GNSS CALIBRATION REPORT

G1G2_1013_2019

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

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

Authorized by: BIPM

Project:	PTB_G1G2_NIMB_SIQ
Code:	1013_2019
Version:	1.0
Safe date:	19.03.2020 14:19

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, BRAUNSCHWEIG, MARCH 2020

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

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**
GNSS	**Global Navigation Satellite System**
NIMB	**National Institute of Metrology Bucharest**
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**
SIQ	**Slovenian Institute of Quality and Metrology; SIQ Ljubljana**
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 NIMB, Romania, and SIQ, Slovenia, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GPS dual-frequency time links to PTB in the context of realization of TAI. Its delays were determined with respect to receiver PT09 which in turn had got its last calibration from BIPM as reported with Cal_Id=1001-2018 [RD01]. PTB provided its receiver PTBT for the purpose as travelling equipment.

Due to inconclusive information on the installation of the GPS receivers involved at NIMB, the results for NIMB will be published in Version 2 at a later time.

The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1013_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 PT13 as the reference. Unfortunately, the PTBT antenna did not function after return and thus no second common-clock campaign could be evaluated. As a consequence, in Table 9-1 no uncertainty contribution that would reflect the stability of the travelling equipment is given.

The final results are included in Table 10-1 and Table 10-3. The internal delays of the two receivers involved were determined with an uncertainty of order 1 ns for P1 and P2, respectively. The uncertainty for P3 time transfer links to PTB is only slightly larger.

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 the BIPM Time and Frequency Group by EURAMET G1 laboratories, PTB conducted a relative calibration of the GNSS equipment of NIMB, Romania, and SIQ, Slovenia, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GPS dual-frequency time links to PTB in the context of realization of TAI. Its delays were determined with respect to receiver PT09 which in turn had got its last calibration from BIPM as 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, was compared to the "golden" receiver, PT13, and the offset between the actual and the assumed PTBT delay values is determined.

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

Nominally, the stability of the PTBT delay should be 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 should be calculated. Unfortunately, the PTBT antenna did not work any longer after return. PTBT immediately functioned with a spare antenna of the same type and showed similar instability as during CC1 and delay offsets in the low ns-region. But a CC2 could not be evaluated.

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, NIMB and SIQ. The final results and the uncertainty discussion close the report. In the Annex the BIPM information tables are reproduced.

Due to inconclusive information on the installation of the GPS receivers involved at NIMB, the results will be published version 2 at a later time.

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
NIMB	Violeta Ciociea T: 0040 (0) 729002926 vciociea@inm.ro	Institutul National de Metrologie Soseaua Vitan -Barzesti, nr 11 sector 4,Bucuresti,Romania cod 042122
SIQ	Borut Pinter T: +386 (0)1 4778 322 F: +386 (0)1 4778 444 borut.pinter@siq.si	SIQ Ljubljana Mašera-Spasićeva ulica 10 SI-1000 Ljubljana Slovenia

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2019-10- 23 until 2019-10-27	PTB	First common-clock comparison between PTBT and PT13	5 days used for evaluation, MJD 58779 – 58783 (incl.)
2019-11-13 until 2019-11-17	NIMB	Operation of PTBT in parallel with MB02	5 days used for determination of delays
2019-12-17 until 2019-12-28	SIQ	Operation of PTBT in parallel with SI02, antenna #1	11.5 days used for determination of delays
2020-01-22 until 2020-01-26	SIQ	Operation of PTBT in parallel with SI01, antenna #2	5 days used for determination of delays

Information on the receivers at each site is contained in individual information tables which can be found in the Annex. The designation of the GNSS station at SIQ is provided in Section 7.

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, PT13 (named PTBB when referred to as IGS station) serves as the reference receiver G, its internal delays were transferred from PT09, the delay values of which had been determined by BIPM in the G1 campaign with the identifier Cal_Id=1001-2018. 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 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 TTS-4: RD02, Section 2.3.2, and Annex G specify the procedure for TTS-4, which in detail depends on the software version.

The parameters of PT13 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 [RD07] 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, 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 ionospheric delay for a signal at frequency f is proportional to $1/f^2$. According to [RD07], the column MDIO in CGGTTS V2E files contain the measured ionospheric delay for the higher of the two combined frequencies. The delay for the other frequency is thus MDIO × $(f_1/f_2)^2$. The software cv.py in calibration mode thus calculates:

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

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.

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: $\text{INT DLY(Pi)\_T\_corr} = \Delta\text{Pi(T,G)} + \text{INT DLY(Pi)\_T\_old},$ (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 <ΔPi(T,G)> is usually 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. In this campaign the value obtained at CC1 was the only available and was thus used.

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 1012_2019 and then for some internal tests at PTB. No long-term record can be provided. The stability of PT13 during the current campaign can be inferred from Figure 4-1 in which common-clock common-view (L3P) comparisons with two other receivers are documented, PT10, a MESIT GTR51, and PT09, a Septentrio PolaRx4TR receiver.

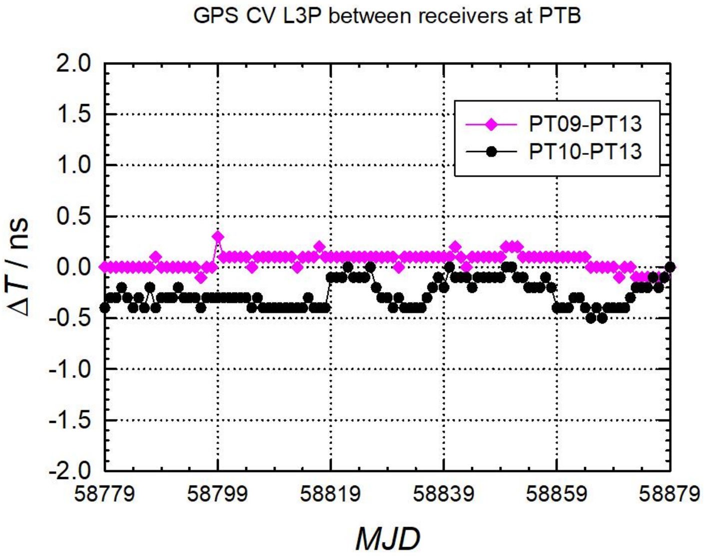

Figure 4-1: Common-clock common-view comparison between PT13 and two other receivers at PTB during campaign 1013-2019

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 PT03 receiver is supplied with 20 MHz from a times 4 multiplier.

