GNSS CALIBRATION REPORT

G1G2_1014_2020

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LIST OF TABLES AND FIGURES

REFERENCES

REFERENCES	
RD01	**BIPM report 2018 Group 1 GPS calibration trip 1001-2018_GPSP3C1_Group1-trip_V2**
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**
RD08	**BIPM / Gerard Petit / TM266 V2.5 19 June 2020, "Continuity of GNSS "INTDLY" values of Group 1 geodetic receivers in successive Group 1 trips", Section C.6**
RD09	**PTB Report GNSS CALIBRATION REPORT PT13 VIA 1001-2018, 01 September 2020**

ACRONYMS

ACRONYMS	
BIPM	**Bureau International de Poids et Mesures, Sèvres, France**
BKG	**Bundesamt für Kartografie und Geodäsie, Frankfurt, Germany**
CGGTTS	**CCTF Generic GNSS Time Transfer Standard**
ESA	**European Space Agency**
EURAMET	**The European Association of National Metrology Institutes**
IFAG	**Institue für Angewandte Geodäsie**
IGS	**International GNSS Service**
GOW	**Geodätisches Observatorium Wettzell**
GNSS	**Global Navigation Satellite System**
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 GNSS equipment operated on the Geodetic Observatory Wettzell with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GNSS dual-frequency time links to PTB in the context of realization of TAI. The PT13 signal delays for GPS and Galileo had been determined with respect to receiver PT09 in several steps. PTB provided its receiver PTBM 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 1014_2020. Primary 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)) and the equivalent for Galileo on frequencies E1 and E5a.

PT13 GPS-signal delays had been provided in [RD01]. Initially, PT13 Galileo delays had been determined with reference to receiver GRCP. With publication of V2 of [RD01] and V2.5 of [RD08] in June 2020, Galileo delay values for the G1 laboratories were published. In case of PTB, values for PT09 were provided. Subsequently, the Galileo delay values of PT13 were aligned using the same method as in 2019 and reported in [RD09].

The final results are included in Table 9-1 and Table 9-2. The internal delays of the two receivers involved were determined with an uncertainty of slightly below 1 ns for single frequency observations. The uncertainty for time transfer links to PTB evaluated in a ionosphere-free linear combination is less than 1.1 ns in all cases.

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

PTB quality management responsibles gave the advice to stress in this report 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 GNSS equipment operated at the Geodetic Observatory Wettzell (GOW, Germany) with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GNSS dual-frequency time links to PTB in the context of realization of TAI. The PT13 signal delays for GPS and Galileo were determined with respect to receiver PT09 which in turn got its last calibration from BIPM as reported with Cal_Id=1001-2018 [RD01]. PTB provided its receiver PTBM for the purpose as travelling equipment.

The observatory is operated jointly by the German Bundesamt für Kartografie und Geodäsie (BKG) and the Forschungsgruppe Satellitengeodäsie (FSG). The local time scale carries the historical designation UTC(IFAG) from Institut für Angewandte Geodäsie", and IFAG is also the acronym used e. g. in BIPM Circular T.

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, PTBM, was compared to the "golden" receiver, PT13, and the offset between the actual and the assumed PTBM delay values were determined.

After that, the receiver was installed at the visited sites and the internal delay values of the devices under test and their statistical properties were determined with respect to PTBM.

Finally, the stability of the PTBM delays was 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 were 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.

1.1. CHANGE LOG

Version	Date	Changes
0	07.07.2020	Version 0, all new
0b	09.09.2020	Version incl. Matgerial GOW / Hessels
02	24.09.2020	Version incl. Evaluation at GOW
1.0	16.10.2020	CC2 included, final draft
1.1	21.10.2020	Final version, typos removed, explanation improved for Table 8-1
1.2	23.10.2020	Further typos removed, Table 8-1 modified so that entries and explanations agree

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	Dipl.Ing. Uwe Hessels Tel: +49 (0) 9941 / 603-208 or -128	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
2020-08- 17 until 2020-08-24	PTB	First common-clock comparison between PTBTM and PT13	7 days used for determination of delays, MJD 59078 – 59084
2020-09-02 until 2020-09-18	GOW	Operation of PTBM in parallel with 2 receivers (WTZS + GOWT)	6 days used for determination of delays (in sequence)
2020-10-10 until 2020-10-15	PTB	Operation of PTBM after return	6 days used for determination of delays, MJD 59132 - 59137

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

3. CALIBRATION PROCEDURE

3.1. GENERAL DESCRIPTION

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 a software routine written by Egle Staliuniene 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 delays were determined with respect to receiver PT09 which in turn got its last calibration from BIPM as reported with Cal_Id=1001-2018 [RD01]. PTBM 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, f1 and f2.

INT DLY(f1) and INT DLY(f2) of receiver V are the basic quantities that are determined during the relative calibration. For calculating ionosphere—free observation data, INT DLY(f3) is calculated as 2.54×INT DLY(f1) - 1.54×INT DLY(f2) for GPS, and as 2.26×INT DLY(f1) - 1.26×INT DLY(f2) for Galileo, respectively. In figures and results tables we use the designation P1, P2 for GPS, and E1, E5a for Galileo, instead of f1, f2.

The following terms are considered frequency independent, i. e. no distinction is made for f1 and f2.

(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 PolaRx4: Xo available at the the 1 PPS-out socket of the receiver
- For Septentrio PolaRx5TR: optionally Xo is determined autonomously by the receiver or it can be determined alike to the PolaRx4.
- For DICOM GTR50, GTR51 and GTR55: $X_O = 0$,
- 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.

PT13 (PolaRx5TR) had been installed in April 2019, and the auto-calibration option was disabled. PTBM (PolaRx5TR) makes use of the auto-calibration option.

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 (f3) data (including correct, accurate antenna coordinates) are needed. As a reminder,

$$REFSYS(j) = [REFSYS_{RAW}(j) - CAB\ DLY_F - INT\ DLY(f3) + REF\ DLY_F] \qquad (1)$$

for reporting results of observation of satellite “j” is valid and reported in column 10 of the standard CGGTTS files. $REFSYS_{RAW}$ designates the uncorrected measurement values, INT DLY(f3) is calculated as explained before, 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 contains 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 in calibration mode thus calculates:

$$REFSYS_{f1}(j) = REFSYS(j) + MDIO(j) \qquad (2a)$$
$$REFSYS_{f2}(j) = REFSYS(j) + (f_1/f_2)^2 \times MDIO(j), \qquad (2b)$$

where $(f_1/f_2)^2 = 1.647$ for GPS and 1.793 for Galileo, respectively, for each satellite observation j and REFSYS(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

$$\Delta IDi(T,G) := REFSYS_{fi}(T) - REFSYS_{fi}(G) \qquad (3)$$

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

The software provides the median value of all individual observations ΔIDi for f1 and f2, and the number of data points used. In addition, a file that contains observation epoch (MJD.frakt) and the average ΔIDi of all satellite observations at that epoch (duration 13 minutes) is generated. 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(fi)_T_corr = ΔIDi(T,G) + INT DLY(fi)_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

INT DLY(fi)_V_new = ΔIDi(V,T) + <ΔIDi(T,G)> + INT DLY(fi)_V_old, (5)

where <ΔIDi(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.

