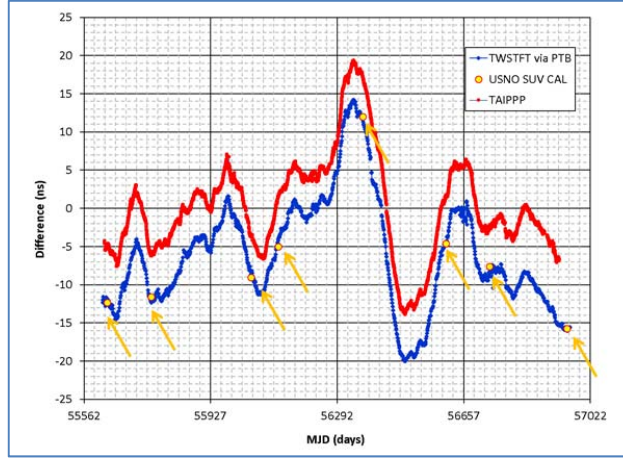


Figure 6.1 The TW and GPSPPP links of NIST-USNO with the calibrations indicated.

Table 6.2 DCD of TW-GPS over the baseline NIST-USNO and the calibration results.

TW CAL	TWCAL - TW	TWCAL - PPP	TW - PPP
Date/Time	(ns)	(ns)	(ns)
03/08/2011	-0.4	-7.5	7.1
07/13/2011	0.8	-5.4	6.2
04/26/2012	-0.5	-5.5	5.0
07/13/2012	-0.8	-6.6	5.8
03/14/2013	0.4	-5.2	5.6
11/09/2013	-0.1	-6.0	5.9
03/14/2014	0.9	-5.1	6.0
10/23/2014	0.1	-8.2	8.3
06/17/2015	0.7	-8.5	9.2
06/08/2016	0.3	-8.0	7.7
Mean $\pm \sigma$	0.14 ± 0.55	-6.60 ± 1.27	6.68 ± 1.27

From Table 6.2, the mean value and the standard deviation of the calibrations of the TW link is 0.14 ± 0.55 ns, consistent with the routine UTC TW Ku-band link. However, the peak-to-peak difference between the GPS links and the calibration results is 3.4 ns with mean -6.60 ± 1.27 ns. During the 15 months, from March 2014 to June 2015, the differences of TW-GPS changed from -5.1 ns to -8.5 ns, or -2.7 ns/year, which is consistent to the results shown in Figure 1.1 and the discussion in Section 4.2. Note here that the means of both TWCAL-PPP and TW-PPP are almost the same, -6.60 ± 1.27 ns vs. 6.68 ± 1.27 ns, and that of the TWCAL-TW is 0.14 ± 0.55 ns. This result agrees with the BIPM 2014-2015 G1-laboratory calibration [9,10]. The constancy of the TW calibrations as shown in this table, and in Figure 6.2 suggests that the GPS link was responsible for the strong drift of about 3 ns per year and is less stable than the TW link.

For the period of this study, USNO has also calibrated the USNO-PTB TW link using the USNO X-band MS every year. The year-to-year differences are always less than 1 ns, the conventional uncertainty. For example, the correction is 0.466 ± 0.766 ns from 2014 to 2015 and -0.517 ± 0.253 ns from 2015 to 2016 [4,9,10]. The difference of the corrections of the two years is <1 ns. The excellent stability of the USNO - PTB and the (USNO - NIST)^{PTB} Ku-band TW links are shown in Figure 6.2

