GNSS CALIBRATION REPORT

G1G2_1201_2021

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_JV
Code:	1201_2021
Version:	1.0
Safe date:	06.04.2021 11:38

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

REFERENCES

REFERENCES	
RD01	**BIPM report 2018 Group 1 GPS calibration trip 1001-2018_GPSP3C1_Group1-trip_V2**
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	**BIPM / Gerard Petit / TM266 V2.5 19 June 2020, "Continuity of GNSS "INTDLY" values of Group 1 geodetic receivers in successive Group 1 trips", Section C.6**
RD09	**PTB Report GNSS CALIBRATION REPORT PT13 VIA 1001-2018, 01 September 2020**
RD10	**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.**
RD11	**P. Krehlik et al., "ELSTAB — Fiber Optic Time and Frequency Distribution Technology — A General Characterization and Fundamental Limits," IEEE Trans. Ultrason., Ferroelect., Freq. Control, vol. 63, 2016, pp. 993–1004.**

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**
JV	**Justervesenet (Norwegian Metrology Service)**
GNSS	**Global Navigation Satellite System**
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 JV 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 JV03 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_2021. Results provided are the JV03 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.

PT13 GPS-signal delays had been provided in [RD01]. Initially, PT13 Galileo delays had been determined with reference to receiver GRCP. With publication of V2 of [RD01] and V2.5 of [RD08] in June 2020, Galileo delay values for the G1 laboratories were published. In case of PTB, values for PT09 were provided. Subsequently, the Galileo delay values of PT13 were aligned using the same method as in 2019 and documented in [RD09].

The final results for JV03 are included in Table 7-1 and Table 7-2. The receivers’s internal delays were determined with an uncertainty of 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 JV with respect to the calibration of 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 JV03 was installed at PTB for the purpose. A campaign like this is denominated as “Golden System Calibration” in the BIPM Guide [RD02].

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	29.03.2021	Version 0, all new
1.0	06.04.2021	Results included, submitted to BIPM and JV

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
JV	Harald Hauglin Phone: +47 64 84 84 43; Fax: +47 64 84 84 85	Fetveien 99 2007 Kjeller Norway

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2021-03-23 until 2021-03-30	PTB	Common-clock comparison between JV03 and PT13	6 days used for determination of delays, MJD 59297 – 59302

Information on the receivers JV03 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 with respect to receiver PT09 which in turn got its last calibration from BIPM as reported with Cal_Id=1001-2018 [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, Section 2.3.2, and 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 ΔIDi for f1 and f2, and the number of data points used. In addition, a file that contains observation epoch (MJD.frakt) and the average ΔIDi 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:

$$\text{INT DLY(fi)\_V\_new} = \Delta\text{IDi(V,G)} + \text{INT DLY(fi)\_V\_old.} \qquad (4)$$

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

3.2. DETERMINATION OF DELAYS OF GALILEO SIGNALS

In the current campaign, Galileo delays of visited receivers are calculated with reference to the values determined by BIPM in campaign 1001-2018 in retrospect [RD08]. The CCTF working group on GNSS, at its meeting held June 3, 2020, decided that the Galileo reference for Group 1 calibrations would be realized through the absolute calibration of the BIPM receiver BP21 performed by ESTEC in 2019. In order to provide in retrospect Galileo INTDLY values for 1001-2018 whenever possible, i.e. for Galileo-capable receivers visited by a Galileo-capable traveling receiver (in the EURAMET and SIM legs), BP21 has been added to the set of 1001-2018 receivers. In doing so, the Galileo absolute calibration was transferred from BP21 to the 1001-2018 reference BP1J, then to all possible receivers. In case of PTB, receiver delays for PT09 were determined [RD08]. These were transferred to PT13 after publication of [RD08] in June 2020 [RD09].

4. CHARACTERIZATION OF PTB EQUIPMENT

At the time of conducting the current campaign, also the BIPM travelling equipment for G1 calibration in campaign 1001-2020 was operated in PTB. This required installation of two antennas, and no third mast was empty for the JV03 antenna. JV03 was thus operated at another site, to which UTC(PTB) is transferred via an optical fiber-based installation. The uncertainty of REF DLY (JV03) wrt to UTC(PTB) can be assured very close to the normal situation if it was installed in the time laboratory. In the following, we document the stability of the installation, showing in Figure 4-1 a comparison between another receiver operated there and PT13 during 30 days, encompassing part of the current campaign.

