

# GNSS CALIBRATION REPORT

## G1G2\_1021-2021

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## TABLE OF CONTENTS

LIST OF TABLES AND FIGURES.....	3
REFERENCES.....	4
ACRONYMS.....	5
EXECUTIVE SUMMARY.....	6
1. CONTENTS OF THE REPORT.....	7
1.1. CHANGE LOG.....	7
2. PARTICIPANTS AND SCHEDULE.....	8
3. CALIBRATION PROCEDURE.....	9
3.1. GENERAL DESCRIPTION.....	9
4. CHARACTERIZATION OF PTB EQUIPMENT.....	13
5. RESULTS OF COMMON-CLOCK SET-UP IN PTB: PERIOD 1.....	16
6. OPERATION OF PTBM AT MBM.....	18
6.1. CALIBRATION OF RECEIVER ME01.....	19
6.2. SUMMARY OF RESULTS OBTAINED AT MBM.....	21
7. OPERATION AT PTB: SECOND PERIOD.....	22
7.1. SUMMARY OF CAMPAIGNS CC1 AND CC2.....	23
8. INT DLY UNCERTAINTY EVALUATION.....	25
9. FINAL RESULTS.....	28
ANNEX: BIPM CALIBRATION INFORMATION SHEETS.....	30

## LIST OF TABLES AND FIGURES

Figure 3-1 PTBM: views of the device and RxControl configuration and messages regarding PPS In and OUT.....	10
Figure 4-1 Common-clock common-view GPS comparison between PTBM and PT13 in a period preceding campaign 1021-2021; thick line: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day. ....	13
Figure 4-2 UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBM, and other receivers; 14	
Figure 4-3 UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, PTBM, and other receivers .....	15
Figure 4-4 Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBM antenna during CC1 and CC2 (orange).....	15
Figure 5-1 Left: Corrections to GPS delay in PTBM during CC1, $\Delta P1$ (brown) and $\Delta P2$ (orange) Right: Corrections to Galileo delays in PTBM during CC1, $\Delta E1$ (black) and $\Delta E5a$ (grey). ....	16
Figure 5-2 TDEV obtained for the two noisier data sets shown in Figure 5-1, GPS dP2 (left), and Galileo dE5a (right).....	16
Figure 5-3 PTBM GPS delay (L1C) during CC1 and TDEV for the data set .....	17
Figure 6-1 PPS and 10 MHz signal distribution at MBM to the receivers.....	18
Figure 6-2 Antenna installation on the roof of the MBM building (PTBM left) .....	19
Figure 6-3 Left: Corrections to GPS INT DLY in ME01, reference PTBM; GPS dP1 (brown) and dP2 (orange), right: TDEV calculated from the dP2 values shown in the left panel. ....	19
Figure 6-4 Left: Galileo INT DLY in ME01, reference PTBM; left: Galileo dE1 (black) and dE5a (red), right: TDEV calculated from the dE5a values shown in the left panel. ....	20
Figure 6-5 GPS L1C delay in ME01, reference PTBM; left: TDEV calculated from the results.....	20
Figure 7-1 Corrections to GPS delay in PTBM during CC2, $\Delta P1$ (dark green) and $\Delta P2$ (light green) Right: Corrections to Galileo delays in PTBM during CC2, $\Delta E1$ (brown) and $\Delta E5a$ (orange). ....	22
Figure 7-2 TDEV obtained for the data sets GPS dP2 (left) and Galileo dE5a (right) from Figure 8-1.....	22
Figure 7-3 PTBM GPS delay (L1C) during CC2 and TDEV for the data set .....	23

## REFERENCES

REFERENCES	
<b>RD01</b>	<b>BIPM report 2021</b>
<b>RD02</b>	<b>BIPM guidelines for GNSS calibration, V3.0, 02/04/2015</b>
<b>RD03</b>	<b>BIPM TM.212 (G. Petit), Nov. 2012</b>
<b>RD04</b>	<b>J. Kouba, P. Heroux, 2002, "Precise Point Positioning Using IGS Orbit and Clock Products," GPS Solutions, Vol 5, No. 2, 12-28</b>
<b>RD05</b>	<b>W. Lewandowski, C. Thomas, 1991, "GPS Time transfers," Proc. IEEE, Vol. 79, No. 7, 991-1000</b>
<b>RD06</b>	<b>P. Defraigne and G. Petit, "CGGTTS-Version 2E: an extended standard for GNSS time transfer", Metrologia 52 (2015) G1</b>

## ACRONYMS

ACRONYMS	
<b>BIPM</b>	<b>Bureau International des Poids et Mesures, Sèvres, France</b>
<b>CGGTTS</b>	<b>CCTF Generic GNSS Time Transfer Standard</b>
<b>ESA</b>	<b>European Space Agency</b>
<b>EURAMET</b>	<b>The European Association of National Metrology Institutes</b>
<b>IGS</b>	<b>International GNSS Service</b>
<b>GNSS</b>	<b>Global Navigation Satellite System</b>
<b>MBM</b>	<b>Zavod za metrologiju, Podgorica, Montenegro</b>
<b>PPP</b>	<b>Precise Point Positioning</b>
<b>PTB</b>	<b>Physikalisch-Technische Bundesanstalt, Braunschweig, Germany</b>
<b>RINEX</b>	<b>Receiver Independent Exchange Format</b>
<b>R2CGGTTS</b>	<b>RINEX-to CGGTTS conversion software, provided by ORB / BIPM</b>
<b>TDEV</b>	<b>Time Deviation</b>
<b>TIC</b>	<b>Time Interval Counter</b>

## 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 MBM, Bureau of Metrology, Podgorica, Montenegro, 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 1021-2021. 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 **Fehler! Verweisquelle konnte nicht gefunden werden.** and Table 9-2 **Fehler! Verweisquelle konnte nicht gefunden werden..** The internal delays of receiver ME01 were determined with an uncertainty around 1 ns for single frequency observations. The uncertainty for time transfer links to PTB evaluated in an ionosphere-free linear combination is between 1.16 ns and 1.25 ns.

As a reminder: All uncertainty values reported in this document are 1- $\sigma$  values.

PTB quality management responsible 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 MBM, Bureau of Metrology, Podgorica, Montenegro, 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 1021-2021. Results provided are the visited receiver's (ME01) 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 (INT DLY (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 MBM. 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	24.11.2021	Version 01, all new
02	24.03.2022	Version 02, including results from MBM
03	06.04.2022	Version 03, including CC2
1.0	15.04.2022	Errors in V.03 removed, some text updated.

