GNSS CALIBRATION REPORT

G1G2_1016_2017

Prepared by: Andreas Bauch (PTB)
Head, Time Dissemination
Working Group

Approved by: Jürgen Becker (PTB)
QM-representative of
Time and Frequency
Department of PTB

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REFERENCES

REFERENCES	
RD01	**BIPM report 1001-2016, 2016 Group 1 GPS calibration trip BV 1.1 2017-01-18**
RD02	**BIPM guidelines for GNSS calibration, V3.0, 02/04/2015**
RD03	**BIPM TM.212 (G. Petit), Nov. 2012**
RD04	**J. Kouba, P. Heroux, 2002, *“Precise Point Positioning Using IGS Orbit and Clock Products,”* GPS Solutions, Vol 5, No. 2, 12-28**
RD05	**W. Lewandowski, C. Thomas, 1991, *“GPS Time transfers,”* Proc. IEEE, Vol. 79, No. 7, 991-1000**
RD06	**PTB GNSS calibration report G1G2_1012_2016**
RD07	**P. Defraigne and G. Petit, “CGGTTS-Version 2E: an extended standard for GNSS time transfer, Metrologia 52 (2015) G1**

ACRONYMS

ACRONYMS	
BIPM	Bureau International de Poids et Mesures, Sèvres, France
BKG	Bundesamt für Kartografie und Geodäsie
CGGTTS	CCTF Generic GNSS Time Transfer Standard
EURAMET	The European Association of National Metrology Institutes
IFAG	Institut für Angewandte Geodäsie
IGS	International GNSS Service
GNSS	Global Navigation Satellite System
GOW	Geodätisches Observatorium Wettzell
ORB	Observatoire Royal Belgique
PPP	Precise Point Positioning
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
RINEX	Receiver Independent Exchange Format
R2CGGTTS	RINEX-to CGGTTS conversion software, provided by ORB / BIPM
TDEV	Time deviation
TIC	Time interval counter

EXECUTIVE SUMMARY

As part of the support of the BIPM Time and Frequency Group by EURAMET, PTB conducted a relative calibration of the GNSS equipment of BKG, operated at the geodetic observatory Wettzell (GOW), Bavarian Forest, Germany, with respect to the calibration of PTB receiver PT02, whose last calibration was reported with Cal_Id=1001-2016 [RD01]. PTB provided its receiver PTBT for the purpose as travelling equipment.

The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1016_2017. Results provided are the visited receivers' internal delays for GPS P-code signals on the two frequencies L1 and L2 (INT DLY (P1), and INT DLY(P2)). The delays for the C/A-code signals on L1 and for GLONASS signals were not determined during this campaign.

The final results are included in Table 9-1. The internal delays of 2 receivers were determined with an uncertainty of about 1.2 ns for P1 and P2, respectively. The uncertainty for P3 time transfer links to PTB is of the order 1.6 ns. This value is marginally larger than in previous similar campaigns and related to an apparent change in the travelling equipment during its long journey.

As a reminder: All uncertainty values reported in this document are 1-σ values.

Following instructions from the PTB quality management responsibles, it should be stressed that the correctness of all results and of the stated uncertainty values relies on the correctness of the entries in the installation report (BIPM information tables) provided by the visited institute.

1. CONTENTS OF THE REPORT

As part of the support of BIPM Time and Frequency Group by EURAMET, PTB conducted a relative calibration of the GNSS equipment of of BKG, operated at the geodetic observatory Wettzell, Bavarian Forest, Germany, designated as GOW, with respect to the calibration of receiver PT02, whose last calibration was reported with Cal_Id=1001-2016 [RD01]. PTB provided its receiver PTBT for the purpose as travelling equipment. This report documents the installation, data taking and evaluation during the campaign.

The determination of the internal delay values of the receivers at the visited site is a three-step process.

At first (Common-Clock 1, CC1) the travelling receiver, PTBT, is compared to the “golden” receiver, PT02, and the offset between the actual and the assumed PTBT delay values is determined.

After that, the receiver is installed at GOW and the internal delay values of the devices under test and their statistical properties are determined.

Finally, the stability of the PTBT delay is assessed by a second Common-Clock measurement (CC2) in PTB. Based thereon, the “final” INT DLY values of the visited receivers and their uncertainty values are calculated.

The structure of this report follows this sequence of work. After presentation of the participants and schedule, a general section follows that contains the (mathematical) calibration procedure, followed by a report of data collection at PTB and GOW. The final results and the uncertainty discussion close the report. In the Annex the BIPM information tables are reproduced.

2. PARTICIPANTS AND SCHEDULE

Table 2-1: List of participants

Institute	Point of contact	Site address
PTB	Thomas Polewka Tel +49 531 592 4418 Thomas.polewka@ptb.de	PTB, AG 4.42 Bundesallee 100 38116 Braunschweig, Germany
GOW	Uwe Hessels Tel. : +49 9941 / 603-208 or -128 G_GPS@fs.wettzell.de uwe.hessels@bkg.bund.de	Bundesamt für Kartographie und Geodäsie, Geodätisches Observatorium Wettzell Betriebsgruppe Mikrowellenverfahren VLBI-GNSS-DORIS Sackenrieder Str. 25 D - 93444 Bad Kötzting

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2017-10-04 until 2017-10-15	PTB	First common-clock comparison between PTBT and PT02	10 days used for evaluation, MJD 58031 – 58040 (incl.)
2017-10-17 Until April 2018	GOW	Operation of PTBT and two GNSS receivers in sequence	58044 – 58050 Rec. WTZS (IF19) 58086 -58095 Rec. WTZA (IF14)
Starting 2018-04-27 – 2018-05-09	PTB	Operation of PTBT after return	9 days used for evaluation, MJD 58237 - 58245

Information on the receivers at each site is contained in individual information tables which can be found in the Annex.

3. CALIBRATION PROCEDURE

The calculation of INT DLY values for the receiver to be calibrated follows the description given in BIPM TM.212 [RD03] and has been coded in software routine cv.py written by Julia Leute of PTB. The following text piece that describes its function is generated via copy-paste from [RD03] with small changes of the designation of quantities.

When dealing with G1G2 calibrations, in principal we distinguish receivers V, T, and G: V for visited, T for travelling, and G for golden_reference. G1 labs committed to ship their T to the other sites. In the current campaign, PT02 (named PTBB when referred to as IGS station) serves as the reference receiver G, its internal delays were determined by BIPM in the second G1 campaign with the identifier Cal_Id=1001-2016. PTBT served as the travelling receiver T.
Conventionally, the receiver delay D is considered as the sum of different terms that are defined subsequently:

(1) INT DLY
The sum $X_R + X_S$ represents the “INT DLY” field in the CGGTTS header:
X_R represents the receiver hardware delay, between a reference point whose definition depends on the receiver type and the internal time reference of the measurements. X_S represents the antenna delay, between the phase center and the antenna cable connector at the antenna body. We distinguish the two quantities for the two frequencies, 1 and 2.

INT DLY(P1) and INT DLY(P2) of receiver V are the basic quantities that are determined during the relative calibration. For calculating ionosphere—free observation data, INT DLY(P3) is calculated as 2.54×INT DLY(P1) - 1.54×INT DLY(P2).

The following terms are considered frequency independent, i. e. no distinction is made for P1 and P2 and other signal frequencies.

(2) CAB DLY
The sum $X_C + X_D$ represents the “CAB DLY” field in the CGGTTS header.
X_C corresponds to the delay of the long cable from the antenna to the input connector at either the antenna splitter or the receiver body directly. If a splitter is installed, X_D corresponds to the delay of the splitter and the small cable up to the receiver body. For a simple set-up with just an antenna cable, $X_D = 0$.

(3) REF DLY
The sum $X_P + X_O$ represents the “REF DLY” field in the CGGTTS header.
X_P corresponds to the delay of the cable between the laboratory reference point for local UTC and the 1 PPS-in connector of the receiver.
X_O corresponds to the delay between the 1PPS-in connector and the receiver internal reference point, the latter depending on the receiver type:

- For Ashtech Z12-T: The first positive zero crossing of the inverted 20 MHz-in following the 1PPS-in, delayed by 15.8 ns,

- For Septentrio PolaRx2: The 1PPS-out, delayed by 8.7 ns,
- For Septentrio PolaRx4: The 1 PPS-out, no further correction
- For DICOM GTR50 and GTR51: The 1PPS-in, i.e. $X_O = 0$,
- For Javad/Topcon: The first positive zero crossing of the 5/10 MHz-in following the 1PPS-in.
- For TTS-4: RD02, Section 2.3.2, and Annex G specify the procedure for TTS-4, which in detail depends on the software version.

