GNSS CALIBRATION REPORT

G1G2_1013-2022

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REFERENCES

REFERENCES	
RD01	**2020 Group 1 GNSS calibration trip (Cal_Id 1001-2020)**
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	**P. Defraigne and G. Petit, "CGGTTS-Version 2E: an extended standard for GNSS time transfer", Metrologia 52 (2015) G1**
RD07	**BIPM Procedure for computing raw difference of GNSS code measurements for geodetic receivers, dclrinex software version 3.1, April 2021**

ACRONYMS

ACRONYMS	
BIPM	**Bureau International des 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**
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 of IMBH, Institute of metrology of Bosnia and Herzegovina, Sarajewo, Bosnia and Herzegovina, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GNSS time links to PTB in the context of realization of TAI. The PT13 signal delays for GPS and Galileo were determined by BIPM as reported with CAL_ID 1001-2020 [RD01]. PTB provided its receiver PTBM for the purpose as traveling equipment. The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1013-2022. 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 C/A-code signal on L1 (L1C) and the equivalent for Galileo on frequencies E1 and E5a.

The final results are included in Table 9-1**Error! Reference source not found.** and Table 9-2**Error! Reference source not found.** The internal delays of receivers BH01 to BH03 were determined with an uncertainty slightly above 1 ns for single frequency observations. For the determination of BH01 GPS delays use was made of the BIPM-provided software dclrinex which. This function of the receiver was corrupted. The uncertainty for time transfer links to PTB evaluated in an ionosphere-free linear combination is between 1.26 ns and 1.44 ns.

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

The responsible party at PTB quality management 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 of IMBH, Institute of metrology of Bosnia and Herzegovina, Sarajewo, Bosnia and Herzegovina, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GNSS time links to PTB in the context of realization of TAI. The PT13 signal delays for GPS and Galileo were determined by BIPM as reported with CAL_ID 1001-2020 [RD01]. PTB provided its receiver PTBM for the purpose as traveling equipment. The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1013-2022. 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 C/A-code signal on L1 (L1C) and the equivalent for Galileo on frequencies E1 and E5a.

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 traveling 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 IMBH. 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
01	22.07.2022	Version 01, all new
02	29.07.2022	Inclusion of BH01 results for GPS based on processing with dclRinex, typo in BH01 report sheet corrected
03		

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	**Sani Šarčević** tel: +387 33 568 944 fax: +387 33 568 909 sani.sarcevic@met.gov.ba	Institute of metrology of Bosnia and Herzegovina Branilaca Sarajeva 25, 71000 Sarajevo, Bosnia and Herzegovina

Table 2-2 Schedule of the campaign

Date	**Institute**	**Action**	**Remarks**
2022-03-08 until 2022-04-03	PTB	First common-clock comparison between PTBM and PT13	6.5 days used for determination of delays, MJD 59666 – 59672
2022-05-23 until 2022-05-31	IMBH	Operation of PTBM in parallel with local receiver	6 days used for determination of delays. MJD 59725-59730
2022-07-15 until 2022-07-21	PTB	Operation of PTBM after return	6 days used for determination of delays, MJD 59776 – 59781

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 principle we distinguish receivers V, T, and G: V for visited, T for traveling, 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. The PT13 signal delays for GPS and Galileo were determined by BIPM as reported with CAL_ID 1001-2020 [RD01]. PTBM served as the traveling 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 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) has been installed in April 2019, and the PPS IN Delay Compensation option has never been used. On the contrary, PTBM (PolaRx5TR) normally makes use of the auto-compensation option as it reduces the number of measurements and potential errors at the visited site. In this case, the REF DLY is the offset between the UTC(k) reference point and the input to the PPS IN socket on the PTBM rack.
For clarity, `Figure 3-1` shows the traveling equipment in two views and screenshots of the PPS configuration menu of the PolaRx5 RxControl software and the receiver message received when the auto-compensation is active.

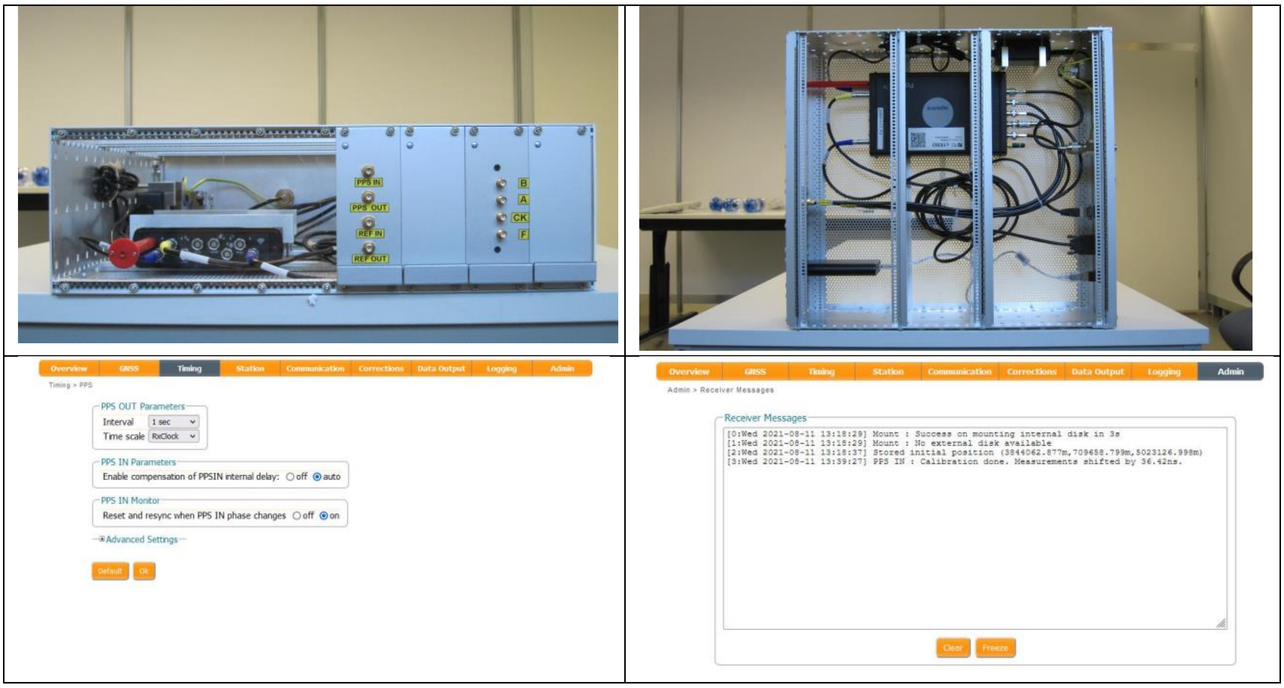

Figure 3-1 PTBM: views of the device and RxControl configuration and messages regarding PPS In and OUT.

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 to be applied is considered 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 iono-free observation (L3P or L3E, in short "f3") data (including correct, accurate antenna coordinates) are needed. If necessary, they are generated based on RINEX observation and navigation files and the software R2CGGTTS V8.3. As a reminder,

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

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 [RD06], 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:

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

where $(f1/f2)^2$ = 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

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

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

$$\mathrm{INT\ DLY(fi)\_V\_new} = \Delta \mathrm{IDi(V,T)} + \langle \Delta \mathrm{IDi(T,G)} \rangle + \mathrm{INT\ DLY(fi)\_V\_old}, \qquad (5)$$

where $\langle \Delta \mathrm{IDi(T,G)} \rangle$ 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 closure of the preceding campaign 1021-2021 consisted of only less than 10 days of operation of PTBM before going on travel again. CC2 of the previous campaign serves as CC1 of the current one. In the following, we document in Figure 4-1 the stability of PT13 in comparison with another receiver, PT09, during the period of the current campaign.

