GNSS CALIBRATION REPORT

G1G2_1202_2024

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REFERENCES

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RD01	**2022 Group 1 GNSS calibration trip (CAL_ID 1001-2022)**
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**
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**
SMU	**Slovak Institute of Metrology**
TDEV	**Time Deviation**
TIC	**Time Interval Counter**

EXECUTIVE SUMMARY

As part of the support of the BIPM Time and Frequency Group by EURAMET G1 laboratories, PTB conducted a relative calibration of GNSS equipment of SMU 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 1001-2022 [RD01]. The receiver SM00 was shipped from SMU to PTB and operated there for the purpose of its calibration. It was subsequently sent back to SMU. The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using CAL_ID 1202-2024. Results provided are the visited receiver's internal delays for GPS P-code signals on the two frequencies L1 and L2 (INT DLY (P1), and INT DLY(P2)) and the C/A-code signal on L1 (L1C). 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].

As mentioned above, the determination of the internal delay values was done as a one-step process. The receiver to be calibrated was send to PTB and directly compared to the "golden" receiver, PT13.

The structure of this report is as follows. 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. 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. The internal delays of receiver SM00 were determined with an uncertainty of 5.8 ns for dual frequency observations.

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

1. DESCRIPTION OF EQUIPMENT AND OPERATIONS

1.1. PARTICIPANTS

Table 1-1 List of participants

Institute	Point of contact	Site address
PTB	Florian Heimbach +49 531 592 4422 florian.heimbach@ptb.de	PTB, AG 4.42 Bundesallee 100 38116 Braunschweig, Germany
SMU	Juraj Slučiak +421 2 602 94 382 sluciak@smu.gov.sk	Slovak Institute of Metrology Karloveská 63 84255 Bratislava, Slovakia

1.2. EQUIPMENT

PTB received the GNSS equipment from SMU and operated it at their local site. The equipment contained a GNSS receiver (Piktime TTS-3), as well as an antenna (Javad MarAnt+) and antenna cable. These are the very same with which the receiver is operated at SMU. Since the antenna cable was too short for the setup at PTB a different cable (LMR-400), provided by PTB, was used instead. The delay from the UTC reference point to the calibration reference point and the antenna cable delay was measured by a Keysight 53230A (SN: 2260) TIC.

Table 1-2 List of the visited equipment

Institute	Status of equipment	Dates of measurement	Receiver type	BIPM code	RINEX name
SMU	Group 2	20.05.2014 – 01.06.2024	TTS-3	SM00	SMU1

1.3. 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 1001-2022 [RD01]. In the current campaign, instead of shipping a traveling receiver to the G2 lab, the so called visited receiver was shipped to the G1 lab. In this constellation, V can directly be compared to G. The nomenclature V will be kept for the visiting receiver.

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.