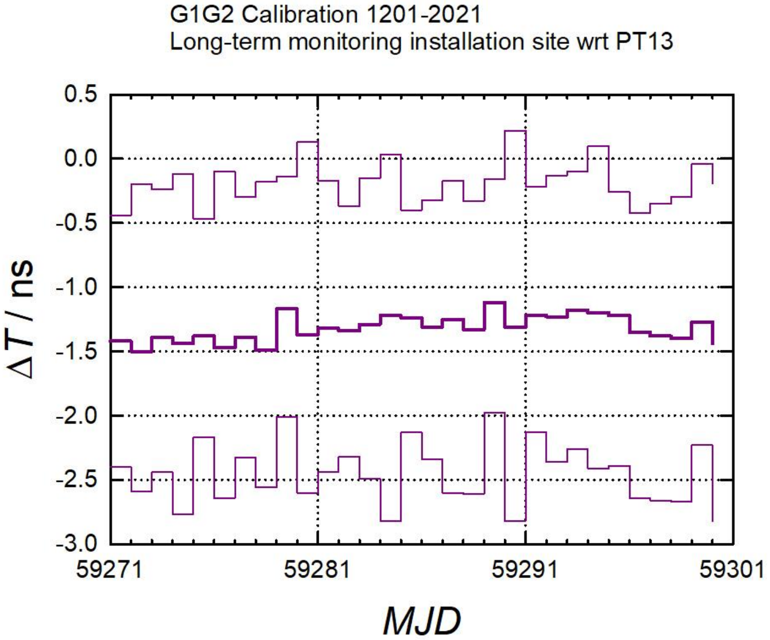

Figure 4-1: Common-clock common-view Galileo comparison between GPTA and PT13 during 30 days: thick lines: daily mean values, thin lines: maximum and minimum value (13-min average) during the respective day.

The installation of the receivers in PTB is depicted in Figure 4-2.

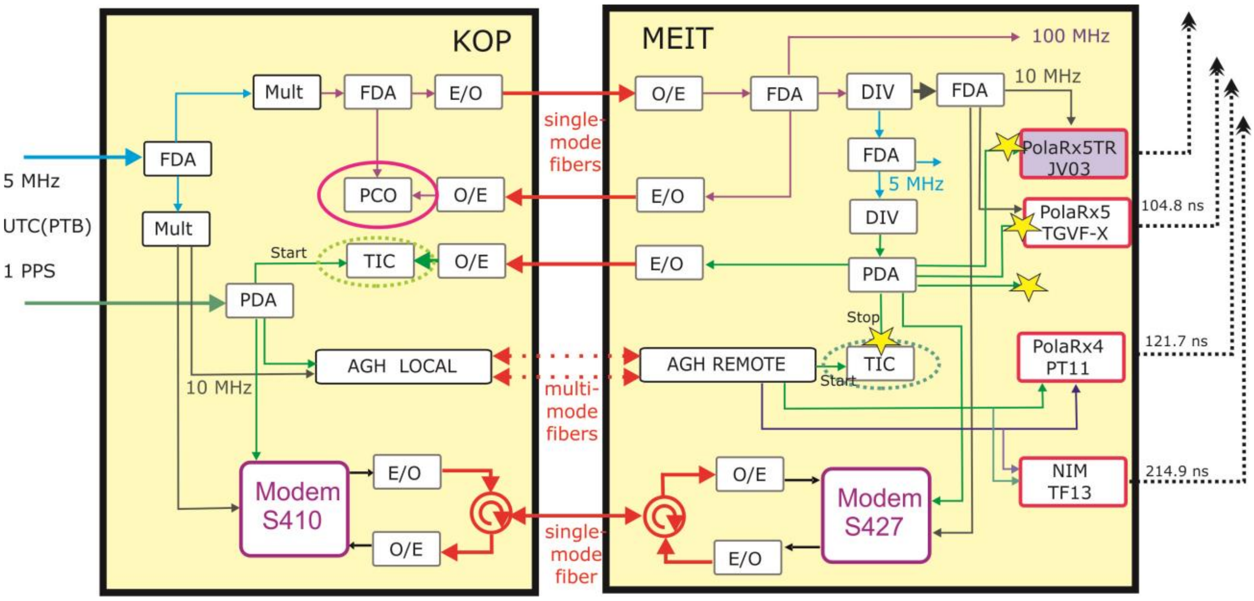

Figure 4-2: UTC(PTB) signal distribution to receiver JV03, and other receivers; PDA stands for pulse distributor, FDA stands for frequency distribution amplifier

Each of the yellow stars represents a 1 PPS signal representing UTC(PTB) as generated in the laboratory Meitner-building. The difference between the four realizations is within 50 ps. The offset from UTC(PTB) as realized in the main time laboratory (Kopfermann-building) is measured with the TIC at Meitner-building with an uncertainty of < 0.5 ns. It receives UTC(PTB) via a calibrated AGH ELSTAB optical time and frequency transfer link [RD11]. This value (0.5 ns) is included in the uncertainty budget reported below.