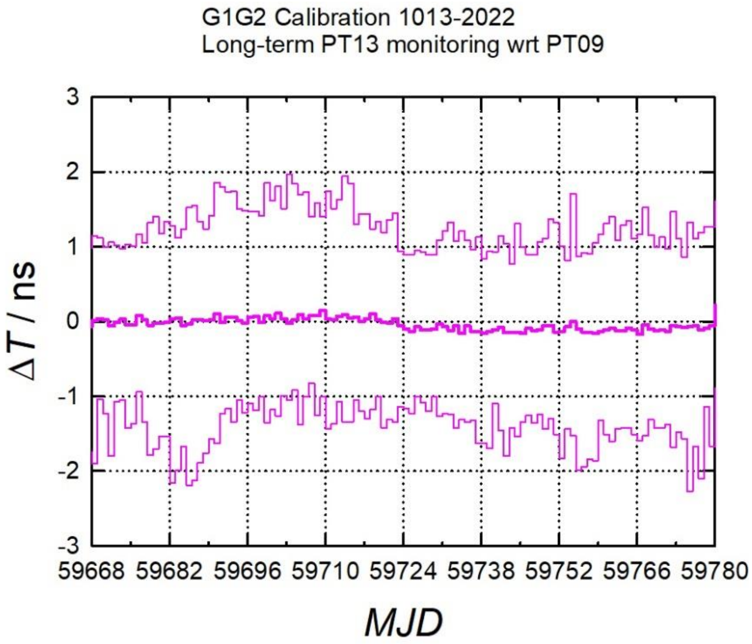

Figure 4-1 Common-clock common-view GPS comparison between PT09 and PT13 in a period covering campaign 1013-2022; thick line: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day.

The installation of the receivers in PTB is depicted in Figure 4-2 for PPS signals and in Figure 4-3 for 5 MHz (and 10 MHz) signals.

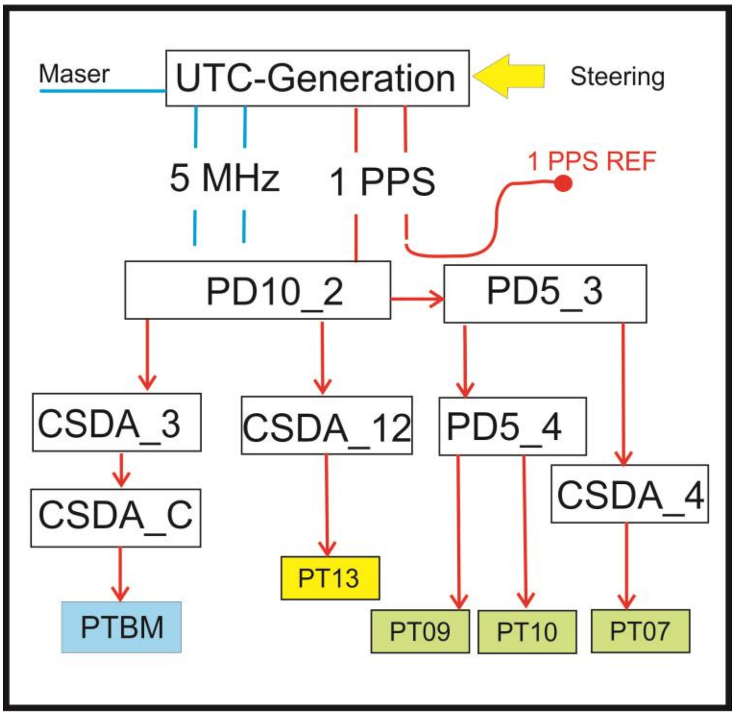

Figure 4-2 UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBM, and other receivers; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

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

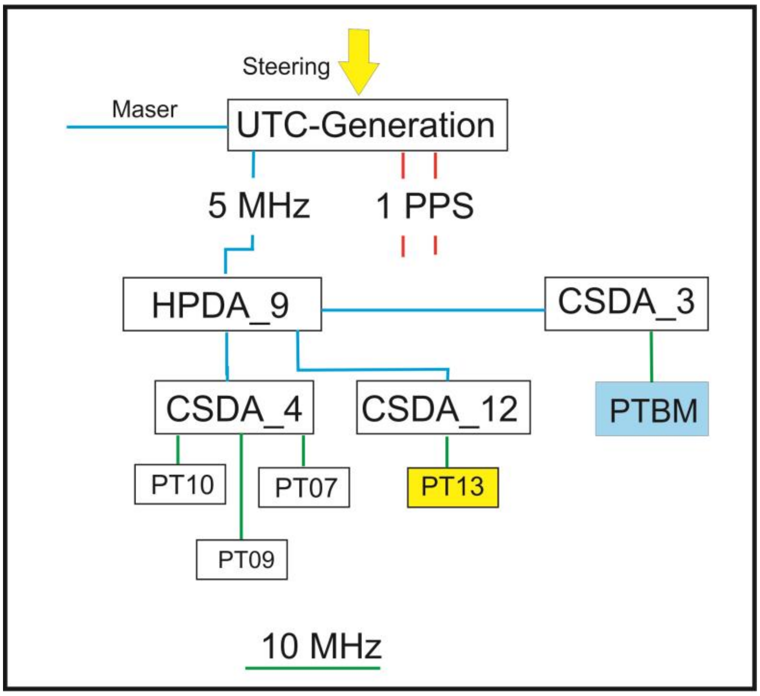

Figure 4-3 UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, PTBM, and other receivers

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

Figure 4-4 Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBM antenna during CC1 and CC2 (orange)

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

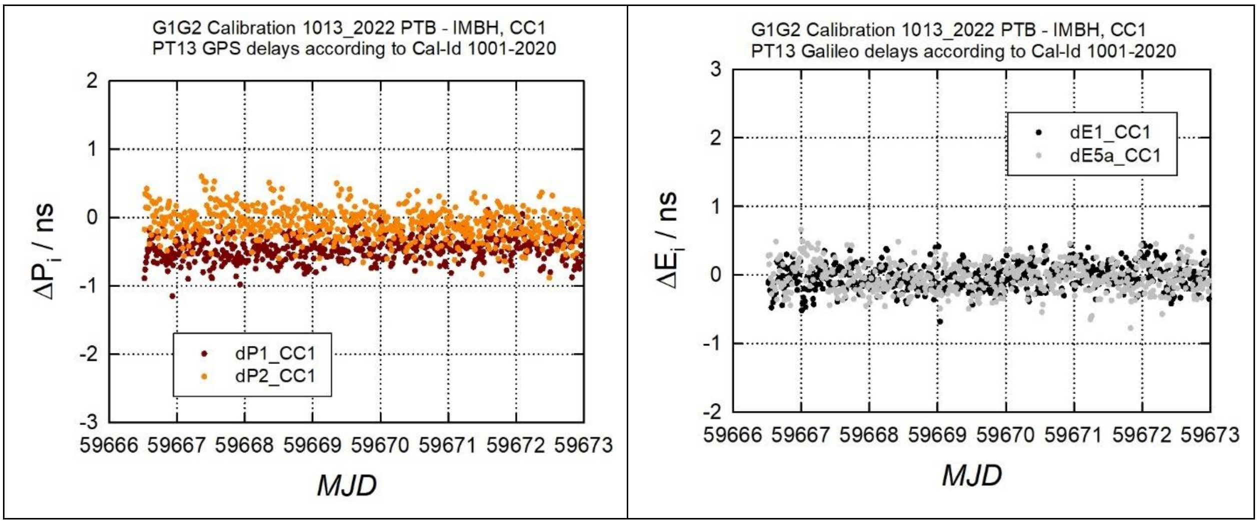

Figure 5-1 Left: Corrections to GPS delay in PTBM during CC1, ∆P1 (brown) and ∆P2 (orange) Right: Corrections to Galileo delays in PTBM during CC1, ∆E1 (black) and ∆E5a (grey).