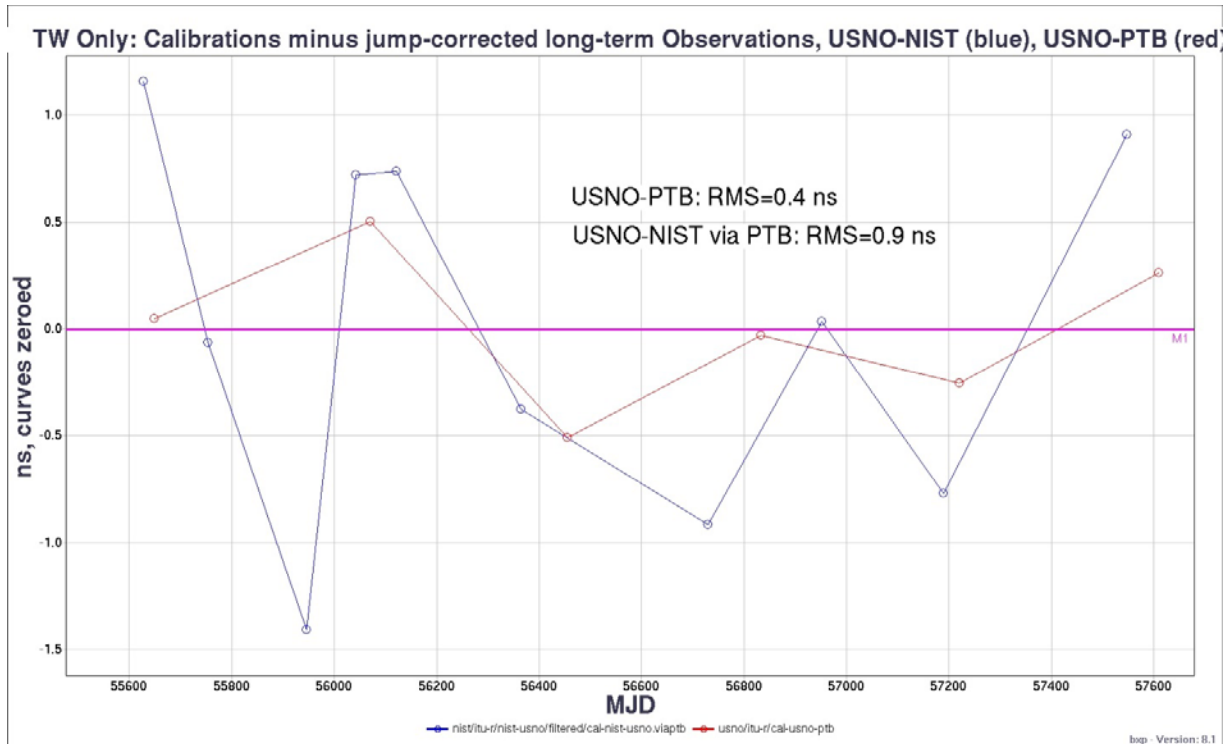


Figure 6.2 The difference between calibrations of the (USNO-NIST)^{PTB} and USNO-PTB links and what would be expected from the operational Ku data, once the operational data are adjusted for configuration changes. The USNO-NIST baseline is calibrated directly; the notation indicates that the operational data are obtained by double-differencing USNO and NIST TW data with the PTB.

From the latest inter-European, inter-US and US-European TW calibrations, the TW links have been largely stable to within their uncertainty (there is one exception). In the case of NIST - USNO, the TW link is much more stable than the GPS link in the sense of long-term stability. However, we cannot conclude how general this result is.

Now based on the repeated calibrations experiences, we have the following observations.

- From the Asia GPS G1 laboratories TL, NICT and NIM, the difference of 2014 and 2016 calibrations are of the order of 1 ns.
- NIST-USNO TW MS calibration between 2011-2016 is less than 1 ns.
- For the Europe TW links OP-PTB, ROA-PTB, SP-PTB, but not for IT-PTB, the differences of the 2014 and 2016 calibration are less than 1.6 ns, the combined uncertainty.
- However, the yearly variation of the DCD of TW-GPS may exceed 2.2 ns, the combined uncertainty of the TW and GPS link calibrations.

VII. SUMMARY AND PROPOSALS FOR DISCUSSION

The following observations are presented in the spirit of discussion, and as tentative conclusions with a view to helping focus our next round of activities.

Many links are stable, but we have also observed several instances of long-term variations of several ns. Several more examples are given in the BIPM's TM263 [4]. These occur in GNSS-only links, TW-only links, and DCD between GNSS and TW links

We have found that past performance is not a reliable indicator of future stability. Long-term drifts can begin, or halt, for no apparent reason. While they can often be quickly identified through comparisons with independent redundant systems, extremely important supplementary information can be obtained via frequent calibrations.

We have also reported evidence of environmental sensitivity including seasonal variations, environmental control malfunctions, and one case of unprotected external connectors leading to long-term aging.

We have found that configuration (including the reference signals) changes can lead to unexpected calibration variations, perhaps subtle enough to not immediately be noticed by the laboratory, and that it is not now standard practice to report such events at any forum.

We suggest that each laboratory, and in particular each G1 and pivot laboratory might want to:

- a. Operate at least 2 completely independent GNSS systems and provide their RINEX and CCGTTS data to the BIPM. These independent GNSS systems should be equipped with their own antenna and cable, and use reference signals directly from UTC(*k*). Three or more independent receiver systems would be much better for G1 and pivot labs, so as to provide CCD resolution of discrepancies and oddities.;
- b. Monitor the CCDs between the receiver systems and the TW-GNSS, either in-house or with the BIPM's web pages, and report any anomalies to the BIPM;
- c. Monitor and record the inside and outside temperature and humidity and provide the data to the BIPM for its web site and database;
- d. Monitor the reference signals at the input to the time transfer equipment (GNSS receivers and TW modems);
- e. Measure the shape of their PPS waveform at key points yearly and as part of the calibration process;
- f. Report all the configuration changes to the BIPM and include the information in the annual report of the TW working group meeting in a format to be determined by the relevant working group;
- g. Participate in a calibration campaign at least once every two years, and conduct calibrations in such a manner that the calibration of a link can apply to redundant operations (with other equipment or techniques) along that same link;
- h. A TW calibration should include a GNSS receiver as a low-cost sanity check and as a way to better understand the accuracy of GNSS-based calibrations. The GNSS calibration may be carried out either by the TW team or by another team, together or in parallel.