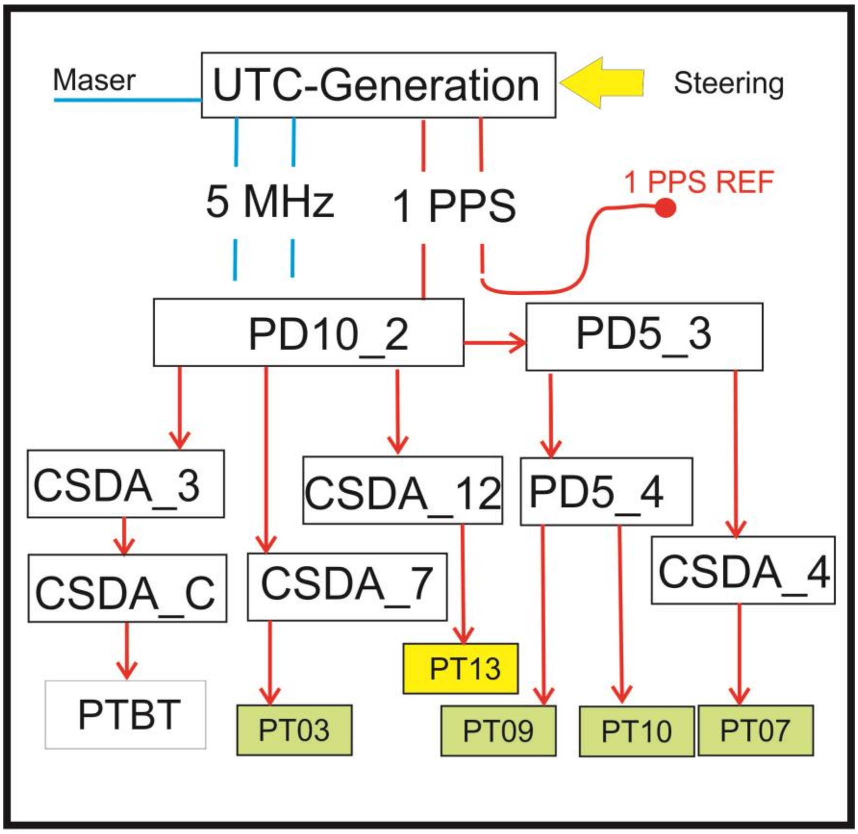

Figure 4-2: UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBT, and other receivers; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

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.

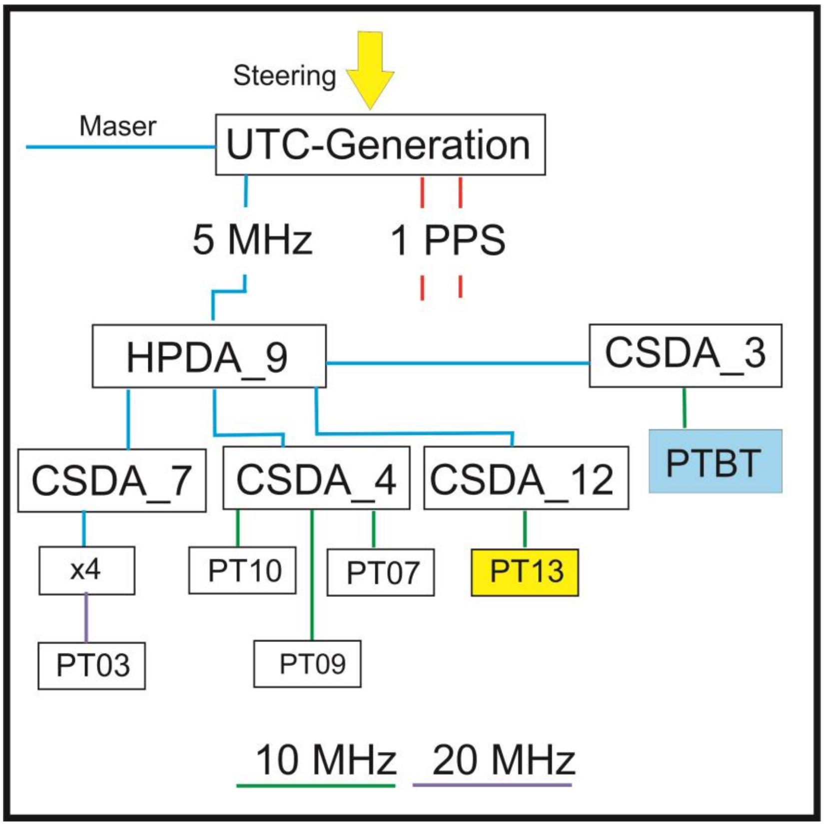

Figure 4-3: UTC(PTB) signal distribution (5 MHz, 10 MHz, 20 MHz) to PT13, PTBT, and other receivers

HPDA stands for High-precision distribution amplifier (for rf frequencies)

Figure 4-4: Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBT antenna position indicated (orange)

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

The period 58779 to 58783 (5 days) was chosen to determine the initial PTBT INT DLY values (CC1). The result of comparison with PT13 as the reference are shown in Figure 5-1 illustrating in total 446 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.