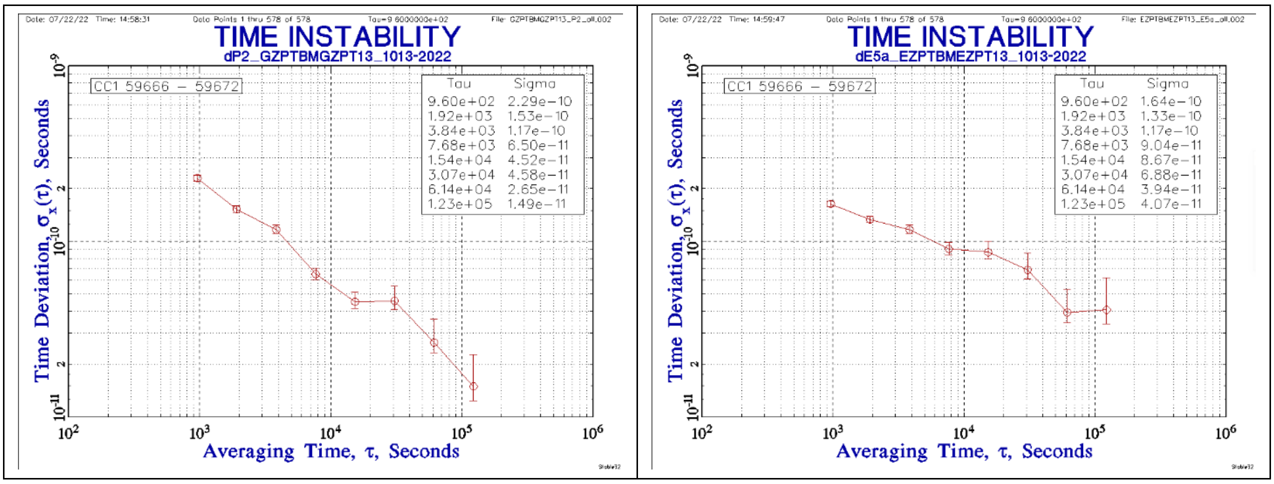

Figure 5-2 TDEV obtained for the two noisier data sets shown in Figure 5-1, GPS dP2 (left), and Galileo dE5a (right).

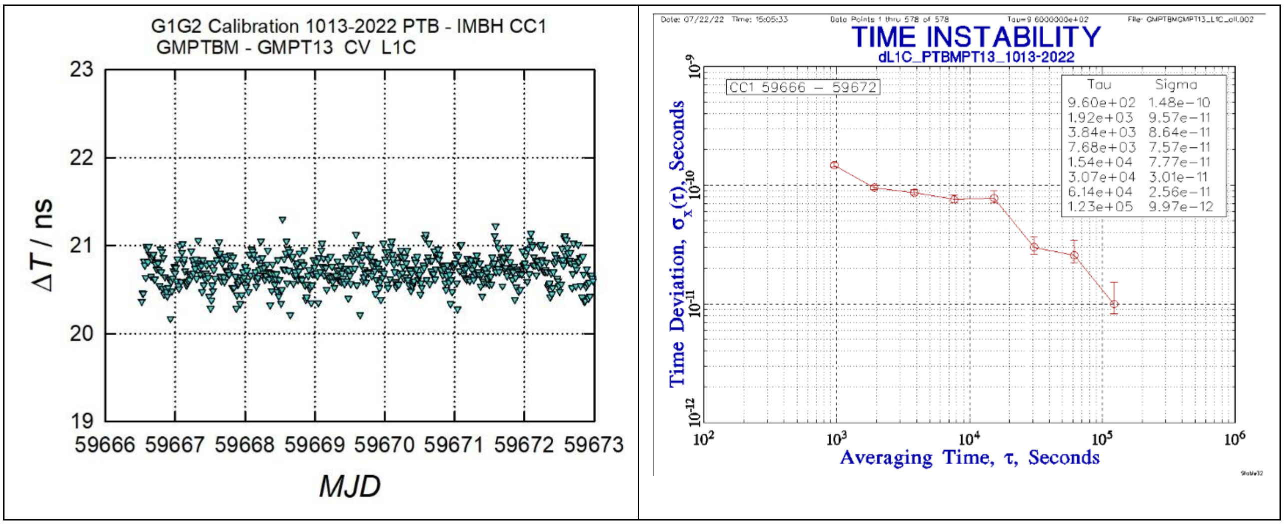

Figure 5-3 PTBM GPS delay (L1C) during CC1 and TDEV for the data set

The period 59666 to 59672 (6.5 days) was chosen to determine the initial PTBM INT DLY values (CC1). The result of comparison with PT13 as the reference are shown in Figure 5-1 illustrating in total 578 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. Inadvertently, no L1C signal delay had been stated in the PTBM parameter file. A large offset in L1C – common view data thus appears in Figure 5-3. This has no impact on the feasibility to provide L1C delays for receivers at IMBH.

6. OPERATION OF PTBM AT IMBH

Shipment of PTBM was delayed due to customs issues. Finally, PTBM was operated from mid-May onwards in IMBH. IMBH operates three GNSS receivers with designation BH01 – BH03 whose delays were determined.

The PPS and 10 MHz signal distribution to receiver PTBM and IMBH receivers is illustrated in Figure 6-1.

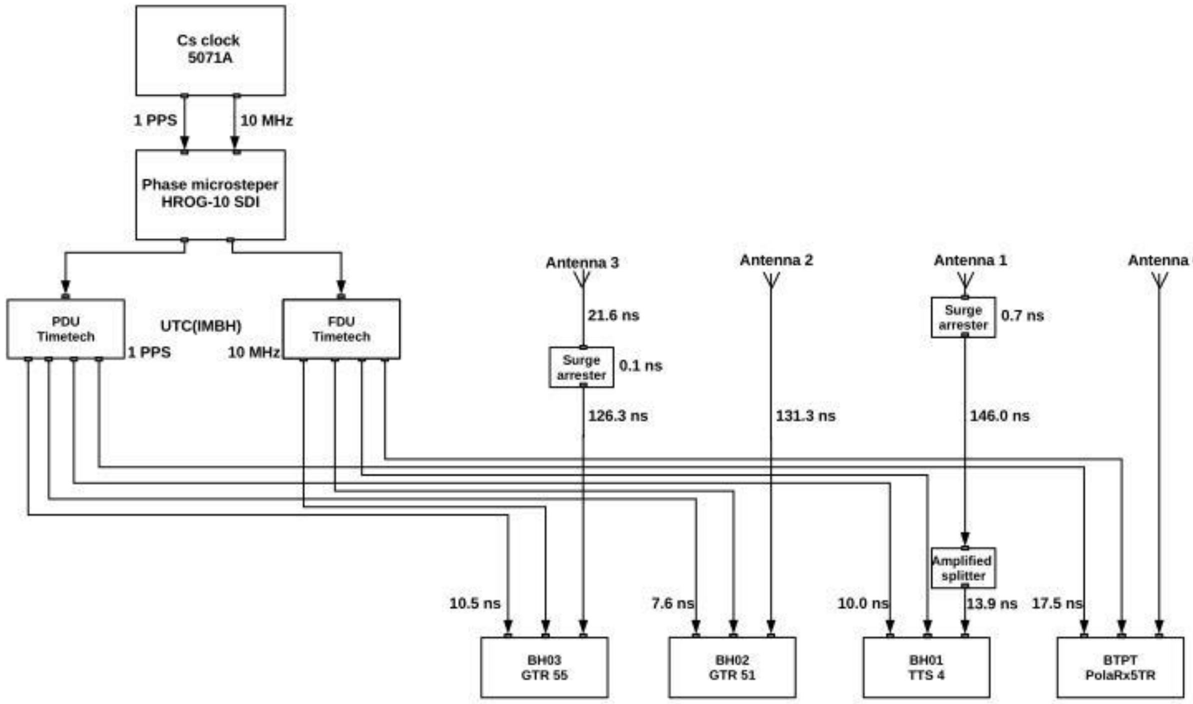

Figure 6-1 PPS and 10 MHz signal distribution at IMBH to the receivers

The antenna installation at IMBH is illustrated in Figure 6-2. PTBM (here designated as BTPT) was operated with its own antenna and antenna cable.

Figure 6-2 Antenna installation on the roof of the IMBH building (PTBM background, middle)

6.1. CALIBRATION OF RECEIVER BH01

The usual method of generating CGGTTS files from RINEX observation and navigation files failed for the GPS part of receiver BH01. It seems that individual 30s-pseudoranges were corrupted that caused the 16min-averages noisy as well. The software dclrinex [RD07] provided by BIPM is apparently able to effectively filter those corrupted data. GPS delay (Table 9-1) could be determined only with this data handling whereas Galileo delays (Table 9-2) could be determined also involving CGGTTS files. The two lines show the agreement achieved.