Figure 4-3 illustrates the installation of the JV03 GNSS antenna on the roof of the Meitner-building. The installation of PT13 was unchanged compared to previous campaigns.

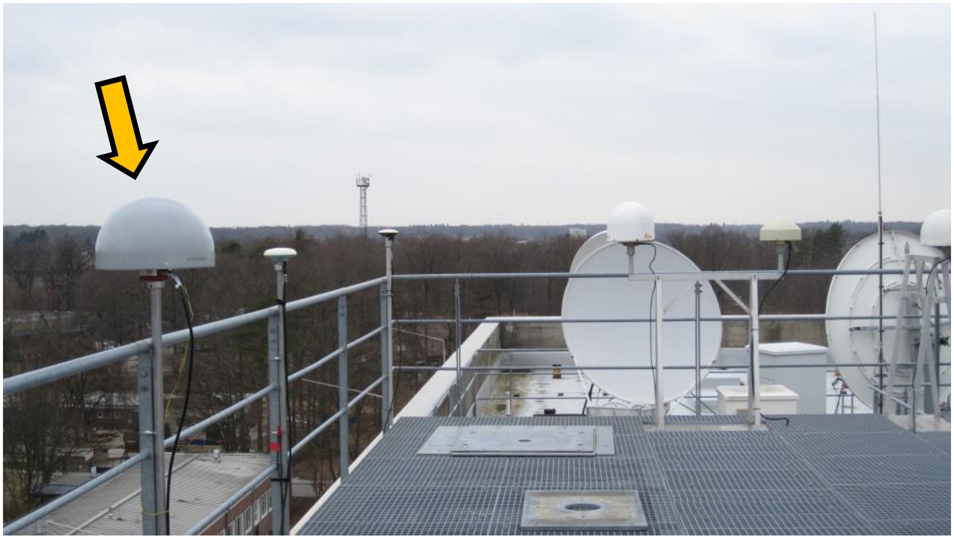

Figure 4-3: Installation of GNSS antennas at PTB Meitner-building, JV03 antenna (orange arrow)

5. RESULTS OF COMMON-CLOCK DATA TAKING IN PTB

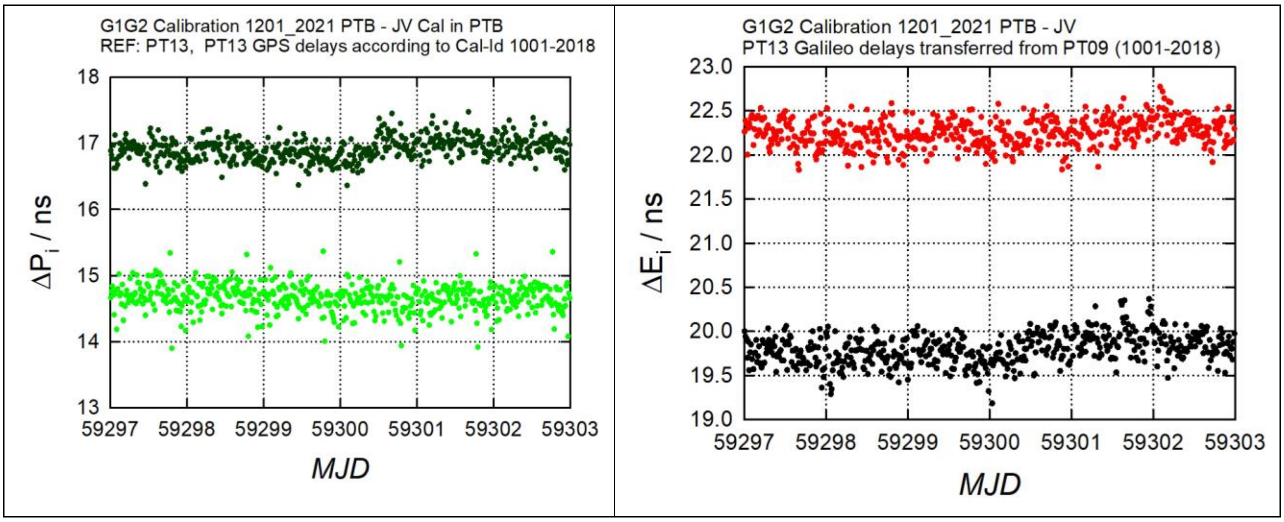

Figure 5-1: Left: GPS delay in JV03, ΔP1 (dark green) and ΔP2 (light green) Right: Galileo delays in JV03, ΔE1 (black) and ΔE5a (red).