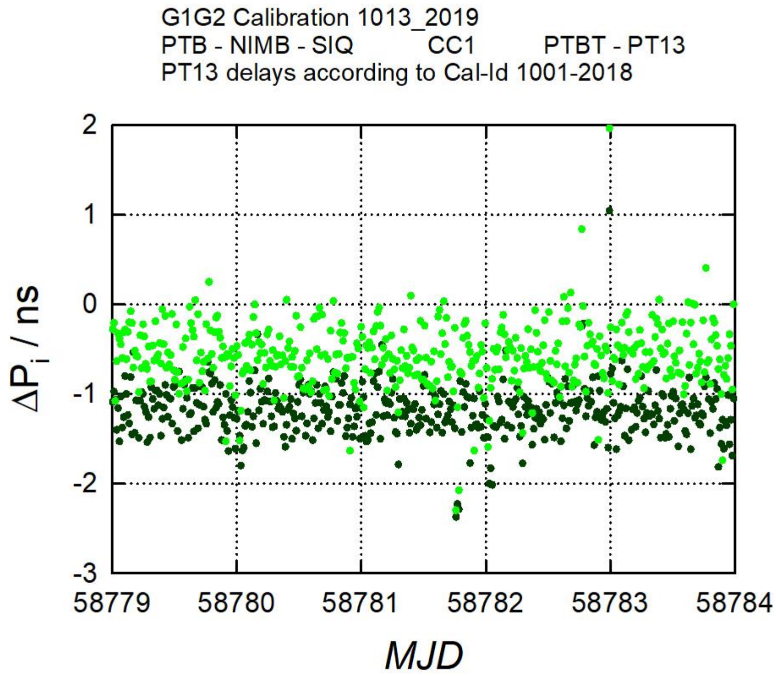

Figure 5-1: ΔP1 (dark green) and ΔP2 (light green) values obtained during the first common-clock set-up in PTB.

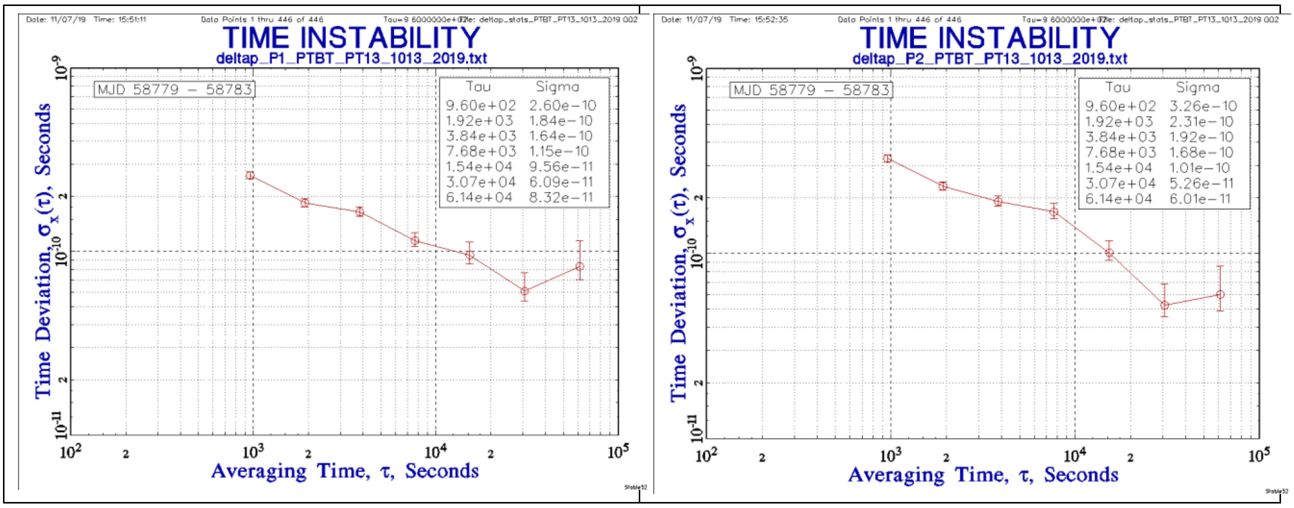

Figure 5-2: TDEV obtained for the two data sets shown in, ΔP1 left, ΔP2 right.

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)).

5.1. DETERMINATION OF L1C DELAY

The receiver delays for L1C signals were determined with respect to the same PTB receiver, PT13. 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 PT13 during CC1. The differences between PTBT and visited receivers 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.

