GNSS CALIBRATION REPORT

G1G2_1201_2022

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REFERENCES

REFERENCES	
RD01	**BIPM report 2021 1001-2020_GPSP3C1-GALE3_Group1-trip_V1-2**
RD02	**BIPM guidelines for GNSS calibration, V4.0, 05/08/2021**
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**

ACRONYMS

ACRONYMS	
BIPM	**Bureau International de Poids et Mesures, Sèvres, France**
CGGTTS	**CCTF Generic GNSS Time Transfer Standard**
ESA	**European Space Agency**
EURAMET	**The European Association of National Metrology Institutes**
IGS	**International GNSS Service**
GNSS	**Global Navigation Satellite System**
NSC	**National Scientific Centre "Institute of Metrology", Charkiv, Ukraine**
PPP	**Precise Point Positioning**
PTB	**Physikalisch-Technische Bundesanstalt, Braunschweig, Germany**
RINEX	**Receiver Independent Exchange Format**
R2CGGTTS	**RINEX-to CGGTTS conversion software, provided by ORB / BIPM**
TDEV	**Time Deviation**
TIC	**Time Interval Counter**

EXECUTIVE SUMMARY

As part of the support of the BIPM Time and Frequency Group by EURAMET G1 laboratories, PTB conducted a relative calibration of a GNSS receiver of NSC with respect to PTB receiver PT13, which currently serves as the reference receiver in all GNSS dual-frequency time links to PTB in the context of realization of TAI. The receiver with designation UA04 (CGGTTS) and BORL (RINEX) was installed at PTB for the purpose. A campaign like this is denominated as "Golden System Calibration" in the BIPM Guide [RD02], and we followed as much as possible the Guide. Results will be reported using Cal_Id 1201_2022. Results provided are the UA04 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 equivalent for Galileo on frequencies E1 and E5a. The delay for GPS single-frequency C/A-code signals (L1C) was determined as well.

The PT13 signal delays for GPS and Galileo had been determined by BIPM as reported with CAL_ID 1001-2020 [RD01]

The final results for UA04 are included in Table 7-1 and Table 7-2. The receivers's internal delays were determined with an uncertainty below 1 ns for single frequency observations. The uncertainty for time transfer links to PTB evaluated in a ionosphere-free linear combination is also below 1 ns.

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

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 a GNSS receiver of NSC with respect to PTB receiver PT13, which currently serves as the reference receiver in all GNSS dual-frequency time links to PTB in the context of realization of TAI. The receiver with designation UA04 (CGGTTS) and BORL (RINEX) was installed at PTB for the purpose. A campaign like this is denominated as “Golden System Calibration” in the BIPM Guide [RD02], and we followed as much as possible the Guide. Results will be reported using Cal_Id 1201_2022.

This report documents the installation, data taking and evaluation during the campaign.

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 table is reproduced.

1.1. CHANGE LOG

Version	Date	Changes
0.1	29.04.2022	Version 01, all new
1.0	11.05.2022	Clarification of NSC receiver history, installation at PTB, and designation

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
NSC	Volodymyr Soldatov "metrology" <time.metrology@ukr.net>	Mironositska str., 42, Kharkiv-2, 61002, Ukraine

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2022-04-12 until 2022-04-18	PTB	Common-clock comparison between UA04 and PT13	7 days used for determination of delays, MJD 59681 – 59687

Information on the receivers UA04 and PT13 is contained in the information table which can be found in the Annex.

3. CALIBRATION PROCEDURE

3.1. GENERAL DESCRIPTION

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

When dealing with G1G2 calibrations, in general we distinguish receivers V, T, and G: V for visited, T for travelling, and G for golden_reference. In the current case, V designates the receiver visiting PTB, i. e. the Device under Test. PT13 (named PTBB when referred to as IGS station) serves as the reference receiver G. Its delays were determined as reported in [RD01].

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

(1) INT DLY

The sum $X_R + X_S$ represents the “INT DLY” field in the CGGTTS header:

X_R represents the receiver hardware delay, between a reference point whose definition depends on the receiver type and the internal time reference of the measurements. X_S represents the antenna delay, between the phase center and the antenna cable connector at the antenna body. We distinguish the two quantities for the two frequencies, f1 and f2.