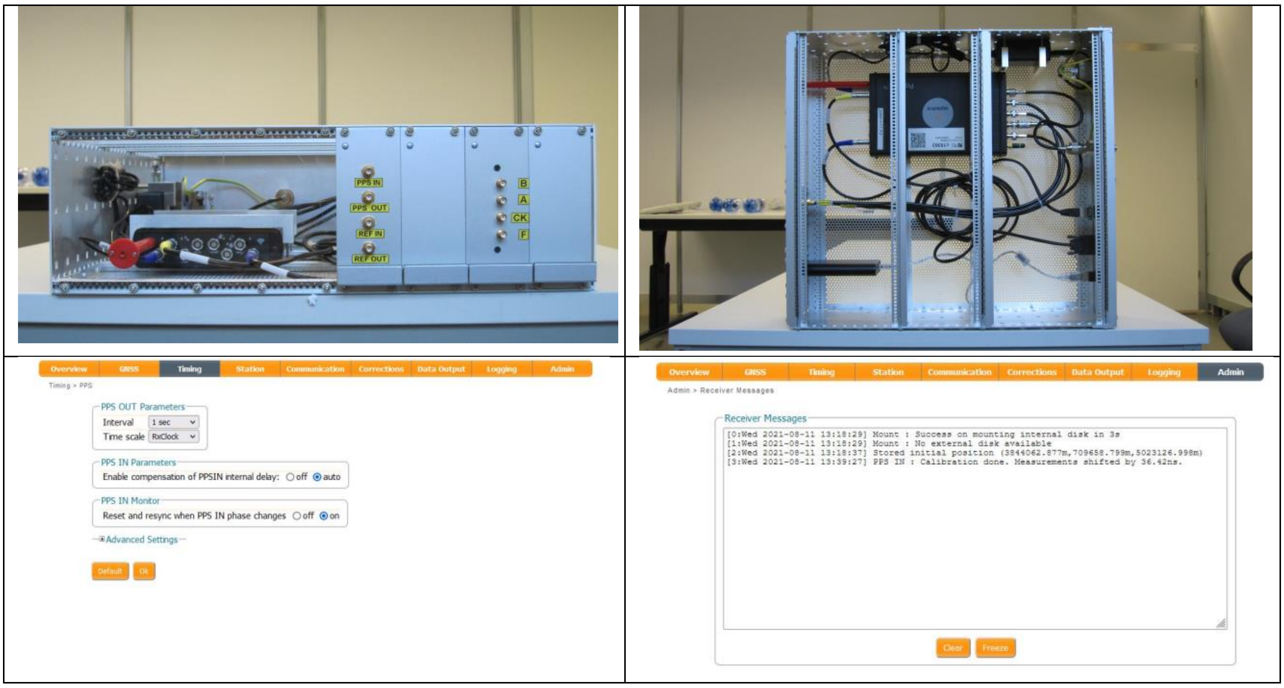

Figure 1-1 PTBM: views of the device and RxControl configuration and messages regarding PPS In and OUT.

2. DATA USED

The G and V receivers are all GNSS geodetic receivers and provide RINEX observation files. 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

$$\mathrm{RAW\ DIF_{V-G}}(f) = \mathrm{TOT\ DLY}_V(f) - \mathrm{TOT\ DLY_G}(f), \quad (1)$$

with $TOT\ DLY_G(f)$ and $TOT\ DLY_V(f)$ representing the total delays of the reference and visited receiver respectively. Note that in this case the visited receiver is visiting the reference lab. The nomenclature was kept the same. The total delay of G, or V can be written as

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

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.

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

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

$$\Delta\mathrm{SYS\ DLY_{V-G}}(f) = \mathrm{RAW\ DIF}_{\mathrm{V-G},median}(f) + \mathrm{REF\ DLY}_V - \mathrm{REF\ DLY_G}. \quad (4)$$

Therefore, the equation

$$\mathrm{INT\ DLY_V}(f) = \mathrm{INT\ DLY_G}(f) + \Delta\mathrm{SYS\ DLY_{V-G}}(f) + \mathrm{CAB\ DLY_G} - \mathrm{CAB\ DLY_V} \quad (7)$$

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 pair 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 uncertainty is derived from the maximum TDEV.

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

Pair	Date	RAWDIF(C1)	RAWDIF(P1)	RAWDIF(P2)	Unc.
SM00-PT13	60450 - 60461	126.9	128.7	140.6	2.4

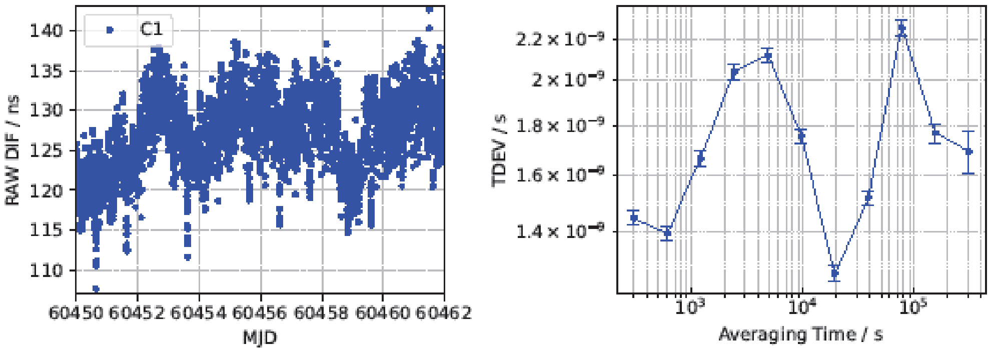

Figure 3-1 Left: Raw code differences between V and G for GPS C1 signals in a common clock setup, Right: TDEV of the raw code differences between T and G for GPS C1 signals.

