GNSS CALIBRATION REPORT

G1G2_1011_2019

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REFERENCES

REFERENCES	
RD01	**BIPM report 2018 Group 1 GPS calibration trip 1001-2018_GPSP3C1_Group1-trip_V1-3**
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**
CGGTTS	**CCTF Generic GNSS Time Transfer Standard**
EURAMET	**The European Association of National Metrology Institutes**
IGS	**International GNSS Service**
IMBH	**Institute of Metrology of Bosnia and Herzegovina**
GNSS	**Global Navigation Satellite System**
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 G1 laboratories, PTB conducted a relative calibration of the GNSS equipment of IMBH, Bosnia-Herzegovina, with respect to the calibration of PTB receiver PT09, whose last calibration was reported with Cal_Id=1001-2018 [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 1011_2019. Results provided are the visited receiver's 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 were also determined during this campaign using PT09 as the reference.

The final results are included in Table 9-1 and Table 9-3. The internal delays of the two receivers involved were determined with an uncertainty of slightly below 1 ns for P1 and P2, respectively. The uncertainty for P3 time transfer links to PTB is of the order 1.5 ns.

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

Following instructions from the PTB quality management responsibles, we want to stress that the correctness of all results and of the stated uncertainty values relies partially 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 IMBH, Bosnia-Herzegovina, with respect to the calibration of receiver PT09, whose last calibration was reported with Cal_Id=1001-2018 [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 receiver 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, PT09, and the offset between the actual and the assumed PTBT delay values is determined.

After that, the receiver is installed at the two sites in sequence and the internal delay values of the device under test and their statistical properties are determined with respect to PTBT.

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 IMBH. 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
IMBH	Osman Sibonjic Tel: ++ 387 33 568 923 osman.sibonjic@met.gov.ba	IMBH Augusta Brauna 2 71 000 Sarajevo, Bosnia and Herzegovina

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2019-01- 26 until 2019-02-02	PTB	First common-clock comparison between PTBT and PT09	7 days used for evaluation, MJD 58509 – 58516 (incl.)
2019-03-03 Until 2019-03-12	IMBH	Operation of PTBT in parallel with BH01 and BH02	6 days used for determination of delays
2019-06-11 until 2019-06-17	PTB	Operation of PTBT after return	7 days used for evaluation, MJD 58645 – 58651 (incl.)

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

Initially, the campaign was scheduled to include NIMB (Bucarest; Romania). But operation of the travelling equipment failed at NIMB because of a defect of the communication between the PC hosting the receiver and the time-interval counter. Transportation between the sites was substantially delayed because of customs regulations.

For PT09, the internal delays during the campaign CC1 were after the fact corrected to match the values reported in RD01. CC2 was accomplished without re-establishment of full operations capability of PTBT in a manual mode.

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 PolaRx3: The 1 PPS-out, no further correction
- 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,

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

where REFGPS(k) is reported in column 10 of the standard CGGTTS files, $REFGPS_{RAW}$ designates the uncorrected measurement values, INT DLY(P3) is calculated as $2.54 \times INT\ DLY(P1)_F – 1.54 \times INT\ DLY\ (P2)_F$, 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:

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

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

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

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: $\text{INT DLY(Pi)\_T\_corr} = \Delta\text{Pi(T,G)} + \text{INT DLY(Pi)\_T\_old},$ (4)

where the last summand >_old < is the value reported in the CGGTTS file up to now.

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

$$\text{INT DLY(Pi)\_V\_new} = \Delta\text{Pi(V,T)} + \langle\Delta\text{Pi(T,G)}\rangle + \text{INT DLY(Pi)\_V\_old}, \quad (5)$$

where $\langle\Delta\text{Pi(T,G)}\rangle$ 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 campaign 1018_2018 which ended with its second CC data taking between MJD 58466 and 58471. The stability of PT09 during the current campaign can be inferred from Figure 4-1 in which common-clock common-view (L3P) comparisons of two other receivers are documented, PT10, a MESIT GTR51, and PT11, another Septentrio PolaRx4TR receiver. The apparent steps are due to the introduction of new signal delay values following advice of BIPM [RD01].

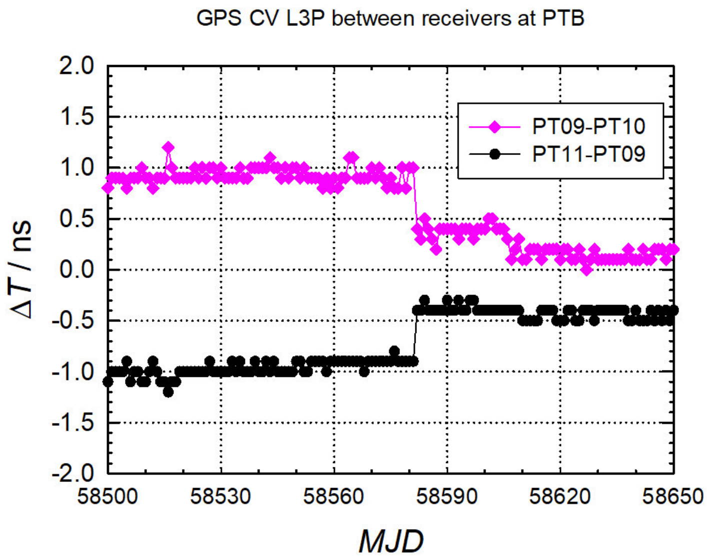

Figure 4-1: Common-clock common-view comparison between PT09 and two other receivers at PTB during campaign 1011-2019

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.

