Project :	PTB_G1G2_VTT
Code:	1016_2019
Date:	27/01/2020
Version:	1.0
Page:	

GNSS CALIBRATION REPORT

G1G2_1016_2019

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

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

Authorized by: BIPM

Project:	PTB_G1G2_VTT
Code:	1016_2019
Version:	1.0
Safe date:	27.01.2020 09:48

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, BRAUNSCHWEIG, JANUARY 2020

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

REFERENCES

REFERENCES	
RD01	**BIPM report 2018 Group 1 GPS calibration trip 1001-2018_GPSP3C1_Group1-trip_V1-3**
RD02	**BIPM guidelines for GNSS calibration, V3.0, 02/04/2015**
RD03	**BIPM TM.212 (G. Petit), Nov. 2012**
RD04	**J. Kouba, P. Heroux, 2002, "*Precise Point Positioning Using IGS Orbit and Clock Products,*" GPS Solutions, Vol 5, No. 2, 12-28**
RD05	**W. Lewandowski, C. Thomas, 1991, "*GPS Time transfers,*" Proc. IEEE, Vol. 79, No. 7, 991-1000**
RD06	**PTB GNSS calibration report G1G2_1012_2016**
RD07	**P. Defraigne and G. Petit, "CGGTTS-Version 2E: an extended standard for GNSS time transfer, Metrologia 52 (2015) G1**
RD08	**Defraigne, P., Aerts, W., Cerretto, G., Cantoni, E., and Sleewaegen, J.-M., "Calibration of Galileo signals for time metrology," IEEE Trans. Ultrason. Ferroelect. Freq. Contr., vol. 61, no. 12, 2014, pp. 1967-1975.**
RD09	**Piriz, R., Rodriguez, D., Roldan, P., Mudrak, A., Bauch, A., Leute, J., Pánek, P., and Kuna, A., "Relative Calibration of Galileo Receivers within the Time Validation Facility (TVF)," Proc. 2015 Joint Conference of the IEEE International Frequency Control Symposium & European Frequency and Time Forum, 12-16 Apr 2015, Denver, Colorado, USA, pp. 245-249, 2015**
RD10	**Buist, P., Mozo, A., and Tork, H., "Overview of the Galileo Reference Centre: Mission, Architecture and Operational Concept," Proc. Of the ION GNSS+, Portland, OR, September 2017.**

ACRONYMS

ACRONYMS	
BIPM	**Bureau International de Poids et Mesures, Sèvres, France**
CGGTTS	**CCTF Generic GNSS Time Transfer Standard**
EURAMET	**The European Association of National Metrology Institutes**
IGS	**International GNSS Service**
GNSS	**Global Navigation Satellite System**
ORB	**Observatoire Royal Belgique**
PPP	**Precise Point Positioning**
PTB	**Physikalisch-Technische Bundesanstalt, Braunschweig, Germany**
RINEX	**Receiver Independent Exchange Format**
R2CGGTTS	**RINEX-to CGGTTS conversion software, provided by ORB / BIPM**
TDEV	**Time deviation**
TIC	**Time interval counter**
VTT	**VTT Technical Research Centre of Finland Ltd**

EXECUTIVE SUMMARY

As part of the support of the BIPM Time and Frequency Group by EURAMET G1 laboratories, PTB conducted a relative calibration of the GNSS equipment of VTT, Finland, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GPS dual-frequency time links to PTB in the context of realization of TAI. Its delays were determined with respect to receiver PT09 which in turn 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 current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1016_2019. 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)). The delays for the C/A-code signals on L1 were also determined during this campaign using PT13 as the reference.

In addition we determined the signal delays for Galileo E1 and E5 of receiver MI05 which are relevant for the use of Galileo signals in a ionosphere-free linear combination although this is currently beyond the scope of the BIPM Guide [2].

The final results are included in Table 9-1, Table 9-2 and Table 9-3. The internal delays of the two receivers involved were determined with an uncertainty of about 1 ns for single frequency observations. The uncertainty for time transfer links to PTB evaluated in a ionosphere-free linear combination is less than 1.5 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 the GNSS equipment of VTT, Finland, with respect to the calibration of PTB receiver PT13, which currently serves as the reference receiver in all GPS dual-frequency time links to PTB in the context of realization of TAI. Its delays were determined with respect to receiver PT09 which in turn 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.

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, is compared to the “golden” receiver, PT13, and the offset between the actual and the assumed PTBM delay values is determined.

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

Finally, the stability of the PTBM delays is assessed by a second Common-Clock measurement (CC2) in PTB. Based thereon, the “final” INT DLY values of the visited receivers and their uncertainty values are calculated.

The structure of this report follows this sequence of work. After presentation of the participants and schedule, a general section follows that contains the (mathematical) calibration procedure, followed by a report of data collection at PTB and VTT. The final results and the uncertainty discussion close the report. In the Annex the BIPM information tables are reproduced.

2. PARTICIPANTS AND SCHEDULE

Table 2-1: List of participants

Institute	Point of contact	Site address
PTB	Thomas Polewka Tel +49 531 592 4418 Thomas.polewka@ptb.de	PTB, AG 4.42 Bundesallee 100 38116 Braunschweig, Germany
VTT	Anders Wallin phone: +358504155975 email: anders.wallin@vtt.fi	VTT MIKES Metrology, Time & Frequency Tekniikantie 1 FIN-02150 Espoo, FINLAND

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2019-11- 15 until 2019-11-19	PTB	First common-clock comparison between PTBTM and PT13	5 days used for evaluation, MJD 58802 – 58806 (incl.)
2019-12-16 until 2020-01-03	VTT	Operation of PTBM in parallel with	8 days used for determination of delays, MJD 58841 – 58848
2020-01-15 until 2020-01-20	PTB	Operation of PTBT after return	5 days used for evaluation, MJD 58864 – 58868 (incl.)

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

3. CALIBRATION PROCEDURE

The calculation of INT DLY values for the receiver to be calibrated follows the description given in BIPM TM.212 [RD03] and has been coded in software routine cv.py written by Julia Leute of PTB. The following text piece that describes its function is generated via copy-paste from [RD03] with small changes of the designation of quantities.

When dealing with G1G2 calibrations, in principal we distinguish receivers V, T, and G: V for visited, T for travelling, and G for golden_reference. G1 labs committed to ship their T to the other sites. In the current campaign, PT13 (named PTBB when referred to as IGS station) serves as the reference receiver G. Its 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, and this was the first campaign involving the new set-up.

Conventionally, the receiver delay D is considered as the sum of different terms that are defined subsequently:

(1) INT DLY

The sum $X_R + X_S$ represents the “INT DLY” field in the CGGTTS header:
X_R represents the receiver hardware delay, between a reference point whose definition depends on the receiver type and the internal time reference of the measurements. X_S represents the antenna delay, between the phase center and the antenna cable connector at the antenna body. We distinguish the two quantities for the two frequencies, 1 and 2.

INT DLY(P1) and INT DLY(P2) of receiver V are the basic quantities that are determined during the relative calibration. For calculating ionosphere—free observation data, INT DLY(P3) is calculated as 2.54×INT DLY(P1) - 1.54×INT DLY(P2).

The following terms are considered frequency independent, i. e. no distinction is made for P1 and P2 and other signal frequencies.

(2) CAB DLY

The sum $X_C + X_D$ represents the “CAB DLY” field in the CGGTTS header.
X_C corresponds to the delay of the long cable from the antenna to the input connector at either the antenna splitter or the receiver body directly. If a splitter is installed, X_D corresponds to the delay of the splitter and the small cable up to the receiver body. For a simple set-up with just an antenna cable, $X_D = 0$.

(3) REF DLY

The sum $X_P + X_O$ represents the “REF DLY” field in the CGGTTS header.
X_P corresponds to the delay of the cable between the laboratory reference point for local UTC and the 1 PPS-in connector of the receiver.
X_O corresponds to the delay between the 1PPS-in connector and the receiver internal reference point, the latter depending on the receiver type:

- For Ashtech Z12-T: The first positive zero crossing of the inverted 20 MHz-in following the 1PPS-in, delayed by 15.8 ns,
- For Septentrio PolaRx4: The 1 PPS-out, no further correction
- For Septentrio PolaRx5TR: optionally X0 is determined autonomously by the receiver or it can be determined alike to the PolaRx4.
- For DICOM GTR50 and GTR51: The 1PPS-in, i.e. $X_O = 0$,
- For TTS-4: RD02, Section 2.3.2, and Annex G specify the procedure for TTS-4, which in detail depends on the software version.