3.2. DETERMINATION OF DELAYS OF GALILEO SIGNALS

In the current campaign, Galileo delays of visited receivers are calculated with reference to the values determined by BIPM in campaign 1001-2018 in retrospect [RD08]. The CCTF working group on GNSS, at its meeting held June 3, 2020, decided that the Galileo reference for Group 1 calibrations would be realized through the absolute calibration of the BIPM receiver BP21 performed by ESTEC in 2019. In order to provide in retrospect Galileo INTDLY values for 1001-2018 whenever possible, i.e. for Galileo-capable receivers visited by a Galileo-capable traveling receiver (in the EURAMET and SIM legs), BP21 has been added to the set of 1001-2018 receivers. In doing so, the Galileo absolute calibration was transferred from BP21 to the 1001-2018 reference BP1J, then to all possible receivers. In case of PTB, receiver delays for PT09 were determined [RD08]. These were transferred to PT13 after publication of [RD08] in June 2020 [RD09].

4. CHARACTERIZATION OF PTB EQUIPMENT

In the following, we document the stability of PTBM in comparison with the reference PT13 during periods of a few weeks. In Figure 4-1, the period preceeding the previous campaign 1013-2020 is documented, in Figure 4-2 a similar plot is provided for the weeks before shipment to GOW.

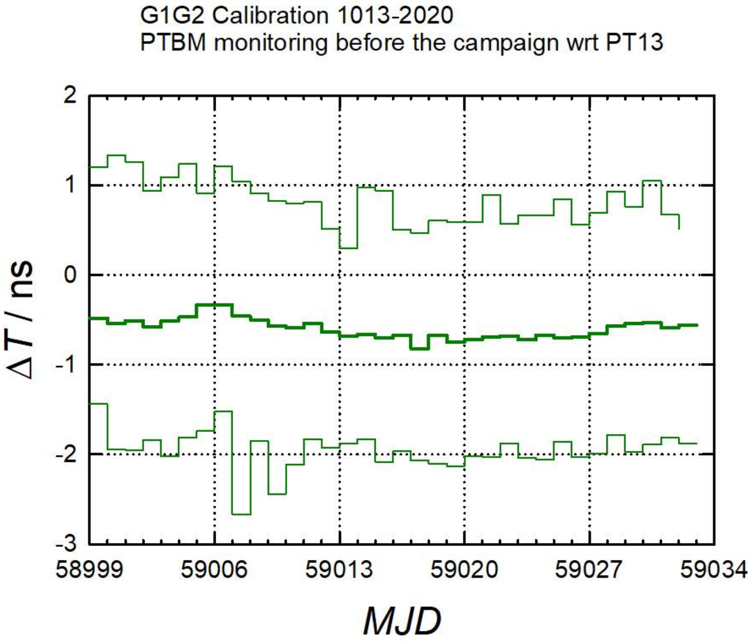

Figure 4-1: Common-clock common-view GPS comparison between PTBM and PT13 in a period preceding campaign 1013-2020; thick lines: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day.

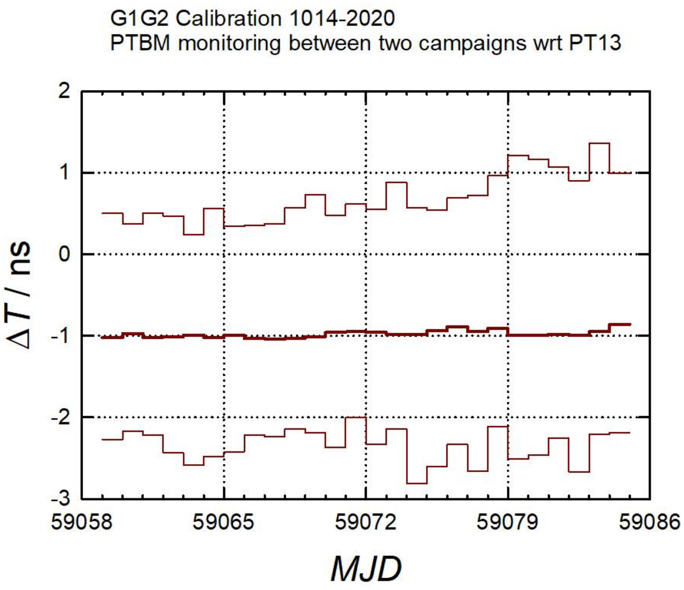

Figure 4-2: Common-clock common-view GPS comparison between PTBM and PT13 in the period preceding campaign 1014-2020; thick lines: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day.

The installation of the receivers in PTB is depicted in Figure 4-3 for 1 PPS signals and in Figure 4-4 for 5 MHz signals.

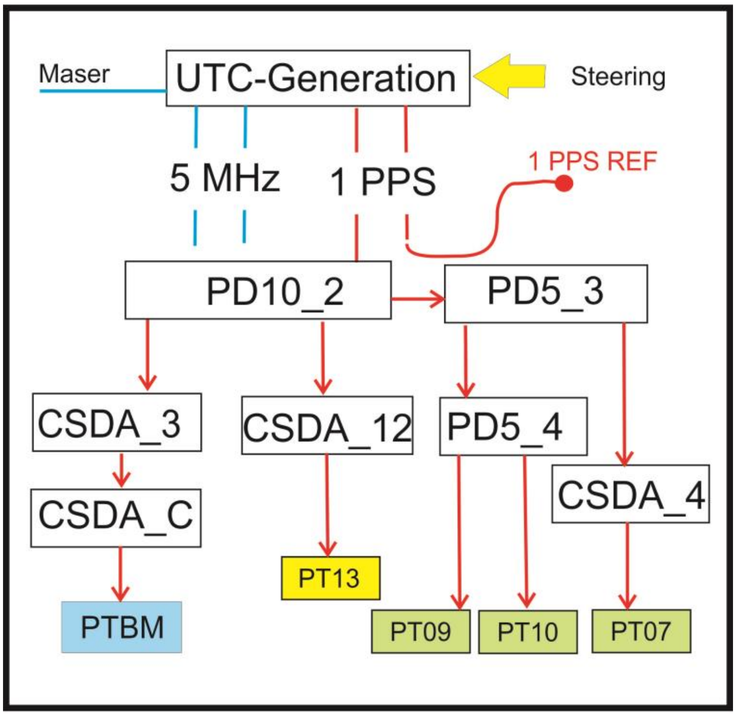

Figure 4-3: UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBM, and other receivers; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

A clarification may be helpful regarding the 1 PPS REF point. When measuring with a TIC the time difference between Port A = UTC(PTB), and Port B = 1 PPS REF then the result is + 2.7 ns.

Figure 4-5 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall) during CC1.

