# GNSS CALIBRATION REPORT

## G1G2_1019_2023

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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 Procedure for computing raw difference of GNSS code measurements for geodetic receivers, dclrinex software version 3.1, April 2021** |
| **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** | **D. A. Howe and N. Schlossberger, "Characterizing Frequency Stability Measurements Having Multiple Data Gaps", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 69, No. 2 (2022)** |
| **RD08** | **BIPM Template for calibration report to the BIPM, V3.1, 29/08/2015** |

# ACRONYMS

| ACRONYMS | |
|---|---|
| **BIPM** | **Bureau International des Poids et Mesures, Sèvres, France** |
| **CAB DLY** | **Antenna Cable Delay** |
| **CGGTTS** | **CCTF Generic GNSS Time Transfer Standard** |
| **DCLRINEX** | **Differential calibration software using the pseudoranges directly read from the RINEX files, software was provided by the BIPM** |
| **EURAMET** | **The European Association of National Metrology Institutes** |
| **ESTEC** | **European Space Research and Technology Centre** |
| **IGS** | **International GNSS Service** |
| **INT DLY** | **Internal Signal Delay** |
| **GNSS** | **Global Navigation Satellite System** |
| **PPP** | **Precise Point Positioning** |
| **PTB** | **Physikalisch-Technische Bundesanstalt, Braunschweig, Germany** |
| **REF DLY** | **Reference Delay** |
| **RINEX** | **Receiver Independent Exchange Format** |
| **R2CGGTTS** | **RINEX-to CGGTTS conversion software, provided by ORB / BIPM** |
| **TDEV** | **Time Deviation** |
| **TIC** | **Time Interval Counter** |
| **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 GNSS equipment of VTT, Finland, 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 1019-2023. 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 delays were determined using the DCLRINEX software, which was provided by the BIPM [RD03].

This report documents the installation, data taking and evaluation during the campaign. Its structured based on the BIPM template [RD08].

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

The final results are included in Table 5-1 and Table 5-2. The internal delays of receivers MI04 and MI05 were determined with uncertainties between 1.0 ns and 1.1 ns for dual frequency observations.

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. DESCRIPTION OF EQUIPMENT AND OPERATIONS

## 1.1. PARTICIPANTS

**Table 1-1 List of participants**

| Institute | Point of contact | Site address |
|---|---|---|
| PTB | Florian Heimbach<br>+49 531 592 4422<br>florian.heimbach@ptb.de | PTB, AG 4.42<br>Bundesallee 100<br>38116 Braunschweig, Germany |
| VTT | Anders Wallin<br>+35 820 722 7994<br>anders.wallin@vtt.fi | VTT Technical Research Centre of Finland Ltd<br>Tekniikantie 1<br>02150 Espoo, Finland |

## 1.2. TRAVELING EQUIPMENT

The PTBM traveling measurement set-up consists of a 19''-chassis, containing a GNSS receiver (Septentrio PolaRx5TR), a TIC (Piktime T4100U) and internal cabling. The auto compensation mode of the GNSS receiver was set to “ON” during the whole calibration trip. The set-up further includes an antenna (Navexperience 3G+C REFERENCE), 25 meters LMR-400 antenna cable, an N to TNC adapter and a laptop.
The delay from the visited UTC reference point to the calibration reference point was measured by a Keysight 53230A (SN: MY62010247) TIC, provided by VTT.

## 1.3. VISITED EQUIPMENT

**Table 1-2 List of the visited equipment**

| Institute | Status of equipment | Dates of measurement | Receiver type | BIPM code | RINEX name |
|---|---|---|---|---|---|
| VTT | Group 2 | 24.08.2023 - 30.08.2023 | DICOM GTR51 | MI04 | MI04 |
| VTT | Group 2 | 24.08.2023 - 30.08.2023 | Septentrio PolaRx5 TR | MI05 | MI05 |

## 1.4. SCHEDULE

**Table 1-3 Schedule of the campaign**

| Date | Institute | Action | Remarks |
|---|---|---|---|
| 2023-08-03 until 2023-08-09 | PTB | First common-clock comparison between PTBM and PT13 | 7 days used for the evaluation, MJD 60159 - 60165 |
| 2023-08-22 until 2023-09-11 | VTT | Operation of PTBM in parallel with local receiver | 7 days used for the evaluation, MJD 60180 - 60186 |
| 2023-09-28 until 2023-10-05 | PTB | Operation of PTBM after return | 7 days used for the evaluation, MJD 60216 - 60222 |

## 1.5. CALIBRATION PROCEDURE

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 have 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 internal signal delay represents the sum of $X_R + X_S$.

$X_R$ 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 antenna cable delay (CAB DLY).

$X_C$ 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 reference delay (REF DLY).

$X_P$ 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 1-1 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.

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 the INT DLY. The 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.