INT DLY(f1) and INT DLY(f2) of receiver V are the basic quantities that are determined during the relative calibration. For calculating ionosphere-free observation data, INT DLY(f3) is calculated as 2.54×INT DLY(f1) - 1.54×INT DLY(f2) for GPS, and as 2.26×INT DLY(f1) - 1.26×INT DLY(f2) for Galileo, respectively. In figures and results tables we use the designation P1, P2 for GPS, and E1, E5a for Galileo, instead of f1, f2.

The following terms are considered frequency independent, i. e. no distinction is made for f1 and f2.

(2) CAB DLY

The sum $X_C + X_D$ represents the “CAB DLY” field in the CGGTTS header.

X_C corresponds to the delay of the long cable from the antenna to the input connector at either the antenna splitter or the receiver body directly. If a splitter is installed, X_D corresponds to the delay of the splitter and the small cable up to the receiver body. For a simple set-up with just an antenna cable, $X_D = 0$.

(3) REF DLY

The sum $X_P + X_O$ represents the “REF DLY” field in the CGGTTS header.

X_P corresponds to the delay of the cable between the laboratory reference point for local UTC and the 1 PPS-in connector of the receiver.

X_O corresponds to the delay between the 1PPS-in connector and the receiver internal reference point, the latter depending on the receiver type:

- For Septentrio PolaRx4: Xo available at the the 1 PPS-out socket of the receiver
- For Septentrio PolaRx5TR: Optionally Xo is determined autonomously by the receiver and measurement results are automatically corrected. Alternatively, X_O can be determined alike to the PolaRx4.
- For DICOM GTR50, GTR51 and GTR55: $X_O = 0$,
- For TTS-4: RD02, Annex1, Annex G specify the procedure for TTS-4, which in detail depends on the software version.

PT13 (PolaRx5TR) had been installed in April 2019, and the auto-calibration option was disabled.

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.

In the process followed by PTB, valid CGGTTS files with dual frequency observation (f3) data (including correct, accurate antenna coordinates) are needed. As a reminder,

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

for reporting results of observation of satellite "j" is valid and reported in column 10 of the standard CGGTTS files. $REFSYS_{RAW}$ designates the uncorrected measurement values, INT DLY(f3) is calculated as explained before, and the values designated as "Q_F" are reported in the CGGTTS file header.

The ionospheric delay for a signal at frequency f is proportional to $1/f^2$. According to [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 in calibration mode thus calculates:

$$REFSYS_{f1}(j) = REFSYS(j) + MDIO(j) \quad (2a)$$
$$REFSYS_{f2}(j) = REFSYS(j) + (f_1/f_2)^2 \times MDIO(j), \quad (2b)$$

where $(f_1/f_2)^2 = 1.647$ for GPS and 1.793 for Galileo, respectively, for each satellite observation j and REFSYS(j) and MDIO(j) are from the line in the CGGTTS file that reports the observation j.

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

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

are calculated and represent the difference delay(new) – delay(old) for receiver V.

The software provides the median value of all individual observations ∆IDi for f1 and f2, and the number of data points used. In addition, a file that contains observation epoch (MJD.frakt) and the average ∆IDi of all satellite observations at that epoch (duration 13 minutes) is generated. Such values are plotted in the figure reporting the result.

The calculation of the INT DLY values comprises a single step:

INT DLY(fi)_V_new = ∆IDi(V,G) + INT DLY(fi)_V_old. (4)

The second summand in (4) on the right represents the INT DLY value that was reported previously in the CGGTTS file of receiver V.