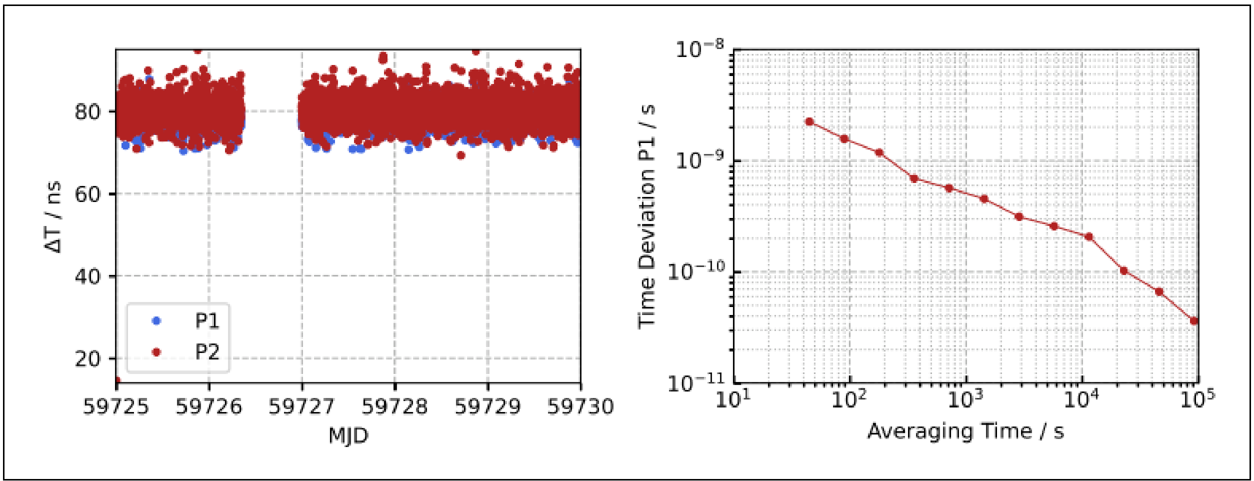

Figure 6-3 Left: Raw differences BH0 – PTBM and instability of the individual differences (P1) as output from the software dclrinex.

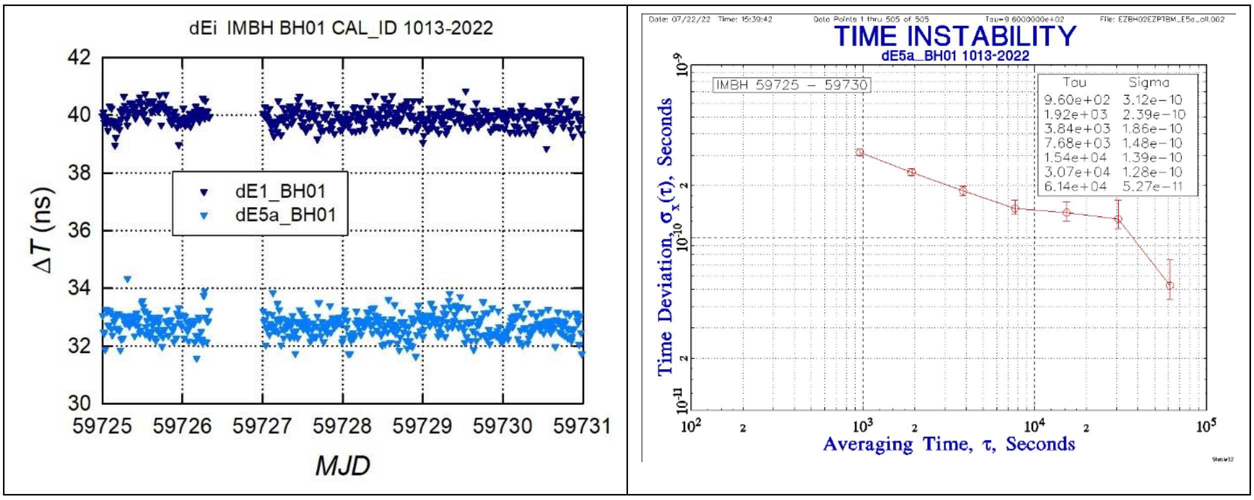

Figure 6-4 Left: Galileo INT DLY in BH01, reference PTBM; left: Galileo dE1 (dark blue) and dE5a (light blue), right: TDEV calculated from the dE5a values shown in the left panel.

In Figure 6-3 the GPS raw differences BH01 – PTBM are shown with a TDEV plot for the P1 differences.**Error! Reference source not found.** Figure 6-4 illustrates the Galileo results which look normal. 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 τ = 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. The latter statements are valid for the three receivers.

6.2. CALIBRATION OF RECEIVER BH02

Figure 6-5 to Figure 6-7 illustrate the results obtained for receiver BH02. In Galileo data some outliers (< 10) were removed from the collected data. The numerical results are collected in Table 6-1. For determination of the L1C delay only 3 days were usable as for the first three days erroneous ionosphere corrections were calculated.

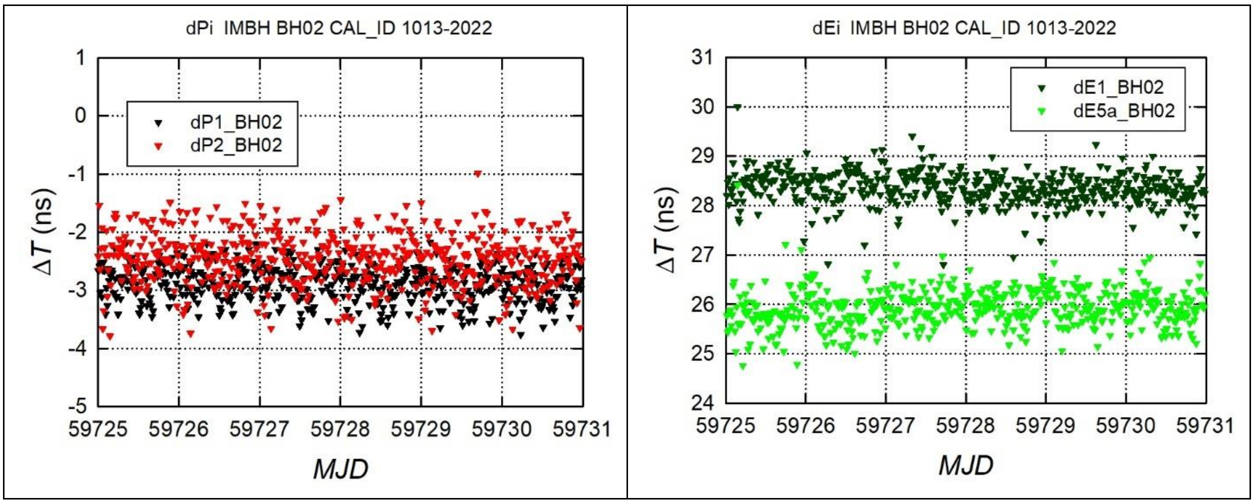

Figure 6-5 Left: Corrections to GPS delay in BH02, ΔP1 (black) and ΔP2 (red)
Right: Galileo delays in BH02, ΔE1 (dark green) and ΔE5a (light green).

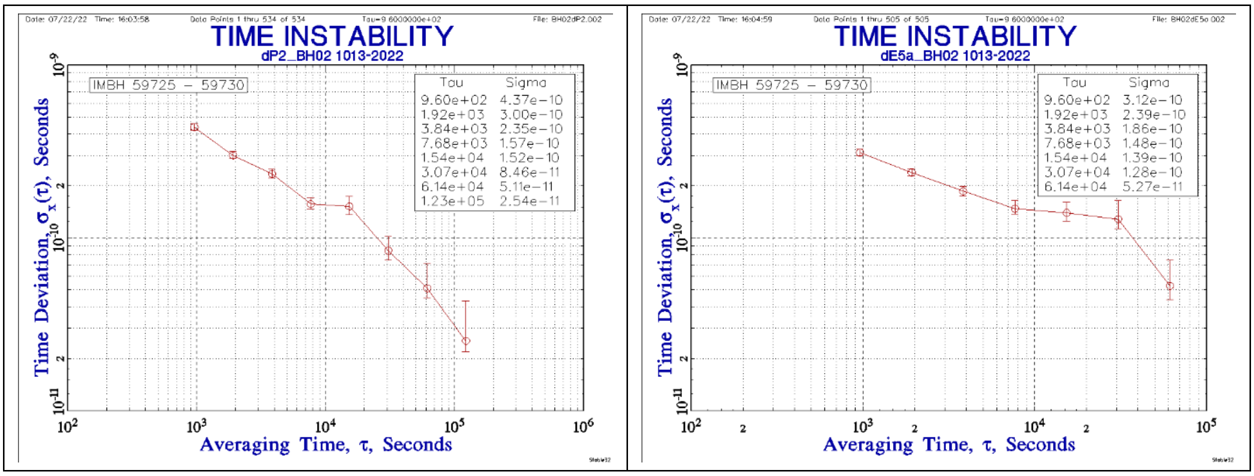

Figure 6-6 TDEV obtained for the two noisier data sets shown in Figure 6-5, GPS dP2 (left), and Galileo E5a (right).