Details of the measurement procedures for the Ashtech Z12-T are given in the BIPM calibration guideline [RD02], but the parameters of PT02 were not determined again on occasion of the current campaign.

The distinction of the individual components of the receiver delay reflects the fact that two of them, 2 and 3, can in principle be measured with standard laboratory equipment. Changes of the receiver installation typically affect cabling and thus such delays.

The quantity to be determined by the relative calibration is INT DLY. INT DLY of the device under test is determined in such a way that the common-clock differences obtained between the device under test and the reference are zero on average. The INT DLY of T may need to be adjusted so that T and G match, but in practice the small correction needed is taken into account only when INT DLY of V is adjusted to G, using T as intermediate for the measurements made at the different sites.

In the process followed by PTB, valid CGGTTS files with dual frequency observation (L3P) data (including correct, accurate antenna coordinates) are needed. As a reminder,

$$\mathrm{REFGPS}(k) = [\mathrm{REFGPS_{RAW}}(k) - \mathrm{CAB\ DLY_F} - \mathrm{INT\ DLY(P3)} + \mathrm{REF\ DLY_F}], \quad (1)$$

where REFGPS(k) is reported in column 10 of the standard CGGTTS files, $\mathrm{REFGPS_{RAW}}$ designates the uncorrected measurement values, INT DLY(P3) is calculated as $2.54 \times \mathrm{INT\ DLY(P1)_F} - 1.54 \times \mathrm{INT\ DLY\ (P2)_F}$, and the values designated as “Q_F” are reported in the CGGTTS file header.

The software cv.py in calibration mode is used to calculate:

$$\mathrm{REFGPS_{P1}}(j) = \mathrm{REFGPS}(j) + \mathrm{MDIO}(j) \quad (2a)$$
$$\mathrm{REFGPS_{P2}}(j) = \mathrm{REFGPS}(j) + \mathrm{MDIO}(j) + (f_1/f_2)^2 \times \mathrm{MDIO}(j), \quad (2b)$$

where $(f_1/f_2)^2 = 1.647$ for GPS for each satellite observation j and REFGPS(j) and MDIO(j) are from the line in the CGGTTS file that reports the observation j. Eq. 2a and 2b build on the rules how CGGTTS L3P data lines are generated.

If the common-view condition is fulfilled for the observations with T and G, the differences

$$\Delta Pi: = \mathrm{REFGPS_{Pi}}(T) - \mathrm{REFGPS_{Pi}}(G) \quad (3)$$

are calculated and represent the difference Pi(new) – Pi(old) for receiver T. The example here involves T and G: Equivalent relations hold for the pair of receivers T and V.

cv.py at the end of the computation edits the median value of all individual observations ΔPi for P1 and P2, and the number of data points used. In addition cv.py generates a file deltap_stats that contains observation epoch (MJD.frakt) and the average ΔP1, ΔP2 of all satellite observations at that epoch. Such values are plotted throughout the report in the various figures.

The calculation of the INT DLY values comprises two steps:

Step 1: INT DLY(Pi)_T_corr = ΔPi(T,G) + INT DLY(Pi)_T_F, (4)

where the last summand >_F < is the value reported in the CGGTTS file.

Step 2: The final results for receiver V is to be calculated as

INT DLY(Pi)_V_new = ΔPi(V,T) + <ΔPi(T,G)> + INT DLY(Pi)_V_F, (5)

where <ΔPi(T,G)> is the mean value obtained during CC1 and CC2. Another option would have been to adjust the INT DLY of receiver T after CC1, but this was not done.

The third summand in (5) on the right represents the INT DLY value that was reported previously in the CGGTTS file of receiver V. In some cases this value may be reported initially as zero.

4. CHARACTERIZATION OF PTB EQUIPMENT

The receiver PTBT had been used during campaigns G1G2_1019_2016 which happened only in Spring 2017 and during G1G2_1015_2017 (June/July 2017). After that it was operated for some weeks in PTB, but only re-activated close to the start of the current campaign. The comparison results against PT02 are shown in Figure 4-1. The installation of the receivers in PTB is depicted in Figure 4-2 for 1 PPS signals and in Figure 4-3 for 5 MHz signals. The PT02 and PT03 receivers are supplied with 20 MHz from a times 4 multiplier.

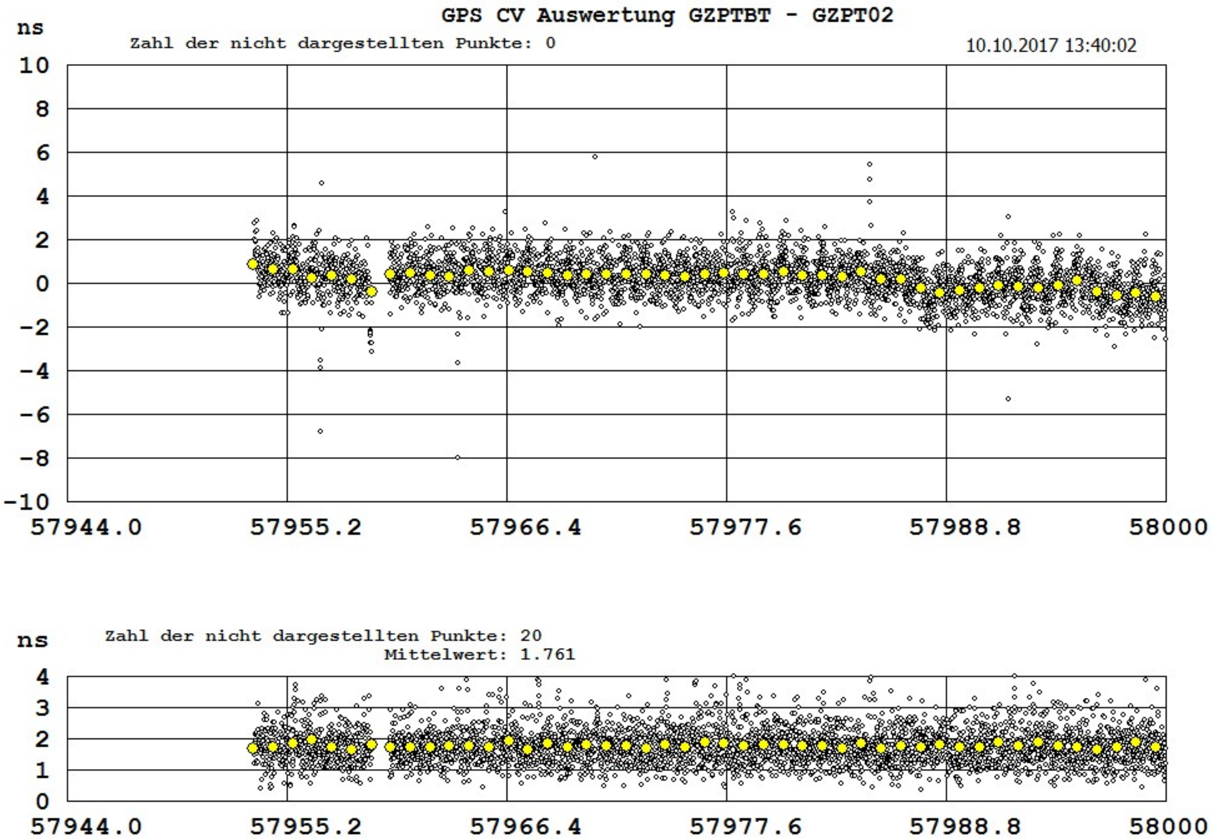

Figure 4-1: Common-clock common-view comparison between PTBT and PT02 at PTB, daily mean values (yellow) and 16-min avg data (grey), time differences (upper graph) and standard deviation (lower graph)

We note from Figure 4-1 that PTBT and PT02 had been almost perfectly aligned during this period. The correct PTBT INT DLY(Pi) values to be used in the calculation of INT DLY of receivers V is determined using eq. (5) as explained before. Data collection and proceing is described in section 5.

