GNSS CALIBRATION REPORT

G1G2_1102_2017

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REFERENCES

REFERENCES	
RD01	**BIPM report 1001-2016, 2016 Group 1 GPS calibration trip BV 1.1 2017-01-18**
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	**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**
EURAMET	**The European Association of National Metrology Institutes**
IGS	**International GNSS Service**
GNSS	**Global Navigation Satellite System**
ORB	**Observatoire Royal Belgique**
PPP	**Precise Point Positioning**
PTB	**Physikalisch-Technische Bundesanstalt, Braunschweig, Germany**
RINEX	**Receiver Independent Exchange Format**
R2CGGTTS	**RINEX-to CGGTTS conversion software, provided by ORB / BIPM**
TDEV	**Time deviation**
UFE	**Institute of Photonics and Electronics, Czech Academy of Sciences**
TIC	**Time interval counter**

EXECUTIVE SUMMARY

As part of the support of the BIPM Time and Frequency Group by EURAMET, PTB conducted a relative calibration of a multi-GNSS receiver designated as TP01 of UFE, while it was temporarily operated in PTB, with respect to the calibration of PTB receiver PT02, whose last calibration was reported with Cal_Id=1001-2016 [RD01].

The current campaign followed as much as possible the BIPM Guide [RD02] and results will be reported using Cal_Id 1102_2017. Results provided are the travelling receiver's internal delays for GPS C/A-code and P-code signals on the two frequencies L1 and L2 (INT DLY (C1), INT DLY (P1), and INT DLY(P2)). The delays for other GNSS signals were not determined during this campaign. The determination of the INT DLY(C1) was made by Alexander Kuna, UFE, and he authored also the description of his procedures in this Report.

The final results are included in Table 7-1. The internal delays of the receiver were determined with an uncertainty of less than 1 ns for C1, P1, and P2, respectively. The uncertainty for P3 time transfer links to PTB is still below 1 ns.

As a reminder: All uncertainty values reported in this document are 1-σ values. Also any potential effects connected with the installation of the travelling receiver at its final destination are not considered.

1. CONTENTS OF THE REPORT

As part of the support of BIPM Time and Frequency Group by EURAMET, PTB conducted a relative calibration of one GNSS receiver of UFE operated temporarily in PTB, with respect to the calibration of receiver PT02, whose last calibration was reported with Cal_Id=1001-2016 [RD01]. This report documents the installation, data taking and evaluation during the short campaign.

The determination of the internal delay values of the visiting receivers at PTB is a straightforward process. The visiting receiver (= Device under Test) is installed at PTB and its internal delay values and their statistical properties are determined with reference to a so-called golden receiver.

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.

2. PARTICIPANTS AND SCHEDULE

Table 2-1: List of participants

Institutes	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
UFE	Alexander Kuna Tel +420 266 773 426 kuna@ufe.cz	UFE AV CR, v. v. i. Chaberska 57 182 51 Prague, Czech Republic

Table 2-2: Schedule of the campaign

Date	Institute	Action	Remarks
2017-11-20 Until 2017-11-22	PTB	Operation of TP01 and PTB GNSS receivers in parallel	44 hours used for evaluation during MJD 58077–58079

3. CALIBRATION PROCEDURE

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

In this type of G1G2 calibration, we distinguish receivers V, and G: V for visiting and G for golden_reference. PT02 (named PTBB when referred to as IGS station) serves as the reference receiver G, its internal delays were recently determined by BIPM in the second G1 campaign with the identifier Cal_Id=1001-2016.

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

(1) INT DLY

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

X_R represents the receiver hardware delay, between a reference point whose definition depends on the receiver type and the internal time reference of the measurements. X_S represents the antenna delay, between the phase center and the antenna cable connector at the antenna body. We distinguish the two quantities for the two frequencies, 1 and 2.

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

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

(2) CAB DLY

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

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

(3) REF DLY

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

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

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

- For Ashtech Z12-T: The first positive zero crossing of the inverted 20 MHz-in following the 1PPS-in, delayed by 15.8 ns,

- For Septentrio PolaRx2: The 1PPS-out, delayed by 8.7 ns,
- For Septentrio PolaRx4: The 1 PPS-out, no further correction
- For DICOM GTR50, GTR51 and GTR55: The 1PPS-in, i.e. $X_O = 0$,

Details of the measurement procedures for the Ashtech Z12-T are given in the BIPM calibration guideline [RD02], but the parameters of PT02 were not determined again on occasion of the current campaign.