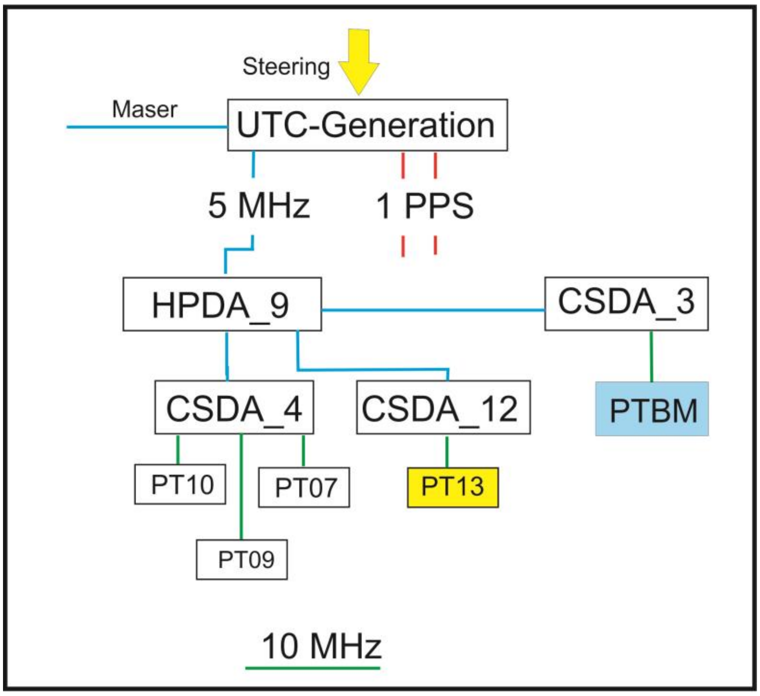

Figure 4-4: UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, PTBM, and other receivers

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

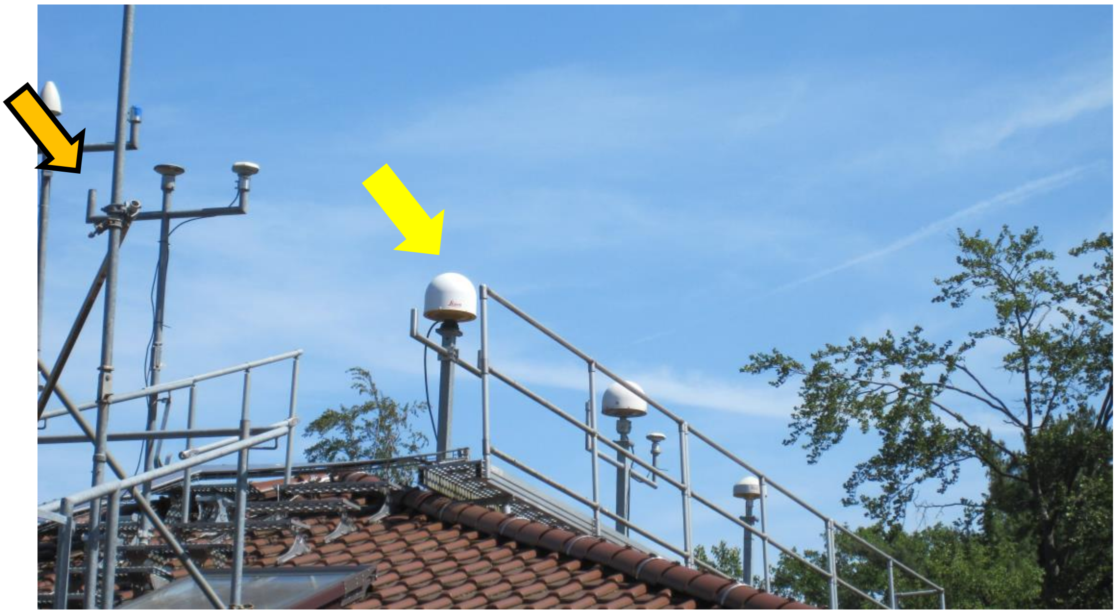

Figure 4-5: Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBM antenna position during CC1 and C2 indicated (orange)

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

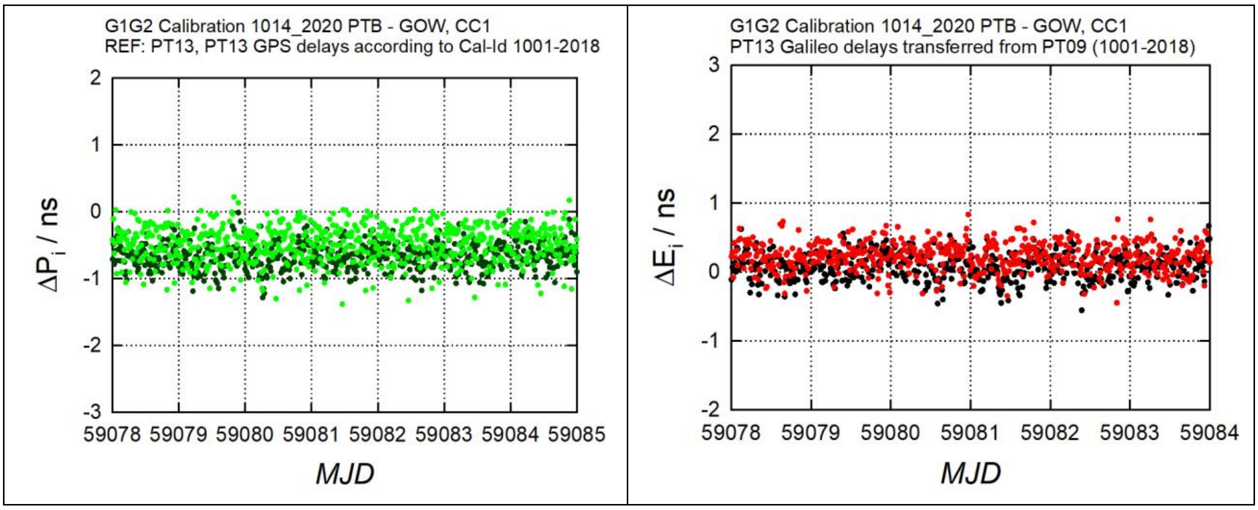

Figure 5-1: Left: Corrections to GPS delay in PTBM during CC1, ΔP1 (dark green) and ΔP2 (light green) Right: Corrections to Galileo delays in PTBM during CC1, ΔE1 (black) and ΔE5a (red).