## 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
MBM	<b>Alina Musić</b> T: + 382 20 601 360 F: + 382 20 634 652 alina.music@metrologija.gov.me	Zavod za metrologiju Aresenija Boljevica bb, Podgorica, Montenegro

**Table 2-2 Schedule of the campaign**

Date	Institute	Action	Remarks
2021-11-11 until 2021-11-15	PTB	First common-clock comparison between PTBM and PT13	5 days used for determination of delays, MJD 59529 – 59533
2022-02-23 until 2022-03-09	MBM	Operation of PTBM in parallel with local receiver	6 days used for determination of delays. MJD 59642- 59647
2022-03-28 until 2022-04-03	PTB	Operation of PTBM after return	6.5 days used for determination of delays, MJD 59666.52 – 59672

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  $2.54 \times \text{INT DLY}(f1) - 1.54 \times \text{INT DLY}(f2)$  for GPS, and as  $2.26 \times \text{INT DLY}(f1) - 1.26 \times \text{INT DLY}(f2)$  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,

$$\text{REFSYS}(j) = [\text{REFSYS}_{\text{RAW}}(j) - \text{CAB DLY}_F - \text{INT DLY}(f_3) + \text{REF DLY}_F] \quad (1)$$

for reporting results of observation of satellite “j” is valid and reported in column 10 of the standard CGGTTS files. REFSYS<sub>RAW</sub> designates the uncorrected measurement values, INT DLY(f<sub>3</sub>) is calculated as explained before, and the values designated as “Q<sub>F</sub>” 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  $\text{MDIO} \times (f_1/f_2)^2$ . The software in calibration mode thus calculates:

$$\text{REFSYS}_{f_1}(j) = \text{REFSYS}(j) + \text{MDIO}(j) \quad (2a)$$

$$\text{REFSYS}_{f_2}(j) = \text{REFSYS}(j) + (f_1/f_2)^2 \times \text{MDIO}(j), \quad (2b)$$

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

$$\Delta \text{IDi}(T,G) := \text{REFSYS}_{f_i}(T) - \text{REFSYS}_{f_i}(G) \quad (3)$$

are calculated and represent the difference  $\text{delay}(\text{new}) - \text{delay}(\text{old})$  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  $\Delta \text{IDi}$  for  $f_1$  and  $f_2$ , and the number of data points used. In addition, a file that contains observation epoch (MJD.frakt) and the average  $\Delta \text{IDi}$  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:

$$\text{Step 1: INT DLY}(f_i)\_T\_corr = \Delta \text{IDi}(T,G) + \text{INT DLY}(f_i)\_T\_old, \quad (4)$$

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

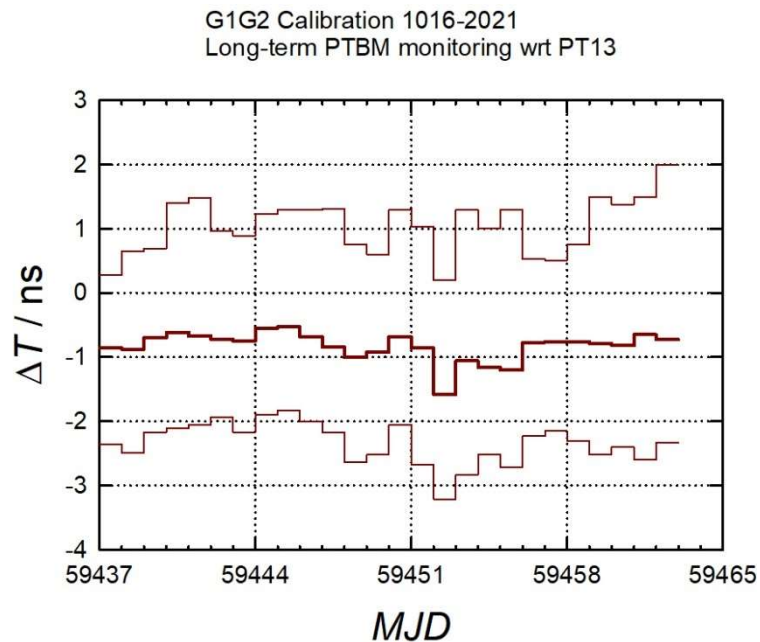
$$\text{INT DLY}(fi)_{V\_new} = \Delta\text{IDi}(V,T) + \langle \Delta\text{IDi}(T,G) \rangle + \text{INT DLY}(fi)_{V\_old}, \quad (5)$$

where  $\langle \Delta\text{IDi}(T,G) \rangle$  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.

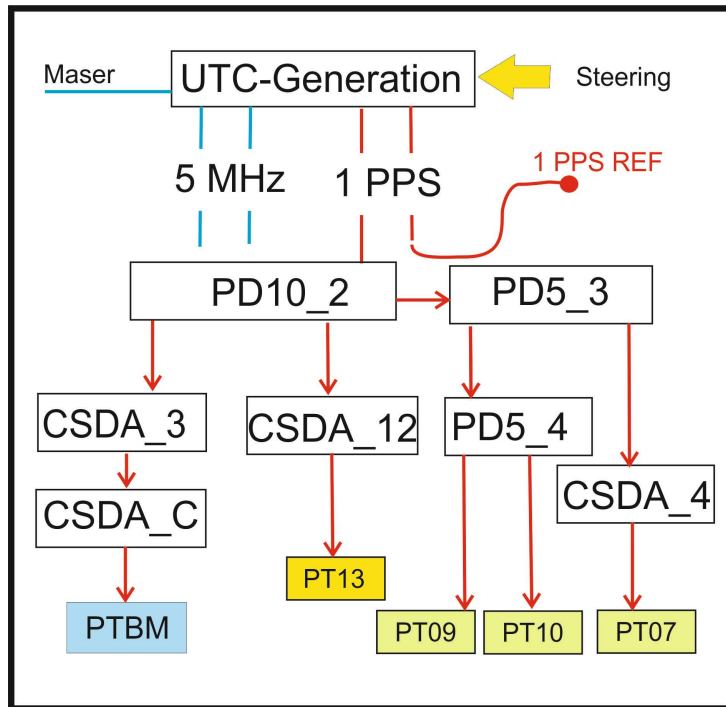
## 4. CHARACTERIZATION OF PTB EQUIPMENT

The closure of the preceding campaign 1016-2021 consisted of some 10 days of operation of PTBM before going on travel again to MBM. CC2 of the previous campaign serves as CC1 of the current one. In the following, we document in Figure 4-1 the stability of PTBM PT13 in comparison with PT13 from an earlier period – before campaign 1016-2021 - as an example of typical behaviour of the two receivers.