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. As an alternative, the sum of the three terms CAB DLY + INT DLY – REF DLY is designated as TOT DLY (frequency dependent) and reported instead of the individual terms.

In the process followed by PTB, valid CGGTTS files with dual frequency observation (L3P) data (including correct, accurate antenna coordinates) are needed. As a reminder,

$$REFGPS(k) = [REFGPS_{RAW}(k) – CAB\ DLY_F – INT\ DLY(P3) + REF\ DLY_F], \quad (1a)$$

or

$$REFGPS(k) = [REFGPS_{RAW}(k) – TOT\ DLY(P3)_F], \quad (1b)$$

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

The software cv.py in calibration mode is used to calculate:

$$REFGPS_{P1}(j) = REFGPS(j) + MDIO(j) \quad (2a)$$

$$REFGPS_{P2}(j) = REFGPS(j) + MDIO(j) + ((f_1/f_2)^2 – 1) \times MSIO(j), \quad (2b)$$

where $(f_1/f_2)^2 = 1.647$ for GPS for each satellite observation j and REFGPS(j), MDIO(j), and MSIO(j) are from the line in the CGGTTS file that reports the observation j. Eq. 2a and 2b build on the rules how CGGTTS L3P data lines are generated.

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

$$\Delta Pi: = REFGPS_{Pi}(V) – REFGPS_{Pi}(G) \quad (3)$$

are calculated.

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

The INT DLY value for receiver V is to be calculated as

$$\text{INT DLY(Pi)\_V\_new} = \Delta\text{Pi(V,G)} + \text{INT DLY(Pi)\_V\_F}. \quad (4)$$

The second summand in (4) on the right represents the INT DLY value that was reported previously in the CGGTTS file of receiver V. These values were reported as zero in case of receiver TP01.

Additionally, the raw data are processed according to the Annex 3 of the Guidelines [RD02] using *dclrinex* software. It reads GPS observations from two RINEX files taken by the two sytems V and G on the same site, forms the L1 and L2 phase differences, checks for gross phase outliers and cycle slips by comparing the evolution of the L1 and L2 phase, and solves for the baseline between the phase centers of the two antennas.
Then it forms the GPS C1, C2 (if any), P1, and P2 pseudorange differences, accounting for the geometric effect of the computed baseline. The list of differences is provided along with a statistical analysis for each code.
These raw differences (RAWDIFF) are subsequently used to compute the results of the calibration trip according to the Annex 4 of the Guidelines [RD02]. For the pair of systems V−G and each code, we note

$$\Delta SYSDLY_{V-G}(Code) = SYSDLY_{V}(Code) - SYSDLY_{G}(Code),$$

which is computed as

$$\Delta SYSDLY_{V-G}(Code) = RAWDIF_{V-G}(Code) + REFDLY_{V} - REFDLY_{G}, \quad (5)$$

One can then compute $\Delta INTDLY_{V-G}(Code)$ when CABDLY values are available.

$$\Delta INTDLY_{V-G}(Code) = \Delta SYSDLY_{V-G}(Code) - CABDLY_{V} + CABDLY_{G}, \quad (6)$$

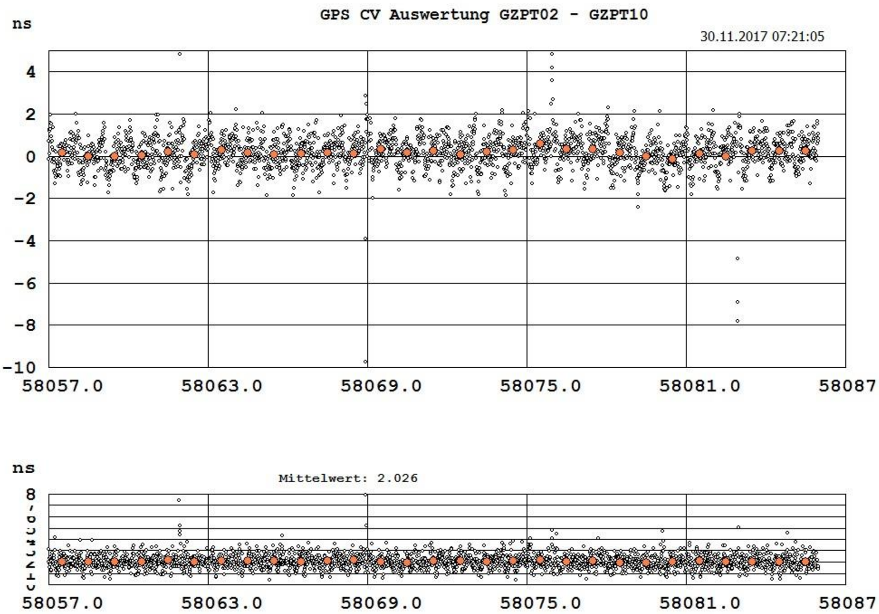
where the values CABDLY are taken from the “information sheets”.