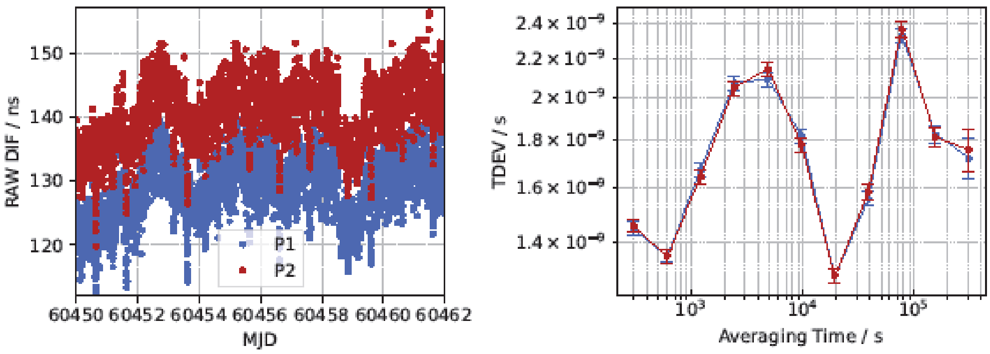

Figure 3-2 Left: Raw code differences between V and G for GPS signals in a common clock setup, ∆P1 (blue) and ∆P2 (red) Right: TDEV of the raw code differences between T and G for GPS signals

3.2. COMMON-CLOCK SET-UP IN PTB

The receiver SM00 was operated at PTB. The period 60450 to 60461 (12 days) was chosen to determine the RAW DIF values. The results of the comparison with PT13 as the reference are shown in Figure 3-1 and Figure 3-2. The figures show the raw code differences and the corresponding TDEVs. The numerical results are given in Table 3-1.

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

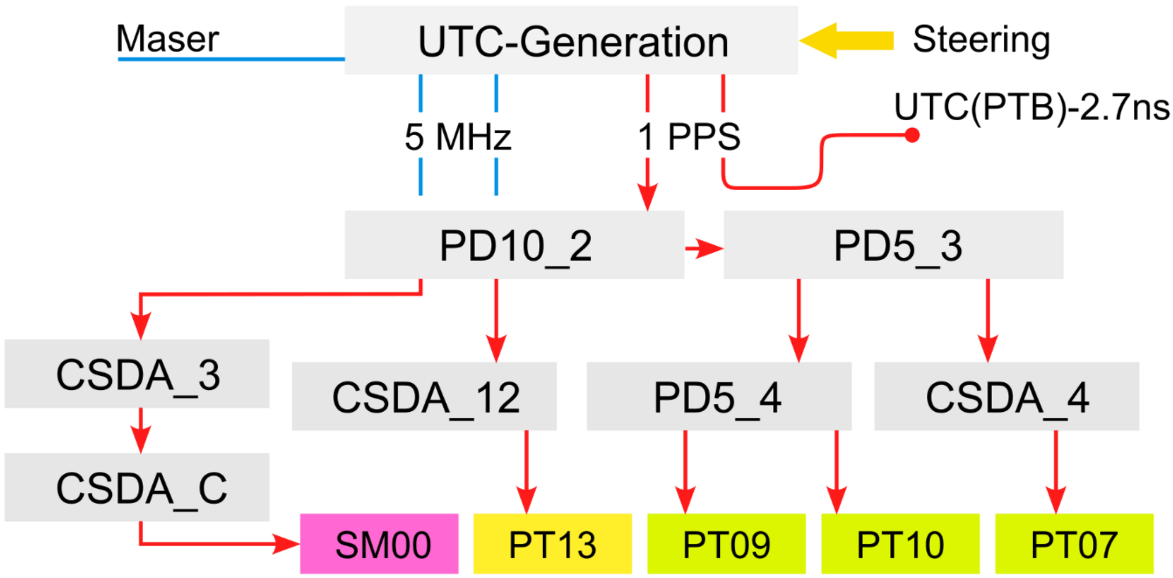

Figure 3-3 UTC(PTB) reference point and 1 PPS signal distribution to PT13, SM00, and other receivers; PD stands for pulse distributor, CSDA stands for clock signal distribution amplifier

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 3-5 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall).