4. INSTALLATIONS AT PTB

4.1. PTB EQUIPMENT

PT13 is continuously compared to other GNSS receivers in PTB. The evaluation and generation of plots is done daily. In Figure 4-1 a comparison between PT13 and PT09 during 30 days, encompassing the current campaign is shown

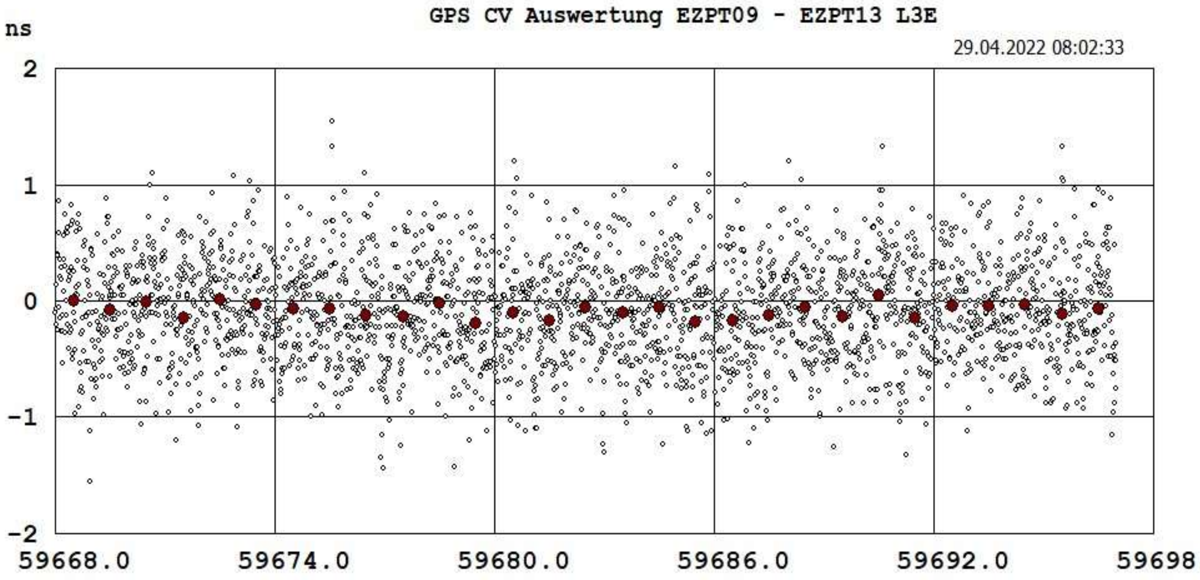

Figure 4-1: Common-clock common-view Galileo comparison between PT09 and PT13 during 30 days: grey symbols: 16-min avg values, red: daily avg.