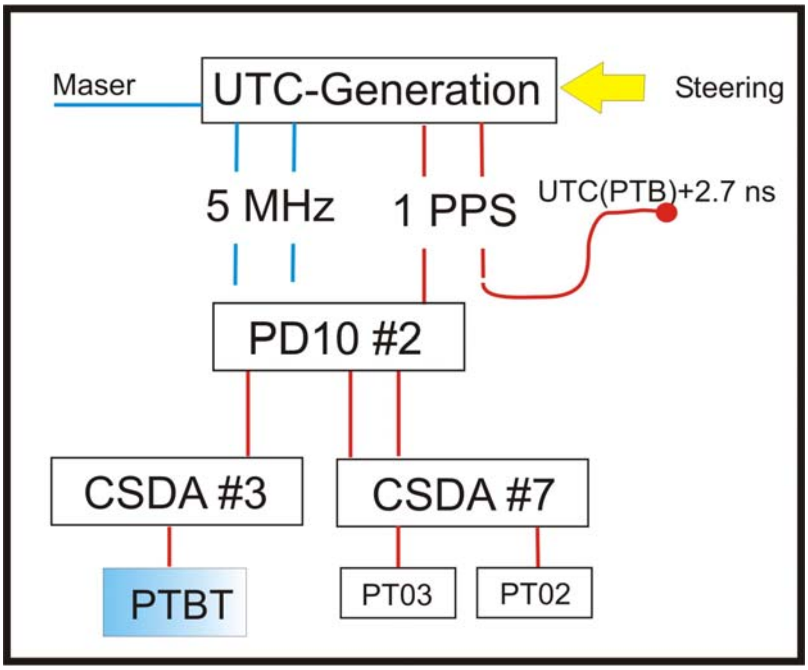

Figure 4-2: UTC(PTB) reference point and 1 PPS signal distribution to PT02, PT03 and PTBT; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

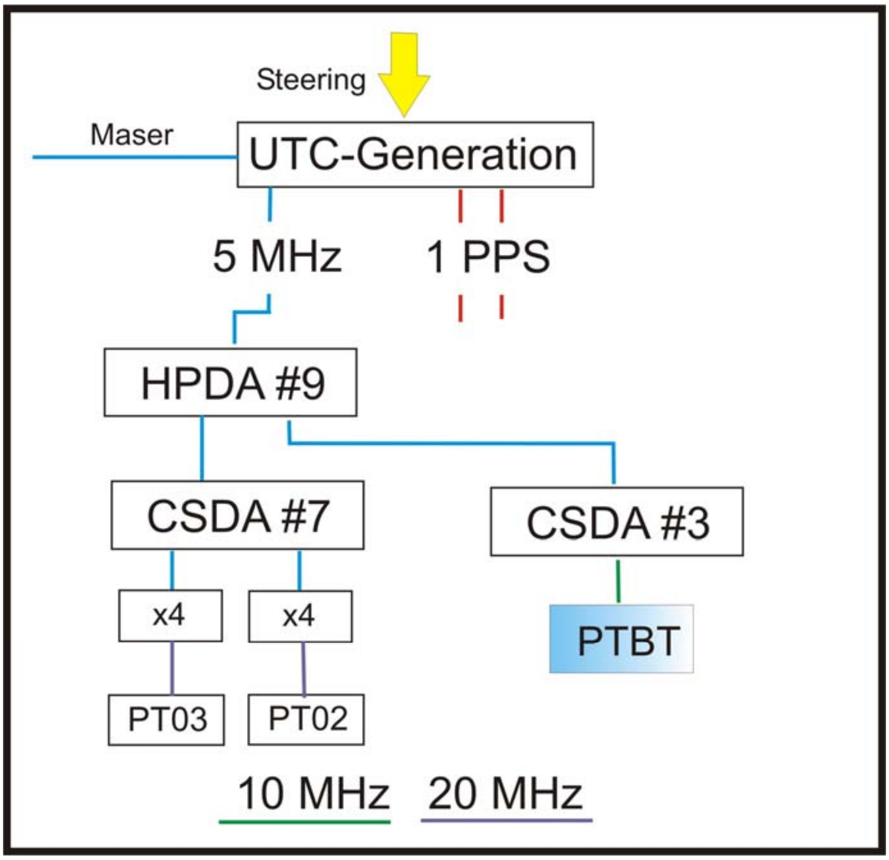

Figure 4-3: UTC(PTB) signal distribution (5 MHz, 10 MHz, 20 MHz) to PT02, PT03 and PTBT, HPDA stands for High-precision distribution amplifier (for rf frequencies)

Figure 4-4: Installation of GNSS antennas at PTB

Figure 4-4 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall) and was taken during the CC1 period of the current campaign. The two Ashtech SNOW antennas (with dome) belong to PT03 (background) and PT02 (middle). The PTBT antenna is seen as the most right antenna in the foreground. The Novatel antenna (hemispherical dome) is part of PT09 based on a Septentrio PolaRx4 receiver that is mentioned below.

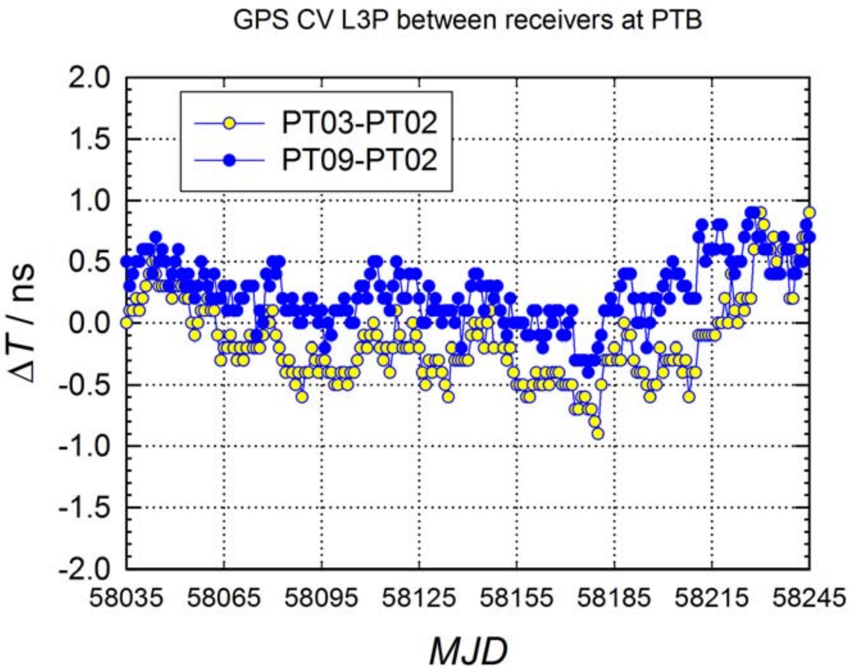

Figure 4-5: Daily mean time difference ΔT between the PTB receivers, PT03 – PT02 and PT09-PT02, during the period of the calibration campaign.

The campaign stretched over 7 months. In Figure 4-5 the common-view common-clock time differences between PT03, PT09 and PT02 during this period is shown. We may suspect a seasonal variation with an amplitude of 0.5 ns to 1 ns peak-to-peak. The differences between the two CC experiments (58031 – 58040 and 58237-58245, respectively) are thus fortunately very small.

5. RESULTS OF COMMON-CLOCK SET-UP IN PTB: PERIOD 1

The period 58031 to 58041 (10 days) was chosen to determine the initial PTBT INT DLY values (CC1). The result of comparison with PT02 as the reference are shown in Figure 5-1 illustrating in total 885 ΔPi (see eq. 3) values obtained as mean over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets follow as Figure 5-2. The numerical results are given in the Summary sub-section at the end of the report on CC2 in PTB.

A slight offset is now noted which is likely due to the different antenna cable used in preparation of the current campaign.

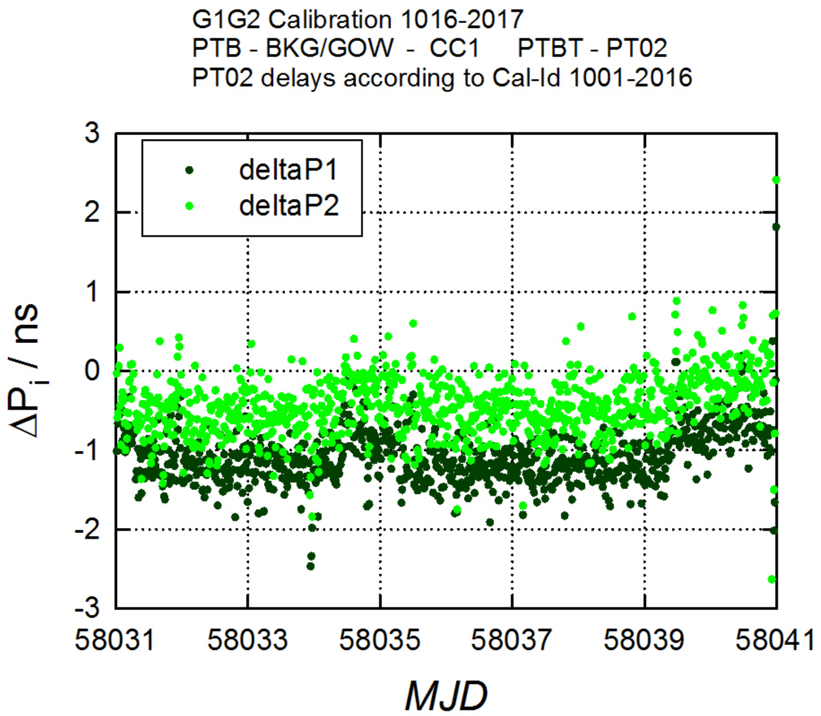

Figure 5-1: ΔP1 (dark green) and ΔP2 (light green) values obtained during the first common-clock set-up in PTB.