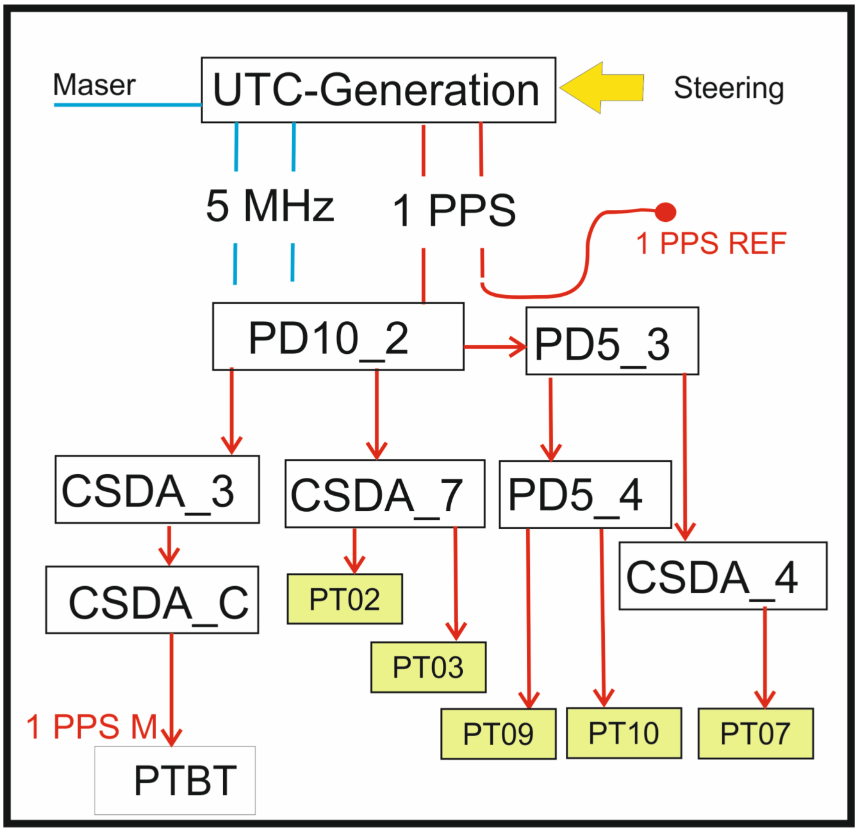

Figure 4-2: UTC(PTB) reference point and 1 PPS signal distribution to PT02, PT07, PT09 and PTBT; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

A clarification may be helpful regarding the 1 PPS REF point. The 1 PPS signal connected to the PTBT port 1 PPS REF is delayed from UTC(PTB) by 2.7 ns. When measuring with a TIC Port A = UTC(PTB), Port B = 1 PPS REF then the result is + 2.7 ns.

Figure 4-4 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall) during CC1. The PTBT antenna during CC1 is marked with a yellow arrow, the PT09 antenna is marked by an orange arrow.

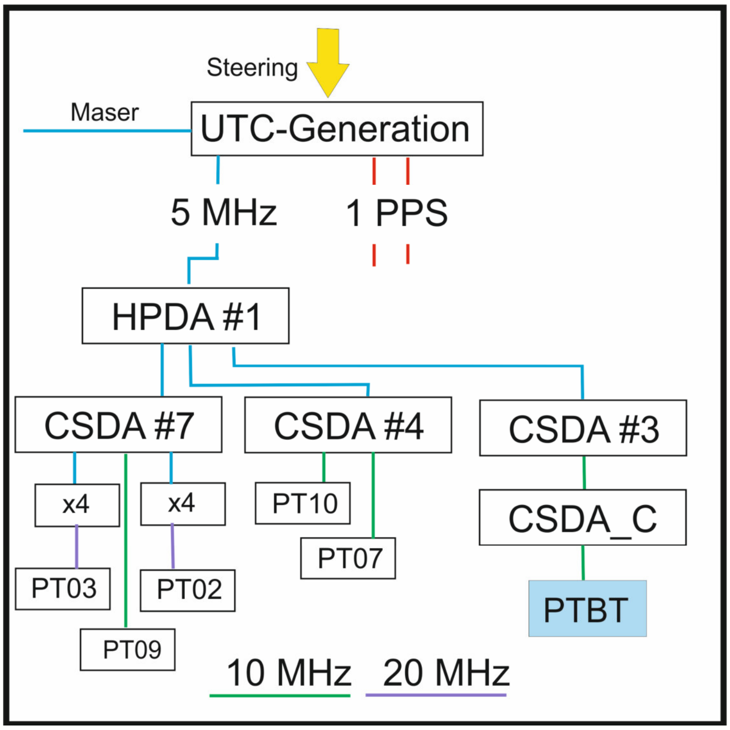

Figure 4-3: UTC(PTB) signal distribution (5 MHz, 10 MHz, 20 MHz) to PT02, PT07, PT09 and PTBT, HPDA stands for High-precision distribution amplifier (for rf frequencies)

Figure 4-4: Installation of GNSS antennas at PTB

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

The period 58509 to 58516 (8 days) was chosen to determine the initial PTBT INT DLY values (CC1). The result of comparison with PT09 as the reference are shown in Figure 5-1 illustrating in total 710 ∆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 5-2. The numerical results are given in the Summary sub-section at the end of the report on CC2 in PTB.

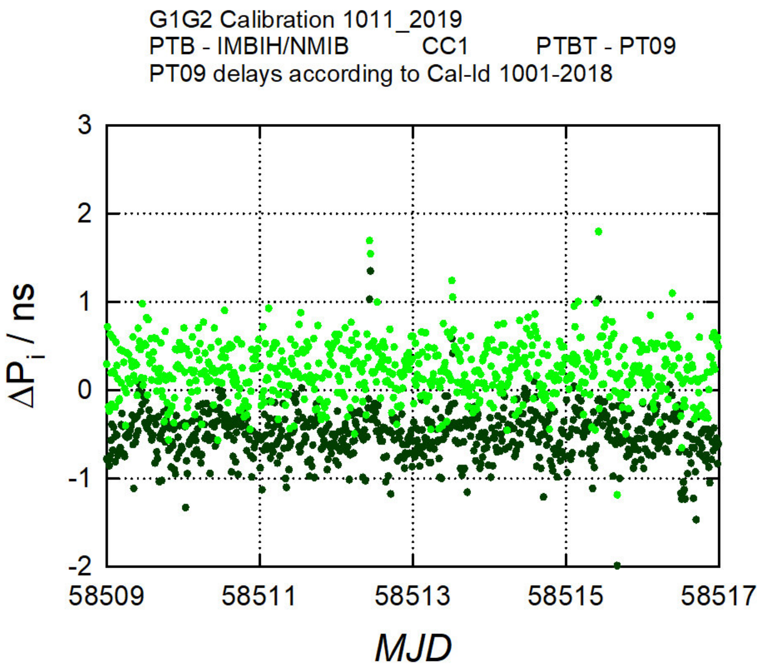

Figure 5-1: ∆P1 (dark green) and ∆P2 (light green) values obtained during the first common-clock set-up in PTB.