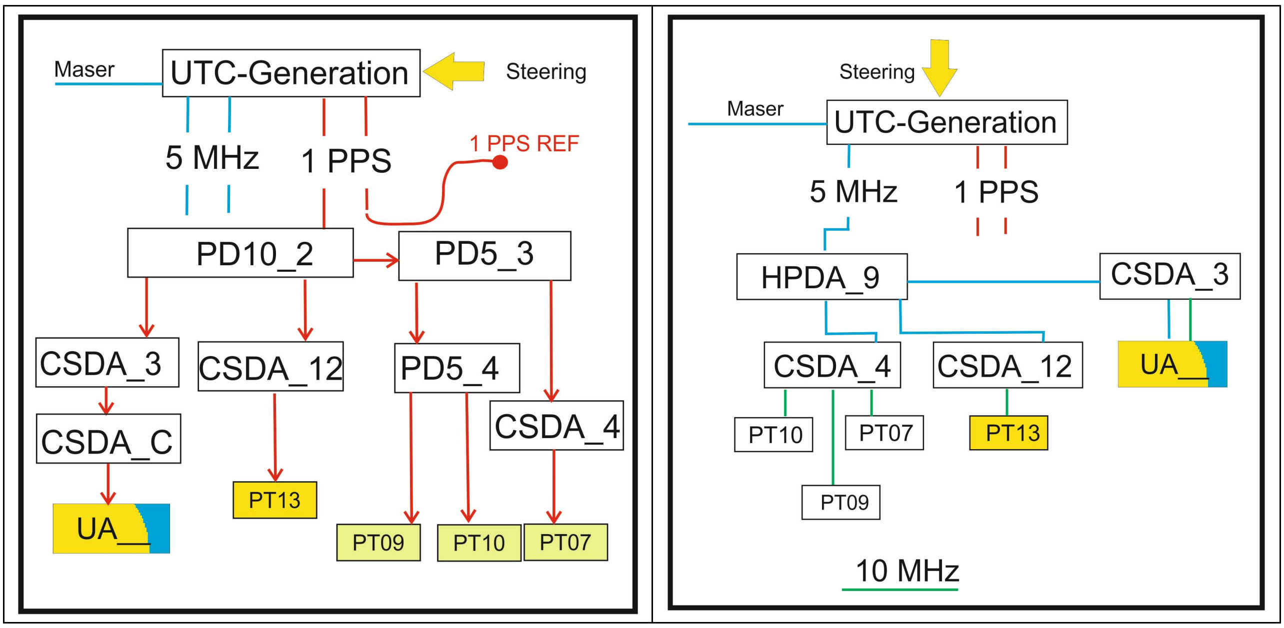

Figure 4-2: UTC(PTB) signal distribution to receiver UA04 and other receivers; PDA stands for pulse distributor, FDA for frequency distribution amplifier, CSDA for Clock Signal Distribution Amplifier

The installation of the receivers, including UA04 in PTB is depicted in Figure 4-2. The TTS-4 recevier can be operated using 5 MHz or 10 MHz reference frequency. Both options were used.

Figure 4-3 illustrates the installation of the UA04 GNSS antenna on the roof of the PTB clock hall. The installation of PT13 was unchanged compared to previous campaigns.

Figure 4-3: Installation of GNSS antennas at PTB, UA04 antenna (orange arrow)

4.2. RECEIVER UA04

The agreement between NSC and PTB to conduct the calibration campaign was signed in late December 2021. The receiver, i.e. the TTS-4 receiver, an antenna cable, and the associated antenna, finally arrived at PTB just before the Russian invasion to the Ukraine started. Initial activities were needed to make the receiver ready for the actual data taking.

According to [RD02, Annex G] and to the receiver manual, a factory calibration is needed before usage. This had happened for using 5 MHz as reference signal, but not for 10 MHz. The manufacturer Piktime, point of contact Pawel Nogas, kindly provided the needed cables for the “factory calibration” which was then done for both signals. The calibration is based on the results obtained. According to the manufacturer, the results can be regarded as a device-related constant values and should not change. For both cases, the offset between PPS rising edge and the next zero crossing (positive slope) of the respective reference signal needs to be measured. Of course, the PPS_in offset from the PTB on-time point was determined as well.

The UA04 CAB DLY value was measured at PTB.

The TTS-4 receiver is a few years old. In the past, GNSS data had been reported to BIPM and the receiver was recorded in the BIPM data base as UA04. After a lightning strike, a new JAVAD OEM board was installed at NSC, a factory calibration for 5 MHz was performed, and some delay values were entered for GNSS signals by NSC. It turned out that these values were grossly incorrect in some cases (in error by > 100 ns). So initially a set of default values, identical for all signals, was assumed, and in comparison to PT13 the individual differences were obtained. The differences visible in figures and reported in Table 7.1 should not be used to relate current results with those found in the BIPM data base.

All required CGGTTS files were generated from BORL RINEX 3.01 observation files and PT13 navigation files using r2cggtts V 8.3.