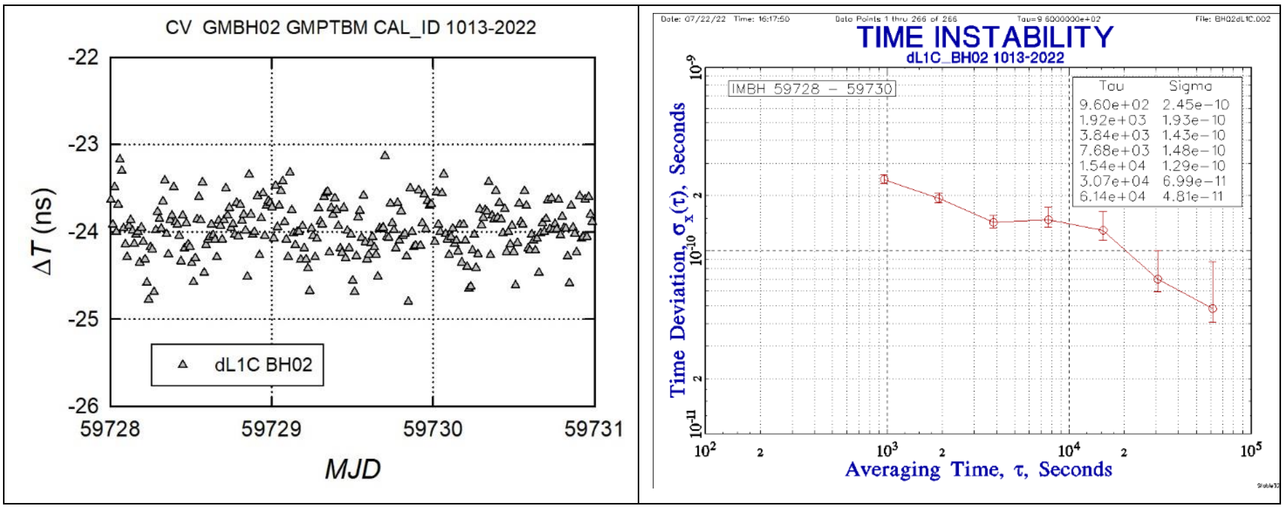

Figure 6-7 Correction to BH02 GPS delay (L1C) and TDEV for the data set

6.3. CALIBRATION OF RECEIVER BH03

Figure 6-8 to Figure 6-10 illustrate the results obtained for receiver BH03. In Galileo data some outliers (< 10) were removed from the collected data. The numerical results are collected in Table 6-1. For determination of the L1C delay only 3 days were usable as for the first three days erroneous ionosphere corrections were calculated.

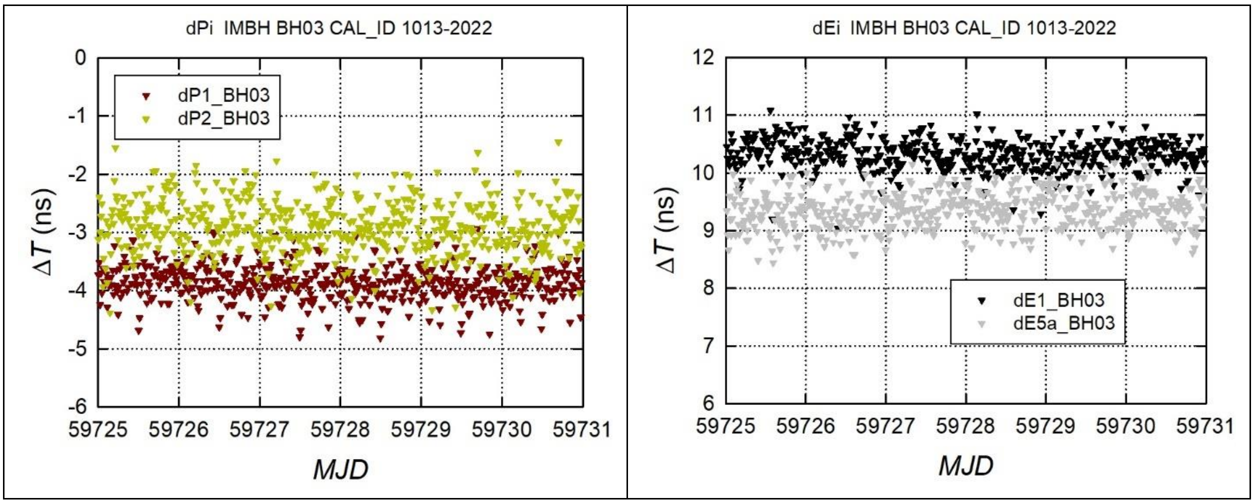

Figure 6-8 Left: Corrections to GPS delay in BH03, ΔP1 (brown) and ΔP2 (olive)
Right: Galileo delays in BH02, ΔE1 (black) and ΔE5a (grey).

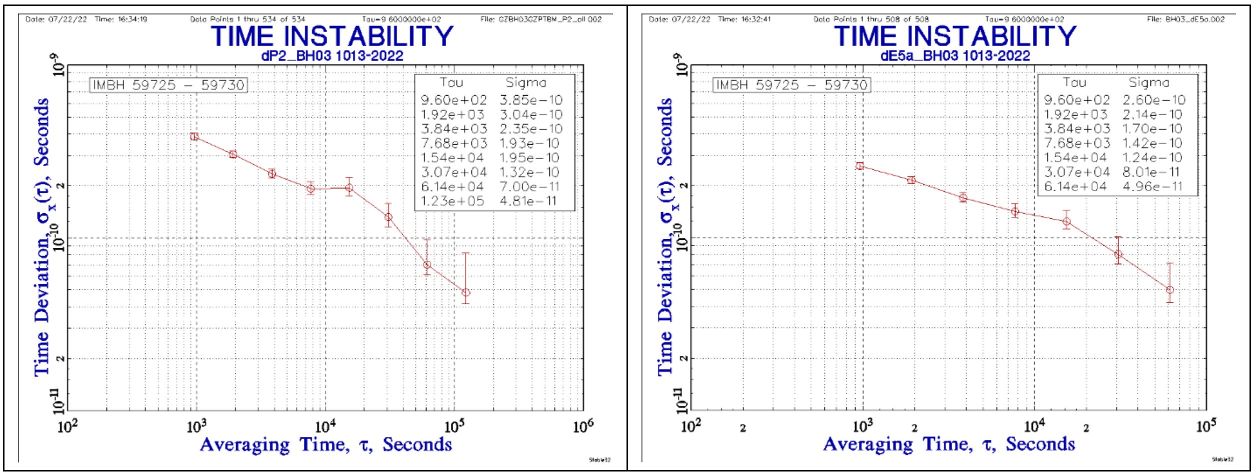

Figure 6-9 TDEV obtained for the two noisier data sets shown in Figure 6-8, GPS dP2 (left), and Galileo E5a (right).