$$\text{New } INTDLY_{V}(Code) = INTDLY_{G}(Code) + \Delta INTDLY_{V-G}(Code), \quad (7)$$

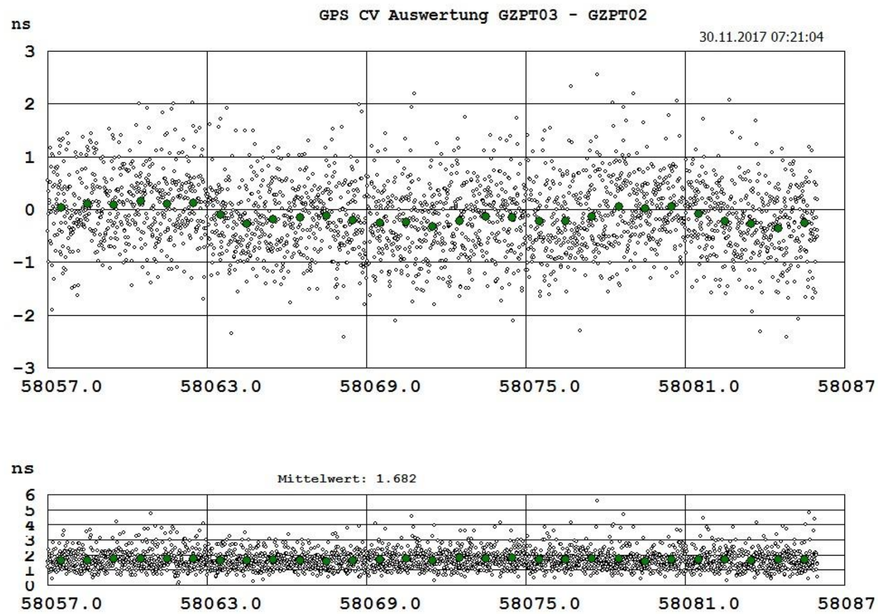
where $\Delta INTDLY_{V-G}(Code)$ is obtained from (6) and where the values $INTDLY_{G}(Code)$ are taken from the “information sheets”.

4. CHARACTERIZATION OF PTB EQUIPMENT

In the following plots we provide evidence that the PTB reference receiver performed reasonably well during the days 58077 to 58079, showing a comparison between PT02 and PT10 and PT03, respectively, in Figure 4-1 a and b. The installation of the receivers in PTB is depicted in Figure 4-2 for 1 PPS signals and in Figure 4-3 for 5 MHz signals. The PT02 and PT03 receivers are supplied with 20 MHz from a times 4 multiplier.



a)



b)

Figure 4-1: Common-clock common-view comparison between PT02 and PT10 (upper) and PT02 and PT03 (lower) at PTB, daily mean values (coloured) and 16-min avg data (grey); Time differences (upper graph) and standard deviation (lower graph)

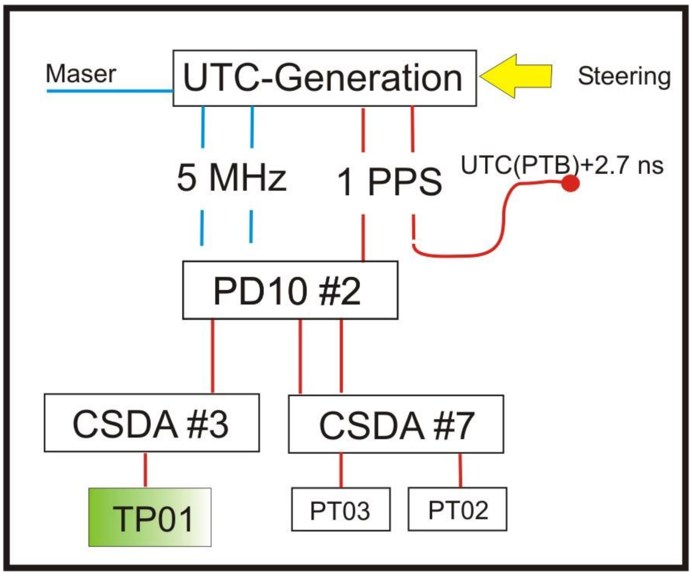


Figure 4-2: UTC(PTB) reference point and 1 PPS signal distribution to PT02, PT03 and TP01