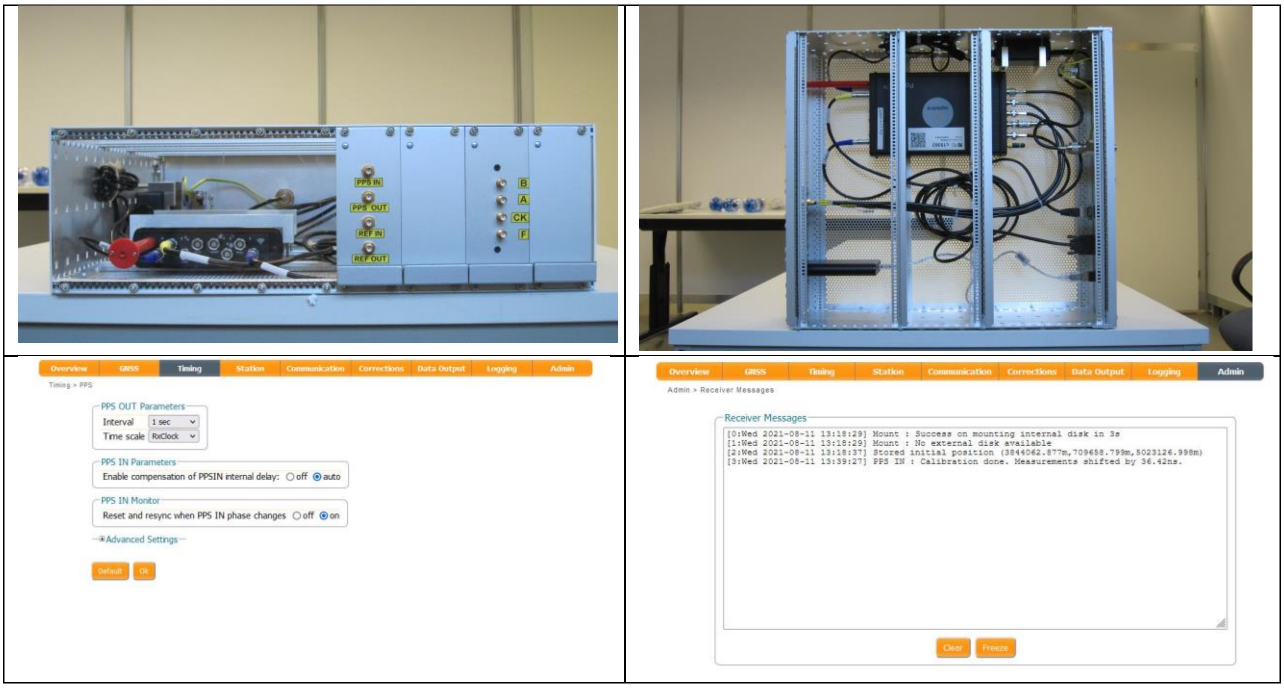


**Figure 1-1 PTBM: views of the device and RxControl configuration and messages regarding PPS In and OUT.**

# 2. DATA USED

The G, T, and V receivers are all GNSS geodetic receivers and provide RINEX observation files. RINEX navigation files produced by the PT13 receiver were used for CC1 and CC2 analysis. RINEX navigation files from PTBM were used at all stages. Code measurements were taken from the pseudoranges directly read from the RINEX files by the software DCLRINEX dedicated to differential calibration, as provide by BIPM [RD03]. The software produces raw code differences of co-located receivers from the pseudoranges as

$$\mathrm{RAW\ DIF}_{\mathrm{T-G}}(f) = \mathrm{TOT\ DLY}_{\mathrm{T}}(f) - \mathrm{TOT\ DLY}_{\mathrm{G}}(f), \tag{1}$$

with $TOT\ DLY_R(f)$ and $TOT\ DLY_T(f)$ representing the total delays of the reference and traveling receiver respectively. The total delay of G, or T can be written as

$$\mathrm{TOT\ DLY}(f) = \mathrm{INT\ DLY}(f) + \mathrm{CAB\ DLY} - \mathrm{REF\ DLY}. \tag{2}$$

This report states the differences in system delays ΔSYS DLY according to [RD08]. The system delay is described as the sum of the INT DLY and the CAB DLY.

$$\mathrm{SYS\ DLY}(f) = \mathrm{INT\ DLY}(f) + \mathrm{CAB\ DLY} \tag{3}$$

The ΔSYS DLY for T-G and T-V can therefore be calculated from the raw code differences and the reference delays as

$$\Delta\mathrm{SYS\ DLY}_{\mathrm{T-G}}(f) = \mathrm{RAW\ DIF}_{\mathrm{T-G},median}(f) + \mathrm{REF\ DLY}_{\mathrm{T}} - \mathrm{REF\ DLY}_{\mathrm{G}} \tag{4}$$

and

$$\Delta\mathrm{SYS\ DLY}_{\mathrm{T-V}}(f) = \mathrm{RAW\ DIF}_{\mathrm{T-V},median}(f) + \mathrm{REF\ DLY}_{\mathrm{T}} - \mathrm{REF\ DLY}_{\mathrm{V}}. \tag{5}$$

For the analysis of a measurement series, the RAW DIFs of all available satellites were averaged for each epoch. From this data, the median and standard deviation were determined.
Using (4) & (5), the ΔSYS DLY for V-G can be written in the form

$$\Delta\mathrm{SYS\ DLY}_{\mathrm{V-G}}(f) = \Delta\mathrm{SYS\ DLY}_{\mathrm{T-G}}(f) - \Delta\mathrm{SYS\ DLY}_{\mathrm{T-V}}(f). \tag{6}$$

Therefore, the equation

$$\mathrm{INT\ DLY}_{\mathrm{V}}(f) = \mathrm{INT\ DLY}_{\mathrm{G}}(f) + \Delta\mathrm{SYS\ DLY}_{\mathrm{V-G}}(f) + \mathrm{CAB\ DLY}_{\mathrm{G}} - \mathrm{CAB\ DLY}_{\mathrm{V}} \tag{7}$$

can be used to calculate the INT DLY of all visited receivers.

The analysis also includes the time deviations of the measurement series. The time instability (TDEV) values were determined from the epoch-averaged timelines. If applicable, data gaps in the timeline were filled using the algorithm developed by D. A. Howe and N. Schlossberger [RD07], before TDEV analysis.

# 3. RESULTS OF RAW DATA PROCESSING

## 3.1. OVERVIEW

The raw code differences of the pairs of co-located receivers during the data acquisition period are generated using the DCLRINEX software. The stated raw calibration results are taken as the median of the raw differences. The associated uncertainties are derived from the TDEV at 50000 s. The default value of 0.1 ns is chosen if the measured TDEV is less than 0.1 ns.

**Table 3-1 Summary information on the raw calibration results for GPS signals (all values in ns)**

| Pair | Date | RAWDIF(P1) | Unc. | RAWDIF(P2) | Unc. |
|---|---|---|---|---|---|
| PTBM-PT13 | 60159 - 60165 | 58.82 | 0.1 | 59.56 | 0.1 |
| PTBM-MI04 | 60180 - 60186 | 275.31 | 0.1 | 273.37 | 0.1 |
| PTBM-MI05 | 60180 - 60186 | 164.93 | 0.1 | 164.12 | 0.1 |
| PTBM-PT13 | 60216 - 60222 | 59.07 | 0.1 | 56.64 | 0.1 |

**Table 3-2 Summary information on the raw calibration results for Galileo signals (all values in ns)**

| Pair | Date | RAWDIF(E1) | Unc. | RAWDIF(E5a) | Unc. |
|---|---|---|---|---|---|
| PTBM-PT13 | 60159 - 60165 | 59.07 | 0.1 | 56.64 | 0.1 |
| PTBM-MI04 | 60180 - 60186 | - | - | - | - |
| PTBM-MI05 | 60180 - 60186 | 164.69 | 0.1 | 162.81 | 0.1 |
| PTBM-PT13 | 60216 - 60222 | 59.94 | 0.1 | 57.31 | 0.1 |

## 3.2. COMMON-CLOCK SET-UP IN PTB: PERIOD 1

For CC1, PTBM was operated for 7 days at PTB. The installation of the receivers in PTB is depicted in Figure 3-1 for PPS signals and in Figure 3-2 for 5 MHz (and 10 MHz) signals.