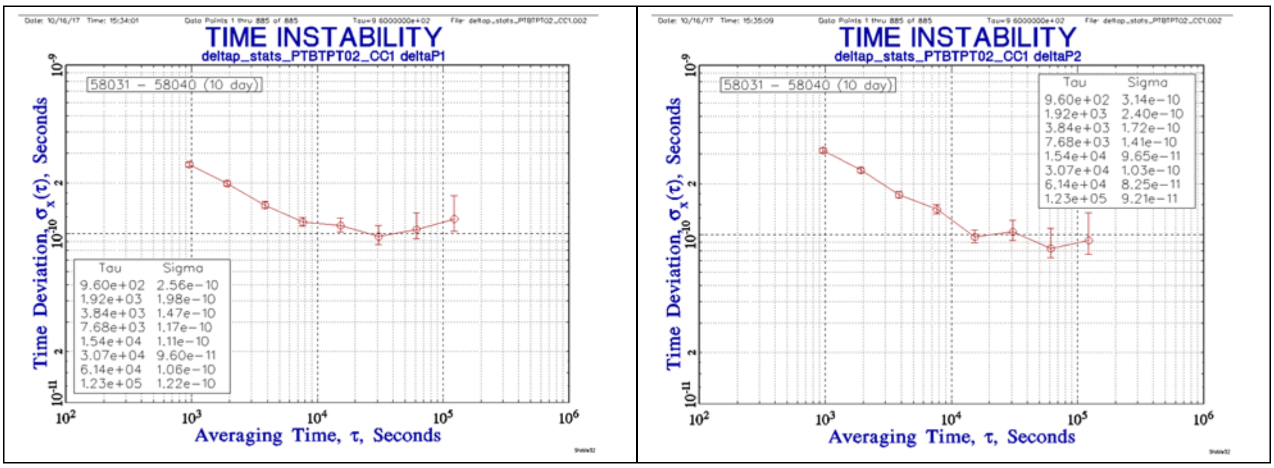

Figure 5-2: TDEV obtained for the two data sets shown in, ΔP1 left, ΔP2 right.

The INT DLY(Pi) of PTBT have not been corrected for the offsets shown in Figure 5-1 before shipment. Instead, the individual value found for the visited receivers will be corrected for the mean value obtained after the second common-clock set-up (see eq. 5)).

6. OPERATION OF PTBT AT GOW, WETTZELL

PTBT was operated at GOW for an extended period, and calibrations of individual receivers were performed in sequence at different sites on the GOW campus. The results are presented in separate subsections. Unfortunately, the calibration of two other GOW receivers failed as data were lost or corrupted.

6.1. CALIBRATION OF RECEIVER WTZS

Seven days between MJD 58044 and 58050 (2017-10-18 – 2017-10-24) were used for the data analysis of receiver WTZS. CGGTTS data of this receiver are designated as GZIF19MJ.DDD). Details on the receiver and its installation are given in the Annex. All antenna coordinates were determined consistently using NRCan PPP immediately before the period of data taking.

The installation of the receivers PTBT and WTZS at GOW is illustrated in Figure 6-1, and the mounting of the antennas is shown in Figure 6-2.

The cable delay of 14.9 ns of the cable connecting the 1 PPS REF of PTBT with the UTC(IFAG) reference point was edited into the PTBT user interface. The REF DLY that is reported in PTBT CGGTTS files is then depending on the second cable connecting to 1 PPS M (for measurement) and is determined from a time interval measurement using a TIC that is part of PTBT and the value 14.9 ns. In this respect, the reporting of the "measured delays" and the REF DLY in the BIPM Calibration Information Sheets (see Annex) is not consistent. PTB practice has been to report only the final value that is found in the CGGTTS file at both instances. BKG reported different values. This led to some confusion in case of the second GOW receiver (see below).

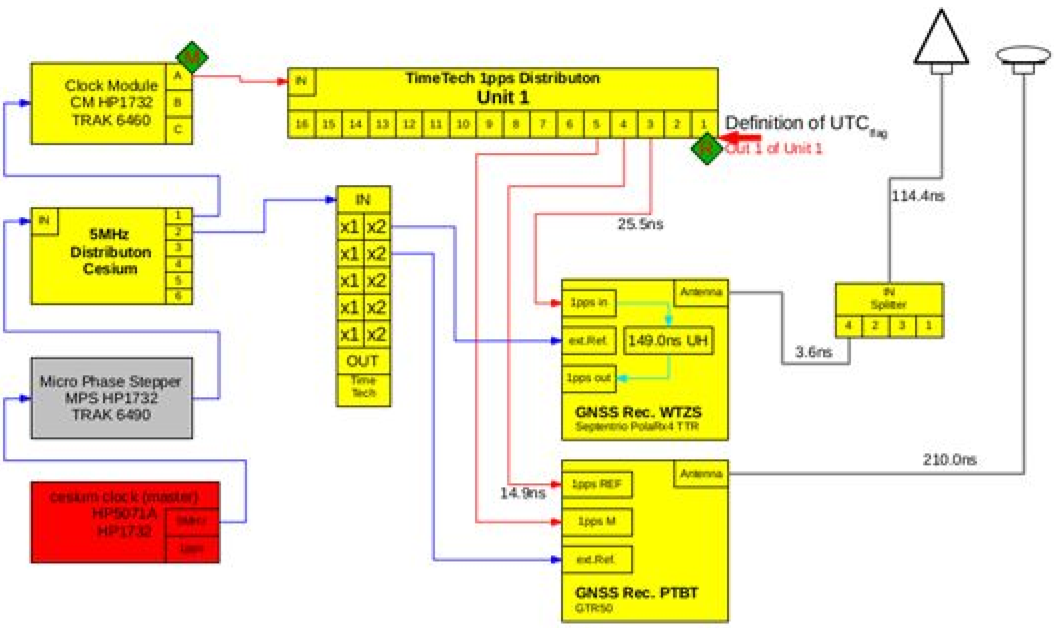

Figure 6-1 Signal distribution at GOW to the receivers WTZS and PTBT

Figure 6-2: Antenna position on the GOW campus and on the rooftop of the GOW building

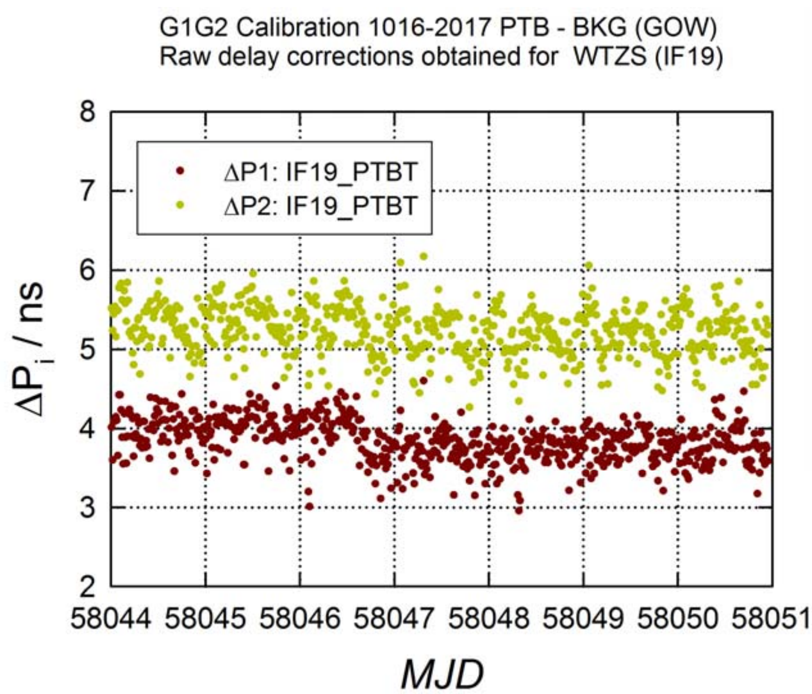

Figure 6-3 ΔP1 (dark red) and ΔP2 (olive) values obtained comparing receiver WTZS (file name GZIF19MJ.DDD) and PTBT.