5. RESULTS OF COMMON-CLOCK DATA TAKING IN PTB

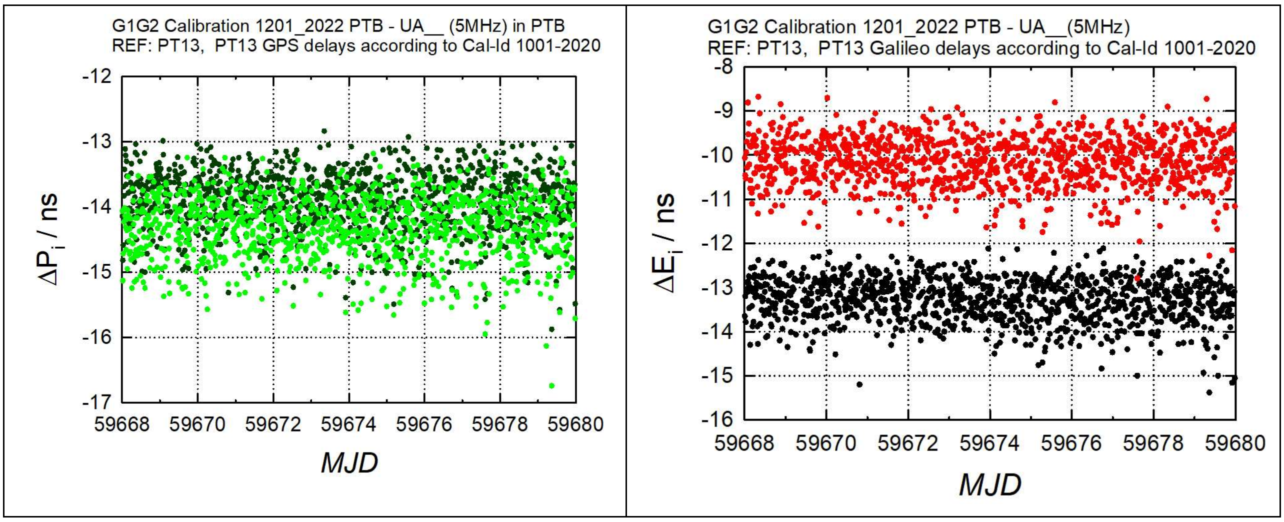

Figure 5-1: Left: GPS delay in UA04, ΔP1 (dark green) and ΔP2 (light green) Right: Galileo delays in UA04, ΔE1 (black) and ΔE5a (red), UA04 operated with 5 MHz reference signal

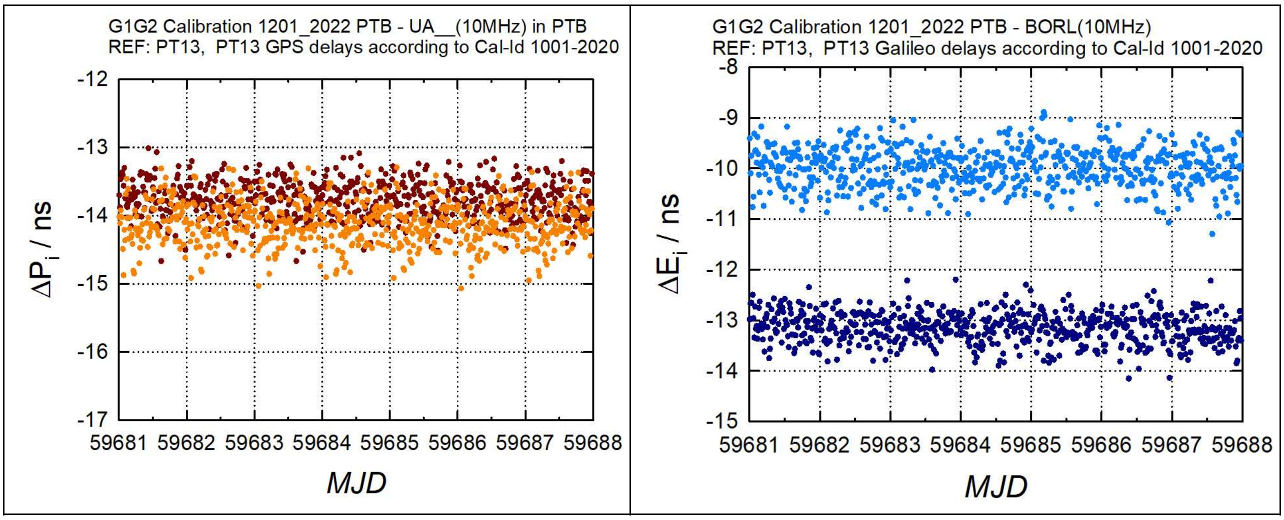

Figure 5-2: : Left: GPS delay in UA04, ΔP1 (brown) and ΔP2 (orange) Right: Galileo delays in UA04, ΔE1 (dark blue) and ΔE5a (light blue), UA04 operated with 10 MHz reference signal

During two intervals the UA04 INT DLY values were determined, initially (MJD 59668 to 59679) with 5 MHz reference frequency and later (MJD 59681 to 59687) with 10 MHz. The latter results are noticeably less noisy so that final delay values have been obtained from the second data set. The maximum difference for INT DLY values between the two sets was 0.21 ns (GPS P2). The results are shown in Figure 5-1 to Figure 5-3. Based on the time instability (TDEV) plots (not shown) the statistical incertainty contribution (Table 6-1) is 0.1 ns in all cases.