PT13 had been installed in April 2019, and the auto-calibration option was disabled. PTBM 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 (L3P) data (including correct, accurate antenna coordinates) are needed. As a reminder,

$$\mathrm{REFGPS}(k) = [\mathrm{REFGPS}_{\mathrm{RAW}}(k) - \mathrm{CAB\ DLY}_{\mathrm{F}} - \mathrm{INT\ DLY}(\mathrm{P3}) + \mathrm{REF\ DLY}_{\mathrm{F}}], \qquad (1)$$

where REFGPS(k) is reported in column 10 of the standard CGGTTS files, $\mathrm{REFGPS}_{\mathrm{RAW}}$ designates the uncorrected measurement values, INT DLY(P3) is calculated as $2.54\times\mathrm{INT\ DLY}(\mathrm{P1})_{\mathrm{F}} - 1.54\times\mathrm{INT\ DLY}\ (\mathrm{P2})_{\mathrm{F}}$, and the values designated as "Q_F" are reported in the CGGTTS file header.

The ionospheric delay for a signal at frequency *f* is proportional to $1/f^2$. According to [RD07], the column MDIO in CGGTTS V2E files 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 cv.py in calibration mode thus calculates:

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

where $(f_1/f_2)^2 = 1.647$ for GPS for each satellite observation j and REFGPS(j) and MDIO(j) are from the line in the CGGTTS file that reports the observation j.

If the common-view condition is fulfilled for the observations with T and G, the differences

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

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

cv.py at the end of the computation edits the median value of all individual observations ΔPi for P1 and P2, and the number of data points used. In addition cv.py generates a file deltap_stats that contains observation epoch (MJD.frakt) and the average ΔP1, ΔP2 of all satellite observations at that epoch. Such values are plotted throughout the report in the various figures.

The calculation of the INT DLY values comprises two steps:

Step 1: INT DLY(Pi)_T_corr = ΔPi(T,G) + INT DLY(Pi)_T_old, (4)

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

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

INT DLY(Pi)_V_new = ΔPi(V,T) + <ΔPi(T,G)> + INT DLY(Pi)_V_old, (5)

where <ΔPi(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.

3.1. DETERMINATION OF DELAYS OF GALILEO SIGNALS

The above procedure has been used with minor modifications to transfer known delays for Galileo signals from one receiver to a second one. The main change in coding of software cve.py is the modification of the frequency ratio in eq. 2b to the Galileo signal frequencies, $(f_1/f_2)^2 = 1.794$ for Galileo.

The method of obtaining Galileo signal delays was published in [RD08] and later adapted by GMV in the context of work in various Galileo projects under contract with ESA and European Commission [RD09]. In May 2018 (Day 137 – 142 of 2018), the delays for GPS and Galileo signals of a new receiver for an installation at PTB as part of the Galileo Reference Center [RD10] were determined in a consistent fashion, using the PTB reference receiver PT02 (PTBB) for providing the GPS signal delays. The data from this receiver (acronym GRCP) are not public. After installation of PT13 as the new PTB reference receiver in April 2019, its Galileo signal delays were determined with reference to GRCP using data from Day 93 – 97 of year 2019.

4. CHARACTERIZATION OF PTB EQUIPMENT

The assembly of receiver PTBM was finished a few days before its shipment to VTT. No long-term record can be provided. The stability of PT13 during the current campaign can be inferred from Figure 4-1 in which common-clock common-view comparisons to PT09, a Septentrio PolaRx4TR receiver are shown. The offset seen in the Galileo data is caused by the older calibration of PT09 Galileo signal delays that has not been updated after new Galileo Broadcast Group Delay Values were published.

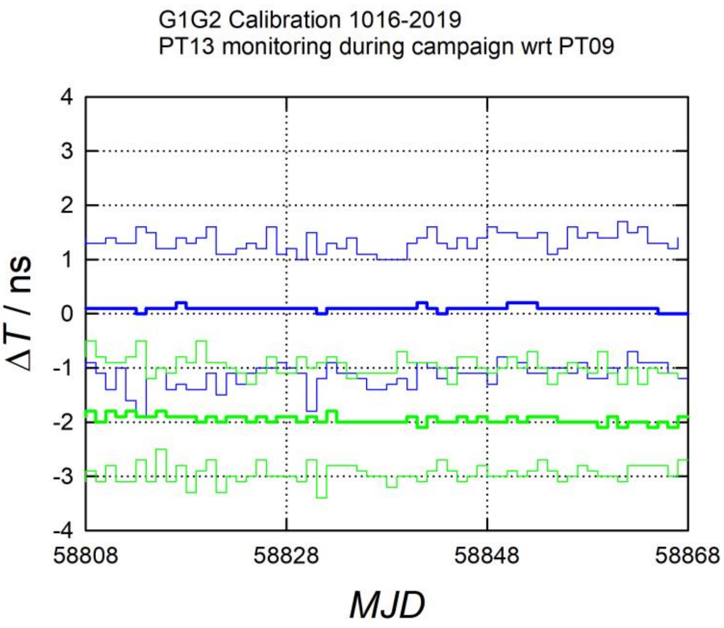


Figure 4-1: Common-clock common-view comparison between PT13 and PT09 receivers at PTB during campaign 1016-2019. Blue: GPS, green: Galileo, thick lines: daily mean values, thin lines: maximum and minimum value (16-min average) during the respective day.

The installation of the receivers in PTB is depicted in Figure 4-2 for 1 PPS signals and in Figure 4-3 for 5 MHz signals. The PT03 receiver (still operated as GPS back-up receiver with a long history) is supplied with 20 MHz from a times 4 multiplier.

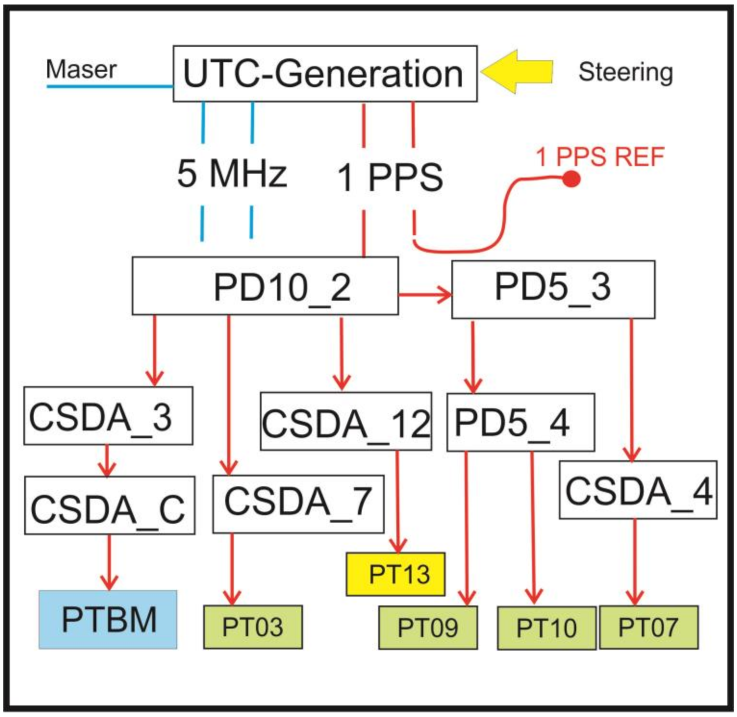


Figure 4-2: UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBT, and other receivers; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier

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

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

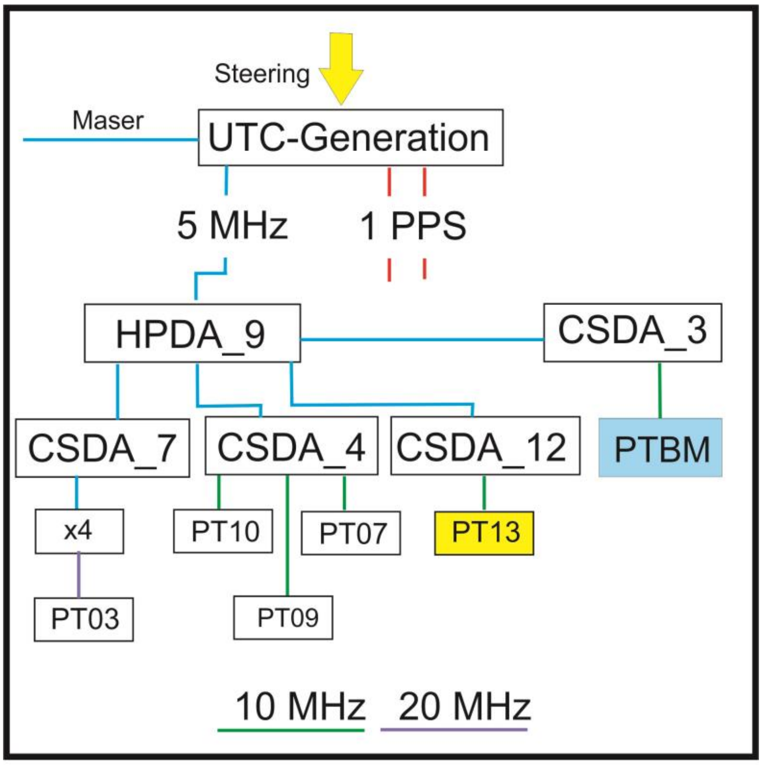


Figure 4-3: UTC(PTB) signal distribution (5 MHz, 10 MHz, 20 MHz) to PT13, PTBT, and other receivers

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

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

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

The period 58802 to 58806 (5 days) was chosen to determine the initial PTBT INT DLY values (CC1). The result of comparison with PT13 as the reference are shown in Figure 5-1 illustrating in total 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 follow as Figure 5-2. The numerical results are given in the Summary sub-section at the end of the report on CC2 in PTB.