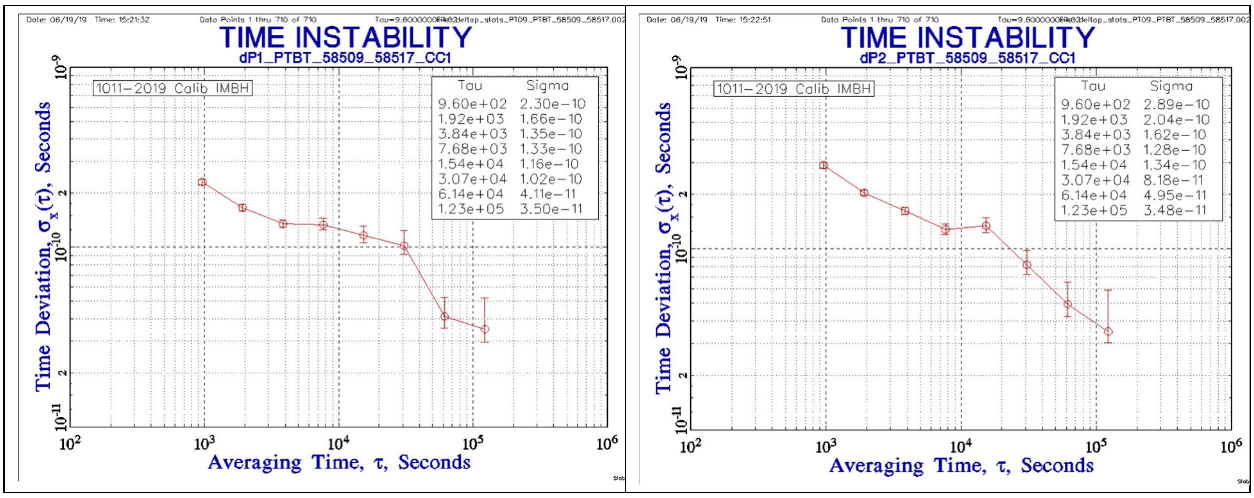

Figure 5-2: TDEV obtained for the two data sets shown in, ∆P1 left, ∆P2 right.

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)).

5.1. DETERMINATION OF L1C DELAY

The receiver delays for L1C signals were determined with respect to the same PTB receiver, PT09. The L1C internal delay of receiver PT09 was adjusted to results obtained in the campaign 1001-2018.

We determine the cv difference between PTBT and PT09 during CC1 and CC2 (see Section 7.) and take the mean for further evaluation. The differences between PTBT, and BH01 and BH02, respectively is then determined in common view as well. This allows an estimate of the GPS L1C delay values in the respective receivers to be made. The results of the comparison during CC1 are shown in Figure 5-3, those during CC2 in Figure 5-4.

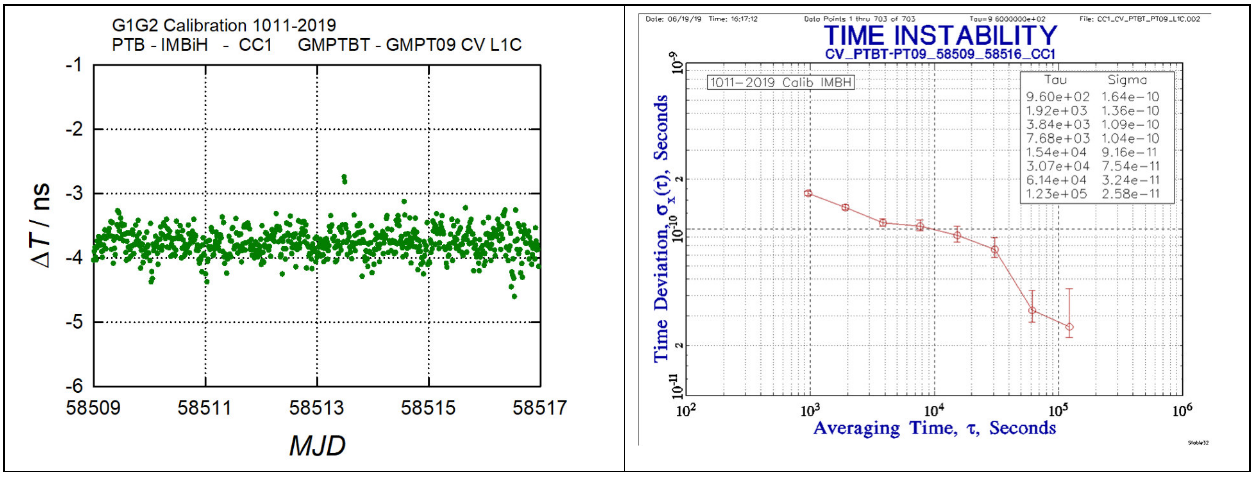

Figure 5-3 CV between receivers PTBT and PT09 using L1C data, time differences (left) and TDEV (right) during CC1

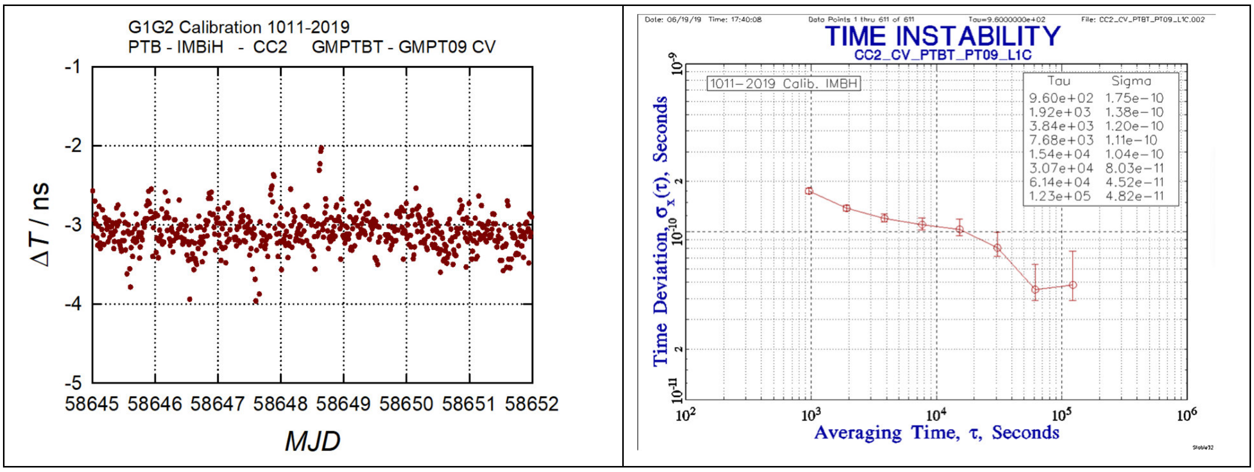

Figure 5-4 CV between receivers PTBT and PT09 using L1C data, time differences (left) and TDEV (right) during CC2

See Section 7. for further analysis of the data.

6. OPERATION OF PTBT AT IMBH

PTBT was operated at IMBH between 05 and 14 March 2019. 6 days were used as the data base for the delay determination of the receivers, BH01 and BH02, respectively. The results are presented below. Details on the receivers and their installation are given in the Annex. The antenna positions were determined from analysis of RINEX data using the NRCan PPP software. The PTBT antenna coordinates were initially estimated from a known position. New coordinates were obtained doing PPP analysis based on two days of observations of PTBT at the IMBH site. PTBT CGGTTS files were then reprocessed using r2cggtts V 8.1 and given file names GZPTBU to distinguish from the files generated on site by the receiver software. The values used are reported in the Annex.

The signal distribution to receivers PTBT, BH01 and BH02 at IMBH is illustrated in Figure 6-1. The mounting position of the antennas is shown in Figure 6-2.