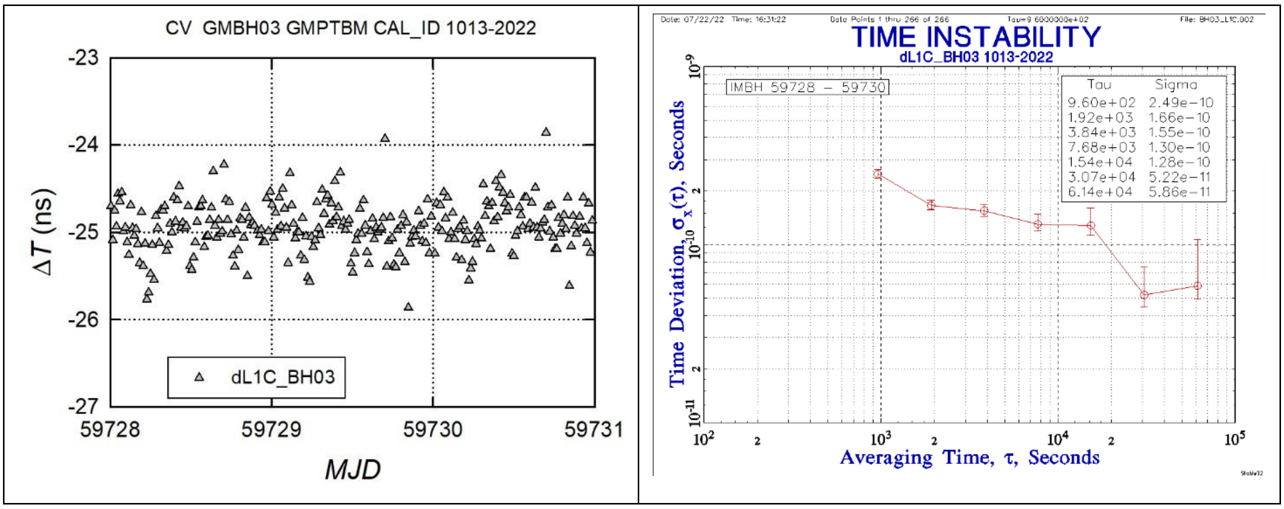

Figure 6-10 Correction to BH03 GPS delay (L1C) and TDEV for the data set

6.4. SUMMARY OF RESULTS OBTAINED AT IMBH

Table 6-1 ∆INT DLY(fi) values for the IMBH receivers and statistical properties obtained initially.

Receiver and signal	Delay / delta delay (ns)	Delay / delta delay(ns)	Sigma (ns)	TDEV (ns)	N
	Mean	Median			
BH01_dE1	39.94	39.93	0.31	0.15	475
BH01_dE5a	32.72	32.73	0.39	0.15	475
BH02_L1C	-23.97	-23.97	0.29	0.15	266
BH02_P1	-2.88	-2.85	0.31	0.10	534
BH02_P2	-2.45	-2.43	0.45	0.10	534
BH02_E1	28.36	28.37	0.35	0.15	502
BH02_E5a	25.93	25.93	0.38	0.15	502
BH03_L1C	-24.93	-24.94	0.29	0.15	266
BH03_P1	-3.87	-3.87	0.30	0.10	534
BH03_P2	-2.91	-2.91	0.46	0.10	534
BH03_E1	10.32	10.33	0.27	0.10	507
BH03_E5a	9.35	9.35	0.32	0.10	507

7. OPERATION AT PTB: SECOND PERIOD

The period 59776 to 59781 (6 days) was chosen to determine PTBM INT DLY values during the common clock period CC2. The configuration of PTBM was "standard", the automatic PPS IN delay compensation was activated. The results of comparison with PT13 as the reference are shown in Figure 7-1, illustrating 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.

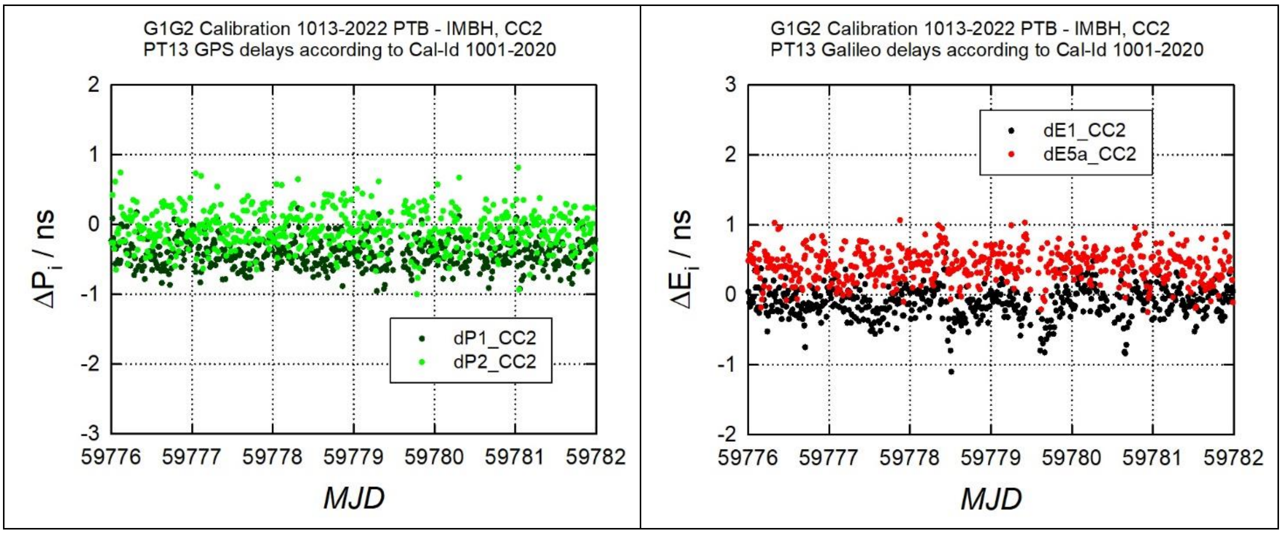

Figure 7-1 Corrections to GPS delay in PTBM during CC2, ΔP1 (dark green) and ΔP2 (light green) Right: Corrections to Galileo delays in PTBM during CC2, ΔE1 (black) and ΔE5a (red).

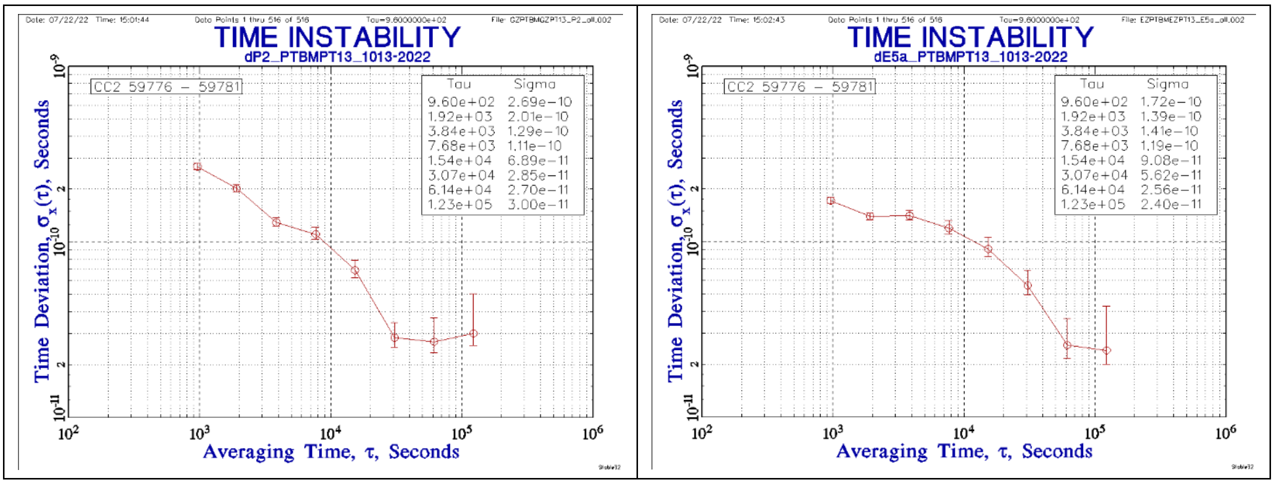

Figure 7-2 TDEV obtained for the data sets GPS dP2 (left) and Galileo dE5a (right) from Figure 7-1