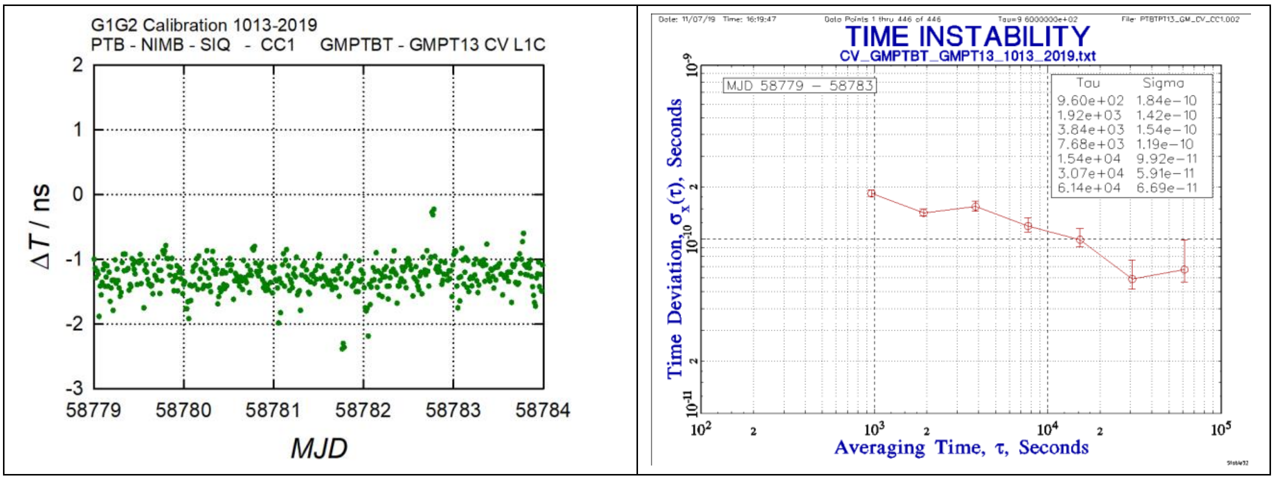

Figure 5-3 CV between receivers PTBT and PT13 using L1C data, time differences (left) and TDEV (right) during CC1

See Section 8. for further analysis of the data.

6. OPERATION OF PTBT AT NIMB

PTBT was operated at NIMB for several days in November 2019. 5 days were used as the data base for the delay determination of the receiver MB02. 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 CGGTTS files from both receivers were reprocessed using r2cggtts V 8.1.

The signal distribution to receivers PTBT, MB02 and MB__ at NIMB is illustrated in Figure 6-1. The mounting position of the antennas is shown in Figure 6-2.

Figure 6-1 Signal distribution at NIMB to the receivers

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

The second NIMB receiver is a PIKTIME TTS-2, single frequency, GPS-only, receiver. CGGTTS data were recorded with the 780 s track length and the standard start-dates only in a scattered fashion. So processing with software building on the cggtts standard could not be used, and thus this receiver could not be considered.

6.1. CALIBRATION OF RECEIVER MB02

As the Piktime TTS-4 receiver does not provide correctly formatted cggtts-files, r2cggtts V 8.1 was used to generate new GZMB02 and GMMB02 files used in the calculations.

Figure 6-3 ∆P1 (dark red) and ∆P2 (orange) values obtained comparing receiver MB02 (file name GZMB02MJ.DDD) and PTBT.

Figure 6-4: TDEV obtained for the two data sets shown in Figure 6-3, ∆P1 left, ∆P2 right.

In Figure 6-3 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 6-4. 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.

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBT at NIMB, provides the second step to determine the L1C internal delays of the receivers MB02. The results are included in Table 6-1.

Figure 6-5 CV between receivers BH01 and PTBT using L1C data, time differences (left) and TDEV (right)

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

∆INT DLY (Pi) for receivers at NIMB	**Mean (ns)**	**Median (ns)**	**Std. Dev. (ns)**	**TDEV (ns)**	**Number of 16-min epochs**
MB02					
∆P1					
∆P2					
∆C1					

7. OPERATION OF PTBT AT SIQ

PTBT was operated at SIQ between mid December 2019 and end of January 2020. Initially, 11.5 days were used as the data base for the delay determination of the receiver SI01. Then the SI01 GNSS antenna failed and was later replaced by a new model.

Finally, SIQ decided to continue operating their receiver with the new antenna, but keeping the designation SI01. Another 5 days were used for the delay determination of the receiver, now with antenna 2. It seems that finally both antennae remain useable, thus the results obtained with both antennae in sequence are presented below. The set-up including the old antenna is now designated as SI02. 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 before the start of data taking.

The signal distribution to receivers PTBT and SI01/SI02 at SIQ is illustrated in Figure 7-1. The mounting position of the antennas is shown in Figure 7-2, PTBT antenna to the left, SIQ new antenna to the right.