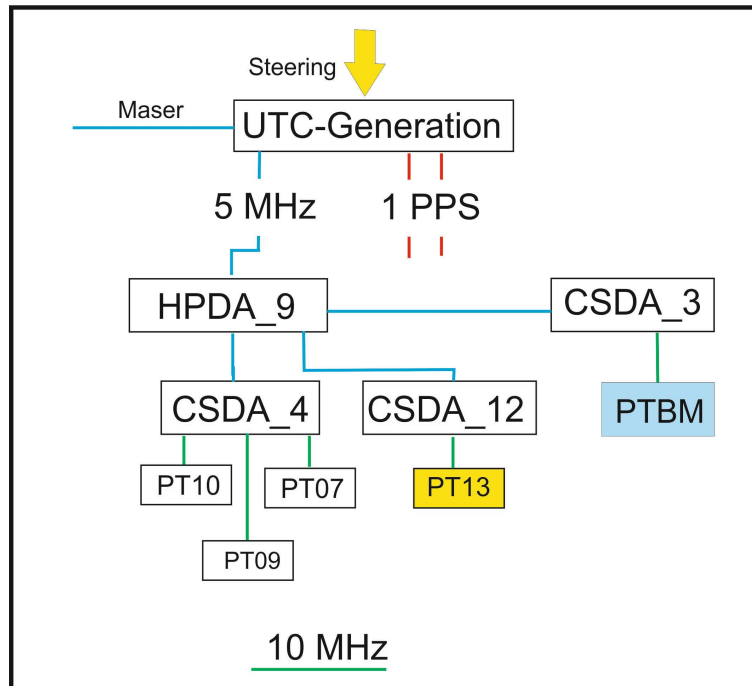
**Figure 4-1 Common-clock common-view GPS comparison between PTBM and PT13 in a period preceding campaign 1016-2021; thick line: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day.**

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.

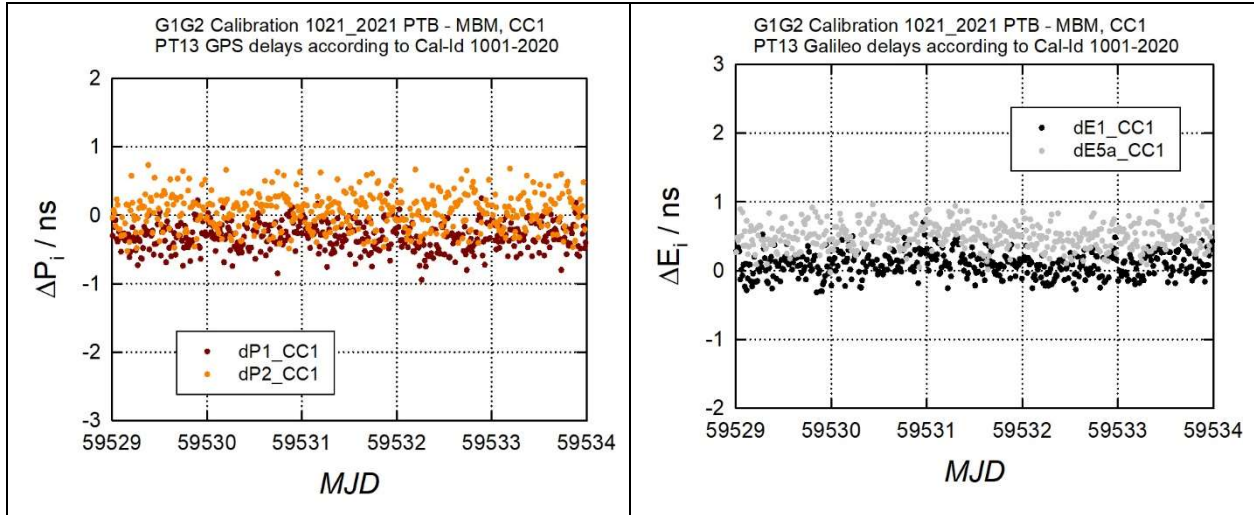


**Figure 4-3 UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, PTBM, and other receivers  
 HPDA stands for High-precision distribution amplifier (for rf frequencies)**