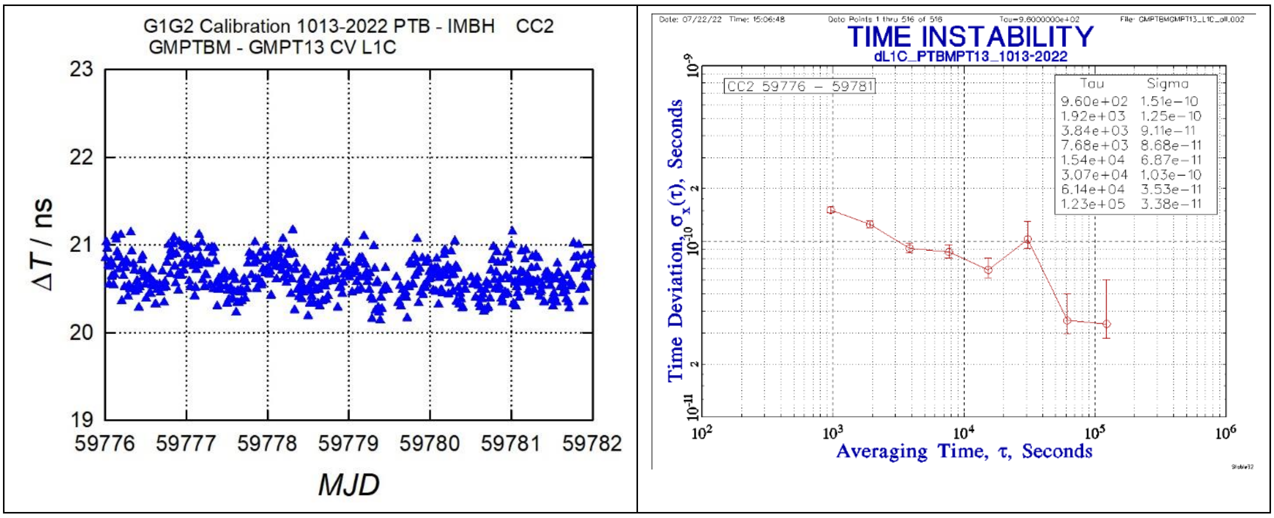

Figure 7-3 PTBM GPS delay (L1C) during CC2 and TDEV for the data set

7.1. SUMMARY OF CAMPAIGNS CC1 AND CC2

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 0.46 ns for ΔE5a. The value obtained in the current CC2 is very close to the value at CC1 of the preceding campaign, 1021-2021, so after a step down followed a step up again. There is no explanation. 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 CC1 and CC2 at PTB

Quantity	Median (ns)	Sigma (ns)	TDEV (ns)
ΔP1 (CC1)	-0.45	0.19	0.1
ΔP2 (CC1)	-0.10	0.23	0.1
ΔP3 (CC1)	-0.99		
ΔC1 (CC1)	20.72	0.17	0.1
ΔE1 (CC1)	-0.04	0.18	0.1
ΔE5a (CC1)	-0.04	0.21	0.1
ΔE3 (CC1)	-0.04		
ΔP1 (CC2)	-0.42	0.21	0.1
ΔP2 (CC2)	-0.09	0.27	0.1
ΔP3 (CC2)	-0.93		
ΔC1 (CC2)	20.62	0.20	0.1
ΔE1 (CC2)	-0.10	0.22	0.1
ΔE5a (CC2)	0.42	0.23	0.1

ΔE3 (CC2)	-0.76		
Mean values used for evaluation of visited receivers' internal delays			
ΔP1	-0.43		
ΔP2	-0.09		
ΔC1	20.67		
ΔE1	-0.07		
ΔE5a	0.19		

8. INT DLY UNCERTAINTY EVALUATION

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

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

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

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

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

Values in column P3 are calculated according to $u(P3) = \sqrt{\{u(P1)^2 + (1.54 \times u(P1\text{-}P2))^2\}}$. Uncertainties for the Galileo delays are calculated according to $\sqrt{\{u(E1)^2 + (1.26 \times u(E1\text{-}E5a))^2\}}$. Both rules do not apply for lines 3a and 3b in Table 8-1 and as stated in the text.

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 at IMBH

	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(IMBH)	0.15	0.15	0.21	0.36	CC measurement uncertainty, for the IMBH receivers
Result of closure measurement at PTB						
3a	$u_{b,1}$ (GPS)	0.1	0.1		0.10	Misclosure, see Table 7-1
3b	$u_{b,1}$ (Galileo)	0.1	0.46		0.76	Misclosure, see Table 7-1
Systematic components due to antenna installation						
4	$u_{b,11}$	0.1	0.1	0.14	0.23	Position error at PTB
5a	$u_{b,12}$(IMBH)	0.1	0.1	0.14	0.23	Position error at IMBH
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 IMBH
Installation of PTBM and visited receivers						
8	$u_{b,21}$	0.2	0.2	0	0.2	Connection of PTBM to UTC(PTB) (REF DLY)
9	$u_{b,22}$	0.5	0.5	0	0.5	Connection of PTBM to UTC(IMBH) (REF DLY)
10	$u_{b,23}$	0.5	0.5	0	0.5	Connection of receivers at IMBH to UTC(IMBH) (REF DEL)
Antenna cable delay						
11	$u_{b,31}$(PTB)	0.5	0.5	0	0.5	Uncertainty estimate for the PTBM CAB DLY when installed at PTB
12	$u_{b,32}$(IMBH)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBM CAB DLY when installed at IMBH
13	$u_{b,33}$(IMBH)	0.5	0.5	0	0.5	Uncertainty estimate for IMBH CAB DLY values

The uncertainty contribution $u_{b,1}$ is based on the difference between the two common clock campaigns involved which was very small for the current campaign, except for the E5a signals. Such step in the opposite direction had been observed during the previous campaign. The value for the linear combination (P3 or E3, respectively) is chosen as the direct difference between CC1 and CC2 (Table 7-1).

At PTB, the PPS IN Delay Compensation has been initiated several times, with the PTBM receiver connected to different 10 MHz cables in sequence. Results reported agreed within 0.1 ns. Thus, when the receiver is operated in the same modus at each site the achievable uncertainty is likely the lowest. This was the case during the current campaign.

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 0.5 ns for all cases.

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 at each occasion. CAB DLY values were measured at PTB in previous campaigns, with the cable rolled out and 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 if 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 IMBH 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_1013_2022 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 [RD06], 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.
The uncertainty values in the lines BH01_dclrinex were set identical to those for the other receivers without detailed proof.

Table 9-1 Results of the Calibration Campaign G1G2_1013_2022: GPS delays, all values in ns

I	INT DLY(P1) old	INT DLY(P2) old	INT DLY (C1) old	ΔP1 (V,T)	ΔP2 (V,T)	ΔC1 (V,T)	ΔP1 (T,G)	Δ(P2) (T,G)	Δ(C1) (T,G)	INT DLY (C1) new	INT DLY (P1) new	u_{cal}, P1	INT DLY(P2), new	u_{cal}, P2	u_{cal}, L3P
IMBH receivers															
BH01	53.4	49.1	54.9												
BH01 dclrinex	53.4	49.1	54.9	0.32	0.57	-20.73	-0.43	-0.09	20.67	54.84	53.29	1.09	49.58	1.09	1.26
BH02	30.2	29.8	30.2	-2.85	-2.43	-23.97	-0.43	-0.09	20.67	26.90	26.92	1.09	27.28	1.09	1.26
BH03	13.9	11.2	14.6	-3.87	-2.91	-24.94	-0.43	-0.09	20.67	10.33	9.6	1.09	8.2	1.09	1.26

Table 9-2 Results of the Calibration Campaign G1G2_1013_2022: 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(E1) new	u_{cal}, E1	INT DLY(E5a) new	u_{cal}, E5a	u_{cal}, L3E
IMBH receivers											
BH01	0.0	0.0	39.93	32.73	-0.07	0.19	39.86	1.09	32.92	1.18	1.44
BH01 dclrinex	0.0	0.0	40.2	32.9	-0.07	0.19	40.13	1.09	33.09	1.18	1.44
BH02	0.0	0.0	28.37	25.93	-0.07	0.19	28.66	1.09	26.12	1.18	1.44
BH03	0.0	0.0	10.33	9.35	-0.07	0.19	10.23	1.09	9.54	1.18	1.44

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2022-03-08 12:00 UTC (MJD 59666)
Date and hour of the end of measurements:	2022-04-03 24:00 UTC (MJD 59672)

Information on the system		
	Local:	**Traveling:**
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 stabilized) /°C		

Measured delays /ns		
	Local:	**Traveling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	9.59 ± 0.1 (#)	48.5 +/- 0.2
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	46.63 ± 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:		Traveling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	31.6 (P1), 29.3 (P2), 33.6 (C1) (*)		18.9 (P1) 17.1 (P2) (****) 0.0 (C1)	
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	33.6 (E1), 33.6 (E5a) (*)		20.8 (E1), 17.9 (E5a) (****)	
☐ CAB DLY (or X_C) /ns:	205.7		264.9	
☐ REF DLY (or X_P+X_O) /ns:	56.2		48.5	
☐ Coordinates reference frame:	ITRF		ITRF	
X /m:	+3844059.86 (***)	Mast P10	+3844062.56 ($)	Mast P7
Y /m:	+709661.56 (***)		+709658.49 ($)	
Z /m	+5023129.87 (***)		+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, peak-to-peak variations 0.5° C

Notes valid for CC1 – CC2:

(#) Local measurements repeated on occasion of campaign 1001-2020.