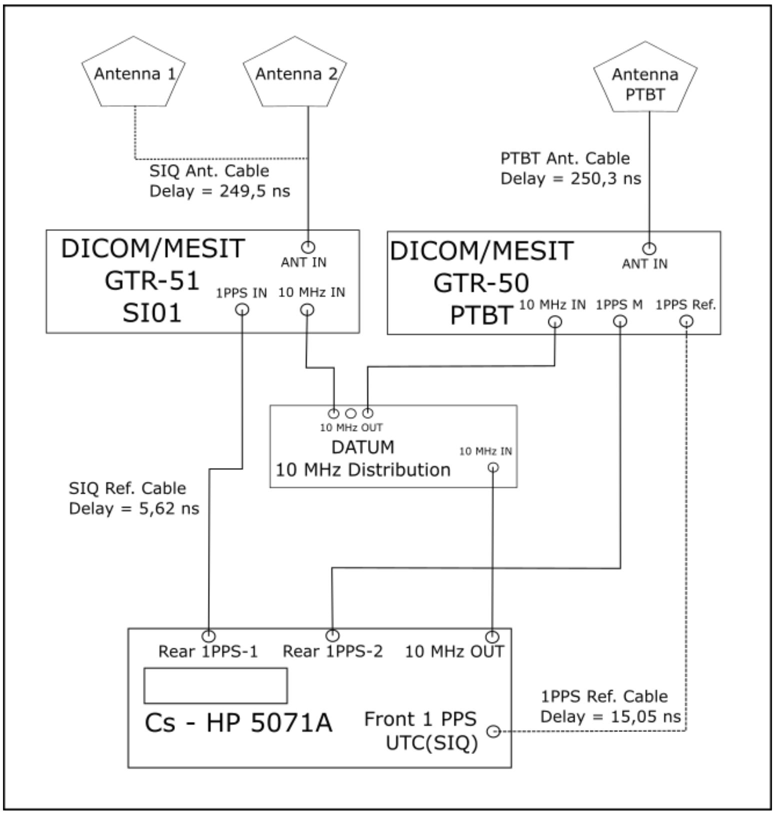

Figure 7-1 Signal distribution at SIQ to the receivers

Figure 7-2 Antenna installations on the rooftop of the SIQ building

7.1. CALIBRATION OF SIQ RECEIVER WITH OLD AND NEW ANTENNA

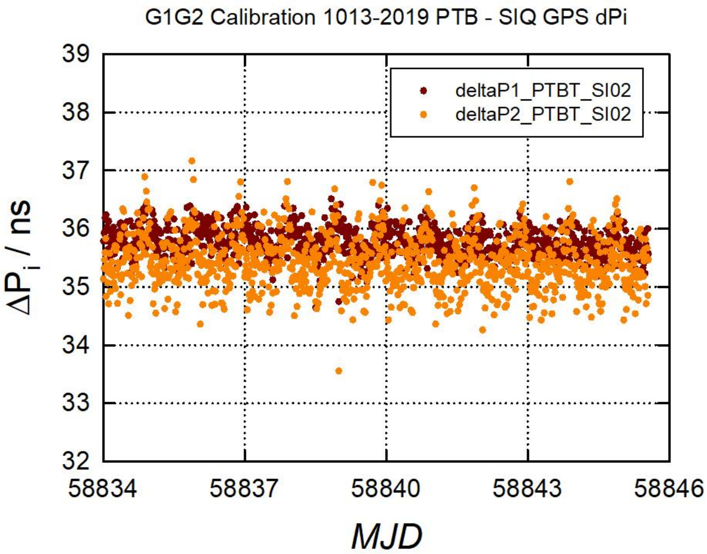

Figure 7-3 ΔP1 (dark red) and ΔP2 (orange) values obtained comparing station SI02, antenna 1, and PTBT.

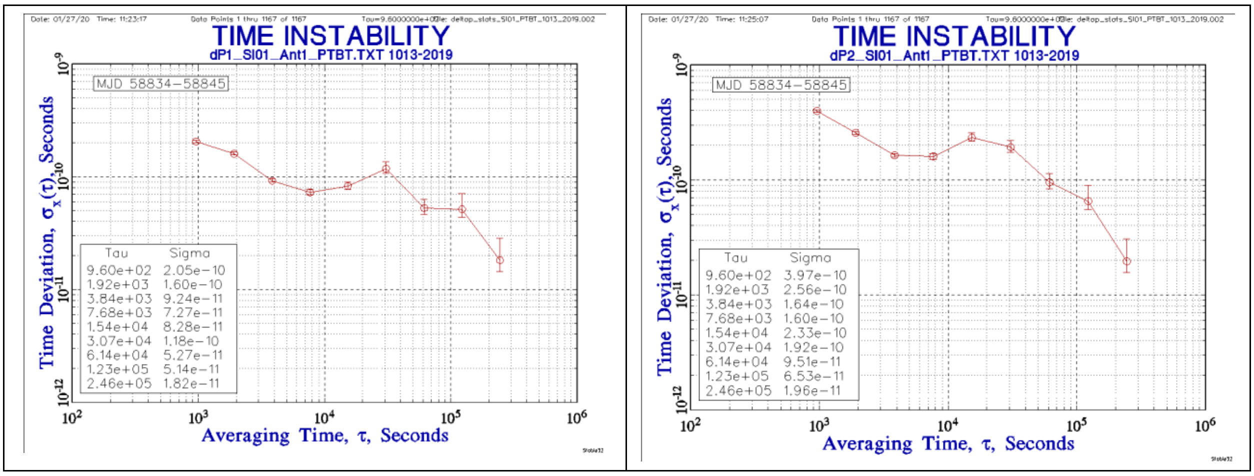

Figure 7-4: TDEV obtained for the two data sets shown in Figure 7-3, ΔP1 left, ΔP2 right.

In Figure 7-3 the ΔPi (3) derived from the raw data are depicted and the result are summarized in Table 7-1, including their statistical uncertainty. The corresponding TDEV plots are shown in Figure 7-4. As a statistical measurement uncertainty the value 0.1 ns has been used.

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBT at SIQ, provides the second step to determine the L1C internal delays of the station SI02. The results are included in Table 7-1.

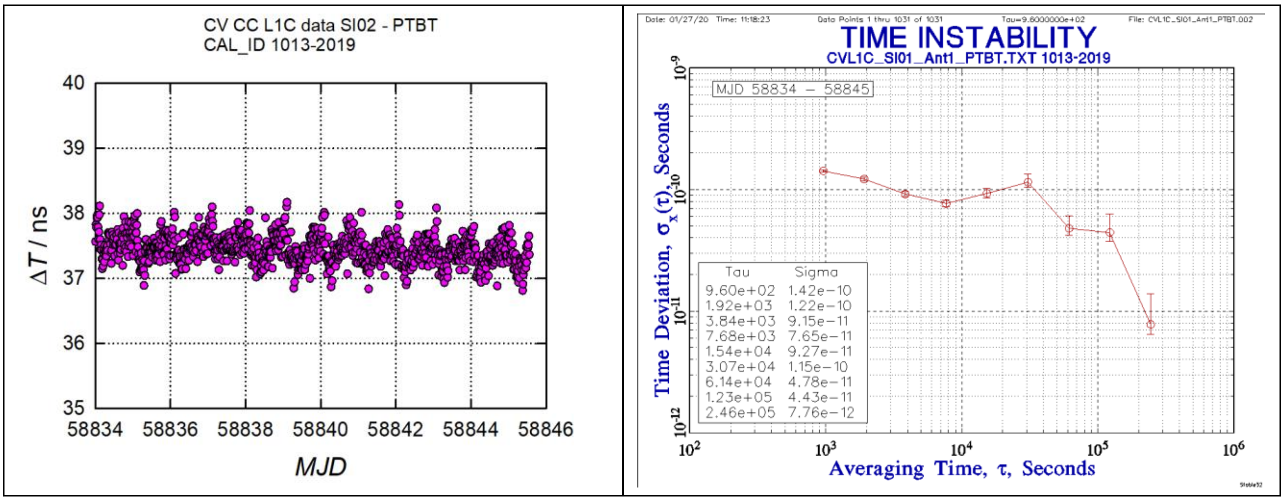

Figure 7-5 CV between SI02, antenna 1, and PTBT using L1C data, time differences (left) and TDEV (right)

The campaign continued in January 2020 when the new antenna was delivered and installed.