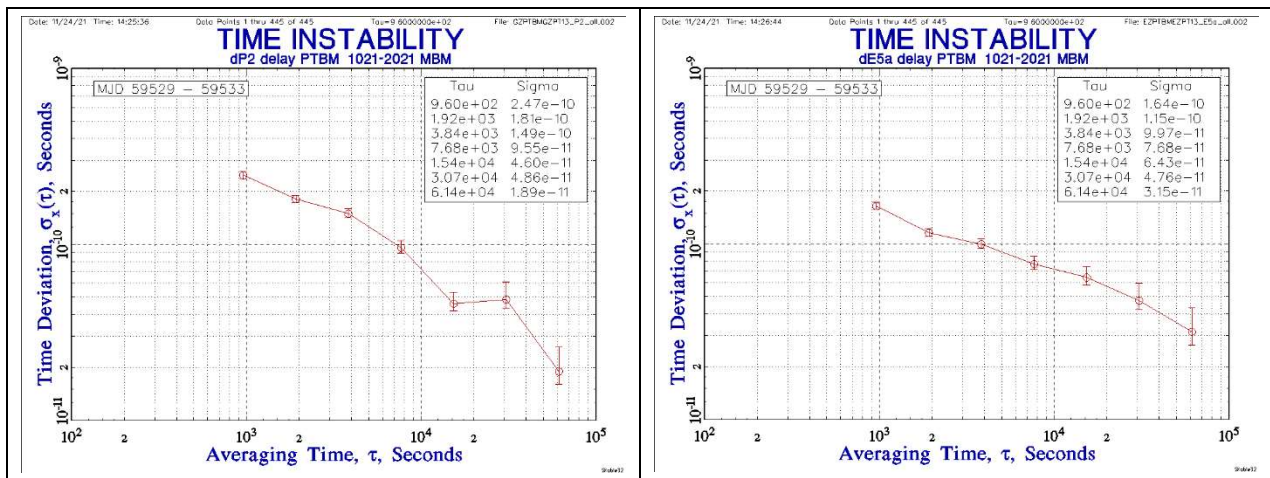


**Figure 4-4 Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBM antenna during CC1 and CC2 (orange)**

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

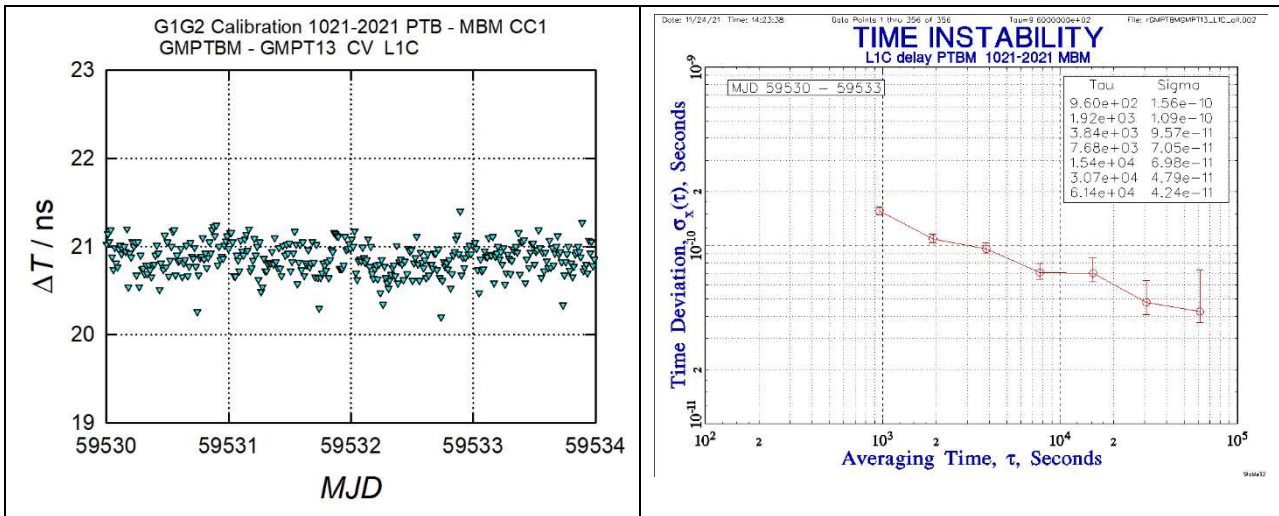


**Figure 5-1 Left: Corrections to GPS delay in PTBM during CC1,  $\Delta P_1$  (brown) and  $\Delta P_2$  (orange) Right: Corrections to Galileo delays in PTBM during CC1,  $\Delta E_1$  (black) and  $\Delta E_{5a}$  (grey).**



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





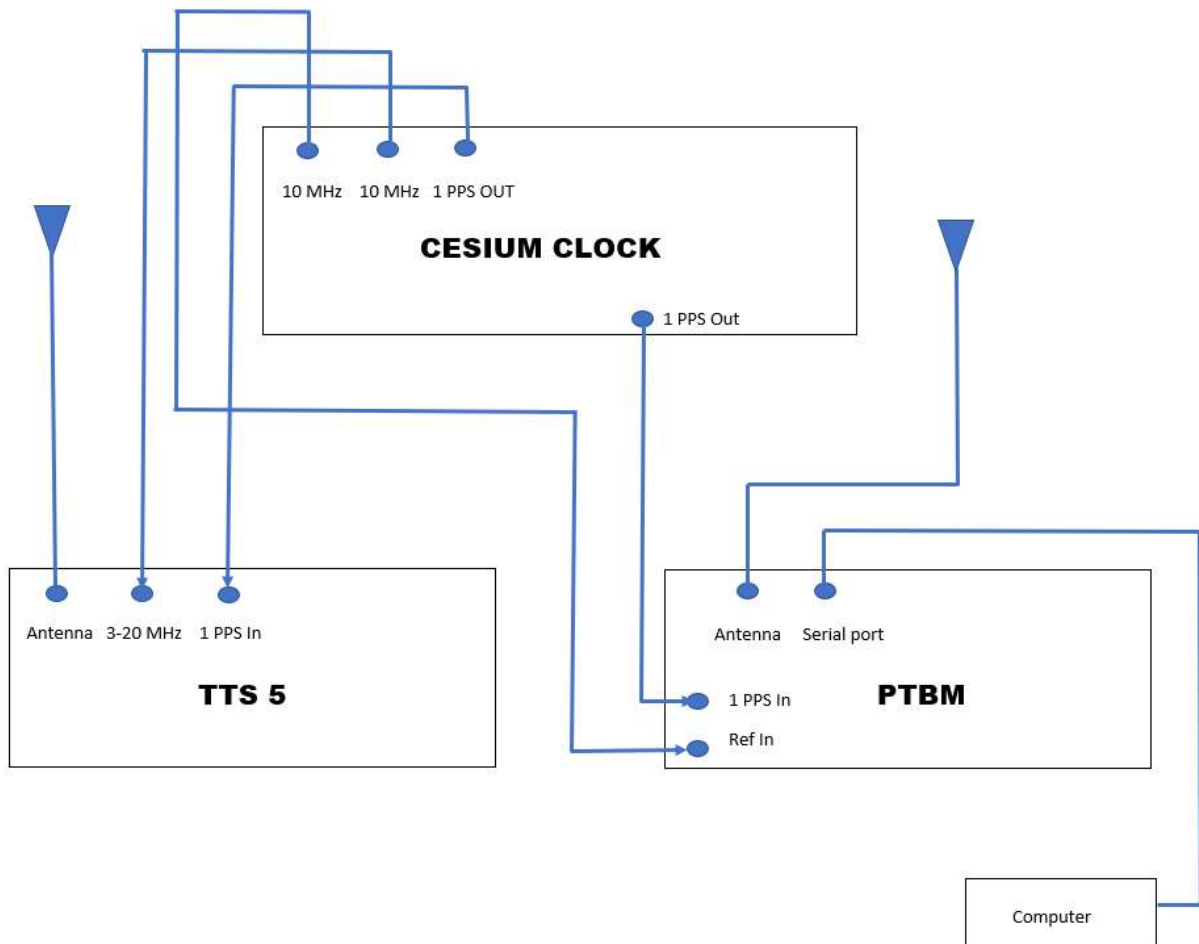
**Figure 5-3 PTBM GPS delay (L1C) during CC1 and TDEV for the data set**

The period 59529 to 59533 (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 445 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 MBM. Due to apparently erroneous correction of the L1C ionospheric delay on day 59529 in PT13, the comparison stretches over 4 days only.

## 6. OPERATION OF PTBM AT MBM

Shipment of PTBM was delayed due to customs issues and the Christmas vacation period. Finally, PTBM was operated from mid-February onwards in MBM. MBM operates a PIKTIME TTS-5 with designation ME01 whose delays were determined.

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



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

The antenna installation at MBM is illustrated in Figure 6-2. PTBM was operated with its own antenna and antenna cable.