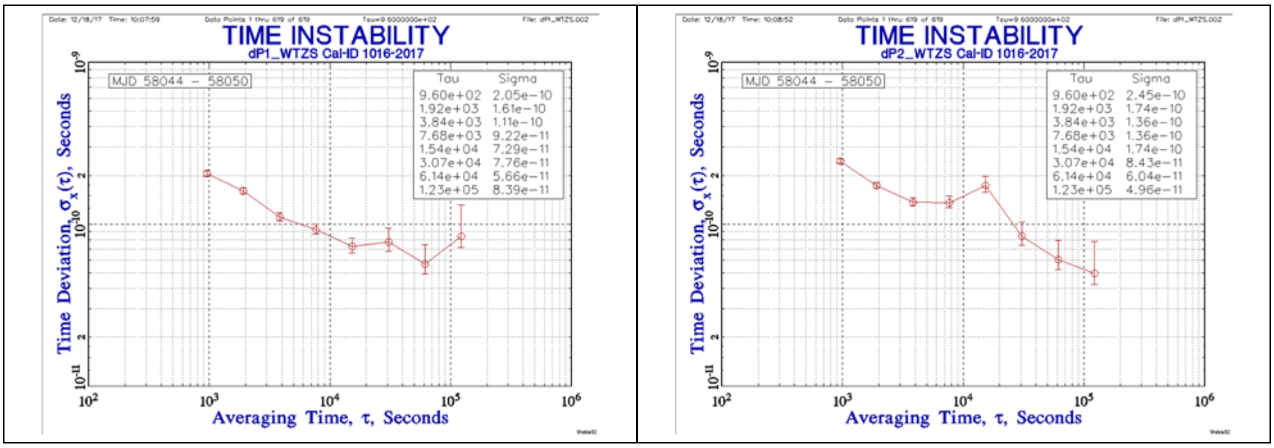

Figure 6-4: TDEV obtained for the two data sets shown in Figure 6-3, ΔP1 left, ΔP2 right.

In Figure 6-4, the ΔPi (3) derived from the raw data are depicted and the result are summarized in Table 6-1, including their statistical uncertainty. The corresponding TDEV plots are shown in Figure 6-4. As a statistical measurement uncertainty the value of TDEV at τ equal to about one tenth of the total measurement time (about 60 000 s) is chosen, cum grano salis, to be not too optimistic.

Table 6-1: ΔINT DLY(Pi) values and statistical properties (in ns) obtained initially.

ΔINT DLY (Pi) for receivers at DTAG	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
IF19 P1	3.84	3.85	0.26	0.1	619
IF19 P2	5.23	5.25	0.31	0.1	619

6.2. CALIBRATION OF GOW RECEIVER WTZA

Ten days between MJD 58086 and 58095 (2017-11-29 – 2017-11-08) were used for the data analysis of receiver WTZA. CGGTTS data of this receiver are designated as GZIF14MJ.DDD). Details on the receiver and its installation are given in the Annex. Antenna coordinates were determined consistently using NRCan PPP immediately before the period of data taking. The installation of the receivers PTBT and WTZA at GOW is illustrated in Figure 6-5. The value 14.9 ns reported at the connection to PTBT is just the cable delay and does neither include the 19 ns offset between UTC_{GNSS} and UTC_{ifag} (labelled in Figure 6-5) nor the delay between port 8 and port 1.

Please note that in the Annex, Section "Measured delays / ns", the correct values are reported with the time reference defined as port 1 of the [1pps Distribution] device Symmetricom 6602. The differential delays between individual ports had been measured beforehand and are recorded on the instrument. In the Annex, Section "Data used for the generation of CGGTTS files" reports the values that are actually found in the cggtts files used in the calculations. The same cables were used to connect PTBT with two ports of the Symmetricom 1PPS distributor. The value 14.9 ns entered in the PTBT user interface, however, does not reflect the correct offset from the time reference plane as can be seen from Figure 6-5. The calculated ΔPi values (3) (see plots below) therefore need to be increased by [(22.2 – 1.5) + (221.4 -221.5)] ns.

The mounting of the antennas is shown in Figure 6-6.

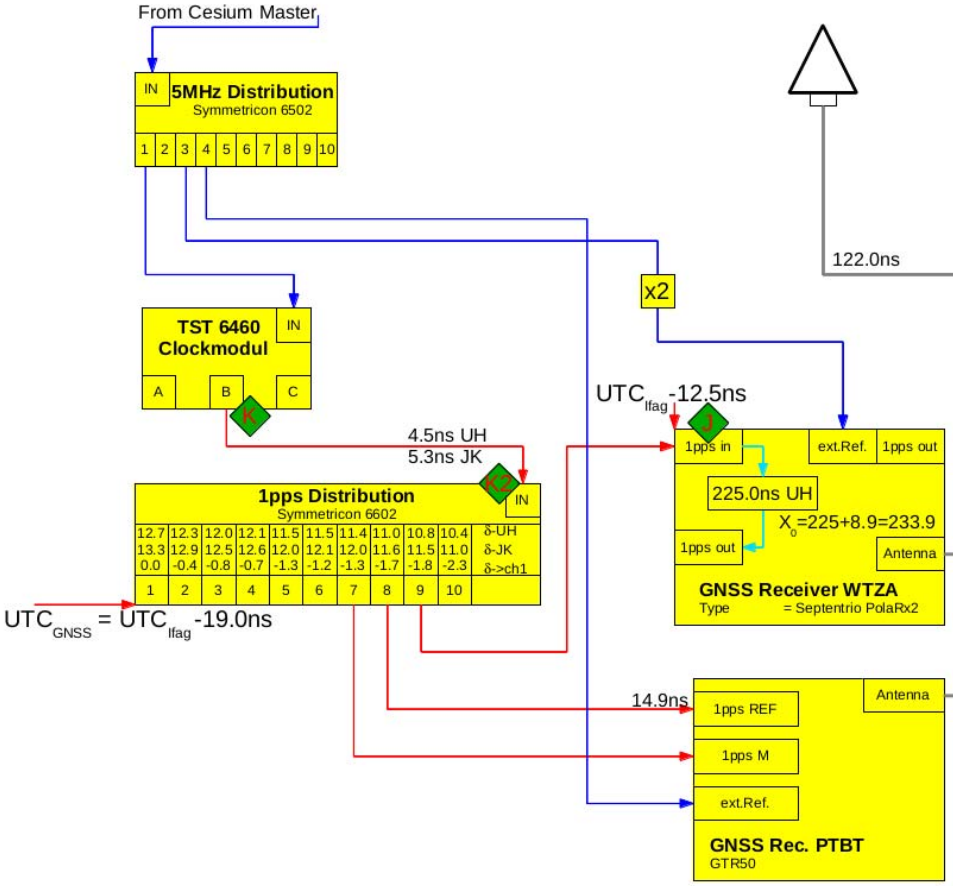

Figure 6-5 Signal distribution at GOW to the receivers WTZA and PTBT

Figure 6-6 Antenna of WTZA (left) and PTBT (right) during data taking

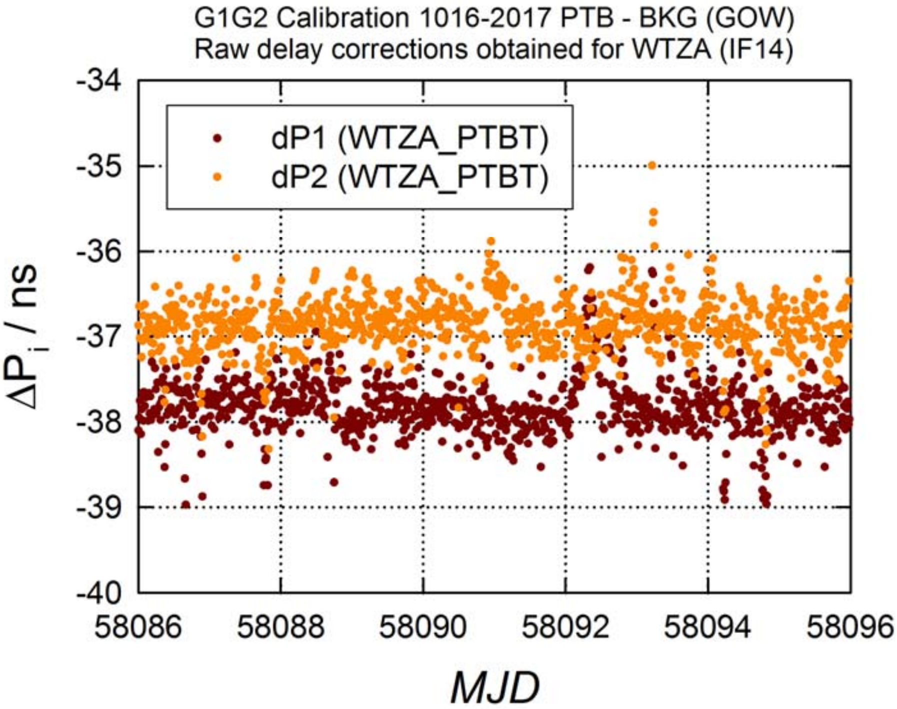

Figure 6-7 ΔP1 (brown) and ΔP2 (orange) values obtained comparing receiver WTZA (file name GZIF14MJ.DDD) and PTBT.

