Report calibration ESTEC 2012

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Relative calibration of ESTEC GPS receivers' internal delays

January 2013

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Executive summary

The European Space Agency ESA and the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, contribute with their clocks and time transfer data to the realization of International Atomic Time. ESA's atomic clocks are operated at the European Space Technology Centre ESTEC, and the local realization of UTC is named UTC(ESTEC. At ESTEC, two Septentrio GNSS receivers, PolaRx3, designation ES03, and PolaRx4, designation ES04, are in operation. Through co-location of a mobile GPS receiver whose internal delays had been determined with respect to the fixed PTB reference receiver PTBB during the 5 days MJD 56227 to 56231, the internal delays for the two GPS frequencies, L1 and L2, of the two ESA receivers were determined as follows:

ES03
INTDLY(P1) = 49.9 ns, INTDLY(P2) = 48.0 ns, uncertainty (1-σ): 2.8 ns

ES04
INTDLY(P1) = 58.1 ns, INTLY(P2) = 55.7 ns, uncertainty (1-σ): 2.8 ns

Details of the data evaluation and uncertainty estimation are given in the following sections. Information on the installation of the travelling receiver and of the fixed receivers at ESTEC and PTB are given in Annex 1 and Annex 2, respectively.

Equipment involved

The relative calibration of the internal delays of the ESTEC GPS receivers was performed using PTB´s calibration set-up, shown as Figure 1, consisting of a DICOM GTR50 receiver (designation PTBT), a SR620 time interval counter (TIC) and a monitor/keyboard. The devices are integrated in a transportable rack. Because of the use of a traveling TIC for the determination of the local UTC reference points at both sites, a potential systematic error related to internal delay differences between different counters at the sites ESTEC and PTB was avoided.

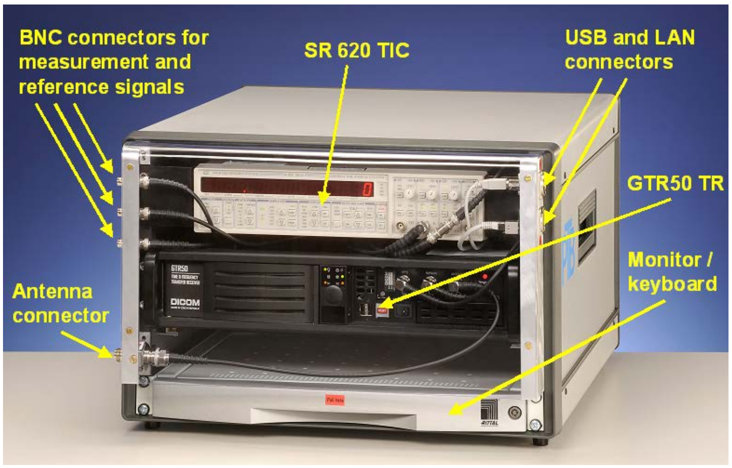


Figure 1. PTB's mobile calibration set-up.

The travelling receiver (TR) is operated together with the fixed GPS receivers in a common-clock (CC) very short baseline at both laboratories involved. It is referenced to the local UTC realization by TIC measurements. The two fixed receivers at PTB and ESTEC which were involved in the campaign are listed in Table 1. The nomenclature used here takes into account that a receiver, in general, produces different kinds of data.

Table 1. Fixed receivers at PTB and ESTEC and their designation when providing data of different kind.

Institute	Receiver	P3	RINEX
PTB	Ashtech Z12-T	PT02	PTBB
PTB	DICOM GTR50	PT07	
ESTEC	Septentrio PolaRx3	ES03	ES03
ESTEC	Septentrio PolaRx4	ES04	ES04

Details on the installation and on the cable delays involved are tabulated in the two Annexes (BIPM report template).