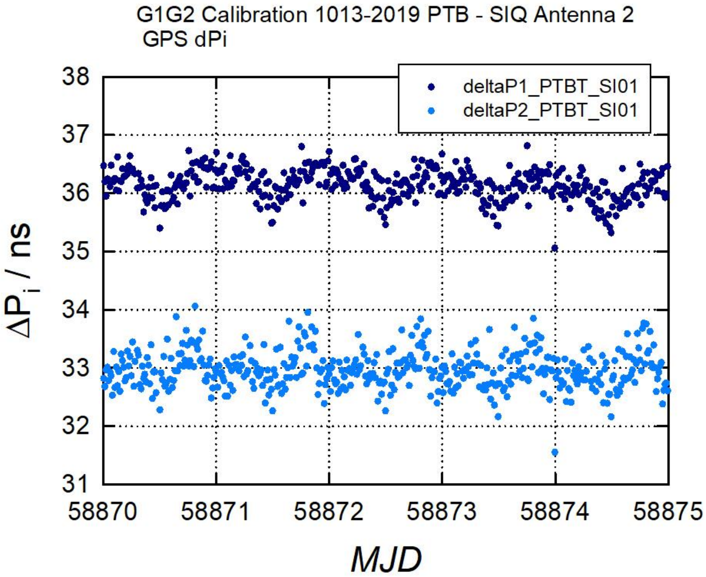

Figure 7-6 ΔP1 (dark blue) and ΔP2 (light blue) values obtained comparing SI01, antenna 2, and PTBT.

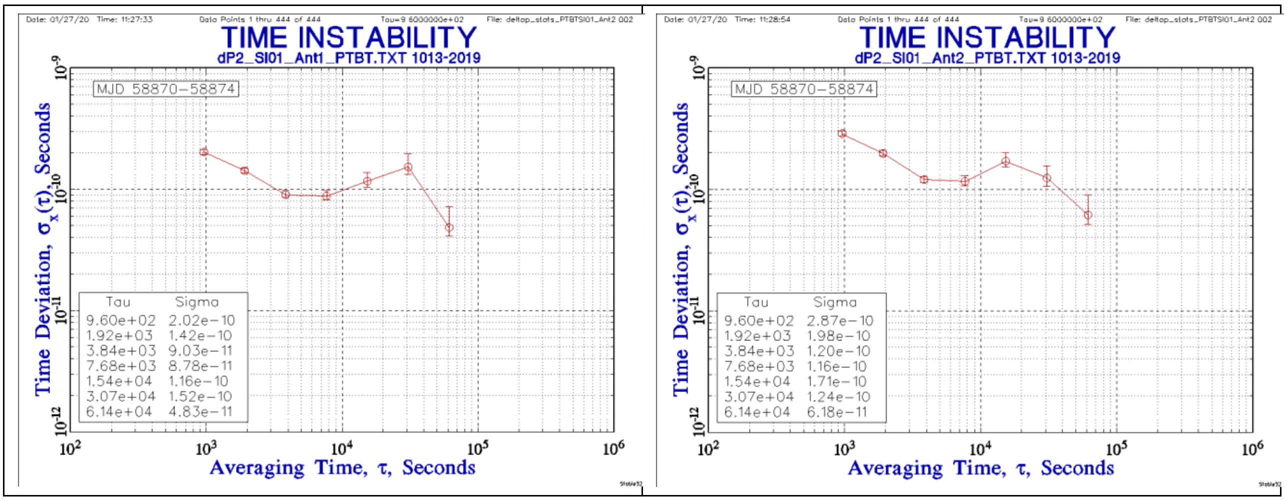

Figure 7-7: TDEV obtained for the two data sets shown in Figure 7-6.

In Figure 7-6 the ΔPi (3) (antenna 2) derived from the raw data are depicted and the result are summarized in Table 7-1, including their statistical uncertainty. The corresponding TDEV plots are shown in Figure 7-7. As a statistical measurement uncertainty the value 0.1 ns has been used as before.

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBT at SIQ, provides the second step to determine the L1C internal delays of the receivers SI01 with antenna 2. The results are included in Table 7-1.