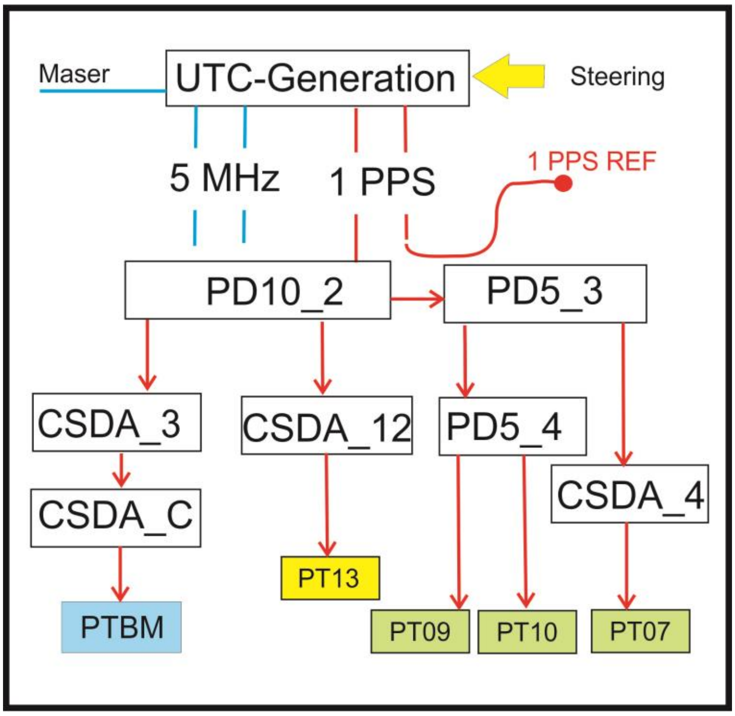


**Figure 3-1 UTC(PTB) reference point and 1 PPS signal distribution to PT13, PTBM, and other receivers; PD10 stands for pulse distributor, CSDA stands for clock signal distribution amplifier**

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 3-3 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall) during CC1.

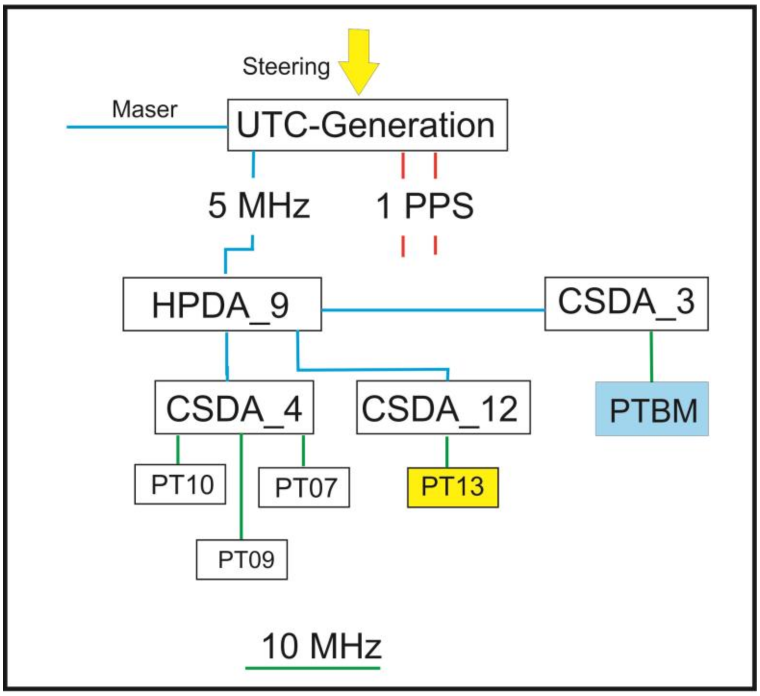


**Figure 3-2 UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, PTBM, and other receivers**

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

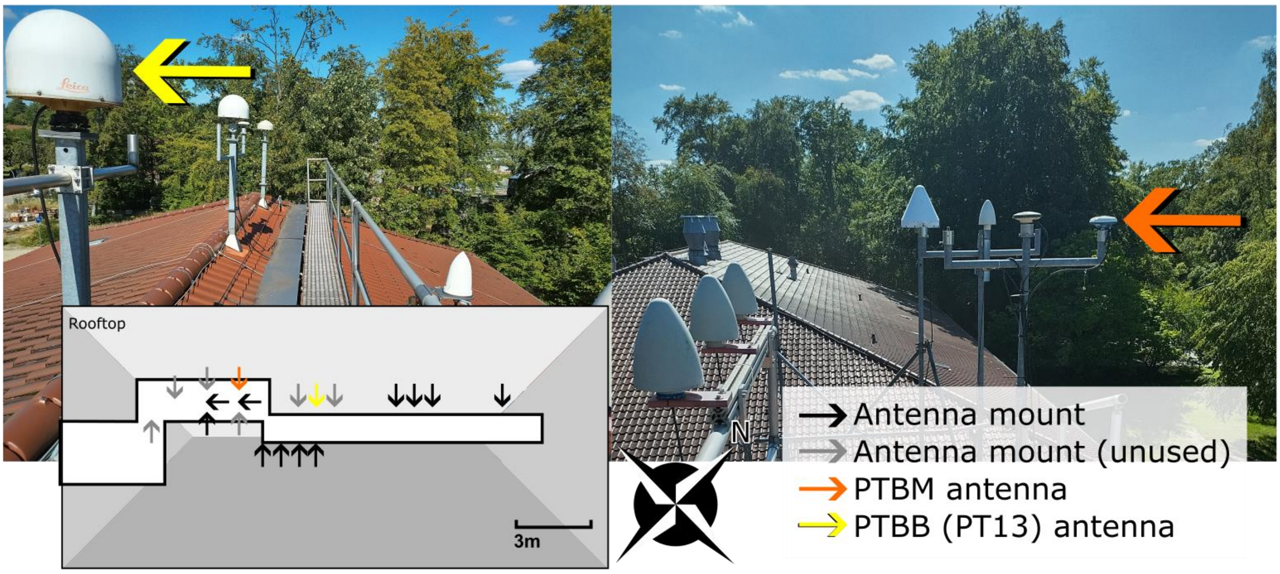


**Figure 3-3 Installation of GNSS antennas at PTB, PT13 antenna (yellow) and PTBM antenna during CC1 and CC2 (orange)**

The period 60159 to 60165 (7 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 B-1 and Figure B-2. The figures show the raw code differences and the corresponding TDEVs. The numerical results are given in Table 3-1 and Table 3-2.