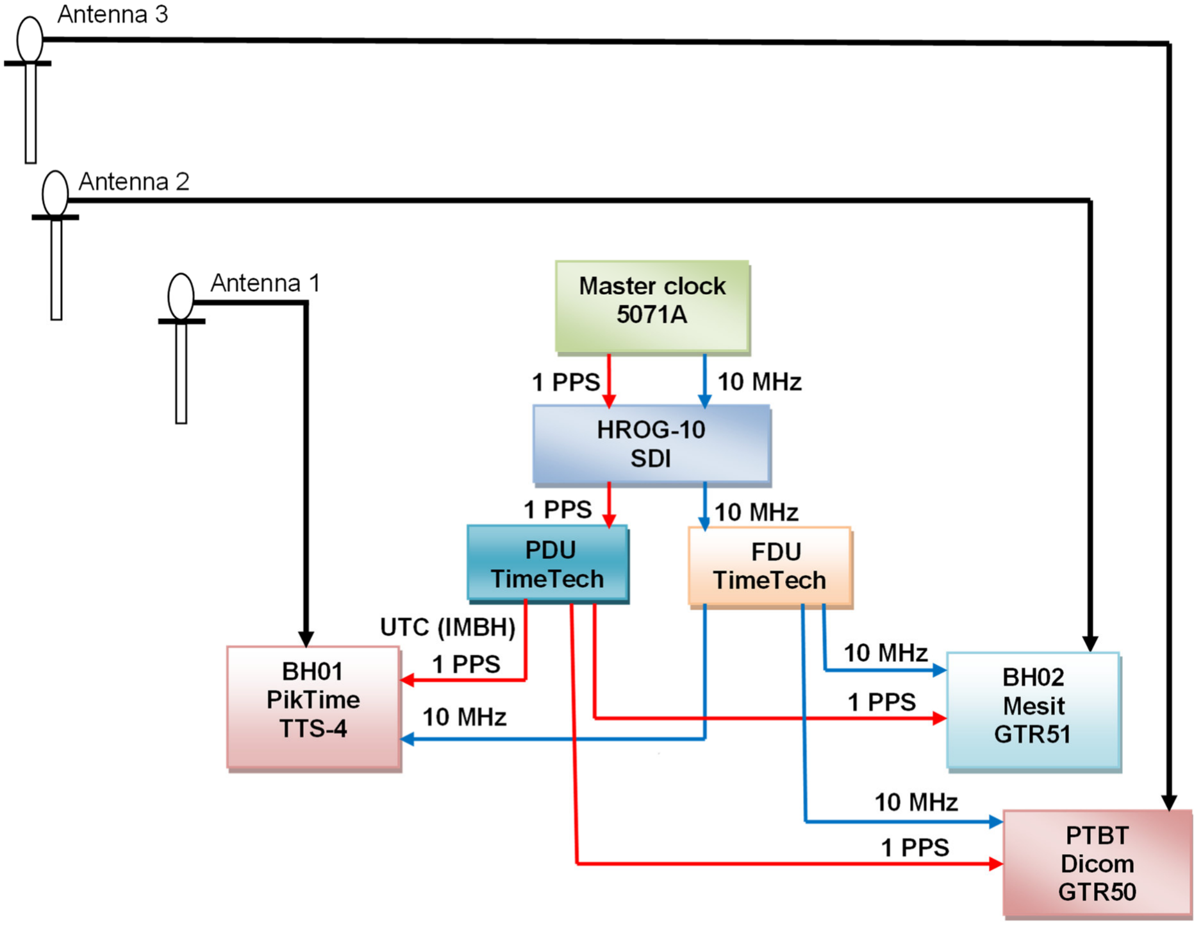

Figure 6-1 Signal distribution at IMBH to the receivers

Figure 6-2: Antennas position on the rooftop of the IMBH building

6.1. CALIBRATION OF RECEIVER BH01

As the Piktime TTS-4 receiver does not provide correctly formatted cggtts-files, r2cggtts V 8.1 was used to generate new GZBH01 files used in the calculations.

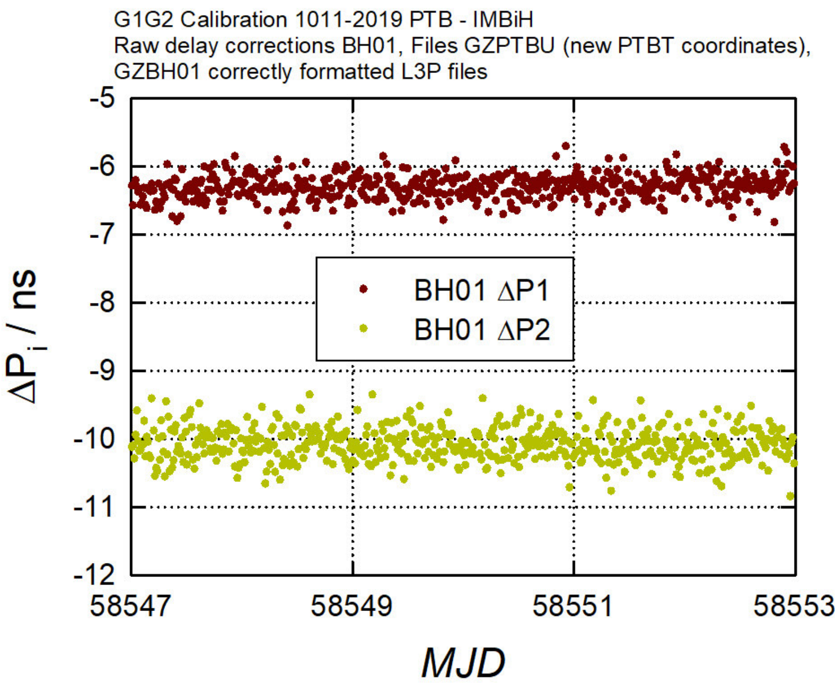

Figure 6-3 ΔP1 (dark red) and ΔP2 (olive) values obtained comparing receiver BH01 (file name GZH01MJ.DDD) and PTBT.