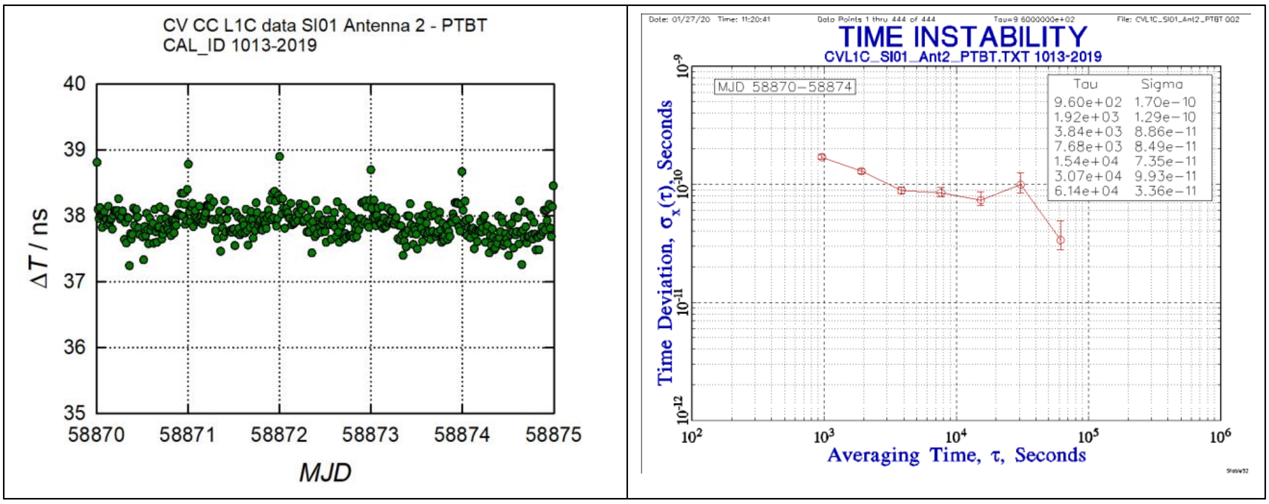

Figure 7-8 CV between SI01, antenna 2, and PTBT using L1C data, time differences (left) and TDEV (right)

Table 7-1 ΔINT DLY(Pi) values and statistical properties (in ns) obtained initially at SIQ.

ΔINT DLY (Pi) for receivers at SIQ	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
SI02 antenna 1					
ΔP1	35.76	35.76	0.25	0.1	1031
ΔP2	35.42	35.39	0.45	0.1	1031
ΔC1	37.45	37.44	0.20	0.1	1031
SI01 antenna 2					
ΔP1	36.15	36.16	0.26	0.1	444
ΔP2	32.97	32.95	0.33	0.1	444
ΔC1	37.90	37.89	0.22	0.1	444

8. OPERATION OF PTBT AT PTB: SECOND PERIOD

PTBT operation was started on 5 Feb 2020 after return, but the antenna did not function any more and no satellites were tracked. No second CC campaign could be recorded.

8.1. SUMMARY

The numerical results of the common-clock campaign CC1 at PTB is given in Table 8-1. The estimate of the uncertainty contribution is given in Section 9.

Table 8-1: Result of common clock measurements at PTB

Quantity	Median (ns)	Sigma (ns)	TDEV (ns)
ΔP1 (CC1)	-1.18	0.29	0.1
ΔP2 (CC1)	-0.56	0.36	0.1
ΔP3 (CC1)	-2.13		
ΔC1 (CC1)	-1.26	0.24	0.1

9. INT DLY UNCERTAINTY EVALUATION

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

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}\,, \qquad (6)$$

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 NIMB, SIQ and PTB, respectively. The systematic uncertainty is given by

$$u_b = \sqrt{\sum_n u_{b,n}}\,. \qquad (7)$$

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

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

Note that the uncertainty of the INT DLY values of PTB's fixed receiver PT13 (G) which served as the reference is not included.

Table 9-1: 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	0.23	CC measurement uncertainty at PTB, TDEV max. of the two CC campaigns
2a	u_a(NIMB)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver MB02
2b	u_a(SIQ_1)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver SI01_ant1
2c	u_a(SIQ_2)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver SI02_ant2
Result of closure measurement at PTB						
3						
Systematic components due to antenna installation						
4	$u_{b,11}$	0.1	0.1	0.14	0.28	Position error at PTB
5a	$u_{b,12}$	0.1	0.1	0.14	0.28	Position error at NIMB and SIQ
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 NIMB and SIQ
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(k) (REF DLY), k = NIMB and SIQ, resp.
10a	$u_{b,23}$	0.2	0.2	0	0.2	Connection of receivers at "k" to UTC(NIMB) (REF DEL),
10b	$u_{b,23}$	0.2	0.2	0	0.2	Connection of receivers at "k" to UTC(SIQ) (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 NIMB and SIQ
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
14a	$u_{b,32}$(NIMB)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBT CAB DLY when installed at NIMB
14b	$u_{b,32}$(SIQ)	0.5	0.5	0	0.5	Uncertainty estimate for the PTBT CAB DLY when installed at SIQ
15a	$u_{b,33}$(NIMB)	0.8	0.8	0	0.8	Uncertainty estimate provided by NIMB for the MB02 CAB DLY
15b	$u_{b,33}$(SIQ)	0.5	0.5	0	0.5	Uncertainty estimate provided by SIQ for the SI01 CAB DLY

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. The visited institutes 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 NIMB but not at SIQ. PTBT 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 NIMB and SIQ 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.

10. FINAL RESULTS

The results of the calibration campaign G1G2_1013_2019 are summarized in Table 10-1. 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 9-1, 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 10-1. Results of the Calibration Campaign G1G2_1013_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
MB02	0	0	139.93	137.24	-1.18	-0.56	138.75	0.88	136.68	0.88	0.96
SI02_Ant1	0	0	35.76	35.42	-1.18	-0.56	34.58	1.01	34.86	1.01	1.08
SI01_Ant2	0	0	36.16	32.95	-1.18	-0.56	34.98	1.01	32.39	1.01	1.08

In a similar way we obtain from equation (1) corrected values of the L1C signal delay in receiver MB02 and SI01 as
INT DLY(L1C);new = INT DLY(L1C);old - Δ(T-V) + ΔT(T-G),
where R designates the receiver PT13 chosen as reference for this action. We estimate the uncertainty of the new value to 1.5 ns.