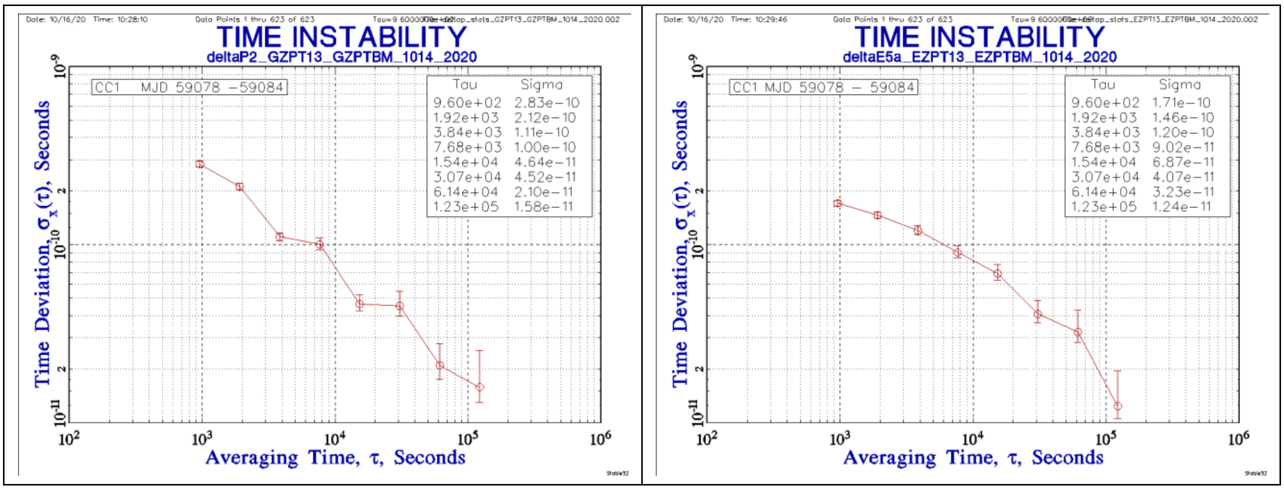

Figure 5-2: TDEV obtained for the two noisier data sets shown in Figure 5-1, GPS dP2 (left), and Galileo dE5a (right).

The period 59078 to 59084 (7 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 623 values obtained for each GNSS frequency as mean over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets representing dP2 and dE5a, respectively, follow as Figure 5-2. TDEV for the other data are even lower. The numerical results are given in the Summary sub-section at the end of the report on CC2 in PTB.

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 PTBM AT GOW

PTBM was operated at GOW during week 36, 37 and 38, 2020, at two different sites of the campus.

The signal distribution to receivers PTBM and GOW receivers is illustrated in Figure 6-1 and Figure 6-2. The installation of the antennas is shown as Figure 6-3 and Figure 6-4.