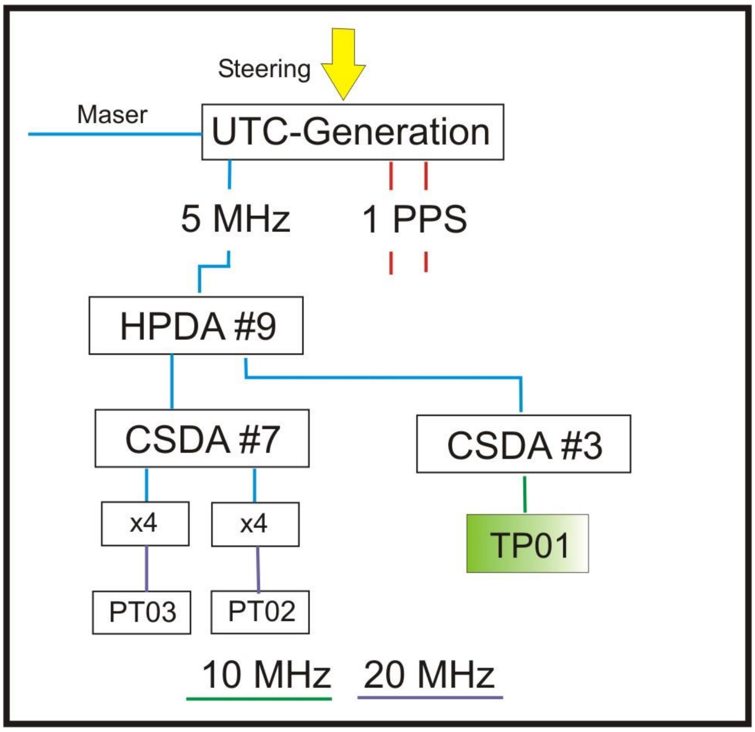


Figure 4-3: UTC(PTB) signal distribution (5 MHz, 10 MHz, 20 MHz) to PT02, PT03 and TP01

Figure 4-4: Installation of GNSS antennas at PTB

Figure 4-4 illustrates the installation of GNSS antennas on the roof of the PTB time laboratory (clock hall) and was taken during the CC1 period of a previous calibration campaign. The two Ashtech SNOW antennas (with dome) belong to PT03 (background) and PT02 (middle). The TP01 antenna replaced the 3G+C antenna belonging to PTB's travelling receiver PTBT (red antenna body).

5. RESULTS OF COMMON-CLOCK SET-UP IN PTB

5.1. RESULTS FROM THE CGGTTS DATA

During the days MJD 58077 to 58079 in total 44 hours were chosen to determine the TP01 INT DLY values. The result of comparison with PT02 as the reference are shown in Figure 5-1 illustrating in total 158 ΔPi (see eq. 3) values obtained as mean over all common view observations at a given epoch. The time instability (TDEV) plots for the two data sets follow as Figure 5-2. The numerical results are given in Table 5-1. The estimate of the uncertainty contribution is given in Section 6.