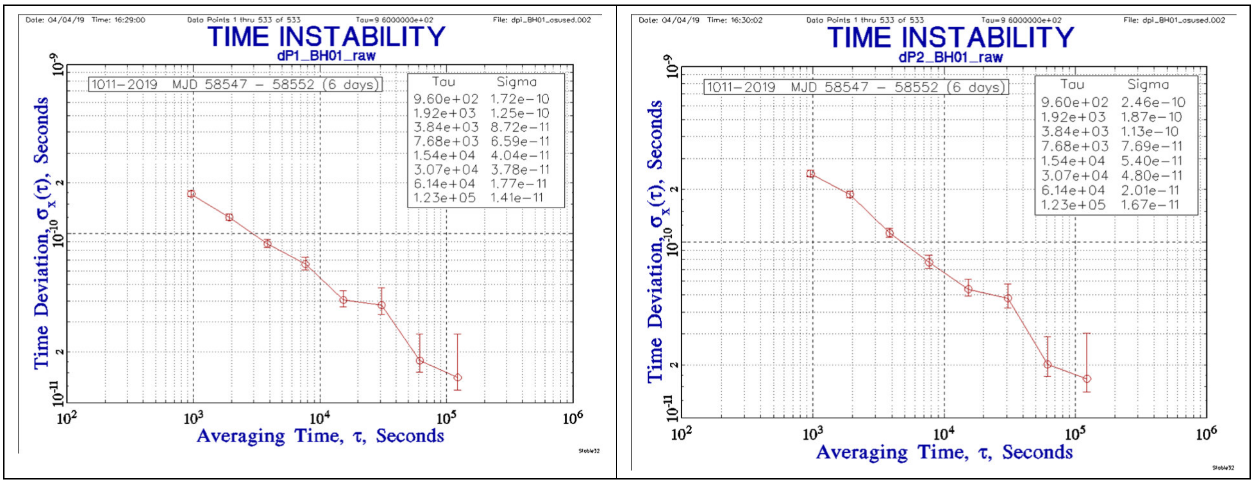

Figure 6-4: TDEV obtained for the two data sets shown in Figure 6-3, ΔP1 left, ΔP2 right.

In Figure 6-3 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 0.1 ns has been used which is a very conservative estimate in view of the excellent stability.

6.2. CALIBRATION OF RECEIVER BH02

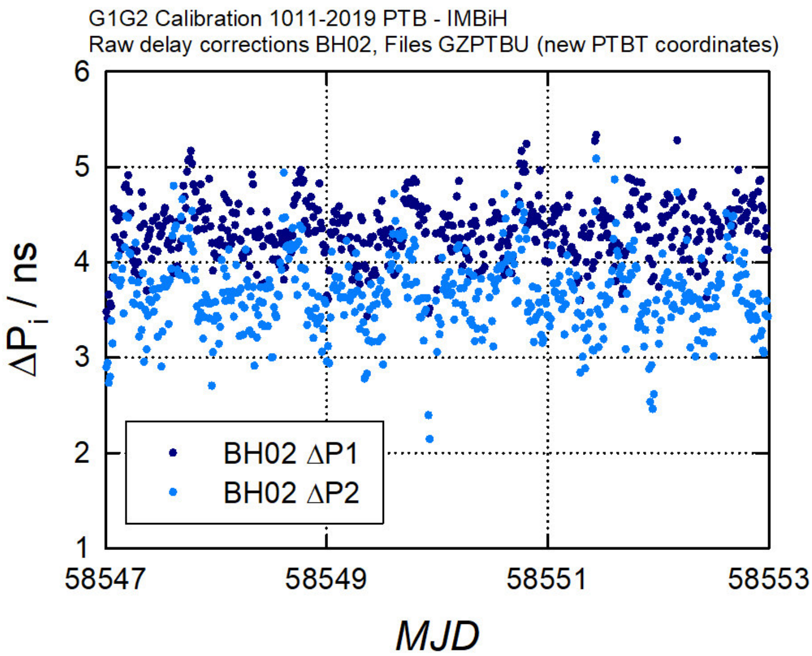

Figure 6-5 ΔP1 (dark blue) and ΔP2 (light blue) values obtained comparing receiver BH02 (file name GZBH02MJ.DDD) and PTBT.

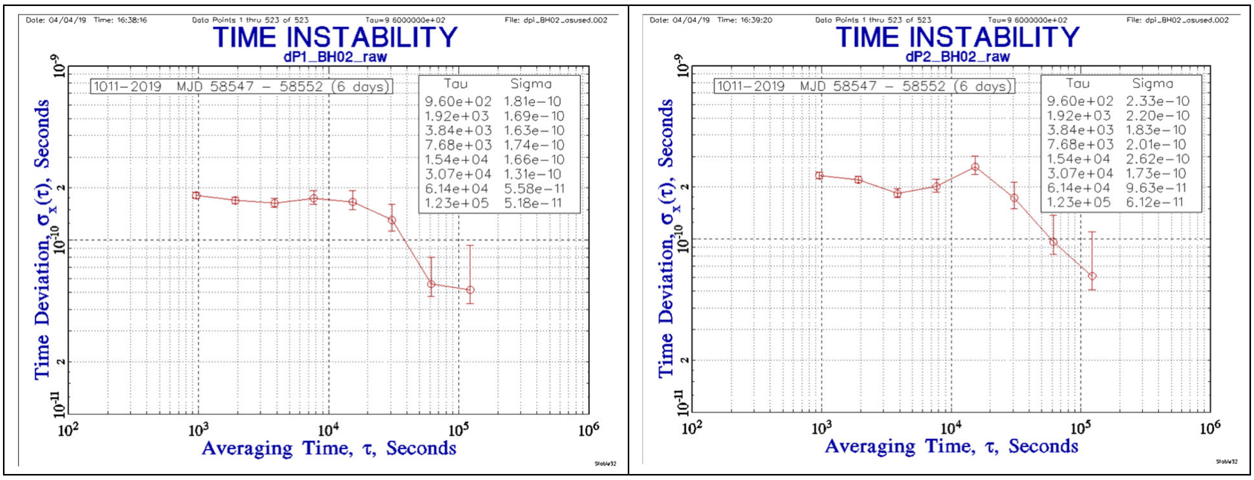

Figure 6-6: TDEV obtained for the two data sets shown in Figure 6-5, ∆P1 left, ∆P2 right.

In Figure 6-5 the ∆Pi (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 6-6. As a statistical measurement uncertainty the value of TDEV at τ equal to about one tenth of the total measurement time (at about 60 000 s) is chosen, cum grano salis, to be not too optimistic.

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

∆INT DLY (Pi) for receivers at IMBH	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
BH01					
∆P1	-6.29	-6.30	0.18	0.10	553
∆P2	-10.07	-10.08	0.25	0.10	553
BH02					
∆P1	4.33	4.33	0.32	0.10	523
∆P2	3.67	3.65	0.41	0.15	523

6.3. DETERMINATION OF L1C DELAY: CV AT IMBH

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBT at IMBH, provides the second step to determine the L1C internal delays of the receivers BH01 and BH02.