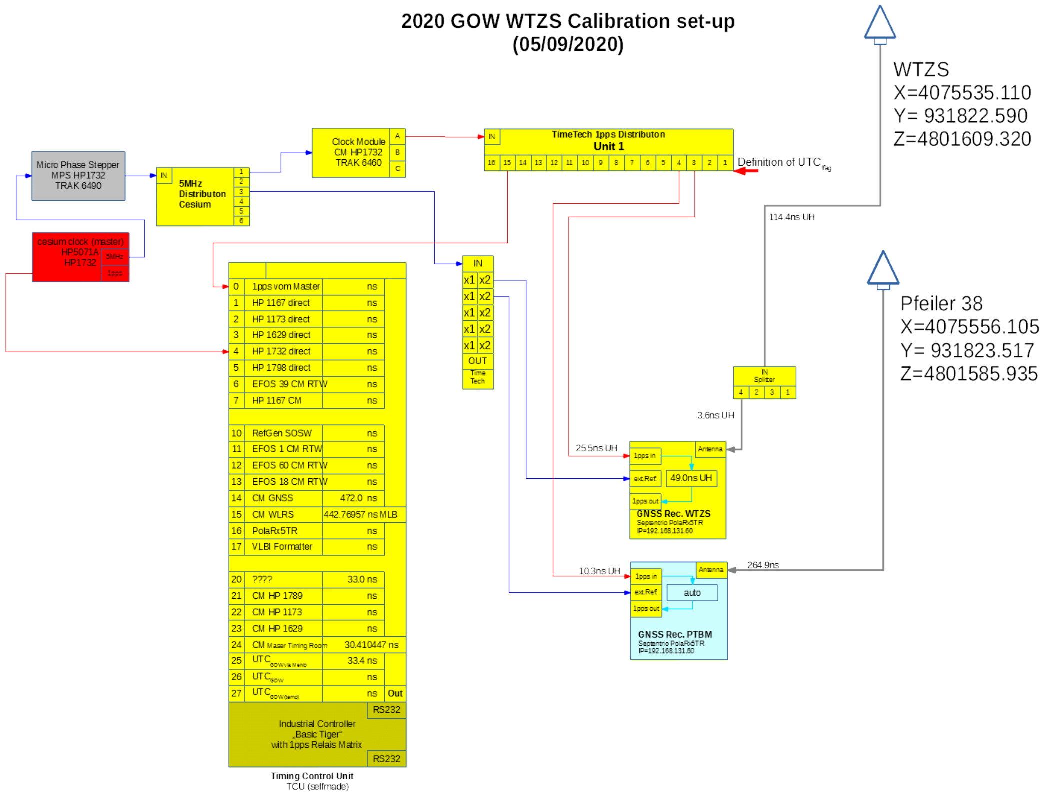

Figure 6-1: Signal distribution at GOW to the receiver WTZS and PTBM

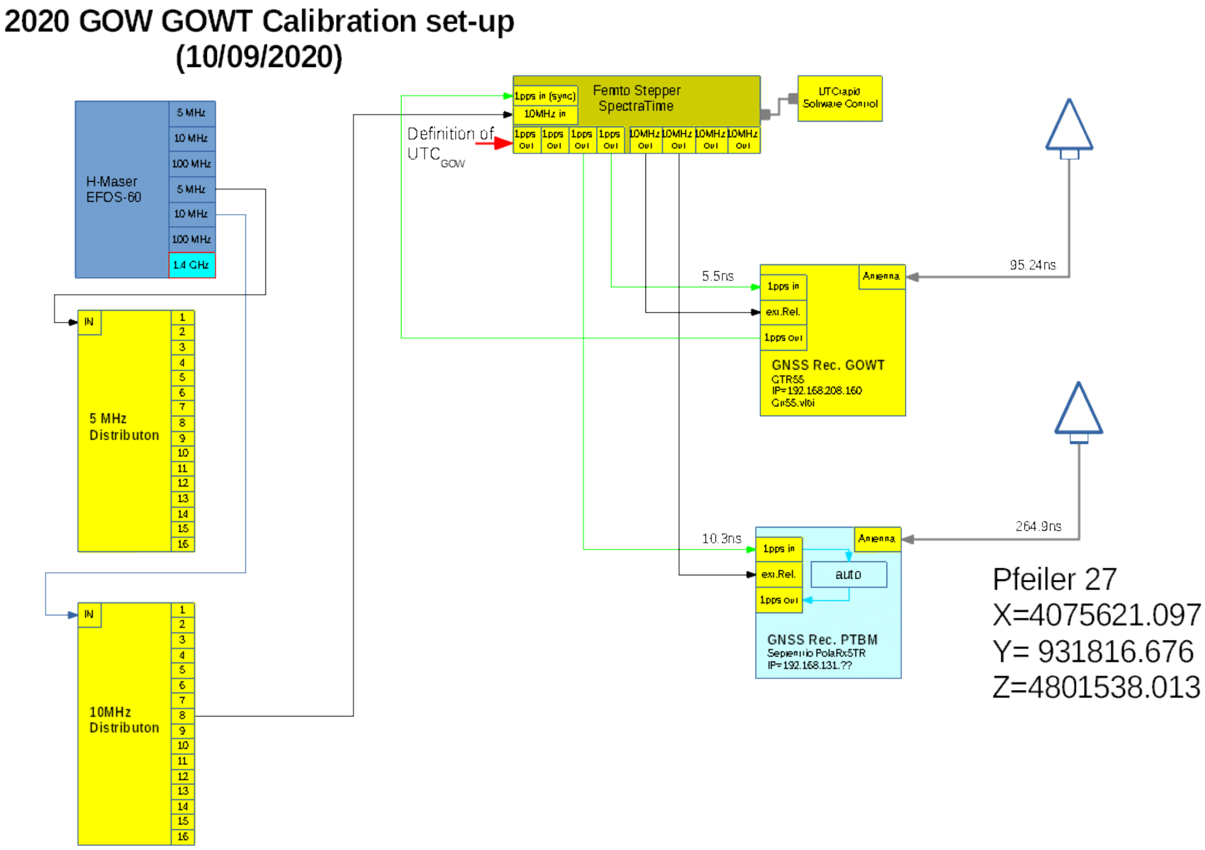

Figure 6-2: Signal distribution at GOW to the receiver GOWT and PTBM

Figure 6-3: GNSS antennas WTZS and PTBM on the GOW area

Figure 6-4 GNSS antennas GOWT and PTBM on the GOW area

6.1. CALIBRATION OF RECEIVER (WTZS)

Internal delays of receiver WTZS (BIPM designation for CGGTTS IF20) had previously been adjusted roughly so that results obtained matched with results from older calibrated receivers operated at GOW.

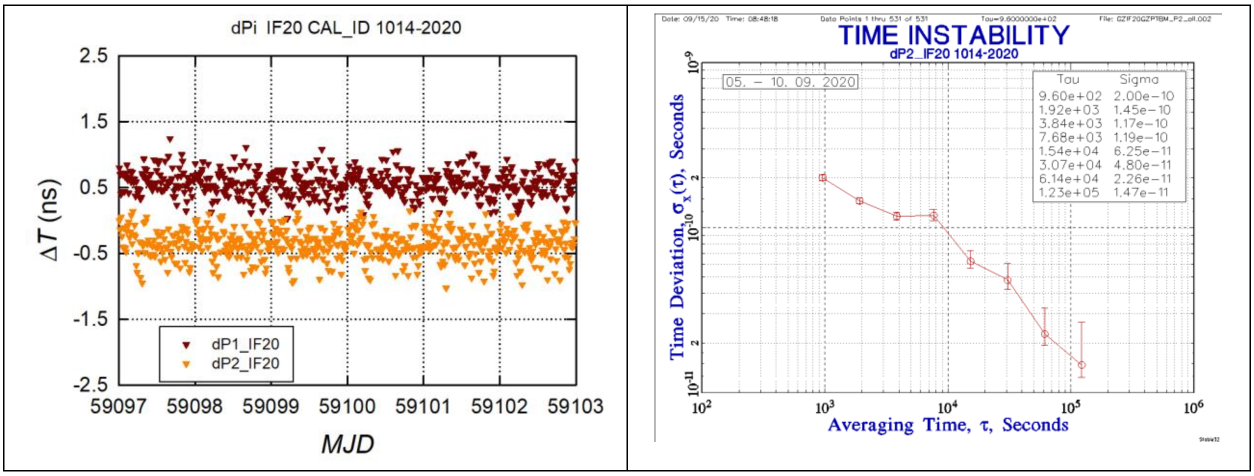

Figure 6-5. Left: Corrections to GPS INT DLY in IF20, reference PTBM; GPS ΔP1 (brown) and ΔP2 (orange), right: TDEV calculated from the dP2 values shown in the left panel.

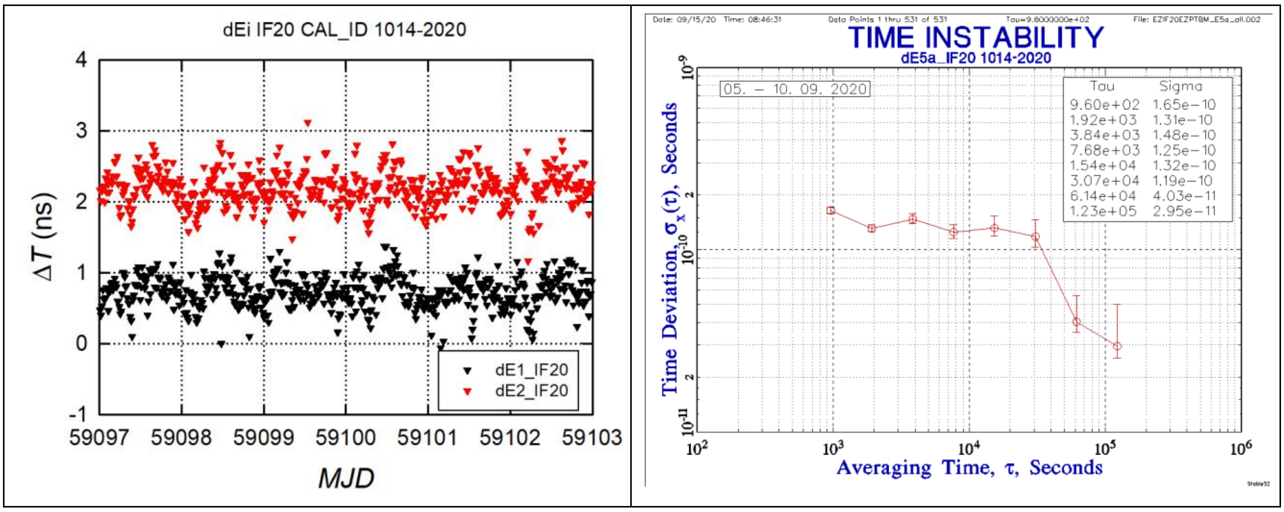

Figure 6-6 Left: Corrections to Galileo INT DLY in IF20, reference PTBM; left: Galileo ΔE1 (black) and ΔE5a (red), right: TDEV calculated from the d5a values shown in the left panel..

In Figure 6-5 and Figure 6-6, the ΔIDi (3) derived from the raw data are depicted. The results are collected in Table 6-1 which contains the mean and the median value, the standard deviation of individual data points and an estimate for the statistical uncertainty which is derived from TDEV at = 50 000 s. The default value of 0.1 ns is chosen if the measured TDEV is less than 0.1 ns. In the figures the TDEV-plot for the noisiest data set is shown.

6.2. CALIBRATION OF RECEIVER GOWT

The receiver GOWT did not have delay values previously determined. The values reported are thus the delays to be used furtheron.