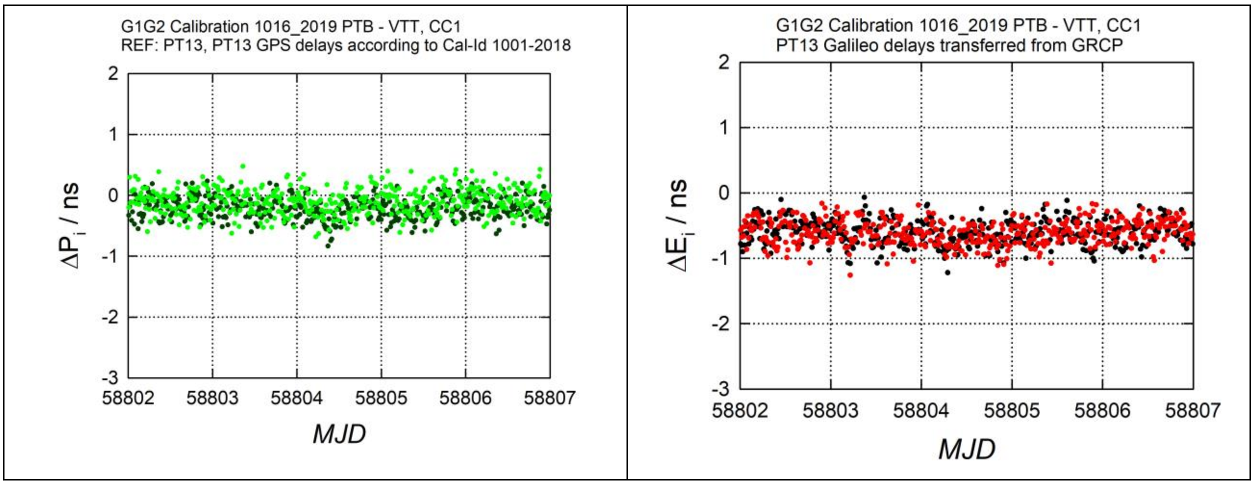


Figure 5-1: Left: Corrections to GPS delay in PTBM during CC1, ΔP1 (dark green) and ΔP2 (light green) values obtained; Right: Corrections to Galileo delays in PTBM during CC1, ΔE1 (black) and ΔE5a (red).

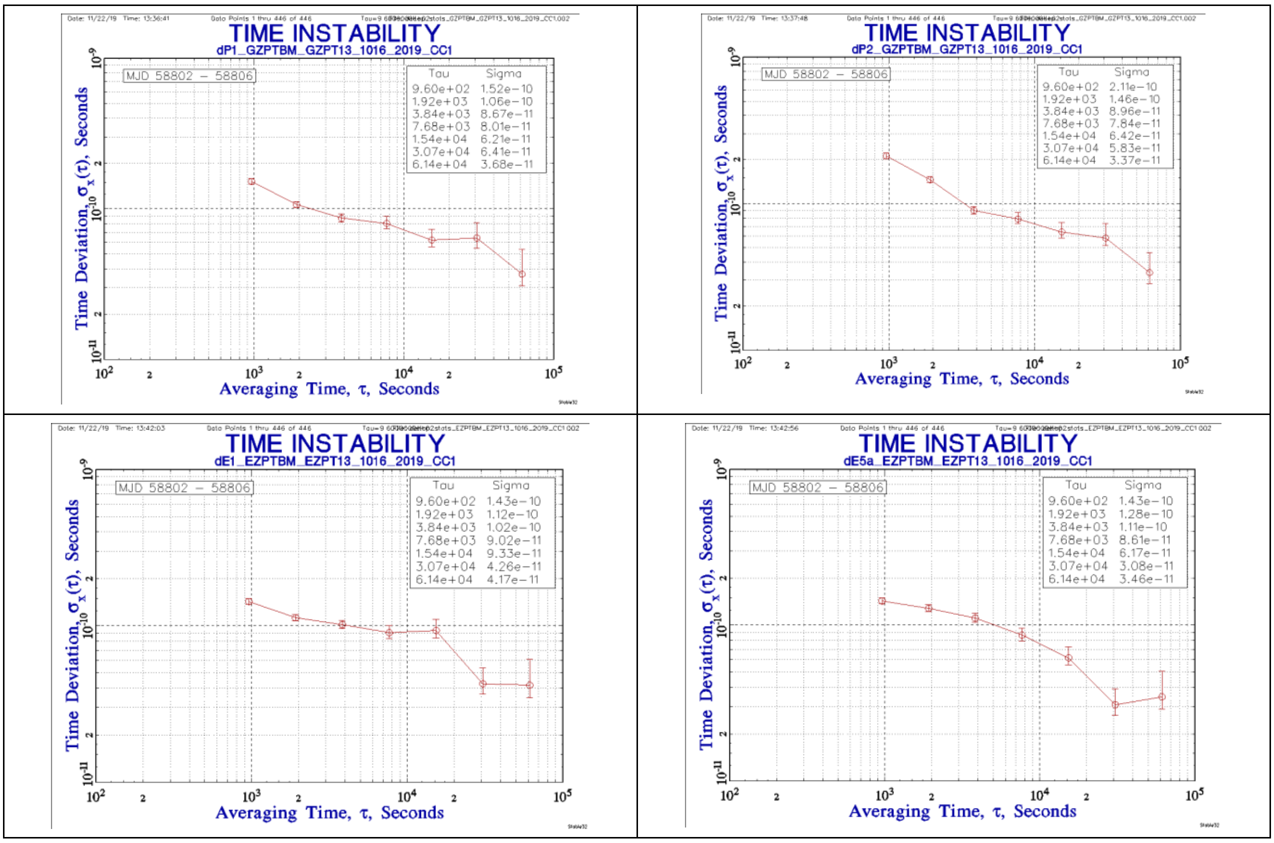


Figure 5-2: TDEV obtained for the four data sets shown in Figure 5-1, GPS (upper row), Galileo (lower row).

The INT DLY(Pi) of PTBT have not been corrected for the offsets shown in Figure 5-1 before shipment. Instead, the individual value found for the visited receivers will be corrected for the mean value obtained after the second common-clock set-up (see eq. 5)).

5.1. DETERMINATION OF SINGLE FREQUENCY DELAYS

The receiver delays for L1C (GPS) were determined with respect to PTB receiver.

We determine the cv difference between PTBM and PT13 during CC1 and CC2 (see Section 7.) and take the mean for further evaluation. The differences between PTBM and visited receivers is then determined in common view as well. This allows an estimate of the GPS L1C delay values in the respective receivers to be made. The results of the comparison during CC1 are shown in Figure 5-3, those during CC2 in Figure 5-4. As only one type of modulation is on Galileo signals, the delay for signals on E1 is the same in single and double frequency data files.