## 3.3. OPERTATION OF PTBM AT VTT

The PTBM was dispatched and set-up at VTT on 22nd of August 2023 and was operated from the same day onwards for 20 days. VTT operates two GNSS receivers with designation MI04 and MI05 whose delays were determined. Information sheets about these receivers are shown in Annex A. MI04 is a DICOM GTR51 GNSS receiver operated during the campaign with the software version 1.2.6. A GTR51 with software version 1.4.0 and older automatically compensates for INT DLY, REF DLY and CAB DLY in it´s produced RINEX files. Therefore, the RAW DIFs for MI04, as listed in table 3-1 and 3-2, already contain these delays. For better understanding, the RAW DIF values in table 4-2 were reverse calculated to not include the aforementioned delays.

The PPS and 10 MHz signal distribution to receiver PTBM and VTT receivers is illustrated in Figure 3-4.

The antenna installation at VTT is illustrated Figure 3-5 PTBM was operated with its own antenna and antenna cable.

Raw code differences and the corresponding TDEVs are shown in Annex B starting with Figure B-3 to B-5. The numerical results are given in Table 3-1 and Table 3-2.

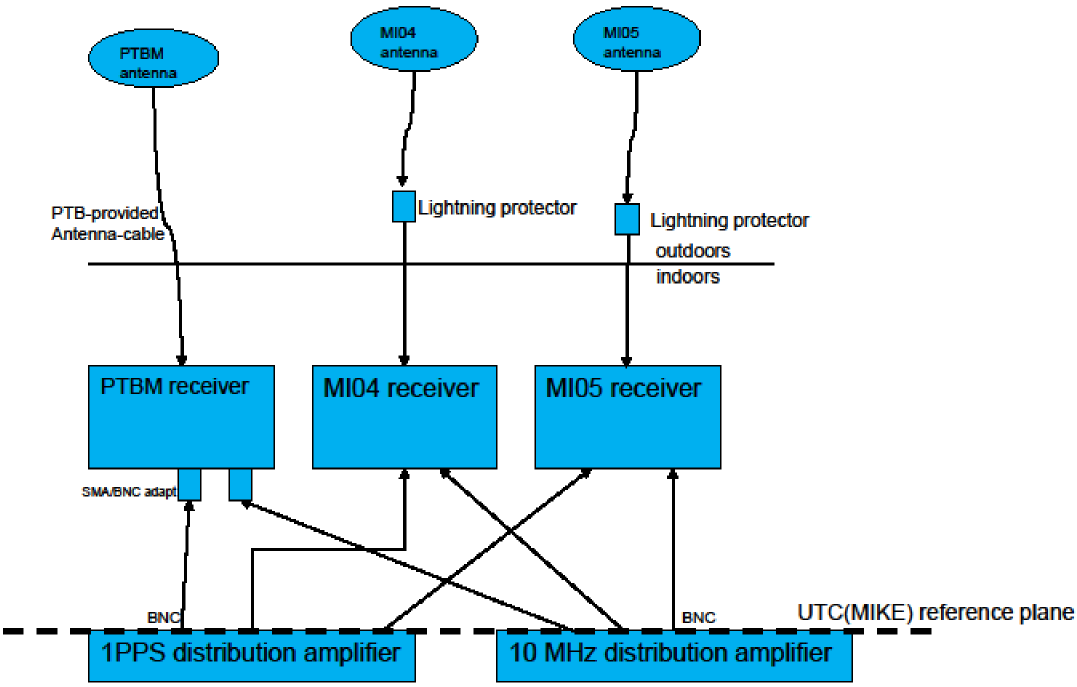


**Figure 3-4 PPS signal distribution at VTT to the receivers**

**Figure 3-5 PTBM antenna installation at VTT**

## 3.4. COMMON-CLOCK SET-UP IN PTB: PERIOD 2

The period 60216 to 60222 (7 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 result of comparison with PT13 as the reference are shown in Figure B- and Figure B-. The figures show the raw code differences and the corresponding TDEVs. The numerical results are given in Table 3-1 and Table 3-2.

# 4. CALIBRATION RESULTS

## 4.1. TRAVELING SYSTEM WITH RESPECT TO THE REFERENCE SYSTEM

**Table 4-1 Calibration results T vs. G (all values in ns)**

| Pair | Date | REF $DLY_T$ | REF $DLY_G$ | RAW DIF | ΔSYS $DLY_{T-G}$ | Code |
|---|---|---|---|---|---|---|
| PTBM-PT13 | 60159 - 60165 | 43.2 | 56.2 | 58.82 | 45.8 | P1 |
| PTBM-PT13 | 60159 - 60165 | 43.2 | 56.2 | 59.56 | 46.6 | P2 |
| PTBM-PT13 | 60159 - 60165 | 43.2 | 56.2 | 59.07 | 46.1 | E1 |
| PTBM-PT13 | 60159 - 60165 | 43.2 | 56.2 | 56.64 | 43.6 | E5a |
| PTBM-PT13 | 60216 - 60222 | 42.8 | 56.2 | 59.68 | 46.3 | P1 |
| PTBM-PT13 | 60216 - 60222 | 42.8 | 56.2 | 60.49 | 47.1 | P2 |
| PTBM-PT13 | 60216 - 60222 | 42.8 | 56.2 | 59.87 | 46.5 | E1 |
| PTBM-PT13 | 60216 - 60222 | 42.8 | 56.2 | 57.31 | 43.9 | E5a |

## 4.2. TRAVELING SYSTEM WITH RESPECT TO THE VISITED SYSTEM

**Table 4-2 Calibration results T vs. V (all values in ns)**

| Pair | Date | REF $DLY_T$ | REF $DLY_V$ | RAW DIF | ΔSYS $DLY_{T-V}$ | Code |
|---|---|---|---|---|---|---|
| PTBM-MI04 | 60180 - 60186 | 8.25 | 8.58 | 107.49 | 107.16 | P1 |
| PTBM-MI04 | 60180 - 60186 | 8.25 | 8.58 | 105.45 | 105.12 | P2 |
| PTBM-MI04 | 60180 - 60186 | - | - | - | - | E1 |
| PTBM-MI04 | 60180 - 60186 | - | - | - | - | E5a |
| PTBM-MI05 | 60180 - 60186 | 8.25 | 5.09 | 164.93 | 168.09 | P1 |
| PTBM-MI05 | 60180 - 60186 | 8.25 | 5.09 | 164.12 | 167.28 | P2 |
| PTBM-MI05 | 60180 - 60186 | 8.25 | 5.09 | 164.69 | 167.85 | E1 |
| PTBM-MI05 | 60180 - 60186 | 8.25 | 5.09 | 162.81 | 165.97 | E5a |