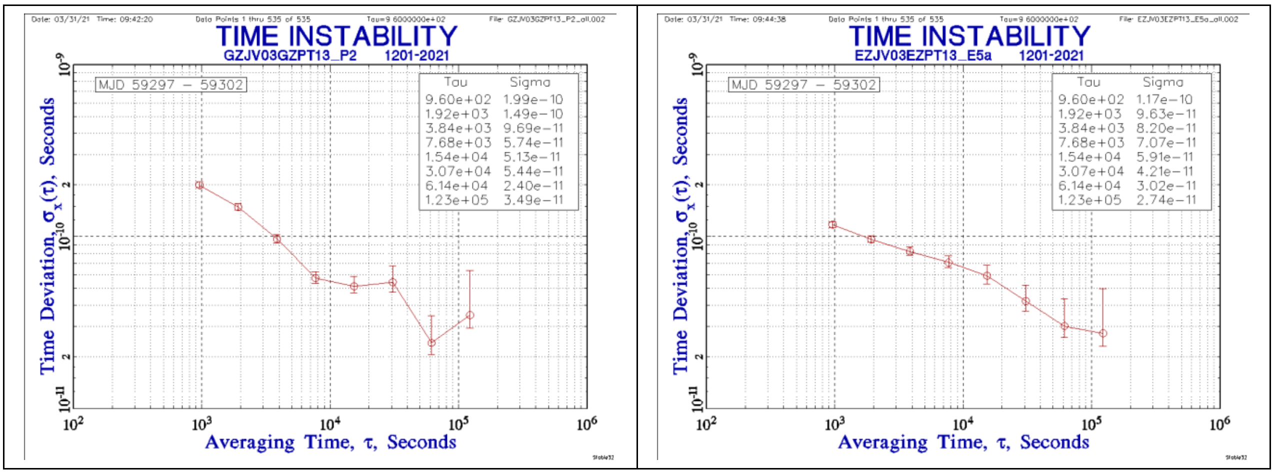

Figure 5-2: TDEV obtained for the two noisier data sets shown in Figure 5-1, GPS dP2 (left), and Galileo dE5a (right).

The period 59297 to 59302 (6 days) was chosen to determine the initial JV03 INT DLY values. The result of comparison with PT13 as the reference are shown in Figure 5-1 illustrating in total 535 values obtained for each GNSS frequency as mean over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets representing dP2 and dE5a, respectively, follow as Figure 5-2. TDEV for the other data are even lower.

In addition, the JV03 delay for GPS L1C signals was determined. In Figure 5-3, the results and the instability are depicted, respectively.

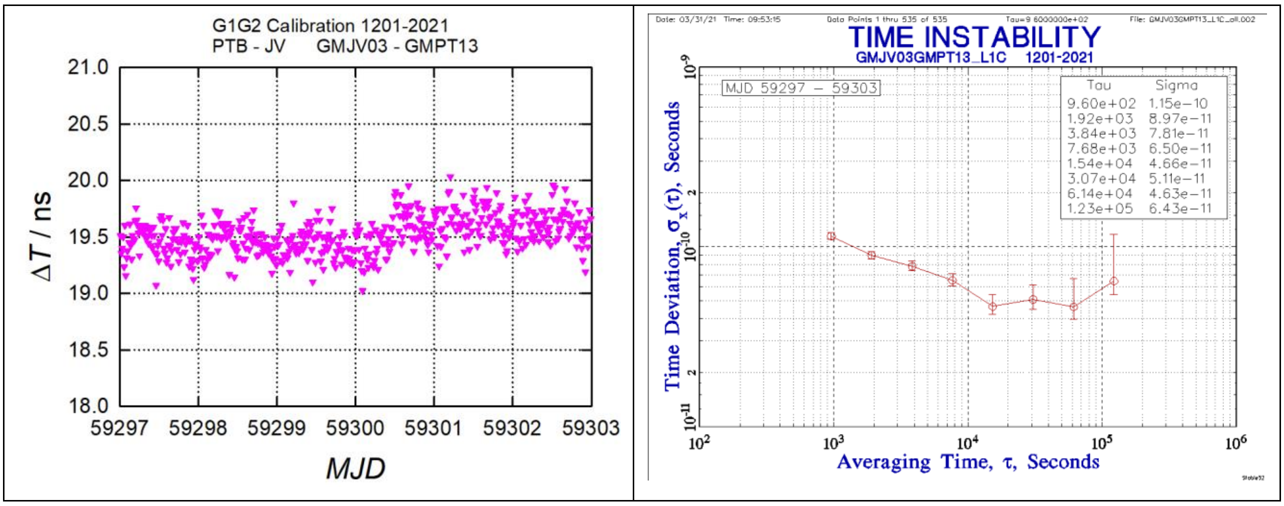

Figure 5-3 GPS L1C delay in receiver JV03 and the instability (TDEV) of the values (right)