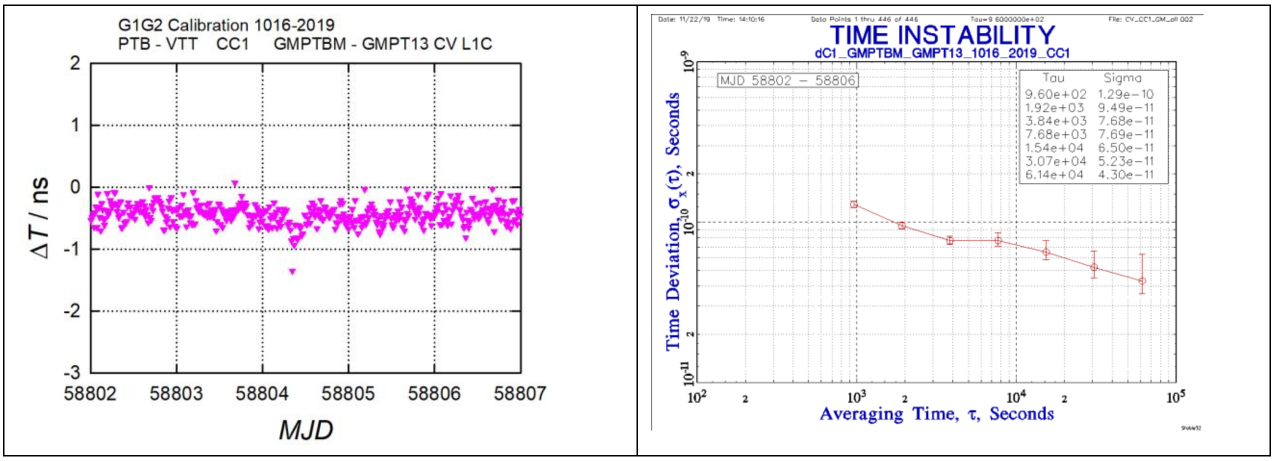


Figure 5-3 CV between receivers PTBM and PT13 using L1C data, time differences (left) and TDEV (right) during CC1

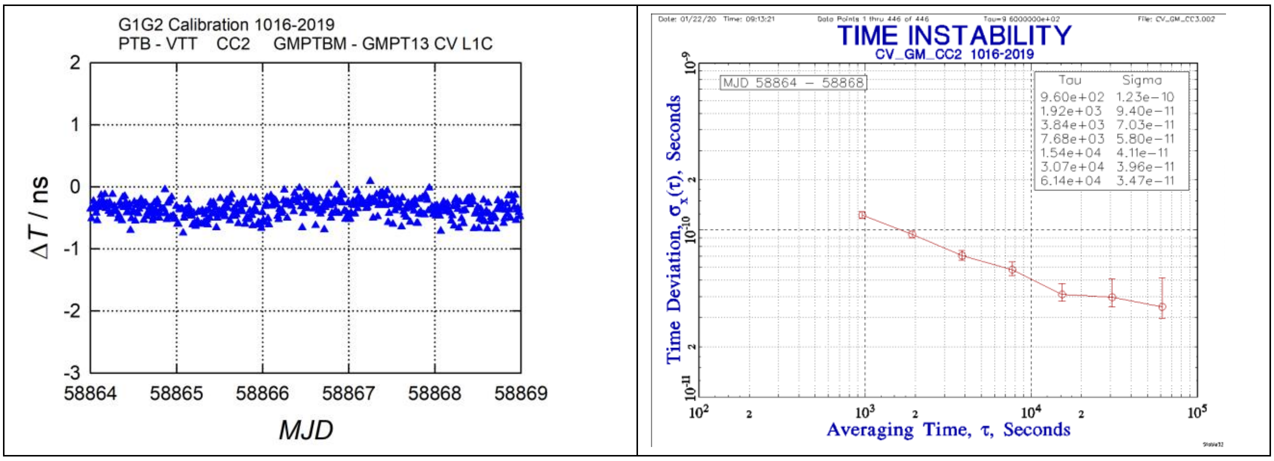


Figure 5-4 CV between receivers PTBT and PT13 using L1C data, time differences (left) and TDEV (right) during CC2

See Section 7. for further analysis of the data.

6. OPERATION OF PTBT AT VTT

PTBM was operated at VTT between mid December 2019 and early January 2020. 8 days were used as the data base for the delay determination of the receivers MI04 and MI05. The results are presented below. Details on the receivers and their installation are given in the Annex. The antenna positions were determined from analysis of RINEX data using the NRCan PPP software. The CGGTTS files from receivers PTBM and MI05 were reprocessed using r2cggtts V 8.1.

The signal distribution to receivers PTBT, MI04 and MI05 at VTT is illustrated in Figure 6-1. The mounting position of the PTBM antenna is shown in Figure 6-2.

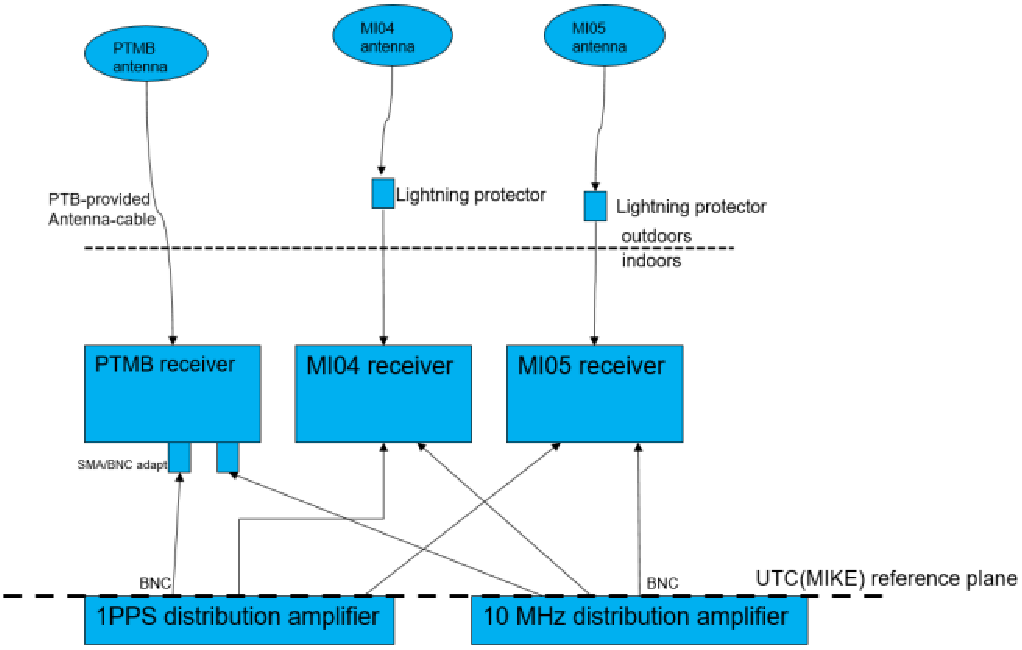


Figure 6-1 Signal distribution at VTT to the receivers

Figure 6-2: PTMB antenna mounted on 2m Aluminium-pole at the VTT MIKES-building

All reveivers were located in the VTT MIKES receiver laboratory, situated in the “tower” part of the MIKES building. Receivers were powered from 230 VAC continuously. 1PPS and 10 MHz signals were connected to the receivers with BNC-BNC cables. On the PTBM receiver SMA/BNC adapters were used.

6.1. CALIBRATION OF RECEIVER MI04

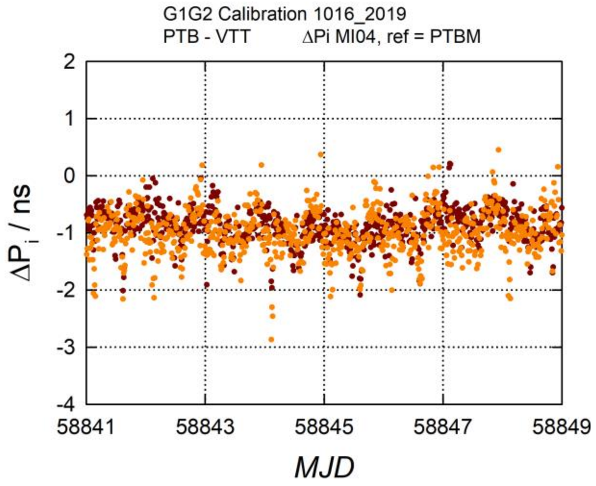


Figure 6-3. ΔP1 (brown) and ΔP2 (orange) values obtained comparing receiver MI04 (file name GZMI04.DDD) and PTBM.