In Figure 6-7, the ΔPi (3) derived from the raw data are depicted and the result are summarized in Table 6-2, including their statistical uncertainty. Note that corrections to the raw data are applied as explained before. The corresponding TDEV plots are shown in Figure 6-8. As a statistical measurement uncertainty the value of TDEV at τ equal to about one tenth of the total measurement time (about 80 000 s) is chosen, cum grano salis, to be not too optimistic.

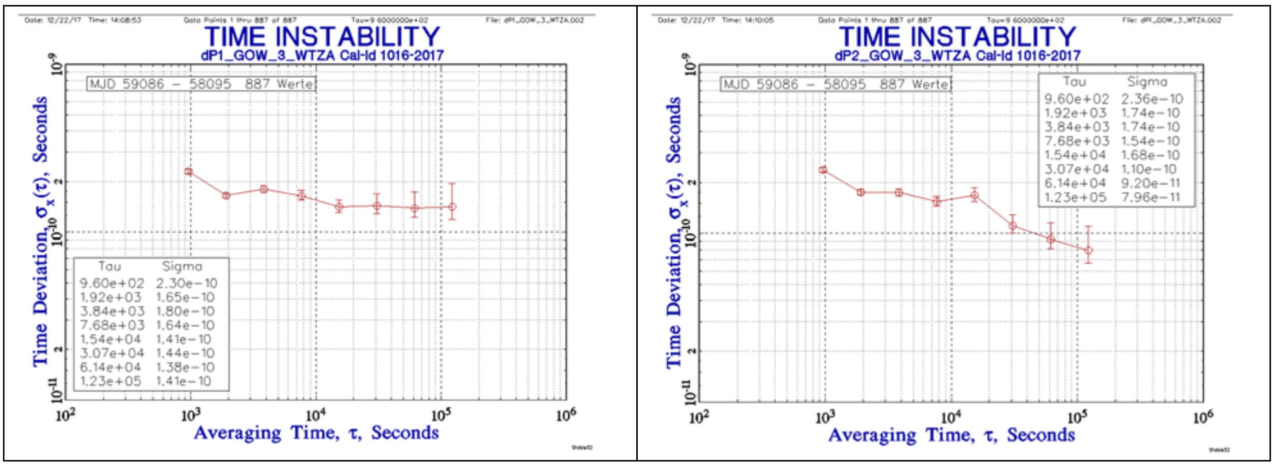

Figure 6-8 TDEV obtained for the two data sets shown in Figure 6-7, ΔP1 left, ΔP2 right.

Table 6-2 ∆INT DLY(Pi) values and statistical properties (in ns) including corrections for erroneous cggtts files.

∆INT DLY (Pi) for receivers at DTAG	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
IF14 P1	-17.22	-17.24	0.34	0.15	887
IF14 P2	-16.27	-16.29	0.33	0.1	887

7. OPERATION OF PTBT AT PTB: SECOND PERIOD

The period 58237 to 58245 (9 days) was chosen to determine PTBT INT DLY values during the common clock period CC2. The result of comparison with PT02 as the reference are shown in Figure 7-1, illustrating in total 798 ∆Pi (see eq. 3) values obtained as mean over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets follow as Figure 7-2.

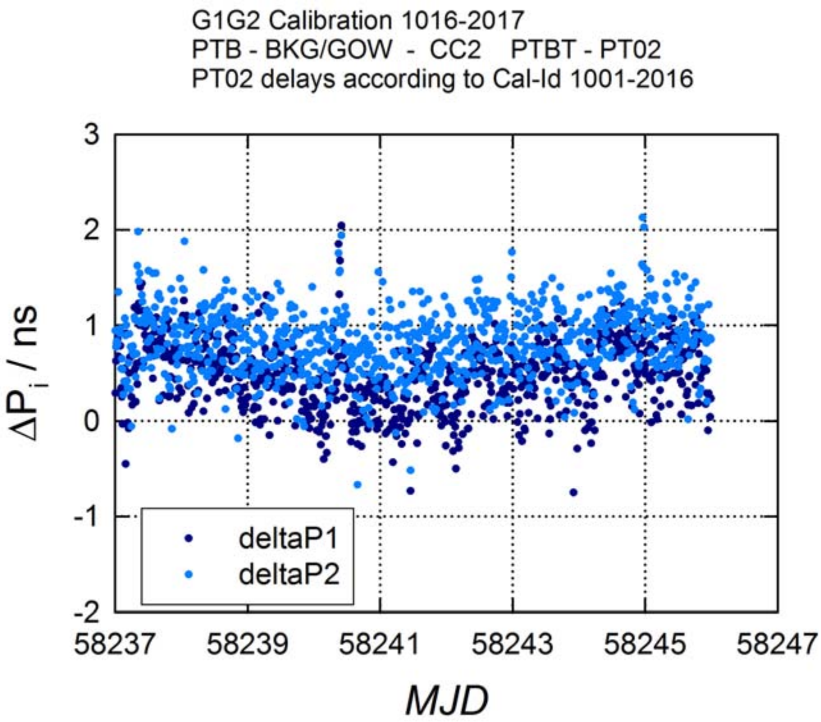

Figure 7-1. ∆Pi values obtained during the second common-clock set-up in PTB.

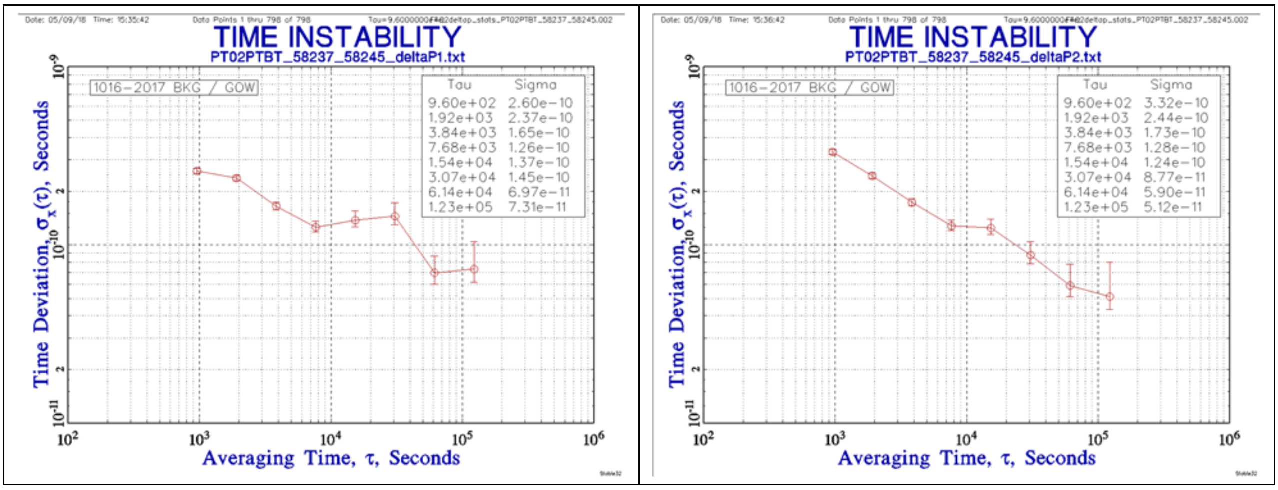

Figure 7-2. TDEV obtained for the two data sets shown in, ∆P1 left, ∆P2 right.

7.1. SUMMARY

The numerical result of the two common-clock campaigns at PTB are given in Table 7-1. The largest change noted between CC1 and CC2 amounts to 1.59 ns for ΔP1. For the evaluation of the delays of the visited receivers the mean values for ΔP1, ΔP2 are used. The estimate of the uncertainty contribution is given in Section 8.