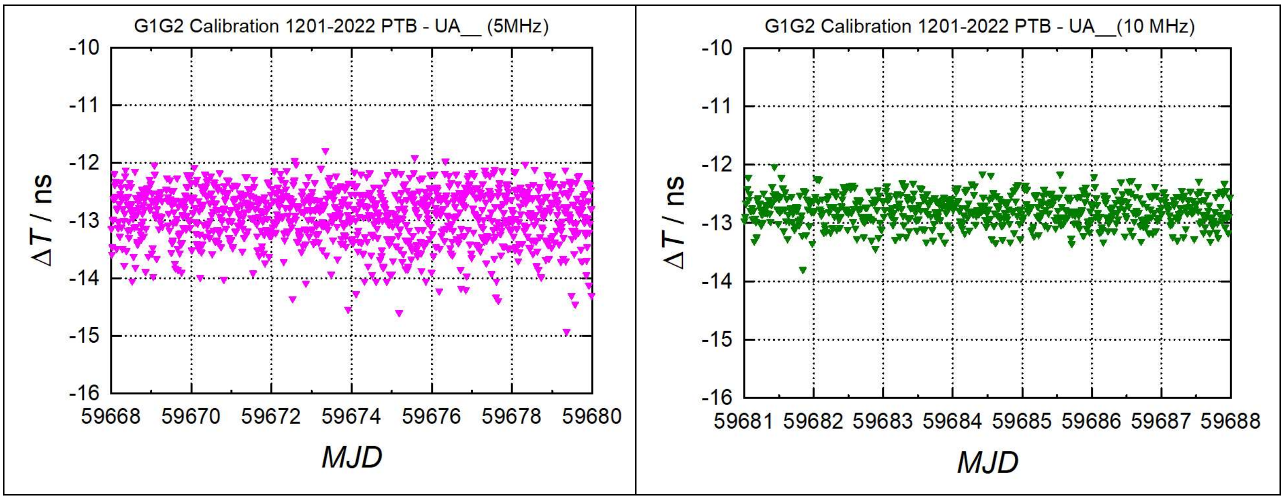

Figure 5-3 GPS L1C delay in receiver UA04 for both modes of operation

6. INT DLY UNCERTAINTY EVALUATION

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

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

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

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

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

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

Table 6-1: 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
Systematic components due to UA04 antenna installation						
4	$u_{b,11}$	0.1	0.1	0.14	0.28	Position error at PTB
6	$u_{b,13}$	0.2	0.2	0.0	0.2	Multipath at PTB
Installation of UA04 at PTB						
8	$u_{b,21}$	0.5	0.5	0	0.5	Connection of UA04 to UTC(PTB) (REF DLY)
Antenna cable delay						
14	$u_{b,31}$(UA04)	0.5	0.5	0	0.5	Uncertainty estimate for UA04 CAB DLY values

For the generation of the CGGTTS data, the UA04 antenna position is manually entered into the processing software in ITRF coordinates before the CC evaluation. This position could in principle differ from the "true" position. This is taken into account by the contribution $u_{b,11}$. As a matter of fact, a position error in general could even affect the f1 and f2 delays in a slightly different way, if the distinction between Antenna Reference Point (ARP) and Antenna Phase Centre (APC) is not accurately made. It has been reported that the difference between the two quantities is different for each antenna type but in addition also for the two frequencies received. To be on the safe side, $u_{b,11}$ is very conservatively estimated.

For other entries, where a frequency dependence can be safely excluded, the entry for f1-f2 is set to zero.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,13}$. 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 contribution $u_{b,21}$ is estimated as 0.5 ns which should cover the different contributions to REF DLY in a TTS-4 receiver.