($) Coordinates of mast P7 (APC) were determined on 26.05.2020 using NRCan PPP

(*) values based on G1 calib 1001-2020 [RD01]]

(***) 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 IMBH: Receiver BH01

Laboratory:	**IMBH**	
Date and hour of the beginning of measurements:	2022-05–17 00:00:00 UTC (59716)	
Date and hour of the end of measurements:	2022-05-22 24:00:00 UTC (59721)	
Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**BH01**	**PTBM**
Receiver maker and type: Receiver serial number:	PIKTIME TTS-4 SN:0142, HW:133.55, SW:3.3j	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:	1.0	1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	Andrew Heliax FSJ1-50A - 1/4" N	N-type, LMR400
Length outside the building /m:	cca 20	cca 20
Antenna maker and type: Antenna serial number:	Javad RingAnt-G3T S/N: 00455	Navexperience 3G+C reference S/N RE 0560
Temperature (if stabilised) /°C	46.5	49.0
Measured delays /ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	10.0	17.5
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	0.81 *	N/A
Antenna cable delay: (X_C) / ns	146.0	264.9
Splitter delay (if any):	0.7 **	N/A
Additional cable delay (if any):	13.9 ***	N/A
Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	54.90(C1) 53.40(P1) 49.10(P2)	18.9 (P1) 17.1 (P2) 0.0 (C1)
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	0.0 (E1), 0.0 (E5a)	20.8 (E1), 17.9 (E5a)
☐ CAB DLY (or X_C) /ns:	160.6	264.9
☐ REF DLY (or X_P+X_O) /ns:	10.8	17.5
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	4370829.79	4370829.27
Y /m:	1455778.47	1455779.89
Z /m	4397117.61	4397117.85
General information		
☐ Rise time of the local UTC pulse:	1 ns	
☐ Is the laboratory air conditioned:	Yes	

Set temperature value and uncertainty:	23 °C ± 1°C

*	REF DLY = 10.81 ns (1PPS DLY: 10.00 ns, phase corr: 0.81 ns, fw corr: 0.00 ns)

**	Surge arrester with connector adapters

***	After GNSS board power supply failure, external antenna power supply is installed. Its internal delay not measured, only additional cable delay

All coordinates (APC) for all 4 receivers controlled or determined before the start of data taking.

All files generated based on RINEX obs and R2CGGTTS V8.3

Traveling receiver GZPTBMMJ.DDD, GMPTBMMJ.DDD, EZPTBMMJ.DDD,
DUT: GZBH01MJ.DDD, GMBH01MJ.DDD, EZBH01MJ.DDD.

PTBM operation at IMBH: Receiver BH02

Laboratory:	**IMBH**
Date and hour of the beginning of measurements:	2022-05–17 00:00:00 UTC (59716)
Date and hour of the end of measurements:	2022-05-22 24:00:00 UTC (59721)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**BH02**	**PTBM**
Receiver maker and type: Receiver serial number:	Mesit, GTR 51 SN: 1808032	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:	1.0	1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	Belden, low loss, H155 PVC N	N-type, LMR400
Length outside the building /m:	cca 15	cca 20
Antenna maker and type: Antenna serial number:	Novatel NOV850 S/N: NMLK18070098S	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	7.6	17.5
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	N/A	N/A
Antenna cable delay: (X_C) / ns	131.3	264.9
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:	30.20(P1), 29.80(P2) 30.20(C1)	18.9 (P1) 17.1 (P2) 0.0 (C1)
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	0.0 (E1) 0.0 (E5a)	20.8 (E1), 17.9 (E5a)
☐ CAB DLY (or X_C) /ns:	131.3	264.9
☐ REF DLY (or X_P+X_O) /ns:	7.6	17.5
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	4370827.89	4370829.27
Y /m:	1455780.70	1455779.89
Z /m	4397118.83	4397117.85

General information	
☐ Rise time of the local UTC pulse:	1 ns
☐ Is the laboratory air conditioned:	Yes

Set temperature value and uncertainty:	23 °C ± 1°C

All files generated based on RINEX obs and R2CGGTTS V8.3

Traveling receiver GZPTBMMJ.DDD, GMPTBMMJ.DDD, EZPTBMMJ.DDD,
DUT: GZBH02MJ.DDD, GMBH02MJ.DDD, EZBH02MJ.DDD.

PTBM operation at IMBH: Receiver BH03

Laboratory:	**IMBH**
Date and hour of the beginning of measurements:	2022-05–17 00:00:00 UTC (59716)
Date and hour of the end of measurements:	2022-05-22 24:00:00 UTC (59721)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**BH03**	**PTBM**
Receiver maker and type: Receiver serial number:	Mesit, GTR 55 SN: 2010004	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:	1.0	1.0
Antenna cable maker and type: Phase stabilised cable (Y/N):	Belden 9104 N	N-type, LMR400
Length outside the building /m:	cca 10	cca 20
Antenna maker and type: Antenna serial number:	Novatel NOV850 S/N: NMLK20250004R	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	10.5	17.5
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	N/A	N/A
Antenna cable delay: (X_C) / ns	126.3	264.9
Splitter delay (if any):	0.1 *	N/A
Additional cable delay (if any):	21.6	N/A

Data used for the generation of CGGTTS files		
	LOCAL:	Travelling
☐ INT DLY (or X_R+X_S) (GPS) /ns:	14.6 (C1), 13.9 (P1), 11.5 (P2)	18.9 (P1) 17.1 (P2) 0.0 (C1)
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	0.0 (E1) 0.0 (E5a)	20.8 (E1), 17.9 (E5a)
☐ CAB DLY (or X_C) /ns:	148.0	264.9
☐ REF DLY (or X_P+X_O) /ns:	10.5	17.5
☐ Coordinates reference frame:	ITRF	ITRF
X /m:	4370828.53	4370829.27
Y /m:	1455781.02	1455779.89
Z /m	4397118.08	4397117.85

General information	
☐ Rise time of the local UTC pulse:	1 ns
☐ Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	23 °C ± 1°C

All files generated based on RINEX obs and R2CGGTTS V8.3

Traveling receiver GZPTBMMJ.DDD, GMPTBMMJ.DDD, EZPTBMMJ.DDD,
DUT: GZBH03MJ.DDD, GMBH03MJ.DDD, EZBH03MJ.DDD.

Second common clock measurement at PTB

Laboratory:	**PTB**			
Date and hour of the beginning of	2022-07-15 00:00 UTC (MJD 59776)			
Date and hour of the end of measurements:	2022-07-21 24:00 UTC (MJD 59781)			
Information on the system				
	Local:		**Traveling:**	
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:		**Traveling:**	
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	9.59 ± 0.1 (#)		43.2	
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	46.63 ± 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:		Traveling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	31.6 (P1), 29.3 (P2), 33.6 (C1)(*) 33.6 (E1), 33.6 (E5a) (*)		18.9 (P1) 17.1 (P2) (****) 0.0 (C1) 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		43.2 (%%)	
☐ Coordinates reference frame:	ITRF (***)		ITRF (****)	
X /m:	+3844059.86 (***)	Mast P10	+3844062.56 ($)	Mast P7
Y /m:	+709661.56 (***)		+709659.49 ($)	
Z /m	+5023129.87 (***)		+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, peak-to-peak variations 0.6° C

Notes valid for CC1 – CC2:

(%%) operation during CC2 with auto delay compensation off.

(#) Local measurements repeated on occasion of campaign 1001-2020.

($) Coordinates of mast P7 (APC) were determined on 26.05.2020 using NRCan PPP

(*) values based on G1 calib 1001-2020 [RD01]]

(***) 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, GMPTBMMJ.DDD, EZPTBMMJ.DDD

Reference receiver GZPT13MJ.DDD, GMPT13MJ.DDD, EZPT13MJ.DDD

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