Table 7-1: Result of common clock measurements at PTB

Quantity	Median (ns)	Sigma (ns)	TDEV (ns)
ΔP1 (CC1)	-1.11	0.36	0.1
ΔP2 (CC1)	-0.45	0.39	0.1
ΔP3 (CC1)	-2.1		
ΔP1 (CC2)	0.48	0.37	0.15
ΔP2 (CC2)	0.84	0.36	0.15
δP3 (CC2)	-0.07		
Mean values used for evaluation of IFxx internal delays			
ΔP1	-0.32		
ΔP2	0.19		

8. INT DLY UNCERTAINTY EVALUATION

The overall uncertainty of the INT DLY values obtained as a result of the calibration is given by

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}\,, \tag{6}$$

with the statistical uncertainty u_a and the systematic uncertainty u_b. The statistical uncertainty is related to the instability of the common clock data collected at GOW and PTB, respectively. The systematic uncertainty is given by

$$u_b = \sqrt{\sum_n u_{b,n}}\,. \tag{7}$$

The contributions to the sum (7) are listed and explained subsequently. In the table, extra lines (a, b,) are introduced for the different receivers calibrated at GOW.

Values in column P3 are calculated according to $u(P3) = \sqrt{\{u(P1)^2 + (1.54 \times u(P1-P2))^2\}}$.

Note that the uncertainty of the INT DLY values of PTB’s fixed receiver PT02 (G) which served as the reference is not included.

Table 8-1: Uncertainty contributions for the calibration of receiver delays

	Uncertainty	Value P1 (ns)	Value P2 (ns)	Value P1-P2 (ns)	Value P3 (ns)	Description
1	u_a (PTB)	0.15	0.15	0.21	0.35	CC measurement uncertainty at PTB, TDEV max. of the two CC campaigns
2a	u_a(GOW)	0.1	0.1	0.14	0.28	CC measurement uncertainty, receiver IF19
2b	u_a(GOW)	0.15	0.15	0.21	0.35	CC measurement uncertainty, receiver IF14
Result of closure measurement at PTB						
3	$u_{b,1}$	0.80	0.65		1.0	Misclosure, see Table 7-1
Systematic components due to antenna installation						
4	$u_{b,11}$	0.1	0.1	0.14	0.28	Position error at PTB
5a	$u_{b,12}$(DTAG)	0.1	0.1	0.14	0.28	Position error at GOW
6	$u_{b,13}$	0.1	0.1	0.14	0.28	Multipath at PTB
7	$u_{b,14}$	0.1	0.1	0.14	0.28	Multipath at GOW
Installation of PTBT and visited receivers						
8	$u_{b,21}$	0.2	0.2	0	0.2	Connection of PTBT to UTC(PTB) (REF DLY)
9	$u_{b,22}$	0.5	0.5	0	0.5	Connection of PTBT to UTC(IFAG) (REF DLY)
10	$u_{b,23}$	0.2	0.2	0	0.2	Connection of receivers at GOW to UTC(IFAG) (REF DEL)
11	$u_{b,24}$	0.1	0.1	0	0.1	TIC nonlinearities at PTB
12	$u_{b,25}$	0.1	0.1	0	0.1	TIC nonlinearities at GOW
Antenna cable delay						
13	$u_{b,31}$(PTB)	0.5	0.5	0	0.5	Uncertainty estimate for the PTBT CAB DLY when installed at PTB
14	$u_{b,32}$(GOW)	0	0	0	0	Uncertainty estimate for the PTBT CAB DLY when installed at GOW
15	$u_{b,33}$(DTAG)	0.5	0.5	0	0.5	Uncertainty estimate provided by GOW for the IFxx CAB DLY

The uncertainty contribution $u_{b,1}$ is based on the difference between the two common clock campaigns in the following way. The standard deviations of the two values around the mean values, individually for P1, P2, and P3, are considered as measures for the uncertainty, and they are treated as statistically independent contributions.

For the generation of the CGGTTS data the PTBT antenna position is manually entered into the processing software in ITRF coordinates before the CCD measurements. These positions could in principle differ from the “true” positions in a different way in each laboratory. This is taken into account by the contributions $u_{b,11}$ and $u_{b,12}$. In the current campaign it was confirmed that the antenna coordinates were determined for all masts involved consistently and the contribution is 0.1 ns at maximum. As a matter of fact, a position error in general could even affect the P1 and P2 delays in a slightly different way, if the distinction between Antenna Reference Point (ARP) and Antenna Phase Centre (APC) is not accurately made. It has been reported that the difference between the two quantities is different for each antenna type but in addition also for the two frequencies received. To be on the safe side, $u_{b,11}$ and $u_{b,12}$ are very conservatively estimated. For other entries, where a frequency dependence can be safely excluded, the entry for P1-P2 is set to zero.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,13}$ and $u_{b,14}$. If at a given epoch in time the recorded time differences REFSYS would be biased by multipath, this might change with time due to the change in the satellite constellation geometry. [RD05] gives an estimate that has often been referred to. It was agreed at the 2017 meeting of the CCTF WG on GNSS that the multipath error need not be considered more significant than reported here.

The uncertainties of the connection of the receivers to the local time scales ($u_{b,21}$, $u_{b,22}$, $u_{b,23}$) are equal but of different origin. As the same counter is employed for the PTBT REF DLY measurements at all sites, the counter’s internal measurement uncertainty for time interval need not be considered. $u_{b,21}$ was estimated by PTB: The cable connecting UTC(PTB) to PTBT is repeatedly controlled and has been used in many calibration exercises. GOW stated the uncertainty of the connection of PTBT and the local receivers to the local time scale, and this is reflected in $u_{b,22}$, $u_{b,23}$.

The uncertainty contributions $u_{b,24}$ and $u_{b,25}$ are related to imperfections in the TIC in conjunction with the relationship between the zero-crossings of the external reference frequency and the 1 PPS signals. This “nonlinearity” is probably caused by the internal interpolation process. By connecting the travelling TIC successively to 5 MHz and 10 MHz generated by different clocks (masers, commercial caesium clocks), respectively, the effect was estimated to be at most 0.1 ns if 1 PPS signals with a slew rate of approximately 0.5 V/ns are used.

The measurement of antenna cable delays causes contributions $u_{b,31}$ $u_{b,32}$ and $u_{b,33}$. It is made with different methods in timing laboratories. On PTB side, the same antenna cable(s) were repeatedly measured using 1 PPS signals from different sources – but always using a differential method so that the TIC-internal error should be small. The uncertainty estimate of 0.5 ns is conservatively made. A similar method was employed in GOW. The PTBT antenna cable could be used at GOW so that no exta uncertainty appears.

Note anyway that this uncertainty contribution $u_{b,33}$ a priori has no impact on the uncertainty of the time transfer link between PTB and the visited institutes. If the started CAB DLY for the GOW fixed receivers would be erroneous, this would be absorbed in the INT DLY values produced as a result of the campaign.

9. FINAL RESULTS

The results of the calibration campaign G1G2_1016_2017 are summarized in Table 9-1. It contains the designation of visited receiver, the INT DLY values hitherto used, the offsets ΔPi(V,T) and ΔPi(T,G) (see Section 5, (5)), the new INT DLY values to be used with consent by BIPM, and the uncertainty with which the new values were determined. For calculation, the respective entries from Table 8-1, individually for P1, P2, and combined for P3, were used. Intermediate delays and uncertainties are reported here with two decimal points. According to [RD07], in CGGTTS V2E file headers all delays should be reported with one decimal only, so the final results to be reported are rounded to one decimal.