Figure 6-2 Antenna installation on the roof of the MBM building (PTBM left)

### 6.1. CALIBRATION OF RECEIVER ME01

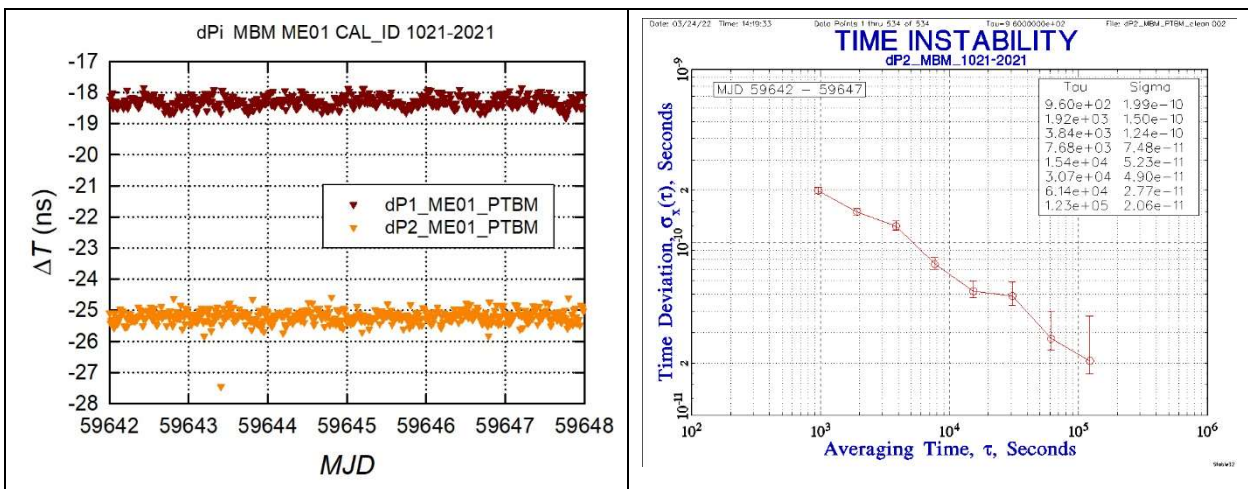


Figure 6-3 Left: Corrections to GPS INT DLY in ME01, reference PTBM; GPS dP1 (brown) and dP2 (orange), right: TDEV calculated from the dP2 values shown in the left panel.

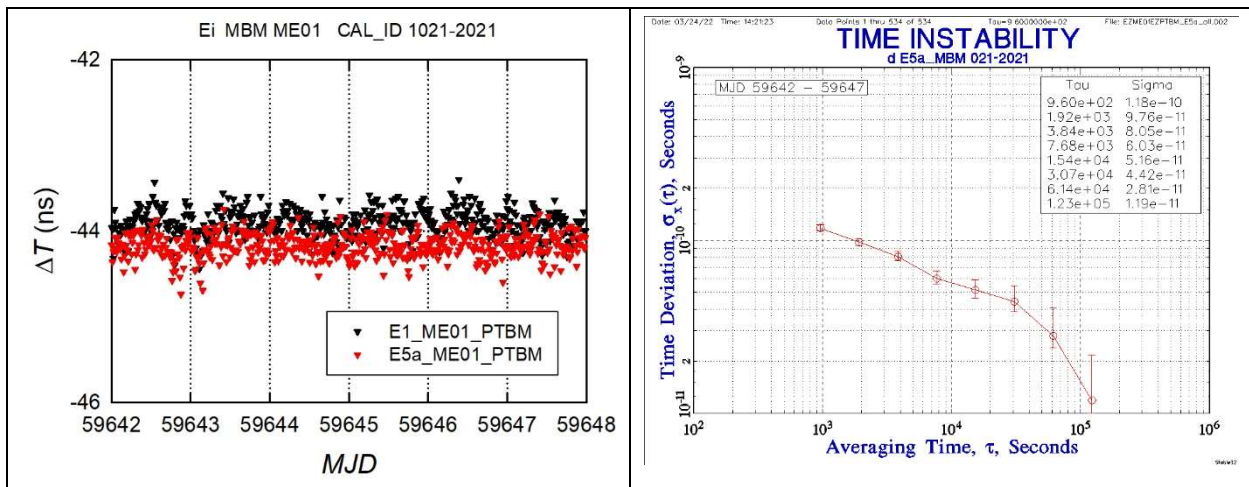


Figure 6-4 Left: Galileo INT DLY in ME01, reference PTBM; left: Galileo dE1 (black) and dE5a (red), right: TDEV calculated from the dE5a values shown in the left panel.

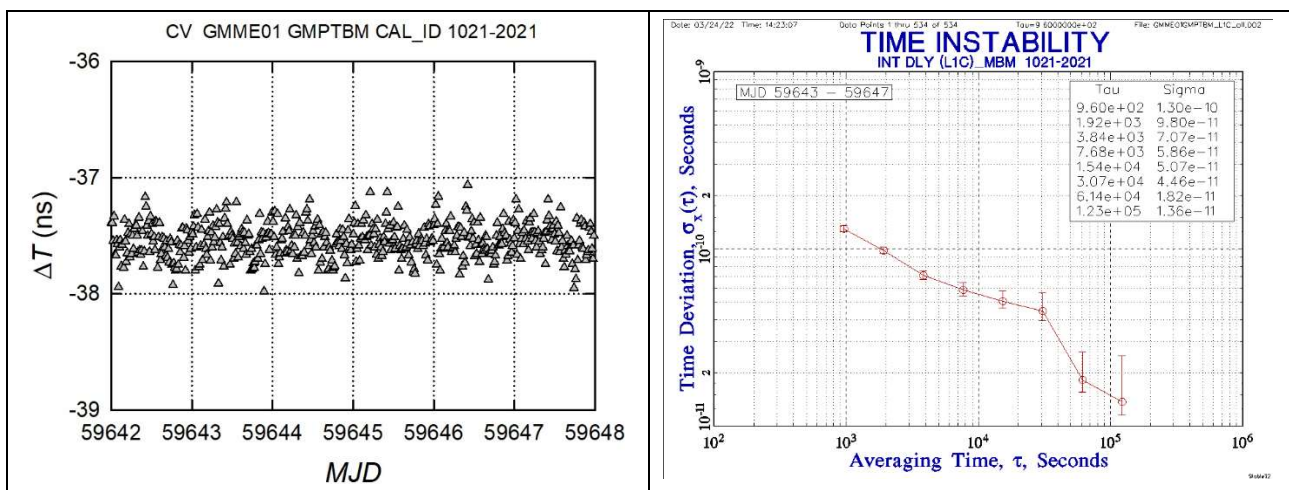


Figure 6-5 GPS L1C delay in ME01, reference PTBM; left: TDEV calculated from the results

In Figure 6-3, Fehler! Verweisquelle konnte nicht gefunden werden. Figure 6-4, and Figure 6-5 the  $\Delta I_D$  (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  $\tau = 50\,000$  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. SUMMARY OF RESULTS OBTAINED AT MBM

**Table 6-1  $\Delta$ INT DLY(fi) values for the MBM receiver and statistical properties obtained initially.**

Receiver and signal	Delay / delta delay (ns)	Delay / delta delay(ns)	Sigma (ns)	TDEV (ns)	N
	Mean	Median			
ME01_dP1	-18.30	-18.32	0.17	0.1	534
ME01_dP2	-25.20	-25.20	0.21	0.1	534
ME01_L1C	-37.54	-37.54	0.14	0.1	534
ME01_E1	-43.91	-43.90	0.14	0.1	534
ME01_E5a	-44.17	-44.17	0.14	0.1	534

## 7. OPERATION AT PTB: SECOND PERIOD

The period 59666.52 to 59672 (6.5 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  $\Delta ID_i$  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.