Data in use

All GPS analysis is primarily based on code-based data in the format CGGTTS version 2. Data were generated by the software R2CGGTTS v4.2 implemented on the ESTEC Septentrio receivers and by DICOM proprietary software implemented in the GTR50 receivers PTBT and PT07. An earlier software version (v2.4.0) was used to produce modified CGGTTS files if necessary, but it was verified that PTBT CGGTTS files which can be retrieved from the receiver are identical (within the resolution of the time differences of 0.1 ns) with CGGTTS files generated with the older software version and the PTBT RINEX files.

Common clock measurements at PTB

Common clock measurements at PTB serve two purposes: It has to be verified that the internal delays of the travelling receiver have been correctly determined. Here the PTB reference receiver PTBB serves as the “truth”. Its calibration uncertainty is not considered in the uncertainty budget.

It has in addition to be verified that the internal delays of the travelling equipment have not significantly changed during the calibration campaign. For this purpose the travelling receiver was compared to the fixed receiver PTB07 at PTB before and after the calibration trip.

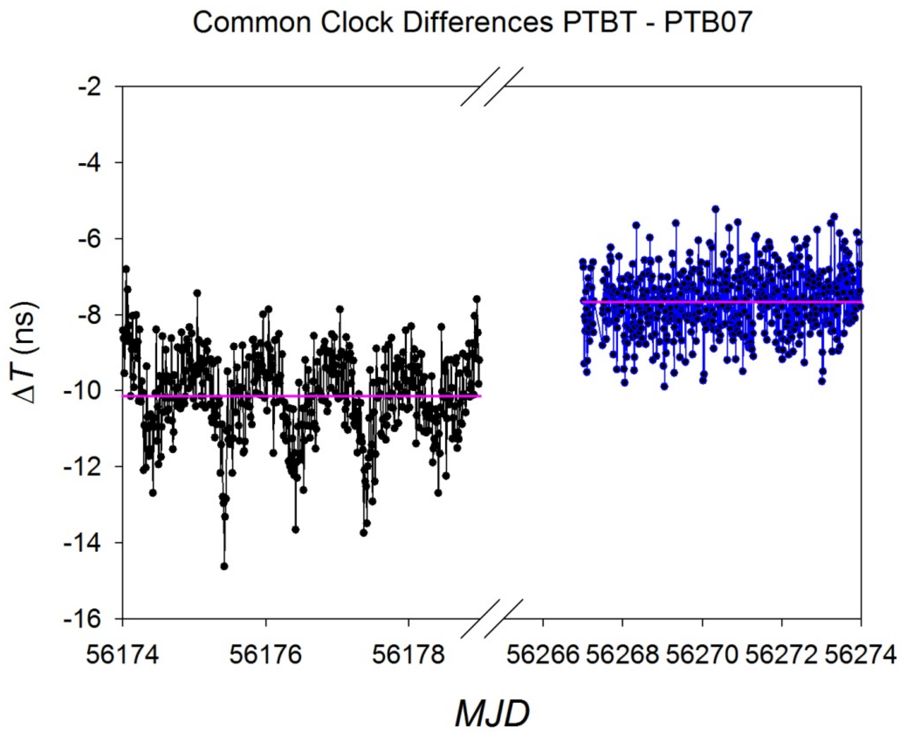


Figure 2. Common clock measurement results at PTB before and after the shipment.

From Figure 2 (and an accompanying measurement of PTBT with PTBB) it is obvious that the conditions of the travelling equipment changed during the campaign. This is also reflected in the results table (Table 2). Two potential reasons for that are known. At ESTEC the receiver board was dismantled and the internal oscillator frequency adjusted. In retrospect there was no reason to do this, but it was done. Back at PTB, the GPS antenna was full of water which had to be removed before exposing the antenna to below zero temperature.

Table 2. Results of common clock measurement at PTB

Date	**Mean (ns)**	**SD (ns)**	**Minimum TDEV (ns) at τ**
56174 - 56178	-10.1	1.1	0.35 at τ = 2 hours
56267 - 56273	-7.7	0.8	0.1 at τ = 24 hours

The difference of 2.4 ns between the mean values is significant, and as the true cause cannot be determined after the fact this difference must be considered as an uncertainty contribution.