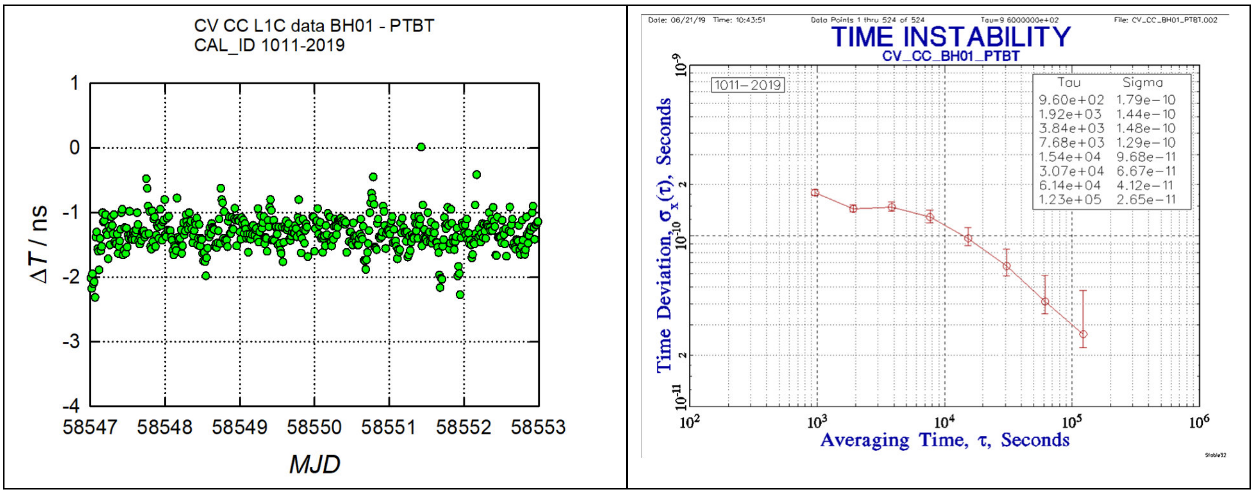

Figure 6-7 CV between receivers BH01 and PTBT using L1C data, time differences (left) and TDEV (right)

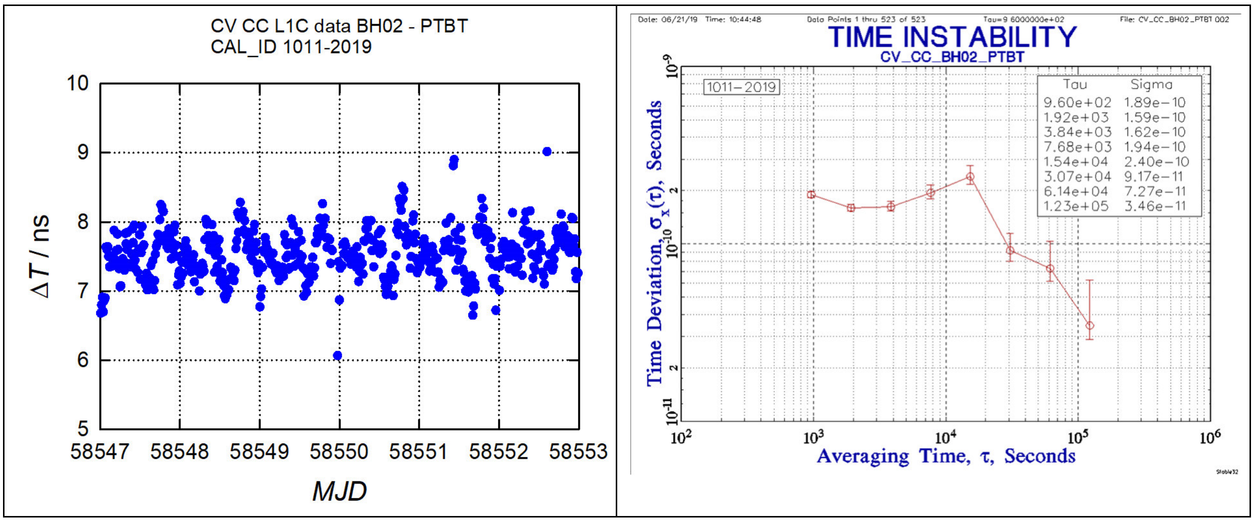

Figure 6-8 CV between receivers BH02 and PTBT using L1C data, time differences (left) and TDEV (right)

7. OPERATION OF PTBT AT PTB: SECOND PERIOD

The period 58645 to 58651 (7 days) was chosen to determine PTBT INT DLY values during the common clock period CC2. The results of comparison with PT09 as the reference are shown in Figure 7-1 illustrating in total 621 ΔPi (see eq. 3) values obtained as mean values over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets follow as Figure 7-2.

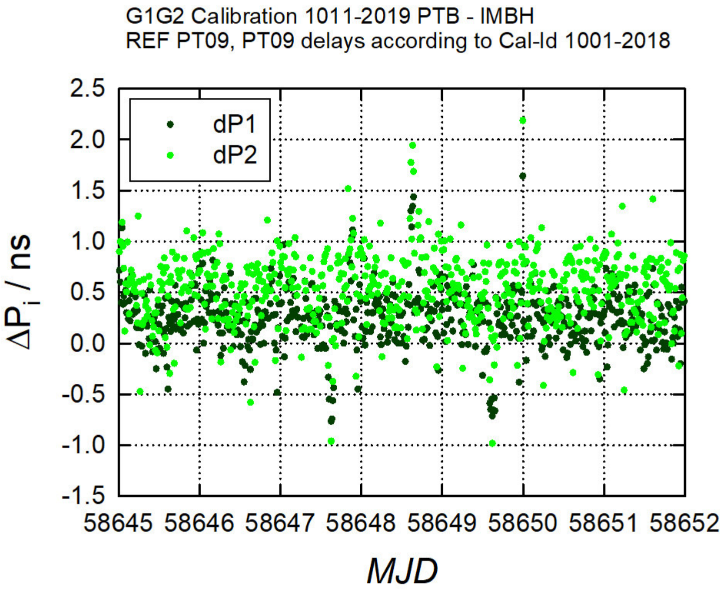

Figure 7-1. ΔPi values obtained during the second common-clock set-up in PTB.

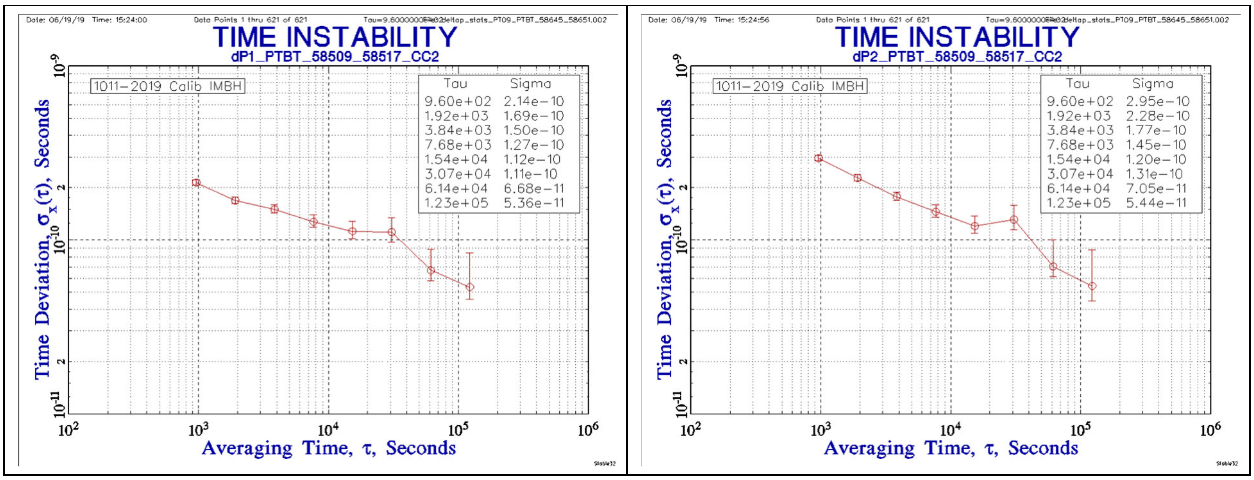

Figure 7-2. TDEV obtained for the two data sets shown in, ΔP1 left, ΔP2 right.