Table 9-1. Results of the Calibration Campaign G1G2_1015_2017, all values in ns

Receiver	INT DLY(P1), old	INT DLY(P2); old	ΔP1 (V,T)	ΔP2 (V,T)	ΔP1 (T,G)	Δ(P2) (T,G)	INT DLY(P1), new	u_{cal}, P1	INT DLY(P2), new	u_{cal}, P2	u_{cal}, P3
GOW, IF19	54.2	51.0	3.84	5.23	-0.32	0.19	57.72	1.25	56.42	1.16	1.59
GOW, IF14	228.0	236.6	-4.61	-2.57	-0.32	0.19	210.46	1.25	220.52	1.16	1.61

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ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2017-10-04 0:00 UTC (MJD 58030)
Date and hour of the end of measurements:	2017-10-15 24:00 UTC (MJD 58041)

Information on the system

	Local:	**Travelling:**
4-character BIPM code	**PTBB**	**PTBT**
Receiver maker and type: Receiver serial number:	ASHTECH Z-XII3T (S/N RT820013901)	Dicom GTR50 0708522 1.7.7
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	Nokia RG214	Andrews FSJ-1 (N)
Length outside the building /m:	approx. 25	25
Antenna maker and type: Antenna serial number:	Ashtech ASH700936 SNOW (S/N CR15930)	Navexperience 3G+C NA0164
Temperature (if stabilised) /°C		

Measured delays / ns

	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	19.9 ± 0.1 (**)	25.6 ± 0.1 (§)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	38.2 ± 0.1 (**) + 15.8	N/A
Antenna cable delay: (X_C) / ns	301.7	210.0 ± 0.1
Splitter delay (if any):	N/A	
Additional cable delay (if any):	N/A	

Data used for the generation of CGGTTS files

	LOCAL:		Travelling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	304.5 (P1), 319.8 (P2) (**)		-42.6 (P1) -49.1 (P2) (***)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	301.7		210.0	
☐ REF DLY (or X_P+X_O) /ns:	73.9 (**)		25.6 (§)	
☐ Coordinates reference frame:	ITRF (*)		ITRF (***)	
X /m:	+3844059.89 (*)	Mast P10	+3844056.64 (***)	Mast P13
Y /m:	+709661.48 (*)		+709664.25 (***)	
Z /m	+5023129.73 (*)		+5023131.88 (***)	

General information	
☐ Rise time of the local UTC pulse:	3 ns
☐ Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	23.0 °C, peakt-to-peak variations 0.6° C

Notes:

(*) values provided by BIPM as part of coordinate alignment 2014 and G1 calibration Cal_Id=1001-2014

(**) values provided by BIPM Cal_Id 1001-2016 / local measurements not repeated
(***) BIPM campaign 1001-2014 provided new INT DLY values for PTB receiver PT02. Subsequently PTBT INT DLY were adjusted so that PTBT – PT02 were close to zero for convenience. Coordinates of mast P13 were interpolated from BIPM results provided for neighbouring masts.

(§) See explanation in Section 6.1 regarding the two delay entries.

Names of files to be used in processing for site PTB CC1

Local receiver: GZPT02MJ.DDD

Travelling receiver GZPTBTMJ.DDD

PTBT operation at GOW: Receiver WTZS

Laboratory:	**IFAG (GOW)**	
Date and hour of the beginning of measurements:	2017-10-18 00:00:00 UTC (58044)	
Date and hour of the end of measurements:	2017-10-24 24:00:00 UTC (58050)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**IF19**	**PTBT**
Receiver maker and type: Receiver serial number:	Septentrio PolaRx4TR 3002042 2.9.6	Dicom GTR50 0708522 1.7.4
1 PPS trigger level /V:	1.0	1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	Ecoflex15	N-type, LMR400
Length outside the building /m:	25 m	25 m
Antenna maker and type: Antenna serial number:	Leica AR25.3 10020020	Navexperience 3G+C NA0164
Temperature (if stabilised) /°C		
Measured delays / ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	25.5	14.9 (§)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	149.0	N/A
Antenna cable delay: (X_C) / ns	114.4	210.0
Splitter delay (if any):	N/A	N/A
Additional cable delay (if any):	3.6	N/A

Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	54.2 (P1), 51.0 (P2)	-42.6 (P1) -49.1 (P2)
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:	N/A	N/A
☐ CAB DLY (or X_C) /ns:	118.0	210.0
☐ REF DLY (or X_P+X_O) /ns:	174.5	22.1 (§)
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	4075535.31	4075556.105
Y /m:	931822.19	931823.517
Z /m	4801608.92	4801585.935
General information		
☐ Rise time of the local UTC pulse:	1 ns	
☐ Is the laboratory air conditioned:	Yes	
Set temperature value and uncertainty:	22.5 °C, peak-to-peak variation 2°C	

(§) See explanation in Section 6.1 regarding the two delay entries.

Names of files to be used in processing for site Ifag:

Local receiver: GZIF19MJ.DDD
Travelling receiver GZPTBTMJ.DDD

Notes:
All coordinates determined consistently using NRCan PPP immediately before the period of data taking

PTBT operation at GOW: Receiver WTZA

Laboratory:	**IFAG (GOW)**	
Date and hour of the beginning of measurements:	2017- 11 – 28 00:00:00 UTC (58086)	
Date and hour of the end of measurements:	2017- 12 – 08 24:00:00 UTC (58095)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**IF14**	**PTBT**
Receiver maker and type: Receiver serial number:	Septentrio PolaRx2 1219	Dicom GTR50 0708522 1.7.4
1 PPS trigger level /V:	1.0	1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	Ecoflex15	N-type, LMR400
Length outside the building /m:	5 m	25 m
Antenna maker and type: Antenna serial number:	LEICA AR25.4 726130	Navexperience 3G+C NA0164
Temperature (if stabilised) /°C		
Measured delays / ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	-12.5	-5.8 (§)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	225+8.9=233.9	N/A
Antenna cable delay: (X_C) / ns	122.0	210.0
Splitter delay (if any):	-	-
Additional cable delay (if any):	-	-

Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	228.0 (P1), 236.6 (P2)	-42.6 (P1) -49.1 (P2)
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:	N/A	N/A
☐ CAB DLY (or X_C) /ns:	122.0	210.0
☐ REF DLY (or X_P+X_O) /ns:	221.5	22.2 (§)
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	4075578.36	4075577.9094
Y /m:	931852.88	931854.1032
Z /m	4801570.14	4801570.1634
General information		
☐ Rise time of the local UTC pulse:	1 ns	
☐ Is the laboratory air conditioned:	Yes	
Set temperature value and uncertainty:	22.5°C peak-to-peak variation 1.5°C	

(§) See explanation in Section 6.1 regarding the two delay entries.

Names of files to be used in processing for site GOW

Local receiver: GZIF14MJ.DDD
Travelling receiver GZPTBTMJ.DDD

Notes:
All coordinates determined consistently using NRCan PPP immediately before the period of data taking
Inconsistencies between entries in “measured delays” and “Data used in cggtts” are explained in Section 6.2.

Second common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of measurements:	2018-04-29 (MJD 58237)
Date and hour of the end of measurements:	2018-05-07 (MJD 58245)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PTBB**	**PTBT**
Receiver maker and type: Receiver serial number:	ASHTECH Z-XII3T (S/N RT820013901)	Dicom GTR50 0708522 1.7.4
1 PPS trigger level /V:	1 V	1 V
Antenna cable maker and type: Phase stabilised cable (Y/N):	Nokia RG214	Andrews FSJ-1 (N)
Length outside the building /m:	approx. 25 m	25 m
Antenna maker and type: Antenna serial number:	Ashtech ASH700936 SNOW (S/N CR15930)	Navexperience 3G+C NA0164
Temperature (if stabilised) /°C		

Measured delays / ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	19.9 ± 0.1 (**)	59.6 ± 0.1 (§)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	38.2 ± 0.1 (**) + 15.8	N/A
Antenna cable delay: (X_C) / ns	301.7	205.0 ± 0.1
Splitter delay (if any):	N/A	
Additional cable delay (if any):	N/A	

Data used for the generation of CGGTTS files				
	LOCAL:		Travelling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	304.5 (P1), 319.8 (P2) (**)		-42.6 (P1) -49.1 (P2) (***)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	301.7		205.0	
☐ REF DLY (or X_P+X_O) /ns:	73.9 (**)		59.6 (§)	
☐ Coordinates reference frame:	ITRF (*)		ITRF (***)	
X /m:	+3844059.89 (*)	Mast P10	+3844057.71	Mast P11
Y /m:	+709661.48 (*)		+709663.27	
Z /m	+5023129.73 (*)		+5023131.14	

General information	
☐ Rise time of the local UTC pulse:	3 ns
☐ Is the laboratory air conditioned:	yes

Set temperature value and uncertainty:	23.0 °C, peakt-to-peak variations 0.6° C

Notes:

(*) values provided by BIPM as part of coordinate alignment 2014 and G1 calibration Cal_Id=1001-2014

(**) values provided by BIPM Cal_Id 1001-2016 / local measurements not repeated
(***) BIPM campaign 1001-2014 provided new INT DLY values for PTB receiver PT02. Subsequently PTBT INT DLY were adjusted so that PTBT – PT02 were close to zero for convenience. Coordinates of mast P13 were interpolated from BIPM results provided for neighbouring masts.

(§) See explanation in Section 6.1 regarding the two delay entries.

Names of files to be used in processing for site PTB CC2

Local receiver: GZPT02MJ.DDD

Travelling receiver GZPTBTMJ.DDD

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