## 4.3. VISITED SYSTEM WITH RESPECT TO THE REFERENCE SYSTEM

**Table 4-3 Calibration results V vs. G (all values in ns)**

| Pair | Date | CAB $DLY_V$ | CAB $DLY_G$ | ΔSYS $DLY_{V-G}$ | ΔINT $DLY_{V-G}$ | Code |
|---|---|---|---|---|---|---|
| PT13-MI04 | 2023 | 215.4 | 205.7 | -61.11 | -70.8 | P1 |
| PT13-MI04 | 2023 | 215.4 | 205.7 | -58.28 | -68.0 | P2 |
| PT13-MI04 | 2023 | - | - | - | - | E1 |
| PT13-MI04 | 2023 | - | - | - | - | E5a |
| PT13-MI05 | 2023 | 96.2 | 205.7 | -122.04 | -12.5 | P1 |
| PT13-MI05 | 2023 | 96.2 | 205.7 | -120.43 | -10.9 | P2 |
| PT13-MI05 | 2023 | 96.2 | 205.7 | -121.54 | -12.0 | E1 |
| PT13-MI05 | 2023 | 96.2 | 205.7 | -122.19 | -12.7 | E5a |

The numerical results of the two common-clock campaigns at PTB are given in Table 4-1. The ΔSYS $DLY_{T-G}$ values agree very well with the largest change noted between CC1 and CC2 amounting 0.07 ns for P1.

## 4.4. INT DLY UNCERTAINTY EVALUATION

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

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}\,, \qquad (8)$$

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

$$u_b = \sqrt{\sum_n u_{b,n}^2}. \qquad (9)$$

The contributions to the sum (9) are listed and explained subsequently. Values in column P3 are calculated according to $u(P3) = \sqrt{u(P1)^2 + (1.54 \times u(P1-P2))^2}$. Uncertainties for the Galileo delays are calculated according to $\sqrt{u(E1)^2 + (1.26 \times u(E1-E5a))^2}$.

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 4-4 Uncertainty contributions for the calibration of receiver delays at VTT, all values in ns**

| | Uncertainty | Value f1 | Value f2 | Value f1-f2 | Value f3 | Description |
|---|---|---|---|---|---|---|
| 1 | $u_a$ (PTB) | 0.1 | 0.1 | 0.14 | | CC measurement uncertainty at PTB, TDEV max. of the two CC campaigns |
| 2 | $u_a$ (VTT) | 0.1 | 0.1 | 0.14 | | CC measurement uncertainty, for the VTT receivers |
| 3a | $u_a$ (GPS) | 0.14 | 0.14 | 0.2 | 0.34 | |
| 3b | $u_a$ (Galileo) | 0.14 | 0.14 | 0.2 | 0.29 | |
| **Result of closure measurement at PTB** | | | | | | |
| 4a | $u_{b,1}$ (GPS) | 0.43 | 0.49 | 0.65 | | Misclosure, see Table 4-1 |
| 4b | $u_{b,1}$ (Galileo) | 0.44 | 0.34 | 0.55 | | Misclosure, see Table 4-1 |
| **Systematic components due to antenna installation** | | | | | | |
| 5 | $u_{b,11}$ | 0.2 | 0.2 | 0.28 | | Multipath at PTB |
| 6 | $u_{b,12}$ | 0.2 | 0.2 | 0.28 | | Multipath at VTT |
| **Installation of PTBM and visited receivers** | | | | | | |
| 7 | $u_{b,21}$ | 0.2 | 0.2 | 0 | | Connection of PTBM to UTC(PTB) (REF DLY) |
| 8 | $u_{b,22}$ | 0.2 | 0.2 | 0 | | Connection of PTBM to UTC(VTT) (REF DLY) |
| 9 | $u_{b,23}$ | 0.2 | 0.2 | 0 | | Connection of receivers at VTT to UTC(VTT) (REF DEL) |
| 10 | $u_{b,24}$ | 0.1 | 0.1 | 0 | | TIC nonlinearities at PTB |
| 11 | $u_{b,25}$ | 0.1 | 0.1 | 0 | | TIC nonlinearities at VTT |
| **Antenna cable delay** | | | | | | |
| 12 | $u_{b,31}$(PTB) | 0.5 | 0.5 | 0 | | Uncertainty estimation for the PTBM CAB DLY when installed at PTB |
| 13 | $u_{b,32}$(VTT) | 0 | 0 | 0 | | Uncertainty estimation for the PTBM CAB DLY when installed at VTT |
| 14 | $u_{b,33}$(VTT) | 0.5 | 0.5 | 0 | | Uncertainty estimation for VTT CAB DLY values |
| **Total** | | | | | | |
| 15a | $u_{b,INT}$ (GPS) | 0.95 | 0.98 | 0.76 | 1.51 | |
| 15a | $u_{b,INT}$ (Galileo) | 0.95 | 0.91 | 0.68 | 1.28 | |
| 16a | $u_{CAL,0}$ (GPS) | | | | 1.55 | |
| 16a | $u_{CAL,0}$ (Galileo) | | | | 1.31 | |

As demonstrated in Table 3-1 and Table 3-2, the three receivers at VTT show almost the same time instability. The TDEV plots in Annex B show marginal differences, and the value of 0.1 ns is a conservative estimate anyway. Thus, a single uncertainty budget can cover all other contributions.

The uncertainty contribution $u_{b,1}$ is based on the difference between the two common clock campaigns involved which was very small for the current campaign. A conservative estimate of 0.1 ns was chosen.

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.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,11}$ and $u_{b,12}$. 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 all cases.

The uncertainty contributions $u_{b,24}$ and $u_{b,25}$ are related to imperfections in the TIC in conjunction with the relationship between the zero-crossings of the external reference frequency and the 1 PPS signals. This “nonlinearity” is probably caused by the internal interpolation process. By connecting the travelling TIC successively to 10 MHz, using cables of different lengths, the effect was estimated to be at most 0.1 ns if 1 PPS signals with a slew rate of approximately 0.5 V/ns are used.