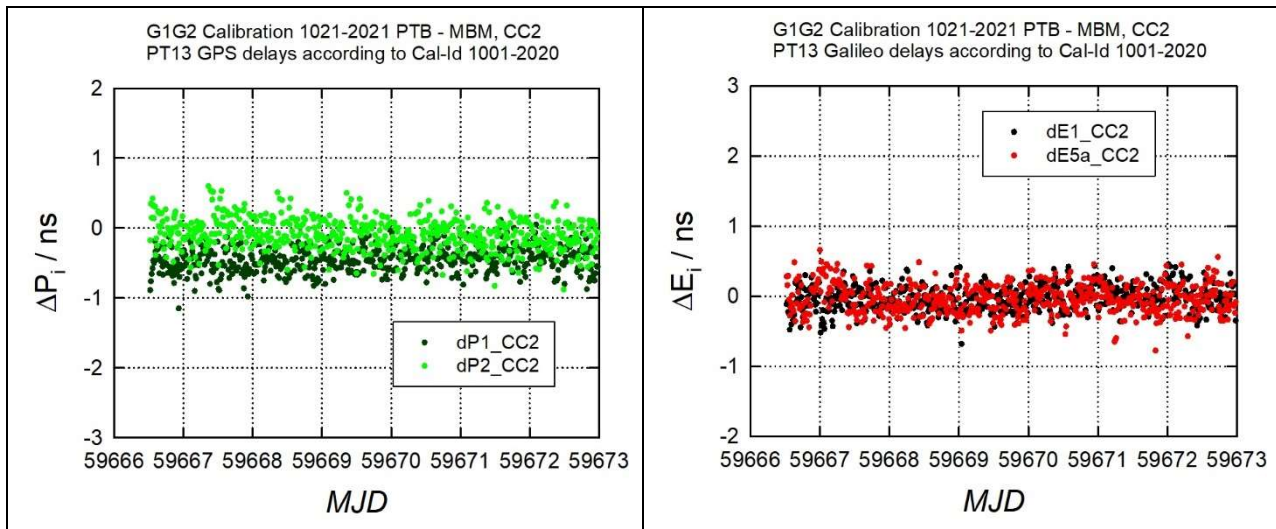


Figure 7-1 Corrections to GPS delay in PTBM during CC2,  $\Delta P_1$  (dark green) and  $\Delta P_2$  (light green) Right: Corrections to Galileo delays in PTBM during CC2,  $\Delta E_1$  (black) and  $\Delta E_5a$  (red).

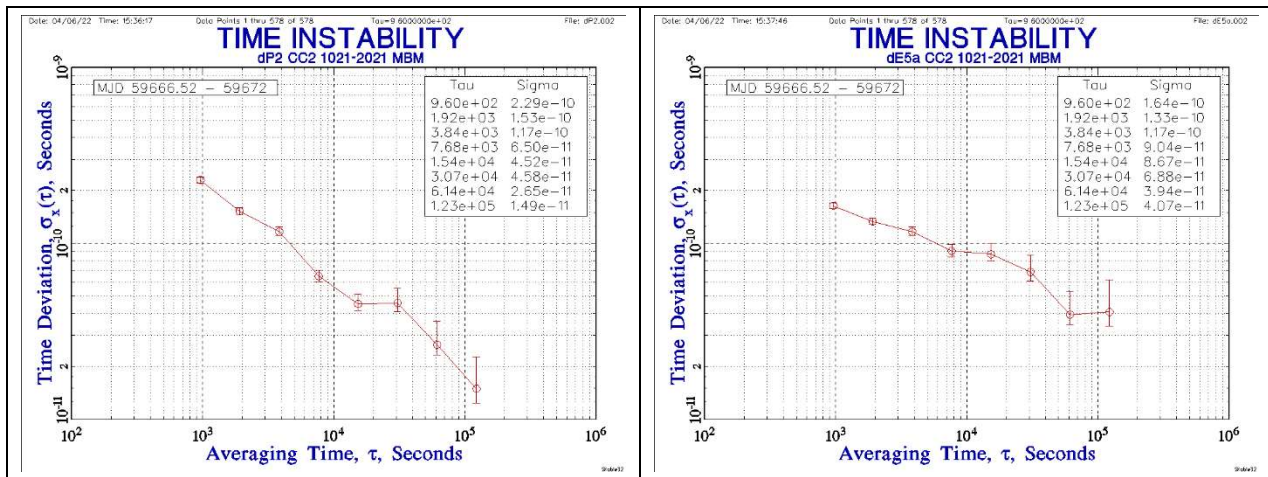


Figure 7-2 TDEV obtained for the data sets GPS dP2 (left) and Galileo dE5a (right) from Figure 7-1