Table 10-2 Results of CC CV L1C comparisons in PTB and at NIMB and SIQ, all values in ns

Receiver couple	CV mean difference	Sigma	TDEV	Number of CV epochs
PTBT-PT13 CC1	-1.26	0.25	0.1	446
MB02-PTBT	173.80	0.32	0.15	439
{SI02_Ant1}-PTBT	37.44	0.20	0.15	1031
{SI01_Ant2}-PTBT	37.89	0.22	0.15	441

Table 10-3 Results of L1C calibration during campaign 1013-2019, all values in ns

Receiver	INT DLY(L1C), old	ΔT (T-V))	ΔT (T-R)	INT DLY(L1C), new	u_{cal}, L1C
MB02	-32.65	-173.80	-1.26	139.89	1.5
SI02_Ant1	0	-37.44	-1.26	36.18	1.5
SI01_Ant2	0	-37.89	-1.26	36.63	1.5

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2019-10-23 0:00 UTC (MJD 58779)
Date and hour of the end of	2019-10-27 24:00 UTC (MJD 58783)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PT13**	**PTBT**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	Dicom GTR50 0708522 1.7.7
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	ECOFLEX15	LMR-400 (N)
Length outside the building /m:	approx. 25	25
Antenna maker and type: Antenna serial number:	LEICA AR25 726333, Calib Geo++ 18.08.2015	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	9.33 ± 0.1 (**)	2.7 +/- 0.1 (to port 1 PPS REF)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	45.0 ± 0.1 (**)	N/A
Antenna cable delay: (X_C) / ns	205.7 ± 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:	29.7 (P1), 27.2 (P2), 31.7 (C1) (**)		-37.7 (P1) -43.9 (P2) (***) -36.0 (C1)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	205.7		209.0	
☐ REF DLY (or X_P+X_O) /ns:	54.3 (**)		42.3	
☐ Coordinates reference frame:	ITRF (*)		ITRF (***)	
X /m:	+3844059.86 (*)	Mast P10	+3844063.48 (***)	Mast P4
Y /m:	+709661.56 (*)		+709658.72 (***)	
Z /m	+5023129.87 (*)		+5023127.31 (***)	

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 via E-Mail 08.08.2019

(**) Local measurement 2019-04-03, other results based on report Cal-ID1001-2018
(***)PTBT INT DLY were adjusted so that PTBT – PT13 were close to zero for convenience.
Coordinates of mast P4 (APC) were determined in 12.03.2018 using NRCan PPP.

Names of files to be used in processing for site PTB CC1
Travelling receiver GZPTBTMJ.DDD, GMPTBTMJ.DDD
Reference receiverGZPT13MJ.DDD, GMPT13MJ.DDD

PTBT operation at NIMB: Receiver MB02

Laboratory:	**NIMB**	
Date and hour of the beginning of measurements:	2019-11-13 00:00:00 UTC (58800)	
Date and hour of the end of measurements:	2019-11-17 24:00:00 UTC (58804)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**MB02**	**PTBT**
Receiver maker and type: Receiver serial number:	PikTime Systems – Poland, TTS4 150	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):	CellPack type C-41506-14 Superflex Coax Cable Not phase stabilised	N-type, LMR400
Length outside the building /m:	Approx. 35	Approx. 45
Antenna maker and type: Antenna serial number:	Javad, RingAnt-435 Antenna 00641	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	179.43	9.67 (to port 1 PPS REF)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	-74.5 ns	N/A
Antenna cable delay: (X_C) / ns	144.02	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:-32.64 L2C:0.00 L1P:0.00 L2P:0.00	-37.7 (P1) -43.9(P2) -36.0 (C1)
CAB DLY (or X_C) /ns:	144.02	209.0
REF DLY (or X_P+X_O) /ns:	104.90	11.3
Coordinates reference frame:	ITRF	ITRF
X /m:	+4098049.60 m	+4098044.54 m
Y /m:	+2011749.39 m	+2011749.79 m
Z /m	+4439407.16 m	+4439409.78 m
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 ± 2,0 °C	

MB02: Original file names GMMB02MJ.DDD
New files generated with correct format using r2cggtts V8.1 and MB02 RINEX files
Antenna phase centre checked using NRCan PPP – okay.
Files produced GZMB02MJ.DDD (for L3P) and GMMB02MJ.DDD for L1C
PTBT: original files with wrong REF DLY and wrong coordinates discarded.
Antenna phase center determined using NRCan PPP and PTBT RINEX files
REFDLY determined through conversation with NIMB
File names GZPTBTMJ.DDD, GMPTBTMJ.DDD

PTBT operation at SIQ: Station SI01 and SI02

Laboratory:	**SIQ**	
Date and hour of the beginning of measurements:	2019-12-18 00:00:00 UTC (58834)	
Date and hour of the end of measurements:	2020-01-26, 00:00 UTC (58874)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**SI01**	**PTBT**
Receiver maker and type: Receiver serial number:	Dicom/Mesit GTR-51 1408137 1.9.5	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):	ROSENBERGER RTK 400 s.n. SIQ19017 Not phase stabilised	ROSENBERGER RTK-400 s.n. SIQ19015
Length outside the building /m:	Approx. 3m	Approx. 3m
Station SI02 Antenna 1 maker and type: Antenna 1 serial number:	NOVATEL GPS-703-GGG-HV; NEG14230011	Navexperience 3G+C NA0164
Station SI01 Antenna 2 maker and type: Antenna 2 serial number:	NOVATEL GNSS-850; NMLK19180046H	
Temperature (if stabilised) /°C	-	
Measured delays /ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	5.98	15.05 (to port 1 PPS REF)
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	N/A	N/A
Antenna cable delay: (X_C) / ns	249.5	250.3
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/A:0.00, L2C:0.00, L1P:0.00, L2P:0.00, L5:0.00	-37.7 (P1) -43.9(P2) -36.0 (C1)
CAB DLY (or X_C) /ns:	249.5	250.3
REF DLY (or X_P+X_O) /ns:	5.98	26.6
Coordinates reference frame:	ITRF	ITRF
X /m:	+ 4291094.929 m	+ 4291095.641 m
Y /m:	+ 1110385.681 m	+ 1110386.310 m
Z /m	+ 4571430.875 m	+ 4571430.026 m

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 ± 2,0°C

END of DOCUMENT