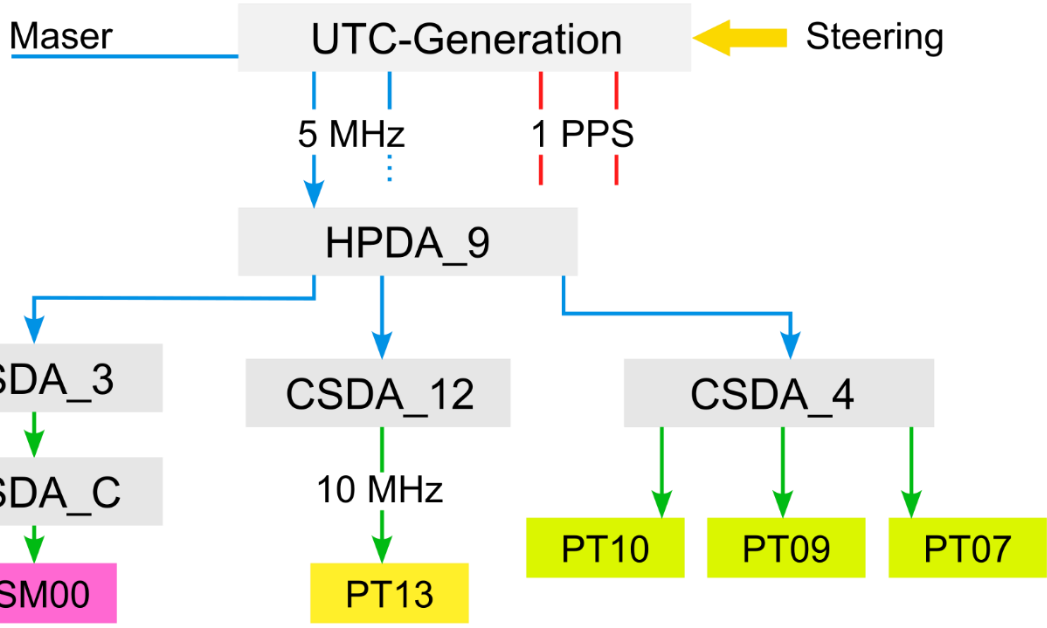

Figure 3-4 UTC(PTB) signal distribution (5 MHz, 10 MHz) to PT13, SM00, and other receivers

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

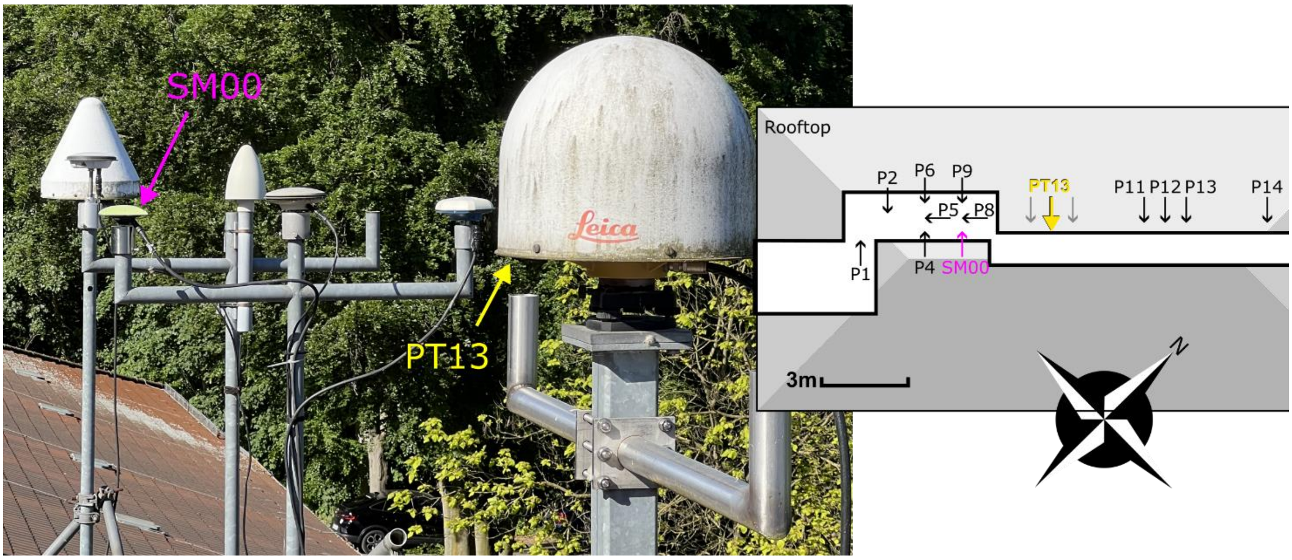

Figure 3-5 Installation of GNSS antennas at PTB, PT13 antenna (yellow) and XXX antenna (magenta)

4. CALIBRATION RESULTS

4.1. VISITED SYSTEM WITH RESPECT TO THE REFERENCE SYSTEM

The numerical results of the common-clock campaign at PTB are given in Table 3-1.