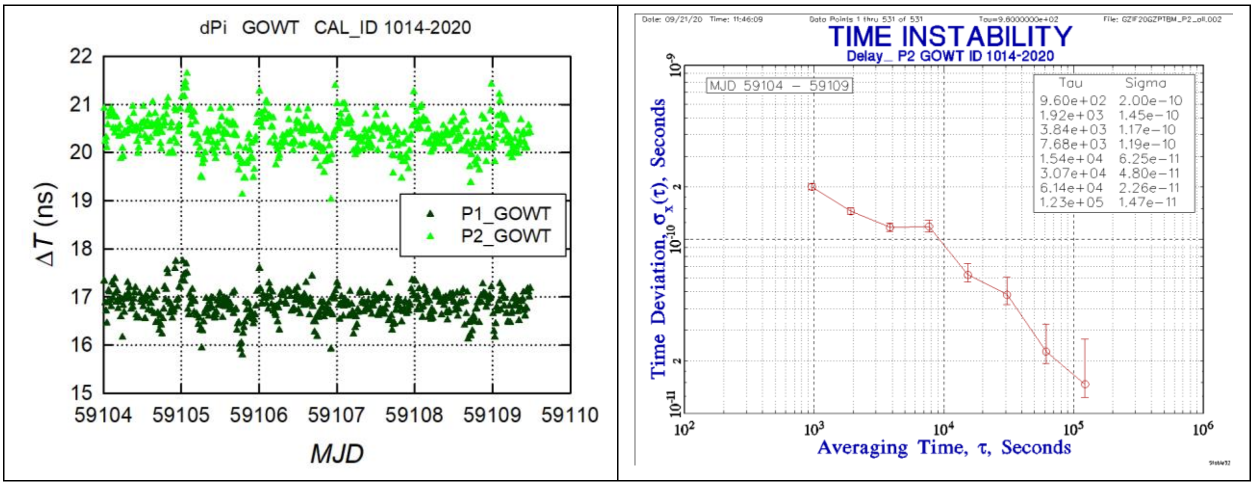

Figure 6-7. Left: INT DLY of GOWT, reference PTBM; GPS P1 (dark) and P2 (light), right: TDEV calculated from the P2 values shown in the left panel.

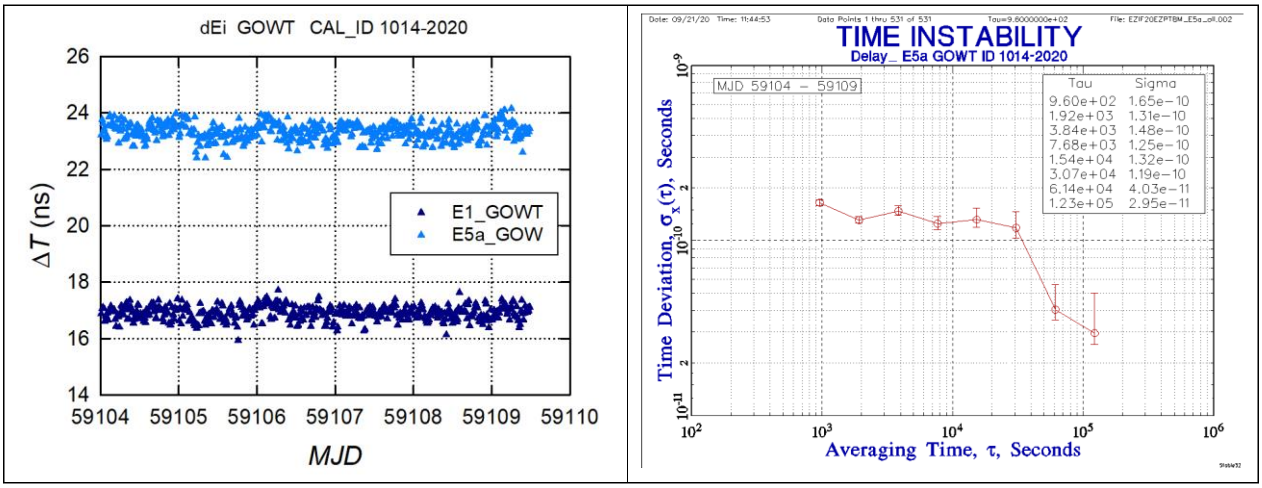

Figure 6-8. INT DLY of GOWT, reference PTBM; left: Galileo E1 (dark) and E5a (light), right: TDEV calculated from the E5a values shown in the left panel.

6.3. SUMMARY OF RESULTS OBTAINED AT GOW

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

ΔINT DLY (fi) for receiver at GOW	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
IF20					
ΔP1	0.56	0.56	0.19	0.1	531
ΔP2	-0.36	-0.35	0.22	0.1	531
ΔE1	0.73	0.73	0.23	0.1	531
ΔE5a	2.19	2.20	0.25	0.1	531
GOWT					
P1	16.83	16.85	0.28	0.1	483
P2	20.38	20.38	0.36	0.15	483
E1	16.90	16.91	0.25	0.1	483
E5a	23.34	23.25	0.29	0.15	483

7. OPERATION OF PTBT AT PTB: SECOND PERIOD

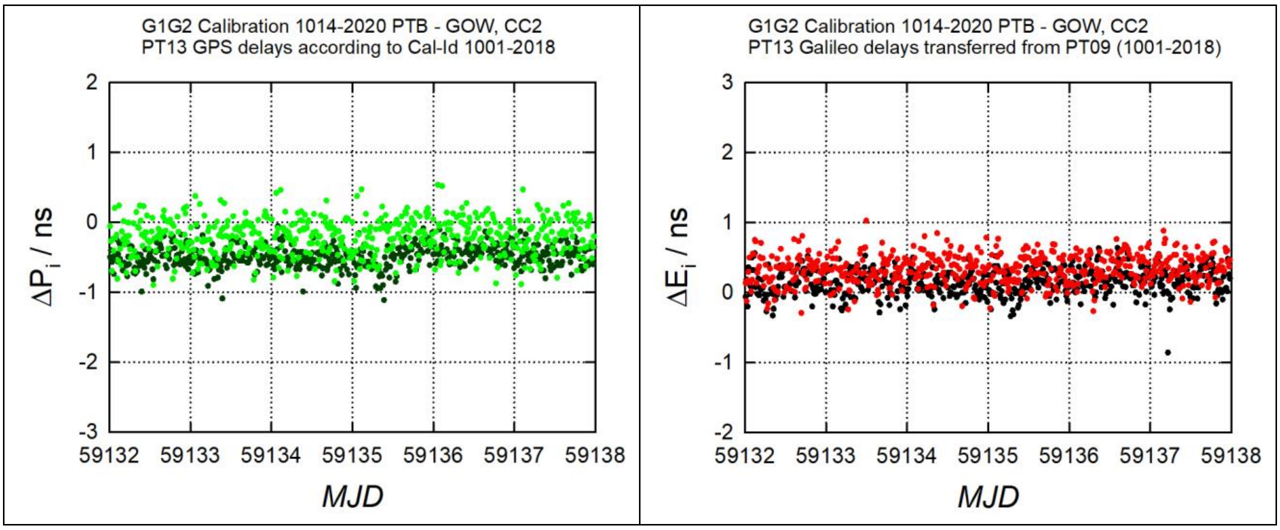

Figure 7-1. Left: Corrections to GPS delay in PTBM during CC2, ΔP1 (dark green) and ΔP2 (light green) Right: Corrections to Galileo delays in PTBM during CC2, ΔE1 (black) and ΔE5a (red).