We ask if it would be a good idea for the BIPM to:

- a. Continue to compute and publish the TWSTFT, PPP, P3, GPS/GLONASS L1C and TWOTT data from all operational as well as all redundant links
- b. Compute all possible CCDs and DCDs, and publish them both as plots and computer-readable files with easy-to-understand self-identifying names on BIPM web pages
- c. Continue to monitor the CCDs and DCDs, informing the laboratories involved of any irregularities;
- d. Collect and make available computer-readable information that fully describe time transfer system configurations as a function of time;
- e. Collect and make available computer-readable environmental information from participating laboratories;
- f. Collect and make available information about the performance of commercial products, to a level of detail that would be useful to people acquiring equipment, as well as manufacturers;
- g. Prepare and implement software so that a change of the assumed value of a link's calibration is reflected in the predictions of the involved clocks. In such a situation the time differences will still reflect the change in assumed calibration, but the weight of the clocks and their contribution to TAI will not be artificially degraded.

In addition, we invite discussion on whether a calibration correction should be incorporated if it is much less than its uncertainty. We note that one reason for hesitancy in a TW calibration implementation is that it requires coordination, due to its effect on all links obtained by Triangle Calibration Closure (TCC). In the case of a GNSS calibration of the PTB's pivot receivers, a change would affect a large set of GNSS UTC time links and create a direct step in the DCD of TW-GPS.

Finally, we suggest studying to use an ensemble of GNSS receiver systems instead of a single one to improve the long-term stability [14], and note that there might be a need for a best-practices manual concerning how to set up, maintain, and document Time Transfer Systems.

VIII. DISCLAIMER

Although equipment is identified for the sake of technical clarity, none of the institutions represented can or will endorse a commercial product. We further caution the reader that none of the described equipment's apparent strengths or weaknesses may be characteristic of items currently marketed.

This paper includes contributions from the U.S. Government and is not subject to copyright.

We also note that the opinions expressed in this paper are solely those of the three authors, and are presented in the spirit of open discussion for the full Working Groups and the entire timekeeping community.

IX. ACKNOWLEDGEMENTS

We particularly wish to thank Andreas Bauch, Dirk Piester, and Franziska Riedel of the PTB not only for their wise advice, but most importantly for their diligent efforts carrying out the PTB's responsibilities as the BIPM's sole pivot lab in the generation of TAI.

X. REFERENCES

- [1] BIPM Circular T 345, <http://www.bipm.org/en/bipm-services/timescales/time-ftp/Circular-T.html>
- [2] D. Matsakis, L. Breakiron, A. Bauch, D. Piester, and Z. Jiang, 2009, "Two-Way Satellite Time and Frequency (TWSTF) Calibration Constancy from Closure Sums", 40th Annual PTTI
- [3] Jiang Z., Czubla A., Nawrocki J., Lewandowski W. and Arias F. (2015), Comparing a GPS time link calibration to an optical fibre self-calibration with 200 ps accuracy, 2015 Metrologia **52** 384
- [4] Jiang Zhiheng et Zhang Victor (2016) Long-term instability in UTC time links, BIPM Technical Memorandum, TM263, 2016
- [5] Galindo F.J., Esteban H., Bauch A., Piester D., Sesia I., Achkar J., Jaldehag K., Rieck C., Piriz R (2016) European TWSTFT Calibration Campaign 2014 of UTC(k) laboratories in the Frame of Galileo FOC TGVF, PTTI2016, Proc. P243-257
- [6] Galindo Francisco Javier and Piester Dirk (2016) Report on the 2016 Calibration of European TWSTFT links, CCTF WG on TWSRFT, Sept. 2016, NIST, USA
- [7] Lin Calvin S.Y. et al. (2010), Proc. EFTF 2010
- [8] Strassler, M. (2012) "[OPERA: What Went Wrong](http://profmattstrassler.com)", *profmattstrassler.com*
- [9] Patla B., Romisch S., Zhang V., Wu W., Tisserand L., Petit G., Arias F. and Jiang Z. (2014) UTC link calibration report - Phase X: at NIST, BIPM Technical Memorandum, TM247, 2015
- [10] Petit G (2015) Determination of reference GPS "INTDLY" values of Group 1 geodetic receivers, BIPM Technical Memorandum, TM243, 2015
- [11] Piester D., Bumgarner R., and McKinley A. (2014) The June 2014 calibration of the link UTC(USNO) – UTC(PTB) by means of the USNO portable X-band TWSTFT station, presented to the 22nd CCTF Working Group on TWSTFT, VNIIFTRI, 15-16 Sept. 2014, Mendeleevo, Russia
- [12] Piester D., Bumgarner R., Wright J., McKinley A., Bauch A. (2015) Report of The July 2015 calibration of the link UTC(USNO) – UTC(PTB) by means of the USNO portable X-band TWSTFT station
- [13] Jiang Z., Lin S. Y., Huang Y. J. and Tisserand L. (2013) METODE Experiments 2013-V -- MEasurement of TOtal DELay for UTC Time Link Calibration Phase V: Measurements at and between TL and PTB, BIPM Technical Memorandum, TM218, 2013
- [14] Jiang Z, Matsakis D., Mitchell S., Breakiron L., Bauch A., Piester D., Maeno H and Bernier L. G. (2011) Long-term instability of GPS-based time transfer and proposals for improvements, *Proc. PTTI 2011*