7.1. SUMMARY

The numerical results of the two common-clock campaigns at PTB are given in Table 7-1. The largest change noted between CC1 and CC2 amounts to 0.766 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)	-0.510	0.28	0.1
ΔP2 (CC1)	0.223	0.32	0.1
ΔP3 (CC1)	-1.63		
ΔP1 (CC2)	0.256	0.28	0.1
ΔP2 (CC2)	0.537	0.35	0.1
ΔP3 (CC2)	-0.176		
Mean values used for evaluation of visited receivers' internal delays			
ΔP1	-0.127		
ΔP2	0.380		

8. INT DLY UNCERTAINTY EVALUATION

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

$$\mathrm{u}_{\mathrm{CAL}} = \sqrt{\mathrm{u}_\mathrm{a}^2 + \mathrm{u}_\mathrm{b}^2}\,, \tag{6}$$

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 IMBH and PTB, respectively. The systematic uncertainty is given by

$$\mathrm{u}_\mathrm{b} = \sqrt{\sum_n \mathrm{u}_{\mathrm{b},n}}\,. \tag{7}$$

The contributions to the sum (7) are listed and explained subsequently.

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)	0.1	0.1	0.14	0.18	CC measurement uncertainty at PTB, TDEV max. of the two CC campaigns
2a	u_a(IMBH)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver BH01
2b	u_a(IMBH)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver BH02
Result of closure measurement at PTB						
3	$u_{b,1}$	0.38	0.16		0.99	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	$u_{b,12}$(IMBH)	0.1	0.1	0.14	0.28	Position error at IMBH
6	$u_{b,13}$	0.2	0.2	0.0	0.20	Multipath at PTB
7	$u_{b,14}$	0.2	0.2	0.0	0.20	Multipath at IMBH
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(IMBH) (REF DLY)
10	$u_{b,23}$	0.2	0.2	0	0.2	Connection of receivers at IMBH to UTC(IMBH) (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 IMBH
Antenna cable delay						
13	$u_{b,31}$(PTB)	0.2	0.2	0	0.2	Uncertainty estimate for the PTBT CAB DLY when installed at PTB
14	$u_{b,32}$(IMBH)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBT CAB DLY when installed at IMBH
15	$u_{b,33}$(IMBH)	0.5	0.5	0	0.5	Uncertainty estimate provided by IMBH for the BH0x CAB DLY

The uncertainty contribution ub,1 is based on the difference between the two common clock campaigns in the following way. The standard deviation of the two values around the mean value is considered as measure for the uncertainty, and they are treated as statistically independent contributions. If this value was smaller than the combined statistical uncertainty of the two CC-data sets, then the latter value would be used, but this situation did not prevail in the current campaign.

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 a 0.2 ns-uncertainty should be attributed to the multipath effect.

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 REFDLY 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 (called 1 PPS REF in Figure 4-2) has been repeatedly controlled and has been used in many calibration exercises. IMBH 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 $u_{b,33}$. During the current campaign the same PTBT cable was employed in CC1 and at IMBH, but another one during CC2. CAB DLY values were measured at PTB in previous campaigns, with the cable rolled out and also with the cable on the spool. Each measurement was made with a differential method so that the TIC-internal error should be small anyway. All results agreed within 0.1 ns, but we retain a uncertainty contribution $u_{b,31}$ of 0.2 ns. For the stationary antenna cables at IMBH we conservatively assume 0.5 ns for the uncertainty of the delay value.

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 stated CAB DLY for the visited fixed receiver(s) 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_1011_2019 are summarized in Table 9-1. It contains the designation of the 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_1011_2019, 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
BH01	-32.2	-32.6	-6.29	-10.07	-0.13	+0.38	-38.62	0.94	-42.29	0.87	1.41
BH02	26.0	25.8	4.33	3.66	-0.13	+0.38	30.20	0.94	29.84	0.87	1.41

In a similar way we obtain from equation (1) corrected values of the L1C signal delay in receiver BH01 and BH02 as
INT DLY(L1C);new = INT DLY(L1C);old - ∆(T-V) + ∆T(T-R),
where R designates the receiver PT07 chosen as reference for this action. We estimate the uncertainty of the new value to 1.5 ns.

Table 9-2 Results of CC CV L1C comparisons in PTB and at IMBH, all values in ns

Receiver couple	CV mean difference	Sigma	TDEV	Number of CV epochs
PTBT-PT09 CC1	-3.76	0.21	0.1	703
PTBT-PT09 CC2	-3.09	0.23	0.1	611
PTBT-PT09_mean	-3.43			
BH01-PTBT	-1.32	0.25	0.15	524
BH02-PTBT	7.54	0.34	0.15	523

Table 9-3 Results of L1C calibration during campaign 1011-2019, all values in ns

Receiver	INT DLY(L1C), old	∆T (T-V))	∆T (T-R)	INT DLY(L1C), new	u_{cal}, L1C
BH01	-32.65	+1.32	-3.43	-37.40	1.5
BH02	26.1	-7.54	-3.43	30.21	1.5

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2019-01-26 0:00 UTC (MJD 58509)
Date and hour of the end of measurements:	2019-02-02 24:00 UTC (MJD 58516)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PT09**	**PTBT**
Receiver maker and type: Receiver serial number:	PolaRx4TR (2.9.6), S/N 3001148	Dicom GTR50 0708522 1.7.7
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	ECOFLEX 15plus	LMR-400 (N)
Length outside the building /m:	approx. 25	25
Antenna maker and type: Antenna serial number:	NOV750.R4	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	35.25 ± 0.1 (**)	2.7 +/- 0.1 (to port 1 PPS REF)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	147.92 ± 0.1 (**)	N/A
Antenna cable delay: (X_C) / ns	198.7 ± 0.1	209.0 ± 0.1
Splitter delay (if any):	N/A	

Data used for the generation of CGGTTS files				
	LOCAL:		Travelling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	56.7 (P1), 55.7 (P2), 58.1 (C1) (**)		-42.6 (P1) -49.1 (P2) (***)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	198.7		209.0	
☐ REF DLY (or X_P+X_O) /ns:	183.2 (**)		59.6	
☐ Coordinates reference frame:	ITRF (*)		ITRF (***)	
X /m:	+3844057.34 (*)	Mast P10	+3844062.56 (***)	Mast P7
Y /m:	+709663.82 (*)		+709659.49 (***)	
Z /m	+5023131.76 (*)		+5023127.88 (***)	

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 2018 reported in TM.281.