Table 4-1 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-SM00	2024	209.2	205.7	157.3	153.8	C1
PT13-SM00	2024	209.2	205.7	159.1	155.6	P1
PT13-SM00	2024	209.2	205.7	167.5	167.5	P2

4.2. INT DLY UNCERTAINTY EVALUATION

The overall uncertainty of the INT DLY values, obtained as a result of the calibration, are 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 4-2 Uncertainty contributions for the calibration of receiver delays at SMU, all values in ns

	Uncertainty	Value f1	Value f2	Value f1-f2	Value f3	Description
1	u_a (GPS)	2.4	2.4	3.4	5.8	CV measurement uncertainty, maximum TDEV at 76750 s
Systematic components due to antenna installation						
2	$u_{b,11}$	0.2	0.2	0.28		Multipath at PTB
Installation of visited receiver						
3	$u_{b,21}$	0.2	0.2	0		Connection of SM00 to UTC(PTB) (REF DLY)
4	$u_{b,22}$	0.1	0.1	0		TIC nonlinearities at PTB
Antenna cable delay						
5	$u_{b,31}$(PTB)	0.5	0.5	0		Uncertainty estimation for the SM00 CAB DLY when installed at PTB
6	$u_{b,32}$(SMU)	0.5	0.5	0		Uncertainty estimation for SM00 CAB DLY values
Total						
7	$u_{b,INT}$ (GPS)	0.77	0.77	0.28	0.88	
8	$u_{CAL,0}$ (GPS)				5.8	

The TDEV plots in Annex B show only marginal differences, thus, a single uncertainty budget was chosen to cover all other contributions.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,11}$. 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 uncertainty of the connection of the receiver to the local time scale ($u_{b,21}$) has been estimated as 0.2 ns.

The uncertainty contribution $u_{b,22}$ is 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 $u_{b,31}$ and $u_{b,32}$. During the current campaign the SM00 cable had to be exchanged, since the original one was too short for the setup at PTB. The measurement was made with a differential method so that the TIC-internal error should be small anyway. During previous campaign those measurement 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 of 0.5 ns.

5. FINAL RESULTS FOR THE VISITED SYSTEMS

The results of the calibration campaign G1G2_1202-2024 are summarized in Table 5-1. INT DLY values for the golden reference receiver PT13 were determined in 2021 [RD01]. The uncertainty values are taken from Table 4-2. The final INT DLY values were calculated using equation (7) with the values listed in Table 3-1 and Table 4-1.

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

Reference system	**Cal_Id**	**Date**		**INT DLY (C1)**	**INT DLY (P1)**	**INT DLY (P2)**
PT13	1001-2022	60054		33.6	30.96	28.50
Visited system	**Cal_Id**	**Date**	**u_{CAL} (P3)**	**INT DLY (C1)**	**INT DLY (P1)**	**INT DLY (P2)**
SM00	1202-2024	60524	5.8	182.3	186.6	196.0

ANNEXES

ANNEX A: BIPM INFORMATION SHEETS

ANNEX A: BIPM CALIBRATION INFORMATION SHEETS

Laboratory:	**PTB**
Date and hour of the beginning of	2023-12-28 00:00 UTC (MJD 60306)
Date and hour of the end of measurements:	2024-01-04 12:32 UTC (MJD 60313)

Information on the system		
	Local:	**Visiting:**
4-character BIPM code	**PT13**	**SM00**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	Piktime TTS-3 S/N
1 PPS trigger level /V:	1	1
Antenna cable maker and type: 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 726333, Calib Geo++ 18.08.2015	JAVAD MarAnt+ S/N 2610
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 (#)	86.6
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	46.63 ± 0.1 (#)	N/A
Antenna cable delay: (X_C) / ns	205.7 ± 0.1	209.2
Splitter delay (if any):	N/A	N/A

Data used for the generation of CGGTTS files				
	LOCAL:		Visiting	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	30.96 (P1), 28.5 (P2) (*)		0 (P1) 0 (P2) -30.7 (C1)	
☐ INT DLY (or X_R+X_S) (GALILEO) /ns:	33.19 (E1), 33.05 (E5a) (*)		-	
☐ CAB DLY (or X_C) /ns:	205.7		209.2	
☐ REF DLY (or X_P+X_O) /ns:	56.2		86.6	
☐ 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 1001-2022 [RD01]]
(***) values provided by BIPM via Mail 2019-08-07

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