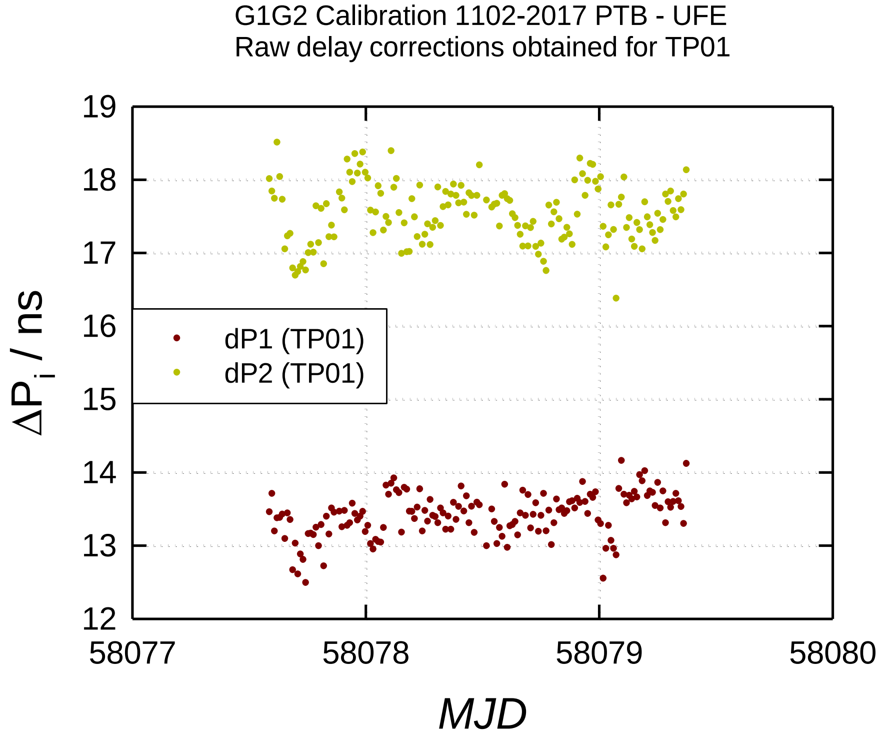


Figure 5-1: ΔP1 (brown) and ΔP2 (green) values obtained during the operation of TP01 in common-clock set-up in PTB.

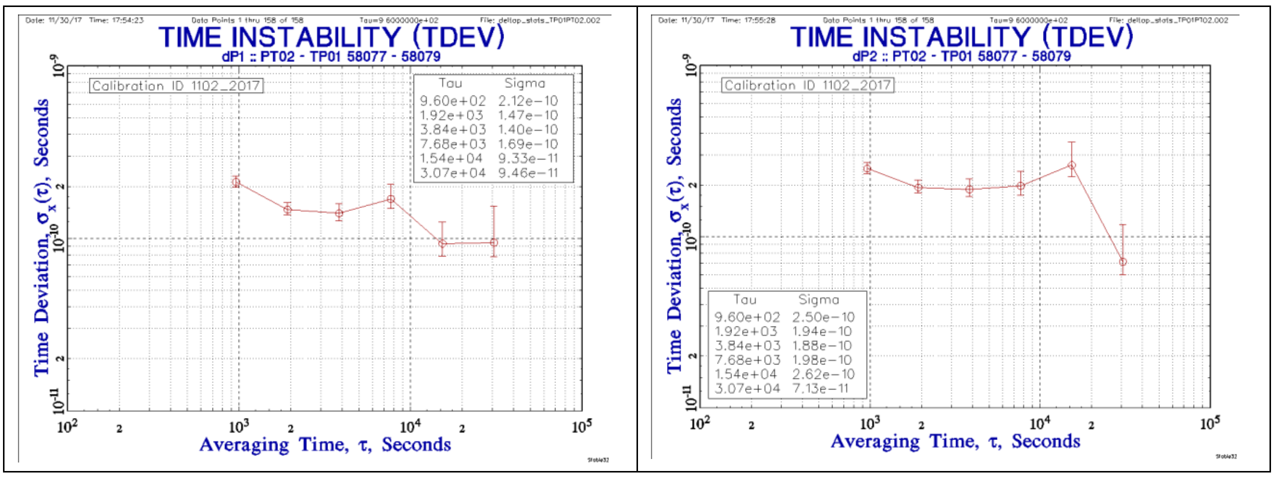


Figure 5-2: TDEV obtained for the two data sets shown in Figure 5-1, ΔP1 left, ΔP2 right.

Table 5-1: Result of common clock measurements at PTB

Quantity	Median (ns)	Sigma (ns)	TDEV (ns)
ΔP1 (CC)	13.43 ns	0.30 ns	0.15 ns
ΔP2 (CC)	17.53 ns	0.40 ns	0.15 ns
ΔP3 (CC)	7.11 ns		

5.2. RESULTS FROM THE RINEX DATA

During the days MJD 58077 to 58079 in total 44 hours were chosen to determine the TP01 INT DLY values. Plot of the raw data differences C1, P1, P2 as well as the plot of the statistical analysis (TDEV) are available in files TP01PTBB17324_3_C12.pdf, TP01PTBB17324_3_P12.pdf.