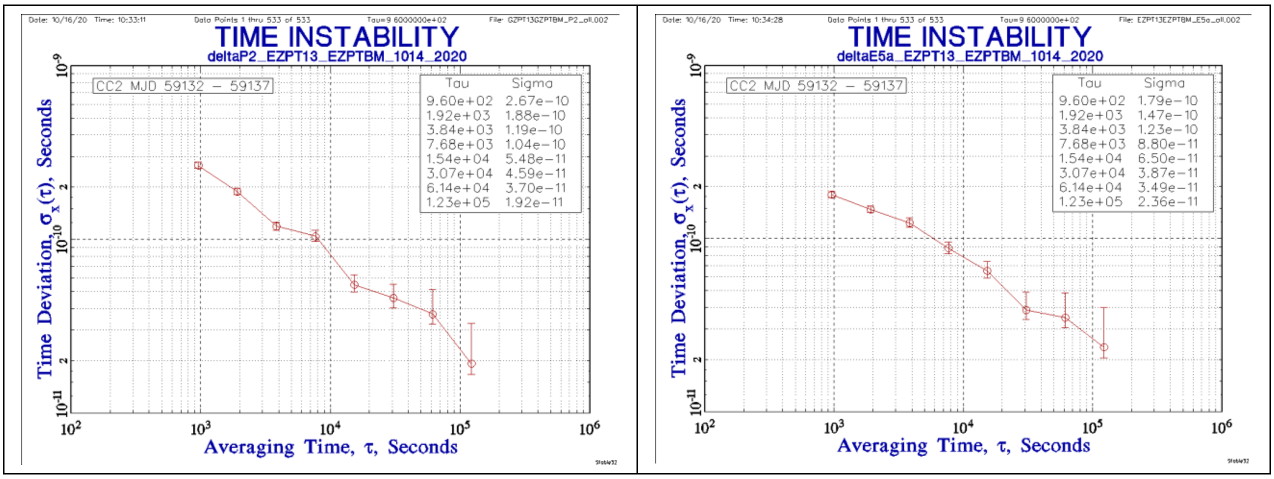

Figure 7-2. TDEV obtained for the data sets GPS dP2 (left) and Galileo dP2 (right) shown in Figure 7-1.

The period 59132 to 59137 (6 days) was chosen to determine PTBM INT DLY values during the common clock period CC2. The results of comparison with PT13 as the reference are shown in Figure 7-1 illustrating in total 533 ΔIDi values obtained as mean values over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets representing dP2 and dE5a, respectively, follow as Figure 7-2. TDEV for the other data are even lower.

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 0.25 ns for ΔP2. For the evaluation of the delays of the visited receivers the mean values 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)	-0.66	0.19	< 0.1
ΔP2 (CC1)	-0.45	0.27	< 0.1
ΔP3 (CC1)	-0.98		
ΔE1 (CC1)	+0.09	0.20	< 0.1
ΔE5a (CC1)	+0.22	0.21	< 0.1
ΔE3 (CC1)	-0.08		
ΔP1 (CC2)	-0.48	0.16	< 0.1
ΔP2 (CC2)	-0.20	0.26	< 0.1
ΔP3 (CC2)	-0.91		
ΔE1 (CC2)	0.14	0.18	< 0.1
ΔE5a (CC2)	0.34	0.21	< 0.1
ΔE3 (CC2)	-0.16		
Mean values used for evaluation of visited receivers' internal delays			
ΔP1	-0.57		
ΔP2	-0.33		
ΔE1	0.12		
ΔE5a	0.28		

8. INT DLY UNCERTAINTY EVALUATION

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

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

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

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

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

Values in column P3 are calculated according to $u(P3) = \sqrt{u(P1)^2 + (1.54 \times u(P1-P2))^2}$. Uncertainties for the Galileo delays are calculated according to $\sqrt{u(E1)^2 + (1.26 \times u(E1-E5a))^2}$, except for lines 3a and 3b in Table 8-1.

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

	Uncertainty	Value f1 (ns)	Value f2 (ns)	Value f1-f2 (ns)	Value f3 (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
2	u_a(GOW)	0.1	0.1	0.14	0.23	CC measurement uncertainty, for the 2 GOW receivers
Result of closure measurement at PTB						
3a	$u_{b,1}$ (GPS)	0.18	0.25		0.42	Misclosure, see Table 7-1
3b	$u_{b,1}$ (Galileo)	0.14	0.14		0.42	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	$u_{b,12}$(GOW)	0.1	0.1	0.14	0.28	Position error at GOW
6	$u_{b,13}$	0.2	0.2	0.0	0.2	Multipath at PTB
7	$u_{b,14}$	0.2	0.2	0.0	0.2	Multipath at GOW
Installation of PTBT and visited receivers						
8	$u_{b,21}$	0.2	0.2	0	0.2	Connection of PTBM to UTC(PTB) (REF DLY)
9	$u_{b,22}$	0.2	0.2	0	0.2	Connection of PTBM 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 PTBM CAB DLY when installed at PTB
14	$u_{b,32}$(GOW)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBM CAB DLY when installed at GOW
15	$u_{b,33}$(GOW)	0.5	0.5	0	0.5	Uncertainty estimate for GOW CAB DLY values

As demonstrated in Table 6-1, the receivers atGOW show almost the same time instability. The TDEV plots (not all reproduced in this Report) show marginal differences, and the value of 0.1 ns is a conservative estimate anyway. Thus, a single uncertainty budget can cover all other contributions.

The uncertainty contribution $u_{b,1}$ is based on the difference between the two common clock campaigns in the following way. The respective differences hardly exceed the statistical measurement uncertainty. So either the difference itself or the statistical measurement uncertainty is considered as measure for the uncertainty, whatever is the larger quantity. The first option was used for the INT DLY(Pi), the second option for the INT DLY(Ei). The entries for f3 are based on the statistical uncertainty of the closure results.

For the generation of the CGGTTS data the PTBM antenna position is manually entered into the processing software in ITRF coordinates before the CC evaluation at both sites. 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 f1 and f2 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 f1-f2 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 ($u_{b,21}$, $u_{b,22}$, $u_{b,23}$) has been estimated as 0.2 ns for PTBM at both locations and as 0.2 ns for the internal set-up at GOW.