The measurement of antenna cable delays causes contributions $u_{b,31,}$ $u_{b,32}$ and $u_{b,33.}$ During the current campaign the same PTBM cable was employed on 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 an 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 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.

# 5. FINAL RESULTS FOR THE VISITED SYSTEMS

The results of the calibration campaign G1G2_1019_2023 are summarized in Table 5-1 and Table 5-2. INT DLY values for the golden reference receiver PT13 were determined in 2021 [RD01]. The uncertainty values are taken from Table 4-4. The final INT DLY values were calculated using equation (7) with the values listed in Table 4-1, Table 4-2 and Table 4-3.

**Table 5-1 Summary of final results for GPS links, all values in ns**

| Reference system | Cal_Id | Date | | INT DLY (P1) | INT DLY (P2) |
|---|---|---|---|---|---|
| PT13 | 1001-2020 | 59303 | | 31.6 | 29.3 |
| **Visited system** | **Cal_Id** | **Date** | **$u_{CAL}$ (P3)** | **INT DLY (P1)** | **INT DLY (P2)** |
| MI04 | 1019-2023 | 60223 | 1.0 | -39.2 | -38.7 |
| MI05 | 1019-2023 | 60223 | 1.0 | 19.1 | 18.4 |

**Table 5-2 Summary of final results for the Galileo links, all values in ns**

| Reference system | Cal_Id | Date | | INT DLY (E1) | INT DLY (E5a) |
|---|---|---|---|---|---|
| PT13 | 1001-2020 | 59303 | | 33.6 | 33.6 |
| **Visited system** | **Cal_Id** | **Date** | **$u_{CAL}$ (P3)** | **INT DLY (E1)** | **INT DLY (E5a)** |
| MI04 | 1019-2023 | - | - | - | - |
| MI05 | 1019-2023 | 60223 | 1.1 | 21.6 | 20.9 |

# ANNEXES

ANNEX A: BIPM INFORMATION SHEETS
ANNEX B: PLOTS OF RAW DATA AND TDEV ANALYSIS

# ANNEX A: BIPM CALIBRATION INFORMATION SHEETS

## First common clock measurement at PTB

| | |
|---|---|
| **Laboratory:** | **PTB** |
| Date and hour of the beginning of | 2023-08-03 00:00 UTC (MJD 60159) |
| Date and hour of the end of measurements: | 2022-08-09 23:59 UTC (MJD 60165) |

| **Information on the system** | | |
|---|---|---|
| | **Local:** | **Traveling:** |
| 4-character BIPM code | **PT13** | **PTBM** |
| Receiver maker and type:<br>Receiver serial number: | PolaRx5TR (5.2.0)<br>S/N 470 1292 | PolaRx5TR (5.4.0)<br>S/N 3048338 |
| 1 PPS trigger level /V: | 1 | 1 |
| Antenna cable maker and type:<br>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<br>726333, Calib Geo++ 18.08.2015 | Navexperience 3G+C REFERENCE<br>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 VTT: Receiver MI04

| **Laboratory:** | **VTT** |
|---|---|
| Date and hour of the beginning of measurements: | 2023-08-22 ca. 13:00+03 |
| Date and hour of the end of measurements: | 2023-09-11 |

| **Information on the system** | | |
|---|---|---|
| | **Local:** | **Travelling:** |
| 4-character BIPM code | **MI04** | **PTBM** |
| Receiver maker and type:<br>Receiver serial number: | Dicom GTR51 (1.2.6)<br>S/N 1403001 | Septentrio PolaRx5TR (5.4.0)<br>3048338 |
| 1 PPS trigger level /V: | 1.0 | 1.0 |
| Antenna cable maker and type:<br>Phase stabilized cable (Y/N): | Armored cable, N-connecntors<br>N | N-type, LMR400, N-connectors<br>N |
| Length outside the building /m: | ca. 10 m | ca. 10 m |
| Antenna maker and type:<br>Antenna serial number: | NOV703GGG.R2<br>NEG1405022 | Navexperience 3G+C reference<br>S/N RE 0560 |
| Temperature (if stabilized) /°C | - | - |

| **Measured delays /ns** | | |
|---|---|---|
| | **Local:** | **Travelling:** |
| Delay from local UTC to receiver 1 PPS-in ($X_P$) / ns | 8.579 | 8.247 |
| Delay from 1 PPS-in to internal Reference (if different): ($X_O$) / ns | N/A | N/A |
| Antenna cable delay: ($X_C$) / ns | 215.4 | 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: | N/A | N/A |
| ☐ INT DLY (or $X_R+X_S$) (GALILEO) /ns: | N/A | N/A |
| ☐ CAB DLY (or $X_C$) /ns: | N/A | N/A |
| ☐ REF DLY (or $X_P+X_O$) /ns: | N/A | N/A |
| ☐ Coordinates reference frame: | N/A | N/A |
| X /m: | N/A | N/A |
| Y /m: | N/A | N/A |
| Z /m | N/A | N/A |

| **General information** | |
|---|---|
| ☐ Rise time of the local UTC pulse: | 1.49 ns 10% to 90% rise time |
| ☐ Is the laboratory air conditioned: | Yes |
| Set temperature value and uncertainty: | 20 °C to 22 °C variation during one week |

# PTBM operation at VTT: Receiver MI05

| **Laboratory:** | **VTT** |
|---|---|
| Date and hour of the beginning of measurements: | 2023-08-22 ca. 13:00+03 |
| Date and hour of the end of measurements: | 2023-09-11 |

| **Information on the system** | | |
|---|---|---|
| | **Local:** | **Travelling:** |
| 4-character BIPM code | **MI05** | **PTBM** |
| Receiver maker and type:<br>Receiver serial number: | Septentrio PolaRx5TR (5.5.0)<br>3046486 | Septentrio PolaRx5TR (5.4.0)<br>3048338 |
| 1 PPS trigger level /V: | 1.0 | 1.0 |
| Antenna cable maker and type:<br>Phase stabilized cable (Y/N): | Phoenix Contact, LMR-400, N-connectors<br>N | N-type, LMR400, N-connectors<br>N |
| Length outside the building /m: | ca. 10 m | ca. 10 m |
| Antenna maker and type:<br>Antenna serial number: | Tallysmann VP6050C<br>VP6050C1901240012 | Navexperience 3G+C reference<br>S/N RE 0560 |
| Temperature (if stabilized) /°C | - | - |