Table 5-2: Summary information on the raw calibration results (all values in ns).

Pair	Date	RAWDIF(C1)	Unc	RAWDIF(P1)	Unc	RAWDIF(P2)	Unc
TP01-PT02	58077-58079	−341.78	0.1	−342.32	0.1	−353.51	0.1

Table 5-3: Summary information on $\Delta SYSDLY_{V-G}$ (all values in ns).

Pair	Date	$REFDLY_V$	$REFDLY_R$	$\Delta SYSDLY_{V-G}$(Code)		
				C1	P1	P2
TP01-PT02	58077-58079	28.52	73.90	−387.16	−387.70	−398.89

Table 5-4: Summary information on $\Delta INTDLY_{V-G}$ (all values in ns).

Pair	Date	$CABDLY_V$	$CABDLY_R$	$\Delta INTDLY_{V-G}$(Code)		
				C1	P1	P2
TP01-PT02	58077-58079	205.0	301.7	−290.46	−291.00	−302.19

Table 5-5: Summary information on New $INTDLY_V$ (all values in ns).

Pair	Date	$INTDLY_G$(Code)			New $INTDLY_V$(Code)		
		C1	P1	P2	C1	P1	P2
TP01-PT02	58077-58079	305.1	304.5	319.8	14.64	13.50	17.61

6. INT DLY UNCERTAINTY EVALUATION

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

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}\,, \qquad (5)$$

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

$$u_b = \sqrt{\sum_n u_{b,n}}\,. \qquad (5)$$

The contributions to the sum (5) are listed and explained subsequently. Note that the uncertainty of the INT DLY values of PTB's fixed receiver PT02 (G) which served as the reference is not included.

Table 6-1: Uncertainty contributions for the calibration of TP01 receiver delays

	Uncertainty	Value C1 (ns)	Value P1 (ns)	Value P2 (ns)	Value P1-P2 (ns)	Value P3 (ns)	Description
1	u_a		0.15	0.15	0.22	0.30	CC measurement uncertainty at PTB, estimate of TDEV at $\tau = 2\times10^4$ s
1	u_a	0.10	0.10	0.10			dclrinex estimate of TDEV
	Uncertainty	**Value C1 (ns)**	**Value P1 (ns)**	**Value P2 (ns)**	**Value P1-P2 (ns)**	**Value P3 (ns)**	**Description**
	Systematic components due to antenna installation						
2	$u_{b,11}$	0.1	0.1	0.1	0.14	0.20	Position error at PTB
3	$u_{b,13}$	0.1	0.1	0.1	0.14	0.20	Multipath at PTB
	Installation of PTBT and visited receivers						
4	$u_{b,21}$	0.2	0.2	0.2	0	0.2	Connection of TP01 to UTC(PTB) (REF DLY)
5	$u_{b,24}$	0.2	0.2	0.2	0	0.2	TIC nonlinearities at PTB
	Antenna cable delay						
6	$u_{b,31}$	0.5	0.5	0.5	0	0.5	Uncertainty estimate for the TP01 CAB DLY when installed at PTB

For the generation of the CGGTTS data the TP01 antenna position (mast P11) is manually entered into the processing software in ITRF coordinates before the CC measurements. The coordinate values could differ from the "true" position that is assumed for PT02. This is taken into account by the contributions $u_{b,11}$. The uncertainty contribution is estimated as 0.1 ns at maximum. As a matter of fact, a position error in general could even affect the P1 and P2 delays in a slightly different way, if the distinction between Antenna Reference Point (ARP) and Antenna Phase Centre (APC) is not accurately made. It has been reported that the difference between the two quantities is different for each antenna type but in addition also for the two frequencies received. To be on the safe side, $u_{b,11}$ is very conservatively estimated. For other entries, for which a frequency dependence can be safely excluded, the entry for P1-P2 is set to zero.

An uncertainty contribution due to potential multipath disturbance is added as $u_{b,13}$. 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 the multipath error need not be considered to be more significant than reported here.

The uncertainty of the connection of the receiver to the local time scale ($u_{b,21}$) was estimated by PTB: The cable connecting UTC(PTB) to a temporary receiver installation is repeatedly controlled and has been used in many calibration exercises (then connecting to PTBT). The uncertainty contribution $u_{b,24}$ 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. As part of previous campaigns a TIC was connected successively to 5 MHz and 10 MHz generated by different clocks (masers, commercial caesium clocks), respectively. The effect on a differential time interval measurement was estimated to be at most 0.2 ns if 1 PPS signals with a slew rate of approximately 0.5 V/ns are used and the trigger level is properly set.