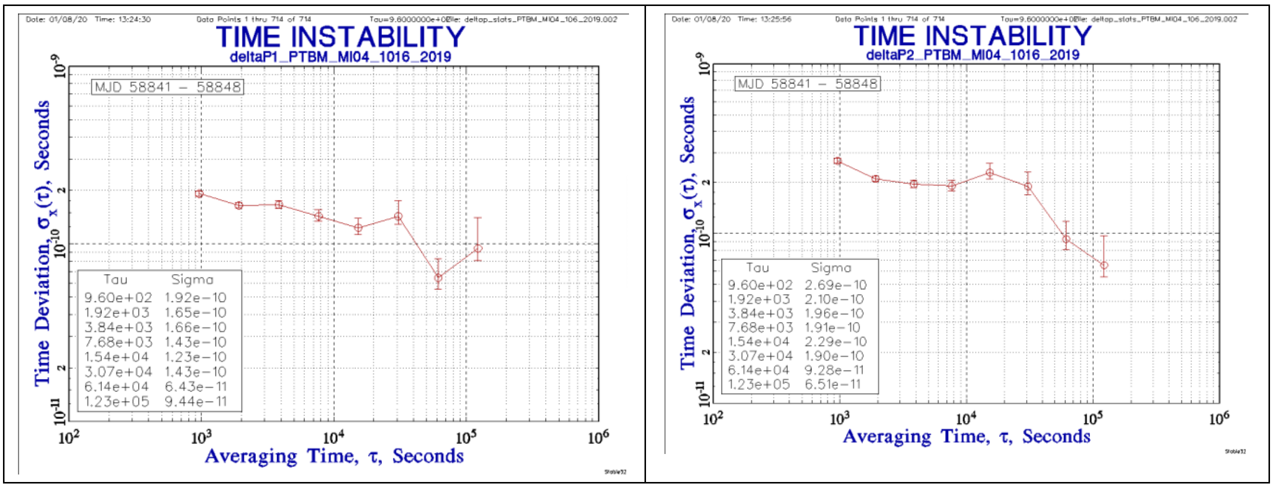


Figure 6-4. TDEV obtained for the two data sets shown in Figure 6-3, ΔP1 left, ΔP2 right.

In Figure 6-3 the ΔPi (3) derived from the raw data are depicted and the result are summarized in Table 6-1, including their statistical uncertainty. The corresponding TDEV plots are shown in Figure 6-4. As a statistical measurement uncertainty the value 0.1 ns has been used which is a very conservative estimate in view of the excellent stability.

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBM at VTT provides the second step to determine the L1C internal delays of the receivers MI04. The results are included in Table 6-1.

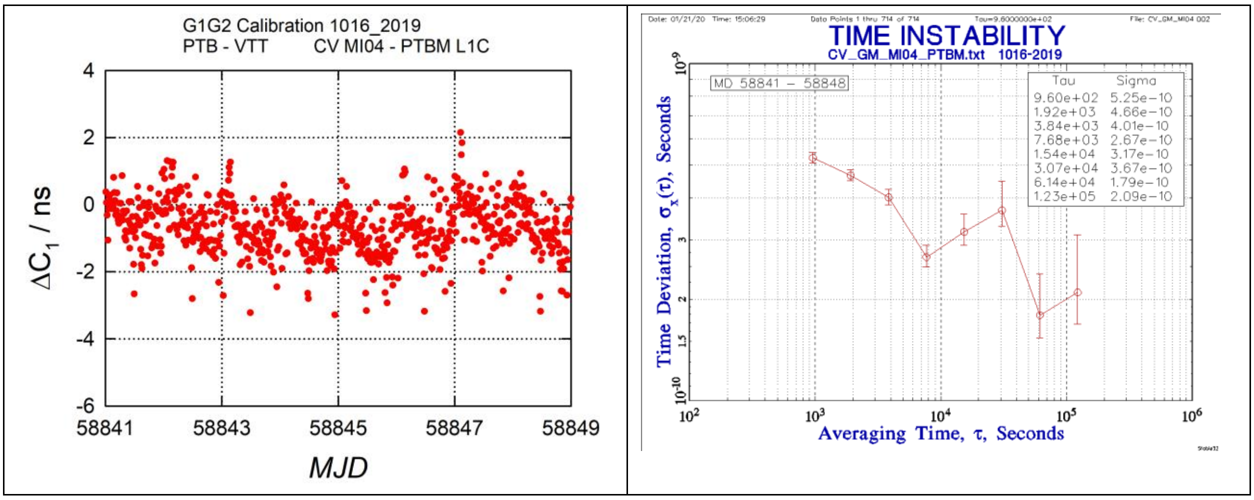


Figure 6-5. CV between receivers MI04 and PTBM using L1C data, time differences (left) and TDEV (right)

6.2. CALIBRATION OF RECEIVER MI05

As MI05 is a true multi-GNSS receiver ist was possible to determine INT DLY for GPS P1, P2 and C1, but also for Galileo E1 and E5a. See Section 3.1 for details.

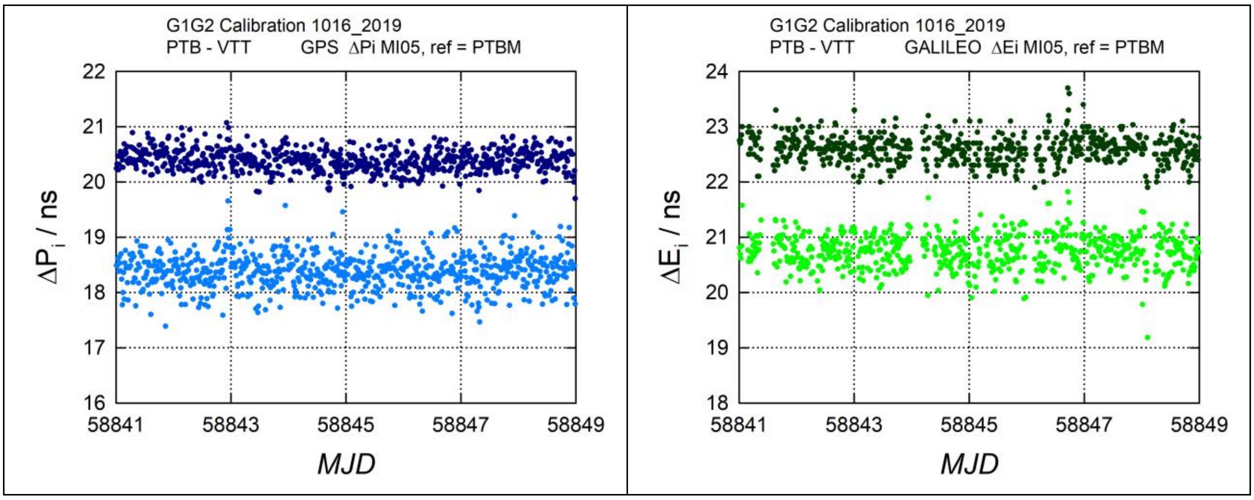


Figure 6-6. Left: Raw INT DLY for GPS signals in MI05, ΔP1 (dark blue) and ΔP2 (light blue) values; Right: Raw INT DLY for Galileo signals in MI05, ΔE1 (dark green) and ΔE5a (light green).