| **Measured delays /ns** | | |
|---|---|---|
| | **Local:** | **Travelling:** |
| Delay from local UTC to receiver 1 PPS-in ($X_P$) / ns | 5.092 | 8.247 |
| Delay from 1 PPS-in to internal Reference (if different): ($X_O$) / ns | N/A | N/A |
| Antenna cable delay: ($X_C$) / ns | 96.2 | 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: | N/A | N/A |
| ☐ INT DLY (or $X_R+X_S$) (GALILEO) /ns: | N/A | N/A |
| ☐ CAB DLY (or $X_C$) /ns: | N/A | N/A |
| ☐ REF DLY (or $X_P+X_O$) /ns: | N/A | N/A |
| ☐ Coordinates reference frame: | N/A | N/A |
| X /m: | N/A | N/A |
| Y /m: | N/A | N/A |
| Z /m | N/A | N/A |

| **General information** | |
|---|---|
| ☐ Rise time of the local UTC pulse: | 1.49 ns 10% to 90% rise time |
| ☐ Is the laboratory air conditioned: | Yes |
| Set temperature value and uncertainty: | 20 °C to 22 °C variation during one week |

# 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:<br>Receiver serial number: | PolaRx5TR (5.2.0)<br>S/N 470 1292 | | PolaRx5TR (5.3.0)<br>S/N 3048338 | |
| 1 PPS trigger level /V: | 1 | | 1 | |
| Antenna cable maker and type:<br>Phase stabilized cable (Y/N): | ECOFLEX15 | | LMR-400 (N) | |
| Length outside the building /m: | approx. 25 | | 25 | |
| Antenna maker and type: Antenna serial number: | LEICA AR25<br>726333, Calib Geo++ 18.08.2015 | | Navexperience 3G+C REFERENCE<br>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 (#) | | 41.13 | |
| 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) (****)<br>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: | 54.3 | | 41.13 | |
| ☐ 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:

(#) 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 CAL_ID 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

# . ANNEX B: PLOTS OF RAW DATA AND TDEV ANALYSIS

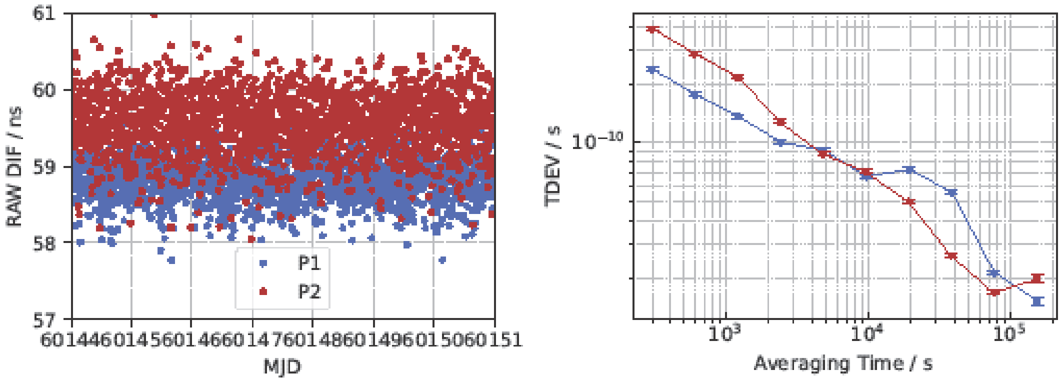


**Figure B-1 Left: Raw code differences between T and G for GPS signals during CC1, ΔP1 (blue) and ΔP2 (red) Right: TDEV of the raw code differences between T and G for GPS signals during CC1.**

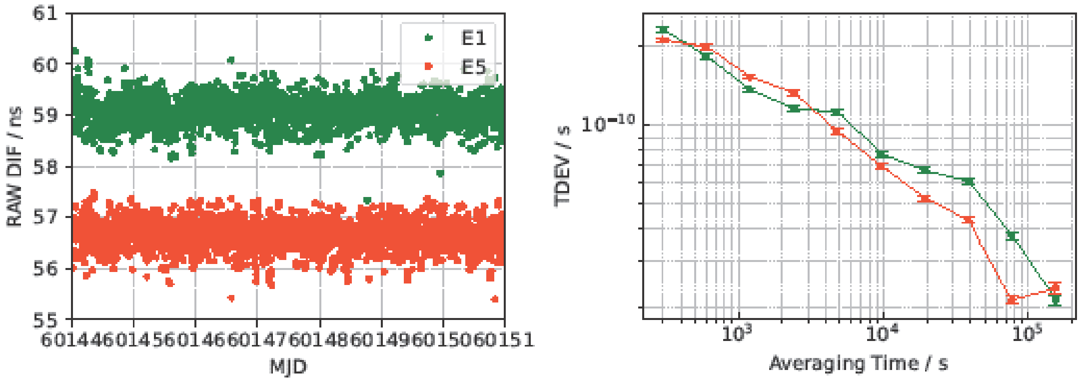


**Figure B-2 Left: Raw code differences between T and G for Galileo signals during CC1, ΔE1 (green) and ΔE5a (orange) Right: TDEV of the raw code differences between T and G for Galileo signals during CC1.**

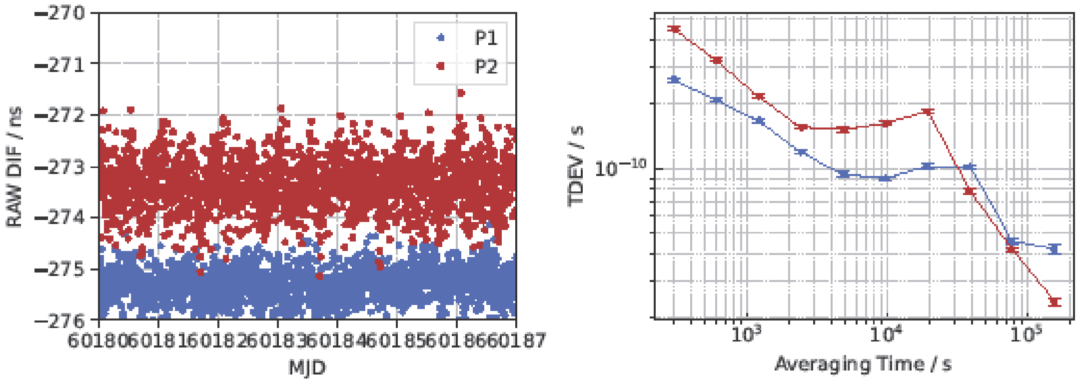


**Figure B-3 Left: Left: Raw code differences between T and MI04 for GPS signals, ΔP1 (blue) and ΔP2 (red) Right: TDEV of the raw code differences between T and MI04 for GPS signals.**