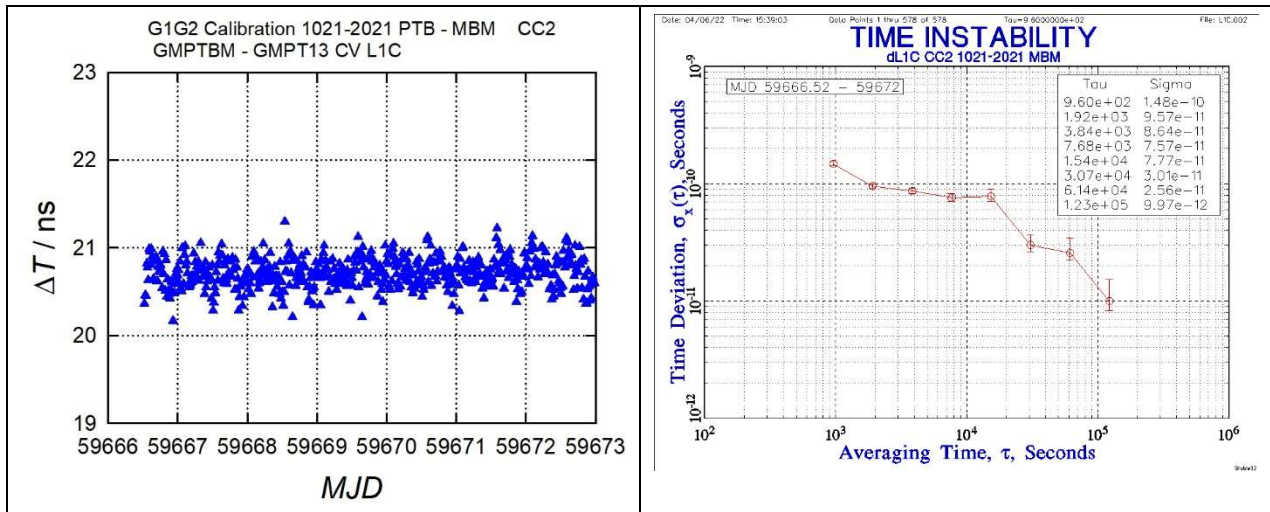


Figure 7-3 PTBM GPS delay (L1C) during CC2 and TDEV for the data set

## 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 0.55 ns for  $\Delta E5a$ . A step of this magnitude had not been noted in previous campaigns. Comparing PTBM with another receiver at PTB, PT09 during the periods CC1 and CC2 showed a similar step. It has been accounted for in the uncertainty budget. 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)
$\Delta P1$ (CC1)	-0.31	0.20	0.1
$\Delta P2$ (CC1)	0.07	0.26	0.1
$\Delta P3$ (CC1)	-0.89		
$\Delta C1$ (CC1)	20.86	0.18	0.1
$\Delta E1$ (CC1)	+0.09	0.18	0.1
$\Delta E5a$ (CC1)	+0.51	0.18	0.1
$\Delta E3$ (CC1)	-0.45		
$\Delta P1$ (CC2)	-0.45	0.17	0.1
$\Delta P2$ (CC2)	-0.10	0.23	0.1
$\Delta P3$ (CC2)	-0.99		
$\Delta C1$ (CC2)	20.72	0.17	0.1
$\Delta E1$ (CC2)	-0.04	0.18	0.1
$\Delta E5a$ (CC2)	-0.04	0.21	0.1

$\Delta E3$ (CC2)	-0.04		
<b>Mean values used for evaluation of visited receivers' internal delays</b>			
$\Delta P1$	-0.38		
$\Delta P2$	-0.02		
$\Delta C1$	20.79		
$\Delta E1$	0.03		
$\Delta E5a$	0.25		



## 8. INT DLY UNCERTAINTY EVALUATION

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

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

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

$$u_b = \sqrt{\sum_n u_{b,n}^2}. \quad (7)$$

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

Values in column P3 are calculated according to  $u(\text{P3}) = \sqrt{\{u(\text{P1})^2 + (1.54 \times u(\text{P1}-\text{P2}))^2\}}$ . Uncertainties for the Galileo delays are calculated according to  $\sqrt{\{u(\text{E1})^2 + (1.26 \times u(\text{E1}-\text{E5a}))^2\}}$ . 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 MBM**

	<b>Uncertainty</b>	<b>Value f1 (ns)</b>	<b>Value f2 (ns)</b>	<b>Value f1-f2 (ns)</b>	<b>Value f3 (ns)</b>	<b>Description</b>
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	$u_a$ (MBM)	0.1	0.1	0.14	0.23	CC measurement uncertainty, for the MBM receivers
<b>Result of closure measurement at PTB</b>						
3a	$u_{b,1}$ (GPS)	0.1	0.1		0.10	Misclosure, see Table 7-1
3b	$u_{b,1}$ (Galileo)	0.1	0.55		0.41	Misclosure, see Table 7-1
<b>Systematic components due to antenna installation</b>						
4	$u_{b,11}$	0.1	0.1	0.14	0.28	Position error at PTB
5a	$u_{b,12}$ (MBM)	0.1	0.1	0.14	0.28	Position error at MBM
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 MBM
<b>Installation of PTBM and visited receivers</b>						
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(MBM) (REF DLY)
10	$u_{b,23}$	0.5	0.5	0	0.5	Connection of receivers at MBM to UTC(MBM) (REF DEL)
<b>Antenna cable delay</b>						
11	$u_{b,31}$ (PTB)	0.5	0.5	0	0.5	Uncertainty estimate for the PTBM CAB DLY when installed at PTB
12	$u_{b,32}$ (MBM)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBM CAB DLY when installed at MBM
13	$u_{b,33}$ (MBM)	0.5	0.5	0	0.5	Uncertainty estimate for MBM 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 0.55 ns step had not been observed before. 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 0.2 ns for the internal set-up at MBM. For PTBM a larger value was chosen.

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 cable at MBM 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\_1021\_2021 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  $\Delta\text{IDi}(V,T)$  and  $\Delta\text{IDi}(T,G)$  (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.

**Table 9-1 Results of the Calibration Campaign G1G2\_1021\_2021: GPS delays, all values in ns**

Receiver	INT DLY(P1) old	INT DLY(P2) old	INT DLY (C1)old	$\Delta\text{P1}$ (V,T)	$\Delta\text{P2}$ (V,T)	$\Delta\text{C1}$ (V,T)	$\Delta\text{P1}$ (T,G)	$\Delta(\text{P2})$ (T,G)	$\Delta(\text{C1})$ (T,G)	INT DLY (C1) new	INT DLY (P1) new	$u_{\text{cal, P1}}$	INT DLY(P2), new	$u_{\text{cal, P2}}$	$u_{\text{cal, L3P}}$
MBM receiver															
ME01	-26.0	-20.5	-26.5	-18.32	-25.2	-37.54	-0.38	-0.02	20.79	-43.25	-44.7	1.08	-45.72	1.08	1.16

**Table 9-2 Results of the Calibration Campaign G1G2\_1021\_2021: Galileo delays, all values in ns**

Receiver	INT DLY(E1), old	INT DLY(E5a); old	$\Delta E1$ (V,T)	$\Delta E5a$ (V,T)	$\Delta E1$ (T,G)	$\Delta(E5a)$ (T,G)	INT DLY(E1) new	$u_{cal, E1}$	INT DLY(E5a) new	$u_{cal, E5a}$	$u_{cal, L3E}$
MBM receivers											
ME01	0.0	0.0	-43.91	-44.17	0.03	0.25	-43.88	1.08	-43.92	1.21	1.25