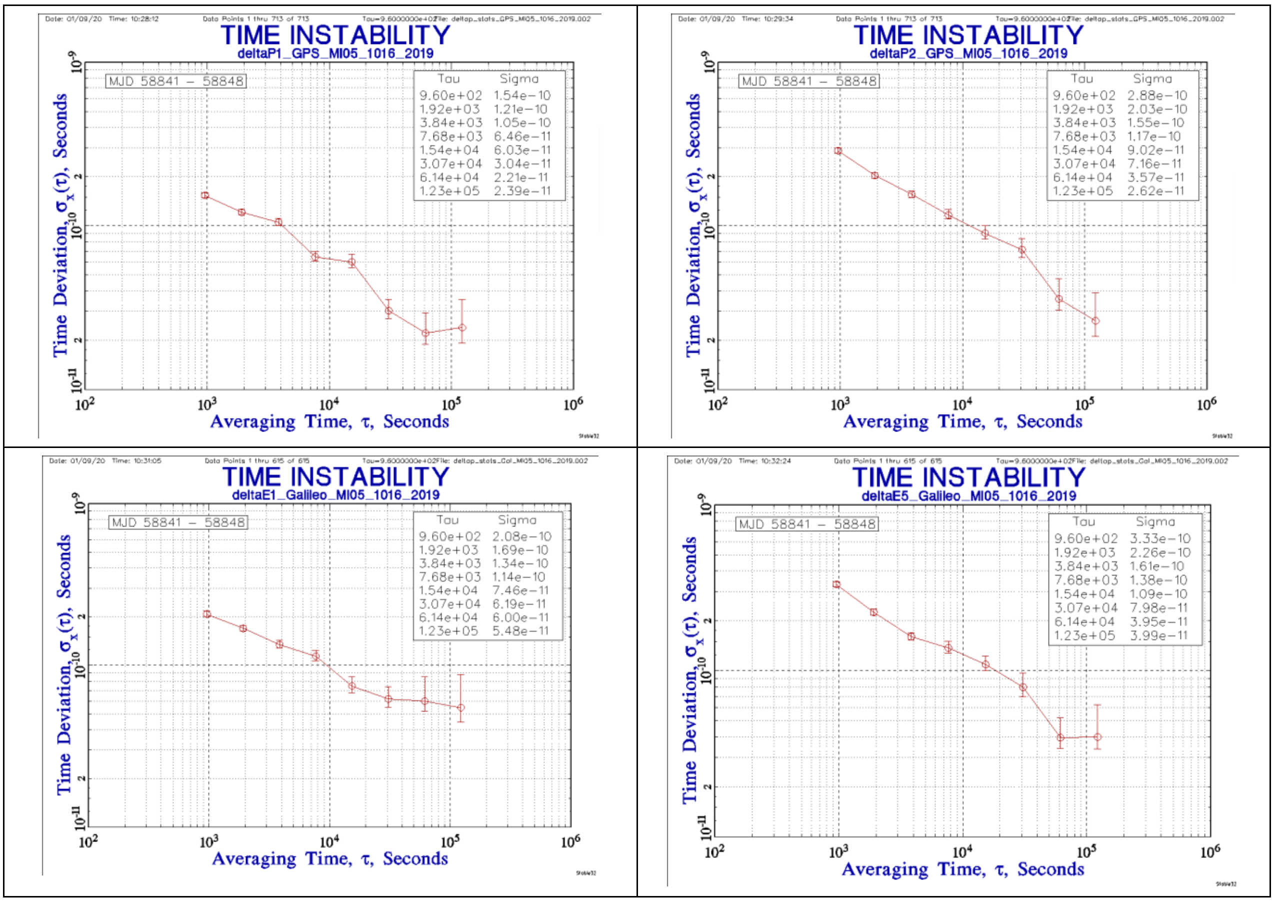


Figure 6-7. TDEV obtained for the four data sets shown in Figure 6-6, GPS (upper row), Galileo (lower row).

Evaluating common-clock common-view the L1C data collected in GMxx files generated during operation of PTBM at VTT provides the second step to determine the L1C internal delays of the receivers MI05. The results are included in Table 6-1.

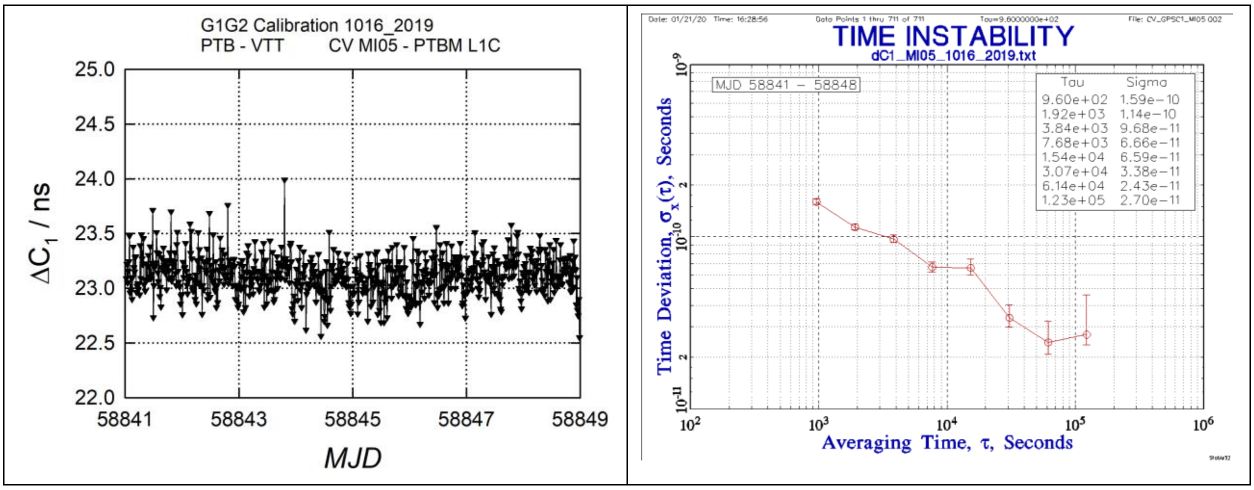


Figure 6-8. CV between receivers MI04 and PTBM using L1C data, time differences (left) and TDEV (right)

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

∆INT DLY (Pi) for receiver at VTT	Mean (ns)	Median (ns)	Std. Dev. (ns)	TDEV (ns)	Number of 16-min epochs
MI04					
∆P1	-0.88	-0.86	0.31	0.15	713
∆P2	-1.00	-1.02	0.41	0.2	713
∆C1	-0.68	-0.67	0.79	0.3	713
MI05					
∆P1	20.41	20.40	0.18	0.1	713
∆P2	18.40	18.40	0.30	0.1	713
∆C1	23.11	23.11	0.19	0.1	707
∆E1	22.60	22.60	0.26	0.1	612
∆E5a	20.74	20.73	0.30	0.1	612

7. OPERATION OF PTBT AT PTB: SECOND PERIOD

The period 58864 to 58868 (5 days) was chosen to determine PTBT 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 446 ΔPi and ΔEi, respectively (see eq. 3) values obtained as mean values over all common view observations at a given epoch. The time instability (TDEV) plots for the data sets follow as Figure 7-2.

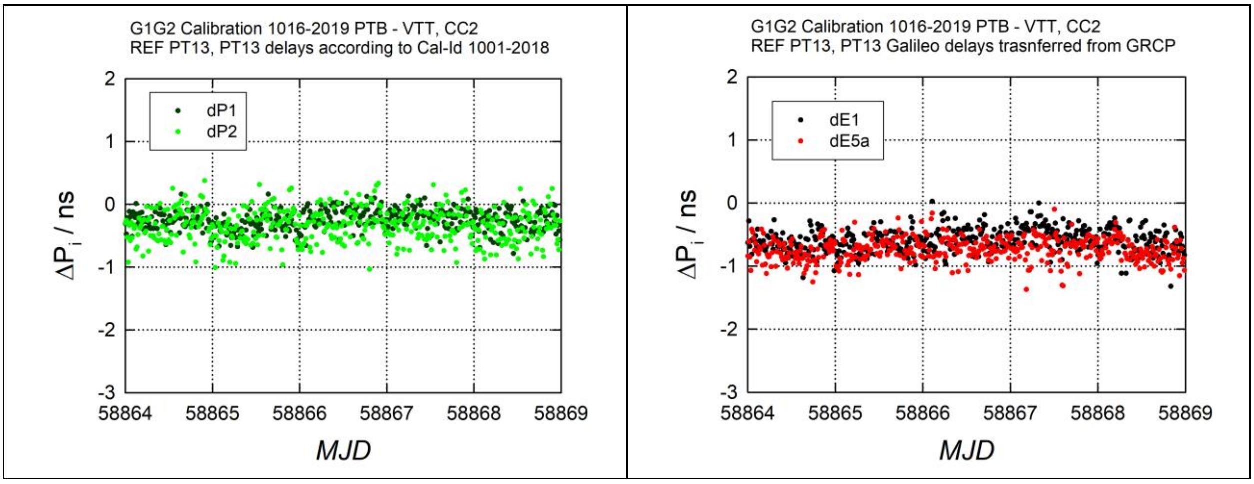
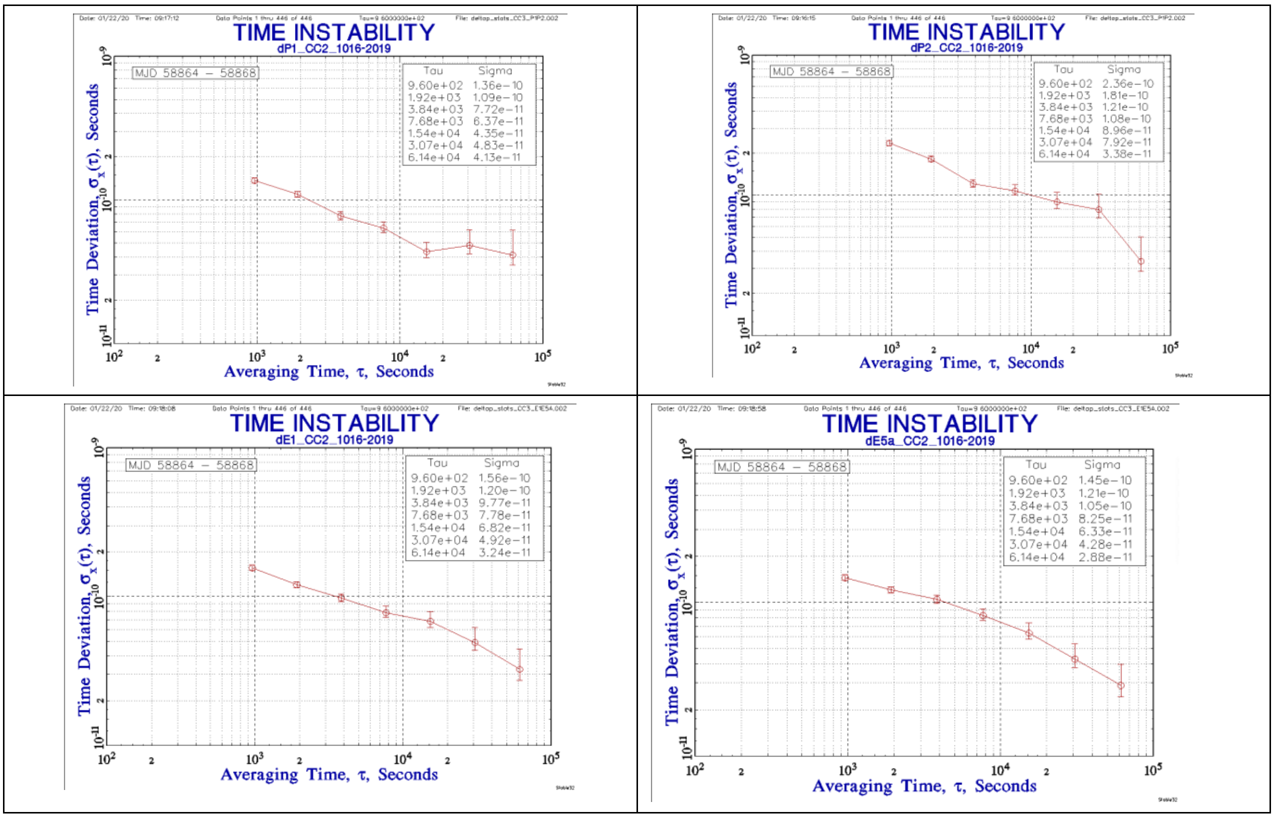