The measurement of the antenna cable delay causes a contribution $u_{b,31.}$ It is made with different methods in timing laboratories. On PTB side, the same antenna cable(s) were repeatedly measured using 1 PPS signals from different sources – but using the same counter – and an uncertainty of 0.5 ns is estimated. A fixed PTB cable was connecting the TP01 antenna and the receiver. Its delay was not measured as part of the campaign reported here.

7. FINAL RESULTS

The results of the calibration campaign G1G2_1102_2017 is summarized in Table 7-1. It contains the designation of visiting receiver, the INT DLY values hitherto used, the offsets ΔPi(V,G), the new INT DLY values to be used with consent by BIPM, and the uncertainty with which the new values were determined. For calculation, the respective entries from Table 6-1, individually for C1, P1, P2, and combined for P3, were used. Intermediate delays and uncertainties are reported here with two decimal points. According to [RD06], 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_1102_2017, all values in ns.

Receiver	INT DLY(Code), old			ΔINT DLY_{V-G}(Code)			INT DLY(Code), new			u_{cal}			
	C1	P1	P2	C1	P1	P2	C1	P1	P2	C1	P1	P2	P3
UFE, TP01	0	0	0	14.64	13.50	17.61	14.6	13.5	17.6	0.6	0.6	0.6	0.7

ANNEX: BIPM CALIBRATION INFORMATION SHEETS

Operation of receiver TP01 at PTB

Laboratory:	**PTB**
Date and hour of the beginning of	2017-11-20 13:00 UTC (MJD 58077)
Date and hour of the end of measurements:	2017-11-22 09:00 UTC (MJD 58079)

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	**PTBB**	**TP01**
Receiver maker and type: Receiver serial number:	ASHTECH Z-XII3T (S/N RT820013901)	MESIT defence GTR55 (S/N 1541941)
1 PPS trigger level /V:	1	1
Antenna cable maker and type: Phase stabilised cable (Y/N):	Nokia RG214	Andrews FSJ-1 (N)
Length outside the building /m:	approx. 25	25
Antenna maker and type: Antenna serial number:	Ashtech ASH700936 SNOW (S/N CR15930)	Novatel NOV-704-WB (S/N NMHB16390010R)
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local:	**Travelling:**
Delay from local UTC to receiver 1 PPS-in (X_P) / ns	19.9 ± 0.1 (**)	28.52 ± 0.1
Delay from 1 PPS-in to internal Reference (if different): (X_O) / ns	38.2 ± 0.1 (**) + 15.8	N/A
Antenna cable delay: (X_C) / ns	301.7	205.0 ± 0.1
Splitter delay (if any):	N/A	
Additional cable delay (if any):	N/A	

Data used for the generation of CGGTTS files				
	LOCAL:		Travelling	
☐ INT DLY (or X_R+X_S) (GPS) /ns:	304.5 (P1), 319.8 (P2) (**)		0 (C1), 0 (P1), 0 (P2)	
☐ INT DLY (or X_R+X_S) (GLONASS) /ns:				
☐ CAB DLY (or X_C) /ns:	301.7		205.0	
☐ REF DLY (or X_P+X_O) /ns:	73.9 (**)		28.5	
☐ Coordinates reference frame:	ITRF		ITRF	
X /m:	+3844059.89 (*)	Mast P10	+3844057.71 (***)	Mast P11
Y /m:	+709661.48 (*)		+709663.27 (***)	
Z /m:	+5023129.73 (*)		+5023131.14 (***)	

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:

(*) values provided by BIPM as part of coordinate alignment 2014 and G1 calibration Cal_Id=1001-2014

(**) values reported with BIPM Cal_Id 1001-2016 / local measurements not repeated
(***) Coordinates of mast P11 were interpolated from BIPM results provided for neighbouring masts.

Names of files to be used in processing for site PTB CC

Local receiver: GZPT02MJ.DDD

Travelling receiver GZTP01MJ.DDD

Names of files to be used in dclrinex processing

Local receiver: PTBBDDD0.17D.Z

Travelling receiver TP01DDD0.17D.Z

END of DOCUMENT