## ANNEX: BIPM CALIBRATION INFORMATION SHEETS

### First common clock measurement at PTB

<b>Laboratory:</b>		<b>PTB</b>		
Date and hour of the beginning of		2021-11-11 00:00 UTC (MJD 59529)		
Date and hour of the end of measurements:		2021-11-15 24:00 UTC (MJD 59533)		
<b>Information on the system</b>				
	<b>Local:</b>	<b>Traveling:</b>		
4-character BIPM code	<b>PT13</b>	<b>PTBM</b>		
Receiver maker and type:	PolaRx5TR (5.2.0)	PolaRx5TR (5.3.0)		
Receiver serial number:	S/N 470 1292	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				
<b>Measured delays / ns</b>				
	<b>Local:</b>	<b>Traveling:</b>		
Delay from local UTC to receiver 1 PPS-in ( $X_P$ ) / ns	9.59 ± 0.1 (#)	43.9 +/- 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			
<b>Data used for the generation of CGGTTS files</b>				
	<b>LOCAL:</b>	<b>Traveling</b>		
<input type="checkbox"/> 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)		
<input type="checkbox"/> INT DLY (or $X_R+X_S$ ) (GALILEO) /ns:	33.6 (E1), 33.6 (E5a) (*)	20.8 (E1), 17.9 (E5a) (****)		
<input type="checkbox"/> CAB DLY (or $X_C$ ) /ns:	205.7	264.9		
<input type="checkbox"/> REF DLY (or $X_P+X_O$ ) /ns:	56.2	43.9 (%%)		
<input type="checkbox"/> 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 (\$)	
<b>General information</b>				
<input type="checkbox"/> Rise time of the local UTC pulse:	3 ns			
<input type="checkbox"/> Is the laboratory air conditioned:	Yes			

Set temperature value and uncertainty:	23.0 °C, peak-to-peak variations 0.5° C
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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
- (%%) operation during CC1 with auto delay compensation on.
- (\*) 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 MBM: Receiver ME01

Laboratory:	MBM	
Date and hour of the beginning of measurements:	2022-03-04 0:00	
Date and hour of the end of measurements:	2022-03-09 24:00	
<b>Information on the system</b>		
	<b>Local:</b>	<b>Travelling:</b>
4-character BIPM code	ME01	PTBM
• Receiver maker and type:  Receiver serial number:	PikTime Systems, TTS-5; 1009 2015, HW:133.57, SW:3.5 2021/04/09	PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:	1.0	1.0
• Antenna cable maker and type: Phase stabilised cable (Y/N):	PikTime Systems, TTS-5 S/N 1009, N-type	N-type, LMR 400
Length outside the building /m:		
• Antenna maker and type:  Antenna serial number:	JAV_GRANT_G3T  S/N 00652	NavExperience 3G+C reference, S/N RE 0560
Temperature (if stabilised) /°C		
<b>Measured delays /ns</b> (if needed fill box "Additional Information" below)		
	<b>Local:</b>	<b>Travelling:</b>
• Delay from local UTC to receiver 1 PPS-in:	5.18	5.626
Delay from 1 PPS-in to internal Reference (if different): (see section 2 for details)	phase corr: -6.00 ns, fw corr: -74.91 ns)-	-
• Antenna cable delay:	146.262	264.9
Splitter delay (if any):	-	n/a
Additional cable delay (if any):	-	n/a
<b>Data used for the generation of CGGTTS files</b>		



• INT DLY (GPS) /ns:	(L1C) -26.5; (L1P) -26.0; (L2P) -20.5;	18.9 (P1) 17.1 (P2), 0.0 (L1C)
• INT DLY (Galileo) /ns:	(E1) 0.0, (E5a) 0.0	20.8 (E1), 17.9 (E5a)
• CAB DLY /ns:	146.3	264.9
• REF DLY /ns:	-75.7	5.6 (%%)
• Coordinates reference frame:	ITRF	ITRF
Latitude or X /m:	+4451319.64	+4451320.19
Longitude or Y /m:	+1553068.06	+1553068.33
Height or Z /m:	+4281594.32	+4281593.81
<b>General information</b>		
• Rise time of the local UTC pulse:	1 ns	
• Is the laboratory air conditioned:	Yes	
Set temperature value and uncertainty:	23°C ± 2°C ; 0,25 °C	
Set humidity value and uncertainty:	50 % ± 20 % ; 2,5 %	

All coordinates (APC) controlled or determined before the start of data taking. 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).

(%%) operation at MBM with auto delay compensation on.

Names of files to be used in processing for ME01, all files generated based on RINEX obs files and R2CGGTTTS V8.3

Traveling receiver GZPTBMMJ.DDD, EZPTBMMJ.DDD, DUT: GZME01MJ.DDD, EZME01MJ.DDD.

## Second common clock measurement at PTB

<b>Laboratory:</b>		<b>PTB</b>		
Date and hour of the beginning of		2022-03-28 12:30 UTC (MJD 59666)		
Date and hour of the end of measurements:		2022-04-03 24:00 UTC (MJD 59672)		
<b>Information on the system</b>				
	<b>Local:</b>	<b>Traveling:</b>		
4-character BIPM code	<b>PT13</b>	<b>PTBM</b>		
Receiver maker and type:	PolaRx5TR (5.2.0)	PolaRx5TR (5.3.0)		
Receiver serial number:	S/N 470 1292	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				
<b>Measured delays / ns</b>				
	<b>Local:</b>	<b>Traveling:</b>		
Delay from local UTC to receiver 1 PPS-in ( $X_P$ ) / ns	$9.59 \pm 0.1$ (#)	48.5 +/- 0.2		
Delay from 1 PPS-in to internal Reference (if different): ( $X_O$ ) / ns	$46.63 \pm 0.1$ (#)	Determined automatically by receiver software		
Antenna cable delay: ( $X_C$ ) / ns	$205.7 \pm 0.1$	$264.9 \pm 0.5$		
Splitter delay (if any):	N/A			
<b>Data used for the generation of CGGTTS files</b>				
	<b>LOCAL:</b>	<b>Traveling</b>		
<input type="checkbox"/> 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)		
<input type="checkbox"/> INT DLY (or $X_R+X_S$ ) (GALILEO) /ns:	33.6 (E1), 33.6 (E5a) (* )	20.8 (E1), 17.9 (E5a) (****)		
<input type="checkbox"/> CAB DLY (or $X_C$ ) /ns:	205.7	264.9		
<input type="checkbox"/> REF DLY (or $X_P+X_O$ ) /ns:	54.3	48.5 (%%%)		
<input type="checkbox"/> 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 (\$)	
<b>General information</b>				
<input type="checkbox"/> Rise time of the local UTC pulse:	3 ns			

<input type="checkbox"/> 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 on.
- (#) 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

END of DOCUMENT