The measurement of antenna cable delays causes contributions $u_{b,31}$. 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.

Note anyway that this uncertainty contribution $u_{b,31}$ a priori has no impact on the uncertainty of the time transfer link between PTB and NSC. If the stated UA04 CAB DLY would be erroneous, this would be absorbed in the INT DLY values produced as a result of the campaign.

As a matter of fact, in case of a “Golden System Calibration” [RD02] the uncertainty budget is quite short and the resulting values are low. This is compensated in BIPM practice by an overhead in the conventional uncertainty attributed to the established time link.

7. FINAL RESULTS

The results of the calibration campaign G1G2_1201_2022 are summarized in Table 7-1 and Table 7-2. They contain the designation of the visited receiver, the INT DLY values used temporarily, the new INT DLY values to be used with consent by BIPM, and the uncertainty with which the new values were determined. 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 7-1. Results of the Calibration Campaign G1G2_1201_2022: GPS delays, all values in ns

Receiver	INT DLYs, old	INT DLY(P1), new	u_{cal}, P1	INT DLY(P2), new	u_{cal}, P2	u_{cal}, L3P	INT DLY(L1C)	Ucal, L1C
UA04	-55.9	-69.7	0.75	-70.1	0.75	0.77	-68.7	0.75

Table 7-2. Results of the Calibration Campaign G1G2_1201_2022: Galileo delays, all values in ns

Receiver	INT DLYs, old	INT DLY(E1), new	u_{cal}, E1	INT DLY(E5a), new	u_{cal}, E5a	u_{cal}, L3E
UA04	-55.9	-69.1	0.75.	-65.9	0.75	0.77

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

Common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of measurements:	2022-04-12 0:00 UTC (MJD 59681)&&
Date and hour of the end of measurements:	2022-04-18 24:00 UTC (MJD 59687)&&

Information on the system		
	Local reference:	**Visiting DUT:**
4-character BIPM code	**PT13**	**UA04**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	PIKTIME TTS-4, SN:0109, 2015, HW:133.57, SW:3.4n 2021/02/03
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	ECOFLEX15	
Length outside the building /m:	approx. 25	20
Antenna maker and type: Antenna serial number:	LEICA AR25 726333, Calib Geo++ 18.08.2015	Javad TRE-G3T S/N 418
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local reference:	**Visiting DUT**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	9.59 ± 0.1 (#)	41.39 +/- 0.5
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	46.63 ± 0.1 (#)	Phase corr. -8.62, fw corr -99 &&
Antenna cable delay: (X_C) / ns	205.7 ± 0.1 (#)	203.9 ± 0.5
Splitter delay (if any):	N/A	

Data used for the generation of CGGTTS files				
	LOCAL:		Visiting DUT	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	31.6 (P1), 29.3 (P2), 33.6 (C1) (*) 33.6 (E1), 33.6 (E5a) (*)		-55.9 for all, default value	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	205.7		203.9	
☐ REF DLY (or X_P+X_O) /ns:	56.2		-66.2	
☐ Coordinates reference frame:	ITRF		ITRF	
X /m:	+3844059.86 (***)	Mast P10	+3844062.10 ($)	Mast P9
Y /m:	+709661.56 (***)		+709658.74 ($)	
Z /m	+5023129.87 (***)		+5023128.29 ($)	

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

&& period of operation with 10 MHz reference frequency, decisive for the obtained INT DLY

(#) values determined on occasion of campaign 1001-2020, local measurements not repeated

(*) values based on G1 calib 1001-2020

(**) temporary values, initially reported by NSC for GPS P1

(***) values provided by BIPM via Mail 2019-08-07

($) Coordinates of mast P9 (APC for UA04 antenna) were determined for DOY 77, 2022, using NRCan PPP

Names of files to be used in processing for site PTB

Visiting DUT GMBORLKJ.DDD, GZBORLMJ.DDD, EZBORLMJ.DDD

Reference receiver GZPT13MJ.DDD, EZPT13MJ.DDD

END of DOCUMENT