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 INRIM and PTB, respectively. 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) = $\sqrt{\{u(P1)^2 + (1.54 \times u(P1\text{-}P2))^2\}}$. Uncertainties for the Galileo delays are calculated according to $\sqrt{\{u(E1)^2 + (1.26 \times u(E1\text{-}E5a))^2\}}$.

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 JV03 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 JV03 at PTB						
8	$u_{b,21}$	0.5	0.5	0	0.5	Connection of JV03 to UTC(PTB) (REF DLY)
Antenna cable delay						
14	$u_{b,31}$(JV03)	0.5	0.5	0	0.5	Uncertainty estimate for IJV03 CAB DLY values

For the generation of the CGGTTS data, the JV03 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 $u_{b,11}$. The JV03 antenna coordinate was determined during the campaign and the contribution is 0.1 ns at maximum. As a matter of fact, a position error in general could even affect the f1 and f2 delays in a slightly different way, if the distinction between Antenna Reference Point (ARP) and Antenna Phase Centre (APC) is not accurately made. It has been reported that the difference between the two quantities is different for each antenna type but in addition also for the two frequencies received. To be on the safe side, $u_{b,11}$ 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.

JV03 was operated in the mode "auto determination of the compensation of the PPSIN delay". The manufacturer specifies the uncertainty as 0.1 ns. It was observed that the compensation value changes with time of operation of the receiver, likely due to a thermal effect. The receiver was thus restarted after several hours of initial operation. The uncertainty contribution $u_{b,24}$ is nevertheless set to 0.5 ns, including also a contribution due to the remote installation that requires transfer of the local time reference.

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 JV. If the stated JV03 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_2021 are summarized in Table 7-1 and Table 7-2. They contain the designation of the visited receiver, the INT DLY values hitherto used, 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_2021: 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
JV03	0	16.91	0.75	14.66	0.75	0.77	19.51	0.75

Table 7-2. Results of the Calibration Campaign G1G2_1201_2021: 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
JV03	0	19.80	0.75.	22.25	0.75.	0.77.

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

Common clock measurement at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2021-03-23 0:00 UTC (MJD 59297)
Date and hour of the end of measurements:	2021-03-29 24:00 UTC (MJD 59302)

Information on the system		
	Local reference:	**Visiting DUT:**
4-character BIPM code	**PT13**	**JV03**
Receiver maker and type: Receiver serial number:	PolaRx5TR (5.2.0) S/N 470 1292	PolaRx5TR (5.3.0) S/N 4701452
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	10
Antenna maker and type: Antenna serial number:	LEICA AR25 726333, Calib Geo++ 18.08.2015	Septentrio VeraChoke S/N 710152 20200626 0143
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local reference:	**Visiting DUT**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	9.33 ± 0.1 (#)	0.9 +/- 0.5
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 (#)	196.1 ± 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:	29.7 (P1), 27.2 (P2), 31.7 (C1) (*) 32.0 (E1), 31.7 (E5a) (*)		0 (P1) 0 (P2) 0 (L1C) 0 (E1), (E5a)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	205.7		196.1	
☐ REF DLY (or X_P+X_O) /ns:	54.3		0.9	
☐ Coordinates reference frame:	ITRF		ITRF	
X /m:	+3844059.86 (***)	Mast P10	+3843994.37 ($)	Mast Mei 9
Y /m:	+709661.56 (***)		+709947.13 ($)	
Z /m	+5023129.87 (***)		+5023159.81 ($)	

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

(#) values determined at installation of PT13 in March 2019, local measurements not repeated
($) Coordinates of mast Mei 9 (APC) were determined on 25.03.2021 using NRCan PPP
(*) values based on G1 calib 1001-2018, transferred from receiver PT09 [RD08, RD09]]
(***) values provided by BIPM via Mail 2019-08-07

Names of files to be used in processing for site PTB
Visiting DUT GZJV03MJ.DDD, EZJV03MJ.DDD
Reference receiver GZPT13MJ.DDD, EZPT13MJ.DDD

END of DOCUMENT