Figure 7-1. ΔPi values obtained during the second common-clock set-up in PTB.



dP1_CC2_1016-2019

Tau	Sigma
9.60e+02	1.36e−10
1.92e+03	1.09e−10
3.84e+03	7.72e−11
7.68e+03	6.37e−11
1.54e+04	4.35e−11
3.07e+04	4.83e−11
6.14e+04	4.13e−11

dP2_CC2_1016-2019

Tau	Sigma
9.60e+02	2.36e−10
1.92e+03	1.81e−10
3.84e+03	1.21e−10
7.68e+03	1.08e−10
1.54e+04	8.96e−11
3.07e+04	7.92e−11
6.14e+04	3.38e−11

dE1_CC2_1016-2019

Tau	Sigma
9.60e+02	1.56e−10
1.92e+03	1.20e−10
3.84e+03	9.77e−11
7.68e+03	7.78e−11
1.54e+04	6.82e−11
3.07e+04	4.92e−11
6.14e+04	3.24e−11

dE5a_CC2_1016-2019

Tau	Sigma
9.60e+02	1.45e−10
1.92e+03	1.21e−10
3.84e+03	1.05e−10
7.68e+03	8.25e−11
1.54e+04	6.33e−11
3.07e+04	4.28e−11
6.14e+04	2.88e−11

Figure 7-2. TDEV obtained for the four data sets shown in Figure 7-1, GPS (upper row) and Galileo (lower row).

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 0.23 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)	-0.21	0.18	0.1
ΔP2 (CC1)	-0.1	0.21	0.1
ΔP3 (CC1)	-0.38		
ΔC1 (CC1)	-0.43	0.16	0.1
ΔE1 (CC1)	-0.60	0.19	0.1
ΔE5a (CC1)	-0.60	0.19	0.1
ΔE3 (CC1)	-0.60		
ΔP1 (CC2)	-0.24	0.16	0.1
ΔP2 (CC2)	-0.33	0.26	0.1
ΔP3 (CC2)	-0.10		
ΔC1 (CC2)	-0.35	0.14	0.1
ΔE1 (CC2)	-0.59	0.20	0.1
ΔE5a (CC2)	-0.73	0.18	0.1
ΔE3 (CC2)	-0.41		
Mean values used for evaluation of visited receivers' internal delays			
ΔP1	-0.23		
ΔP2	-0.22		
ΔC1	-0.39		
ΔE1	-0.60		
ΔE5a	-0.66		

8. INT DLY UNCERTAINTY EVALUATION

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

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

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

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

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

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

Note that the uncertainty of the INT DLY values of PTB’s fixed receiver 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
2a	u_a(VTT)	0.15	0.2	0.25	0.54	CC measurement uncertainty, receiver MI04
2b	u_a(VTT)	0.1	0.1	0.14	0.23	CC measurement uncertainty, receiver MI05
Result of closure measurement at PTB						
3a	$u_{b,1}$ (GPS)	0.14	0.25		0.52	Misclosure, see Table 7-1
3b	$u_{b,1}$ (Galileo)	0.14	0.14		0.36	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	$u_{b,12}$(VTT)	0.1	0.1	0.14	0.28	Position error at VTT
6	$u_{b,13}$	0.2	0.2	0.0	0.20	Multipath at PTB
7	$u_{b,14}$	0.2	0.2	0.0	0.20	Multipath at VTT
Installation of PTBT and visited receivers						
8	$u_{b,21}$	0.5	0.5	0	0.5	Connection of PTBM to UTC(PTB) (REF DLY)
9	$u_{b,22}$	0.5	0.5	0	0.5	Connection of PTBM to UTC(MIKE) (REF DLY)
10	$u_{b,23}$	0.2	0.2	0	0.2	Connection of receivers at VTT to UTC(MIKE) (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 VTT
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	$u_{b,32}$(VTT)	0.0	0.0	0	0.0	Uncertainty estimate for the PTBM CAB DLY when installed at VTT
15	$u_{b,33}$(VTT)	0.5	0.5	0	0.5	Uncertainty estimate provided by VTT for the MI0x CAB DLY

The two receivers MI04 and MI05 are different by design and show a noticeably different time instability. Nevertheless a single uncertainty budget can cover all other contributions. An exemption is the somewhat increased u_A -value (0.3 ns) in comparing L1C data between MI04 and PTBM (see Figure 6-5). A further noticeable difference between GPS and Galileo reception is noted in the (nevertheless) small difference between the two measurement campaigns in PTB.

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.

For the generation of the CGGTTS data the PTBT antenna position is manually entered into the processing software in ITRF coordinates before the CCD measurements. These positions could in principle differ from the "true" positions in a different way in each laboratory. This is taken into account by the contributions $u_{b,11}$ and $u_{b,12}$. In the current campaign it was confirmed that the antenna coordinates were determined for all masts involved consistently and the contribution is 0.1 ns at maximum. As a matter of fact, a position error in general could even affect the P1 and P2 delays in a slightly different way, if the distinction between Antenna Reference Point (ARP) and Antenna Phase Centre (APC) is not accurately made. It has been reported that the difference between the two quantities is different for each antenna type but in addition also for the two frequencies received. To be on the safe side, $u_{b,11}$ and $u_{b,12}$ are very conservatively estimated. For other entries, where a frequency dependence can be safely excluded, the entry for P1-P2 is set to zero.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,13 \text{ and }} u_{b,14}$. 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 0.5 ns for PTBM at both locations and as 0.2 ns for the intenal set-up at VTT.

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 (new) PTBM cable was employed in CC1, CC2 and at VTT. 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 VTT 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 institutes. If the stated CAB DLY for the visited fixed receiver(s) would be erroneous, this would be absorbed in the INT DLY values produced as a result of the campaign.

9. FINAL RESULTS

The results of the calibration campaign G1G2_1016_2019 are summarized in Table 9-1. It contains the designation of the visited receiver, the INT DLY values hitherto used, the offsets ΔPi(V,T) and ΔPi(T,G) (see Section 5, (5)), the new INT DLY values to be used with consent by BIPM, and the uncertainty with which the new values were determined. For calculation, the respective entries from Table 8-1, individually for P1, P2, and combined for 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_1016_2019: 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
Mi04	-37.9	-37.7	-0.86	-1.02	-0.23	-0.22	-38.99	1.02	-38.94	1.04	1.40
Mi05	0	0	20.40	18.40	-0.23	-0.22	20.17	1.01	18.18	1.03	1.31

In a similar way we obtain from equation (1) corrected values of the L1C signal delay in receiver MI04 and MI05, respectively, as
INT DLY(L1C);new = INT DLY(L1C);old - Δ(T-V) + ΔT(T-R),
where R designates the receiver PT13 chosen as reference for this action.