(**) Local measurement 2018-11-05, other results based on report Cal-ID1001-2018
(***) 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 P7 (APC) were determined in Dec. 2018 using NRCan PPP.

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

Travelling receiver GZPTBTMJ.DDD, GMPTBTMJ.DDD

Reference receiverGZPT09MJ.DDD, GMPT09MJ.DDD

PTBT operation at IMBH: Receiver BH01

Laboratory:	**IMBH**	
Date and hour of the beginning of measurements:	2019-03-05 00:00:00 UTC (58547)	
Date and hour of the end of measurements:	2019-03-10 24:00:00 UTC (58552)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**BH01**	**PTBT**
Receiver maker and type: Receiver serial number:	PikTime Systems – Poland, TTS4 142	Dicom GTR50 0708522 1.7.4
1 PPS trigger level /V:		1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	FSJ1-50A - 1/4" Andrew Heliax Superflex Coax Cable Not phase stabilised	N-type, LMR400
Length outside the building /m:	Approx. 25	Approx. 45
Antenna maker and type: Antenna serial number:	Javad, RingAnt-G3T Antenna 00455	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	17.3	15.0
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	-6.02 ns	N/A
Antenna cable delay: (X_C) / ns	144.76	209.0
Splitter delay (if any):	N/A	N/A
Additional cable delay (if any):	N/A	N/A
Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	L1C:-32.65, L2C:-32.41, L1P:-32.19, L2P:-32.62	-42.6 (P1) -49.1 (P2)
☐ CAB DLY (or X_C) /ns:	144.76	209.0
☐ REF DLY (or X_P+X_O) /ns:	11.29	15.0
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	+4 371 185.07 m	4 371 185.67
Y /m:	+1 454 855.00 m	1 454 855.00
Z /m	+4 397 063.10 m	4 397 063.10
General information		
☐ Rise time of the local UTC pulse:	1.47 ns	
☐ Is the laboratory air conditioned:	Yes	
Set temperature value and uncertainty:	23,0 °C ± 1,0 °C	

PTBT operation at IMBH: Receiver BH02

Laboratory:	**IMBH**
Date and hour of the beginning of measurements:	2019-03–05 00:00:00 UTC (58547)
Date and hour of the end of measurements:	2019-03-10 24:00:00 UTC (58552)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**BH02**	**PTBT**
Receiver maker and type: Receiver serial number:	Mesit, Czech Republic, GTR 51 1808032	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):	Belden, 50 Ω, low loss, H155 PVC Not phase stabilized	N-type, LMR400
Length outside the building /m:	Approx. 20	Approx. 45
Antenna maker and type: Antenna serial number:	Novatel GNSS-850 NMLK18070098S	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	7.6	15.0
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	N/A (included above)	N/A
Antenna cable delay: (X_C) / ns	128.2	209.0
Splitter delay (if any):	N/A	N/A
Additional cable delay (if any):	N/A	N/A

Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	26.1 ns (C1), 26.0 ns (P1), 7.8 ns (C2), 25.8 ns (P2), 10.0 ns (L5)	-42.6 (P1) -49.1 (P2)
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:	0.0 ns (C1), 0.0 ns (P1), 0.0 ns (C2), 0.0 ns (P2)	N/A
☐ CAB DLY (or X_C) /ns:	128.2	209.0
☐ REF DLY (or X_P+X_O) /ns:	7.6	15.0
☐ Coordinates reference frame:	WGS-84	ITRF
X /m:	+4 371 184.96 m	4 371 185.67
Y /m:	+1 454 855.78 m	1 454 855.00
Z /m	+4 397 062.73 m	4 397 063.10

General information	
☐ Rise time of the local UTC pulse:	1.47 ns
☐ Is the laboratory air conditioned:	Yes

Set temperature value and uncertainty:	23.0 °C ± 1.0 °C

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

Local receivers: GZBH01MJ.DDD / GMBH01MJ.DDD / GZBH02MJ.DDD / GMBH02MJ.DDD

Travelling receiver GZPTBTMJ.DDD original files with correct delays but incorrect coordinates

GZPTBUMJ.DDD files generated after the fact using r2cggtts V 5.1 with newly determined coordinates

Notes:

All coordinates determined consistently using NRCan PPP immediately before and during the period of data taking

Second common clock measurement at PTB

Laboratory:	**PTB**	
Date and hour of the beginning of	2019-06-11 0:00 UTC (MJD 58645)	
Date and hour of the end of measurements:	2019-06-17 24:00 UTC (MJD 58651)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PT09**	**PTBT**
Receiver maker and type: Receiver serial number:	PolaRx4TR (2.9.6), S/N 3001148	Dicom GTR50 0708522 1.7.7
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	ECOFLEX 15plus	Andrews FSJ-1 (N)
Length outside the building /m:	approx. 25	25
Antenna maker and type: Antenna serial number:	NOV750.R4	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	35.25 ± 0.1 (**)	2.7 +/- 0.1 (to port 1 PPS REF)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	147.92 ± 0.1 (**)	N/A
Antenna cable delay: (X_C) / ns	198.7 ± 0.1	205.0 ± 0.1
Splitter delay (if any):	N/A	

Data used for the generation of CGGTTS files				
	LOCAL:		Travelling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	56.7 (P1), 55.7 (P2), 58.1 (C1) (**)		-42.6 (P1) -49.1 (P2) (***)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	198.7		205.0	
☐ REF DLY (or X_P+X_O) /ns:	183.2 (**)		54.9	
☐ Coordinates reference frame:	ITRF (*)		ITRF (***)	
X /m:	+3844057.34 (*)	Mast P10	+3844062.56 (***)	Mast P7
Y /m:	+709663.82 (*)		+709659.49 (***)	
Z /m	+5023131.76 (*)		+5023127.88 (***)	
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 2018 (TM.281)

(**) Local measurement 2018-11-05, other results based on report Cal-ID1001-2018
(***) 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 P7 (APC) were determined using PTBT data collected during the period CC2 and using NRCan PPP.

Names of files to be used in processing for site PTB CC2
Local receiver: GZPT09MJ.DDD, GMPT09MJ.DDD
Travelling receiver GZPTBTMJ.DDD, GMPTBTMJ.DDD

END of DOCUMENT