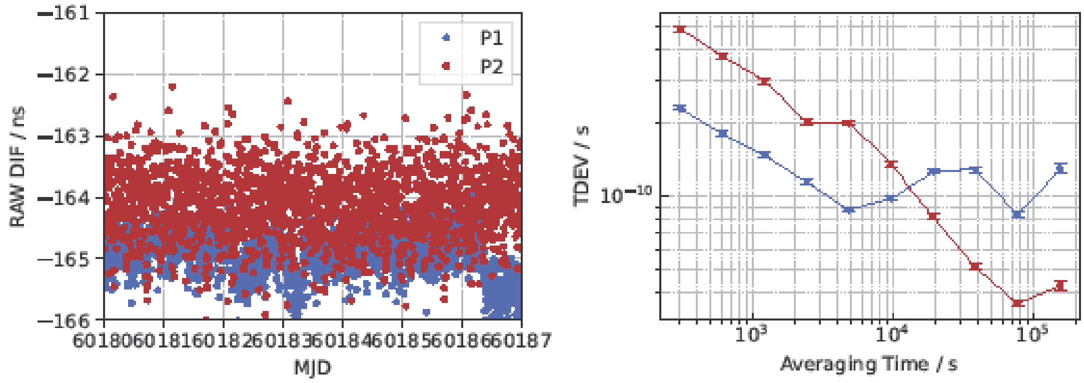


**Figure B-4 Left: Left: Raw code differences between T and MI05 for GPS signals, ΔP1 (blue) and ΔP2 (red) Right: TDEV of the raw code differences between T and MI05 for GPS signals.**

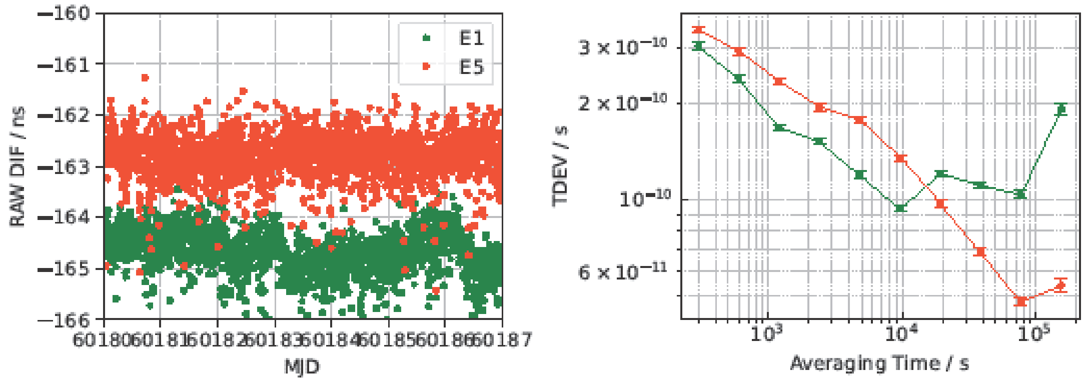


**Figure B-5 Left: Raw code differences between T and MI05 for Galileo signals, ΔE1 (green) and ΔE5a (orange) Right: TDEV of the raw code differences between T and MI05 for Galileo signals.**

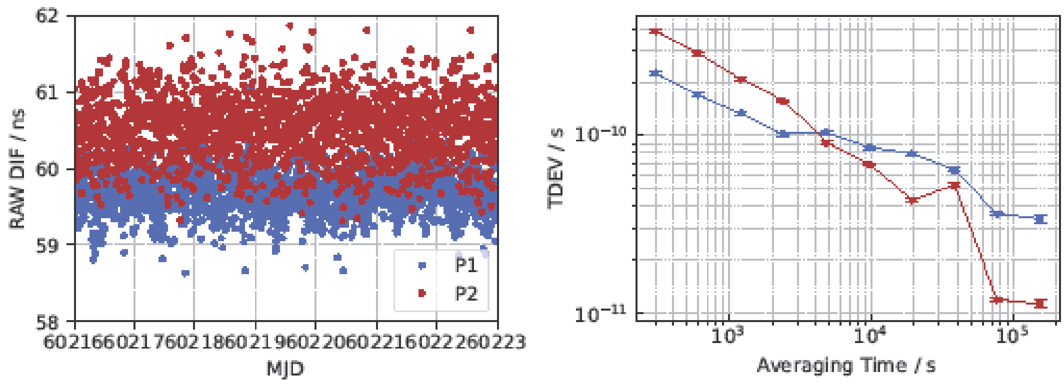


**Figure B-6 Left: Raw code differences between T and G for GPS signals during CC2, ΔP1 (blue) and ΔP2 (red) Right: TDEV of the raw code differences between T and G for GPS signals during CC2.**

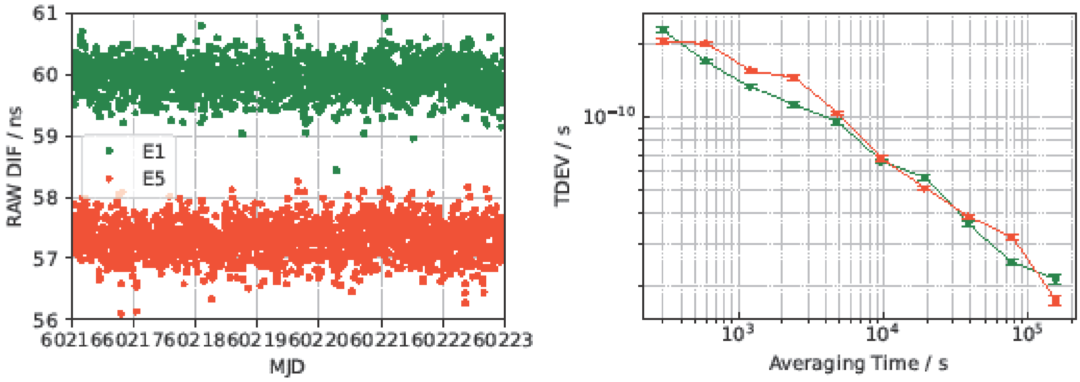


**Figure B-7 Left: Raw code differences between T and G for Galileo signals during CC2, ∆E1 (green) and ∆E5a (orange) Right: TDEV of the raw code differences between T and G for Galileo signals during CC2.**

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