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 10 MHz using cables of different lengths, 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 PTBM cable was employed in CC1, CC2 and at GOW. 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 as long as the same PPS signal source was used, but differed by up to 0.5 ns when the slew rate of the pulse was significantly different. Thus we retain a uncertainty contribution $u_{b,31}$ of 0.5 ns. For the stationary antenna cables at GOW we conservatively assume the same 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 institute. 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_1014_2020 are summarized in Table 9-1 and Table 9-2. They contain the designation of the visited receivers, the INT DLY values hitherto used, the offsets ΔIDi(V,T) and ΔIDi(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 L3P (E1, E5a and L3E), 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_1014_2020: GPS delays, 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}, L3P
IF20	27.9	28.0	0.56	-0.35	-0.57	-0.33	27.89	0.89	27.32	0.91	1.07
GOWT	0	0	16.85	20.38	-0.57	-0.33	16.28	0.89	20.05	0.91	1.07

Table 9-2. Results of the Calibration Campaign G1G2_1014_2020: Galileo delays, all values in ns

Receiver	INT DLY(E1), old	INT DLY(E5a); old	ΔE1 (V,T)	ΔE5a (V,T)	ΔE1 (T,G)	Δ(E5a) (T,G)	INT DLY(1), new	u_{cal}, E1	INT DLY(E5a), new	u_{cal}, E5a	u_{cal}, L3E

IF20	30.0	30.0	0.73	2.19	0.12	0.28	30.85	0.88	32.47	0.88	1.07
GOWT	0	0	16.91	23.25	0.12	0.28	17.03	0.88	23.53	0.88	1.07

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2020-08-17 0:00 UTC (MJD 59078)
Date and hour of the end of measurements:	2020-08-23 24:00 UTC (MJD 59084)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PT13**	**PTBM**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	PolaRx5TR (5.3.0) S/N 3048338
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 REFERENCE S/N RE 0560
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 (#)	49.1 +/- 0.2
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	45.0 ± 0.1 (#)	Determined automatically by receiver software
Antenna cable delay: (X_C) / ns	205.7 ± 0.1	264.9 ± 0.5
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) (*) 32.0 (E1), 31.7 (E5a) (*)		18.9 (P1) 17.1 (P2) (****) 20.8 (E1), 17.9 (E5a) (****)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	205.7		264.9	
☐ REF DLY (or X_P+X_O) /ns:	54.3		49.1+unknown	
☐ Coordinates reference frame:	ITRF		ITRF	
X /m:	+3844059.86 (***)	Mast P10	+3844062.13 ($)	Mast P9
Y /m:	+709661.56 (***)		+709658.71 ($)	
Z /m	+5023129.87 (***)		+5023128.30 ($)	

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 0.5° C

Notes valid for CC1 and CC2:

(#) values determined at installation of PT13 in March 2019, local measurements not repeated
($) Coordinates of mast P9 (APC) were determined on 26.05.2020 using NRCan PPP
(*) values based on G1 calib 1001-2018, transferred from receiver PT09 [RD08, RD09]]
(***) values provided by BIPM via Mail 2019-08-07
(****) PTBM INT DLY were adjusted so that PTBM – PT13 for GPS and Galileo were close to zero for convenience.

Names of files to be used in processing for site PTB
Travelling receiver GZPTBMMJ.DDD, EZPTBMMJ.DDD
Reference receiver GZPT13MJ.DDD, EZPT13MJ.DDD

PTBM operation at GOW: Receiver WTZS

Laboratory:	**GOW**
Date and hour of the beginning of measurements:	2020-09-05 00:00 UTC (59097)
Date and hour of the end of measurements:	

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**WTZS /IF20**	**PTBM**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.3.2) 3022895	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:		
Antenna cable maker and type: Phase stabilised cable (Y/N):	Ecoflex 15	LMR400
Length outside the building /m:		
Antenna maker and type: Antenna serial number:	Leica AR25.R3 10020020	Navexperience 3G+C reference S/N RE 0560
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	25.5	10.3
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	49.0	Determined automatically by receiver software
Antenna cable delay: (X_C) / ns	118.0	264.9
Splitter delay (if any):	0	0
Additional cable delay (if any):	0	0

Data used for the generation of CGGTTS files		
	LOCAL:	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	27.9 , 28.0	18.9 (P1) 17.1 (P2)
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	30.0 , 30.0	20.8 (E1), 17.9 (E5a)
☐ CAB DLY (or X_C) /ns:	118.0	264.9
☐ REF DLY (or X_P+X_O) /ns:	74.5	10.3 + unknown
☐ Coordinates reference frame:	ITRF (WTZS)	ITRF (Pillar 38)
X /m:	4075535.110	4075556.105
Y /m:	931822.590	931823.517
Z /m	4801609.320	4801585.935

General information	
☐ Rise time of the local UTC pulse:	
☐ Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	+/- 2 deg

All coordinates (APC) determined using NRCCan PPP for day 201/2020. CAB DLY values represent the signal delay between output socket of the antenna and input socket of the receiver, including all cables and splitter (if applicable). This applies to all receivers.

Names of files to be used in processing for site GOW / WTZS

Travelling receiver GZPTBMMJ.DDD, EZPTBMMJ.DDD

DUT: GZIF20MJ.DDD, EZIF20MJ.DDD
GZGOWTMJ.DDD, EZGOWTMJ.DDD

PTBM operation at GOW: Receiver GOWT

Laboratory:	**GOW**
Date and hour of the beginning of measurements:	2020-09-12 00:00 UTC (59104)
Date and hour of the end of measurements:	2020-09-17 11:38:00 UTC (59109)

Information on the system

	Local:	**Travelling:**
4-character BIPM code	**GOWT**	**PTBM**
Receiver maker and type: Receiver serial number:	GTR55(1.8.3/3.7.5p1 Jan23,2019) 1803002	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:		
Antenna cable maker and type: Phase stabilised cable (Y/N):	FSJ1-50A	LMR400
Length outside the building /m:		
Antenna maker and type: Antenna serial number:	GNSS-850 NMLK17480012N	Navexperience 3G+C reference S/N RE 0560
Temperature (if stabilised) /°C		

Measured delays /ns

	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	5.4	10.3
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	0.0	0
Antenna cable delay: (X_C) / ns	95.0	264.9
Splitter delay (if any):	0	0
Additional cable delay (if any):	0	0

Data used for the generation of CGGTTS files

	LOCAL:	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	0.0 , 0.0	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:	0.0 , 0.0	
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	0.0 , 0.0	
☐ CAB DLY (or X_C) /ns:	95.0	264.9
☐ REF DLY (or X_P+X_O) /ns:	5.5	10.3
☐ Coordinates reference frame:	ITRF (GOWT)	ITRF (Pillar 27)
X /m:	4075649.724	4075621.097
Y /m:	931793.075	931816.676
Z /m	4801528.313	4801538.013
Antenna Delta H/E/N [m]	0.0 / 0.0 / 0.0	/ 0.0 / 0.0

General information

☐ Rise time of the local UTC pulse:	
☐ Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	+/- 2 deg

Second common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2020-10-10 0:00 UTC (MJD 59132)
Date and hour of the end of measurements:	2020-10-15 24:00 UTC (MJD 59137)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PT13**	**PTBM**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	PolaRx5TR (5.3.0) S/N 3048338
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 REFERENCE S/N RE 0560
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 (#)	49.2 +/- 0.2
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	45.0 ± 0.1 (#)	Determined automatically by receiver software
Antenna cable delay: (X_C) / ns	205.7 ± 0.1	264.9 ± 0.5
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), (*) 32.0 (E1), 31.2 (E5a) (**)		18.9 (P1) 17.1 (P2) (****) 20.8 (E1), 17.9 (E5a) (****)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	205.7		264.9	
☐ REF DLY (or X_P+X_O) /ns:	54.3		49.1+unknown	
☐ Coordinates reference frame:	ITRF (***)		ITRF (****)	
X /m:	+3844059.86 (***)	Mast P10	+3844062.13 (****)	Mast P9
Y /m:	+709661.56 (***)		+709658.71 (****)	
Z /m	+5023129.87 (***)		+5023128.30 (****)	

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

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