Table 9-2 Results of GPS L1C calibration during campaign 1016-2019, all values in ns

Receiver	INT DLY(L1C), old	ΔT (T-V))	ΔT (T-R)	INT DLY(L1C), new	u_{cal}, L1C
Mi04	-33.3	-0.67	-0.39	-34.36	1.04
Mi05	0	23.11	-0.39	22.72	1.03

Table 9-3. Results of the Calibration Campaign G1G2_1016_2019: 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
Mi05	0	0	22.60	20.73	-0.60	-0.67	22.00	1.01	20.07	1.01	1.26

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

First common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2019-11-15 0:00 UTC (MJD 58802)
Date and hour of the end of measurements:	2019-11-19 24:00 UTC (MJD 58806)

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 (**)	40.3 +/- 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) (*) 31.0 (E1), 30.5 (E5a) (**)		18.9 (P1) 17.1 (P2) (****) 21.2 (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		40.3+unknown	
☐ 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, peakt-to-peak variations 0.5° C

Notes valid for CC1 and CC2:

(*) values based on G1 calib 1001-2018, transferred from receiver PT09

(**) Local measurement, transferred from receiver GRCP
(***) values provided by BIPM via Mail 2019-08-07
(****)PTBT INT DLY were adjusted so that PTBM – PT13 for GPS and Galileo were close to zero for convenience. Coordinates of mast P7 (APC) were determined on 12.03.2018 using NRCan PPP.

Names of files to be used in processing for site PTB
Travelling receiver GZPTBTMJ.DDD, GMPTBTMJ.DDD, EZPTBMMJ.DDD
Reference receiverGZPT13MJ.DDD, GMPT13MJ.DDD, EZPT13MJ.DDD

PTBT operation at VTT: Receiver MI04

Laboratory:	VTT MIKES
Date and hour of the beginning of measurements:	2019-12-24 00:00 GPS, MJD 58841, 2019
Date and hour of the end of measurements:	2019-12-31 23:59 GPS, MJD 58848, 2019

Information on the system

	Local:	**Travelling:**
4-character BIPM code	MI04	PTBM
• Receiver maker and type:	Dicom GTR51 (1.2.6)	Septentrio PolaRx5TR (5.3.0)
Receiver serial number:	S/N 1403001	3048338
1 PPS trigger level /V:	1.0 V	1.0 V
• Antenna cable maker and type:	armored cable, N-connectors	PTB-supplied cable, N-connectors
Phase stabilised cable (Y/N):	N	N
Length outside the building /m:	ca 10 m	ca 10 m
• Antenna maker and type:	NOV703GGG	Navexperience 3G+C
Antenna serial number:	NEG1405022	S/N RE 0560
Temperature (if stabilised) /°C	-	-

Measured delays /ns
(if needed fill box "Additional Information" below)

	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	8.579 ns	5.085(21) ns BNC-to-SMA adapter not included.
Delay from 1 PPS-in to internal Reference (if different): (see section 2 for details)	N/A	N/A***
• Antenna cable delay:	215.4 ns	264.9 ns
Splitter delay (if any):	N/A	(1)
Additional cable delay (if any):	N/A	(1)

Data used for the generation of CGGTTS files MI04
Local files from source: ftp://monitor.mikes.fi/GNSS/MI04/
INT DLY values from 1102-2015, coordinates BIPM Technical Memorandum TM281

• INT DLY (GPS) /ns:	L1C/A -33.3 ns, L1P -37.9 ns, L2C 0 ns, L2P -37.7 ns, L5 0 ns..
• INT DLY (GLONASS) /ns:	all values 0 ns.
• CAB DLY /ns:	215.4 ns

• REF DLY /ns:	8.579 ns
• Coordinates reference frame:	ITRF
Latitude or X /m:	2885858.27
Longitude or Y /m:	1335075.79
Height or Z /m:	5510548.53

Data used for the generation of CGGTTS files PTBM

RINEX files collected, r2cgggtts V8.1 for generation of cggtts files

Coordinates determined during operation before 2019-12-24

• INT DLY (GPS) /ns:	18.9 (P1) 17.1 (P2) 21.2 (C1)
• INT DLY (Galileo) /ns:	20.8 (E1), 17.9 (E5a)
• CAB DLY /ns:	264.9 ns
• REF DLY /ns:	5.1 ns
• Coordinates reference frame:	ITRF
Latitude or X /m:	+2885862.04
Longitude or Y /m:	+1335071.01
Height or Z /m:	+5510543.48
• Rise time of the local UTC pulse:	1.49 ns 10% to 90% rise time. 1PPS high-level is 3.49V into 50 Ohm
• Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	+21.5 C to +22.5 C variation during one week
Set humidity value and uncertainty:	RH 28% to 38% variation during one week

PTBT operation at VTT: Receiver MI05

Laboratory:	VTT MIKES
Date and hour of the beginning of measurements:	2019-12-24 00:00 GPS, MJD 58841, 2019
Date and hour of the end of measurements:	2019-12-31 23:59 GPS, MJD 58848, 2019

Information on the system

	Local:	**Travelling:**
4-character BIPM code	MI05	PTBM
• Receiver maker and type: Receiver serial number:	Septentrio PolaRx5TR (5.2.0) 3046486	Septentrio PolaRx5TR (5.3.0) 3048338
1 PPS trigger level /V:	1.0 V	1.0 V
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Phoenix Contact. LMR-400, N-connectors N	PTB-supplied cable, N-connectors N
Length outside the building /m:	ca 20 m	ca 10 m
• Antenna maker and type: Antenna serial number:	Tallysman VP6050C VP6050C1901240012	Navexperience 3G+C S/N RE 0560
Temperature (if stabilised) /°C	-	-

Measured delays /ns
(if needed fill box "Additional Information" below)

	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	5.092(21) ns	5.085(21) ns.
Delay from 1 PPS-in to internal Reference (if different): (see section 2 for details)	N/A	See sheet CC1
• Antenna cable delay:	96.2(1) ns	264.9 ns
Splitter delay (if any):	N/A	(1)
Additional cable delay (if any):	N/A	(1)

Data used for the generation of CGGTTS files MI05
RINEX files collected, r2cgggtts V8.1 for generation of cggtts files
Coordinates determined during operation before 2019-12-24

• INT DLY (GPS) /ns:	L1C/A, L1P, L2P all 0.
• INT DLY (Galileo /ns:	E1, E5a all 0.
• CAB DLY /ns:	96.2 ns
• REF DLY /ns:	5.1 ns

• Coordinates reference frame:	ITRF
Latitude or X /m:	+2885856.96
Longitude or Y /m:	+1335073.83
Height or Z /m:	+5510549.50
Data used for the generation of CGGTTS files PTBM RINEX files collected, r2cgggtts V8.1 for generation of cggtts files Coordinates determined during operation before 2019-12-24	
• INT DLY (GPS) /ns:	18.9 (P1) 17.1 (P2) 21.2 (C1)
• INT DLY (Galileo) /ns:	20.8 (E1), 17.9 (E5a)
• CAB DLY /ns:	264.9 ns
• REF DLY /ns:	5.1 ns
• Coordinates reference frame:	ITRF
Latitude or X /m:	+2885862.04
Longitude or Y /m:	+1335071.01
Height or Z /m:	+5510543.48
• Rise time of the local UTC pulse:	1.49 ns 10% to 90% rise time. 1PPS high-level is 3.49V into 50 Ohm
• Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	+21.5 C to +22.5 C variation during one week
Set humidity value and uncertainty:	RH 28% to 38% variation during one week

Names of files to be used in processing for site VTT:
Local receivers: GZMI04MJ.DDD / GMMI04.DDD / GZMI05MJ.DDD / GMMI05MJ.DDD, EZMI05MJ.DDD
Travelling receiver GZPTBTMJ.DDD, GMPTBMMJ.DDD, EZPTBMMJ.DDD

Second common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2020-01-16 0:00 UTC (MJD 58864)
Date and hour of the end of measurements:	2020-01-20 24:00 UTC (MJD 58668)

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 (**)	43.2 +/- 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), 31.7 (C1) (*) 31.0 (E1), 30.5 (E5a) (**)		18.9 (P1) 17.1 (P2) (****) 21.2 (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+unknown	
☐ 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, peakt-to-peak variations 0.6° C

END of DOCUMENT