Determination of the internal delays for the two GPS signal frequencies.

The following procedure is based on suggestions provided by Gerard Petit, BIPM, Laurent-Guy Bernier, METAS, and Petr Panek, DICOM.

In the CGGTTS data line, the column REFGPS is in general built according to

$$REFGPS_{file} = REFGPS_{raw} – CABDLY –INTDLY +REFDLY –IONODLY, \quad (1)$$

where
CABDLY is the antenna cable delay;
INTDLY is the internal signal delay (antenna + receiver internal);
REFDLY represents the offset between the UTC reference point in the laboratory and the 1 PPS input to the receiver;
IONODLY is the propagation delay through the ionosphere. All other kinds of necessary corrections to raw pseudo-range measurement results are contained in the term $REFGPS_{raw}$.

CABDLY and REFDLY are easily accessible through delay measurements of the cables involved. INTDLY is a priori unknown, and its knowledge requires a calibration, either absolute or relative. This report deals with such a relative calibration with reference to a selected receiver, PTBB, of PTB.

In single frequency CGGTTS data, IONODLY is reported in the column MDIO, in case that it is based on ionosphere model parameters from the GPS Signal in Space, or as MSIO when it is furnished externally. In case that REFGPS (eq. 1) is built as the ionosphere-free combination

$$REFGPS(P3) = 2.546\ REFGPS(P1) – 1.546\ REFGPS(P2), \quad (2)$$

where the two observations on GPS frequencies L1 and L2 are combined such that the ionosphere delay cancels to first order, the field MSIO in CGGTTS P3 data files is a priori not necessary. It allows, however, by construction of the software R2CGGTTS [1], to reconstruct P1 and P2 observations from P3 observations by:

$$REFGPS(P1) = REFGPS(P3) + MSIO$$
$$REFGPS(P2) = REFGPS(P3) + 1.647 \times MSIO. \quad (3)$$

These relations have been used to reconstruct P1 and P2 data files from all receivers involved. With the designation DUT for the receiver whose INT DLY is to be determined and TRU for the receiver whose internal delays serve as reference, one has (for P1)

REFGPS(P1, DUT, RAW) - REFGPS(P1, TRU, RAW)
- CABDLY(DUT) + CABDLY(TRU)
- REFDLY(TRU) + REFDLY(DUT)
+INTDLY(P1, TRU) - INTDLY(P1, DUT) = 0,

under the condition that the two receivers are connected to the same clock and are operated with almost zero baseline so that the ionosphere delay is identical. The effect of disturbances due to signal reflections ("multi-path") is neglected in this context.

Regrouping the above equation leads to

INTDLY(P1, DUT, CAL) =

[REFGPS(P1, DUT, RAW) - CABDLY(DUT) + REFDLY(DUT)]

- {REFGPS(P1,TRU,RAW) - CABDLY(TRU) + REFDLY(TRU) - INTDLY(P1,TRU)} . (4)

Here the terms in square brackets represent REFGPS(P1) (eq. 3) of the DUT when constructed with INTDLY = 0 in the R2CGGTTS software, and the terms in curled brackets represent REFGPS(P1) of the reference receiver.

Replacing P1 by P2, an equivalent relation for INTDLY(P2) is available.

Common clock measurements at ESTEC

The PTBT CGGTTS files collected during data taking during the days 56227 to 56231 (5 days) were corrected in two ways:
The INTDLY values were adjusted such that PTBT agreed with PTBB, based on data collected before shipment. New INTDLY values were determined as explained above, and new CGGTTS files were generated starting from PTBT RINEX files.

PTBT was operated with an antenna cable provided by ESTEC, not with the cable furnished by PTB, and thus the CABDLY value in the CGGTTS file header was a priori erroneous. Considering eq. 1, one gets

$REFGPS_{PTBT,corr} = REFGPS_{PTBT,file} + CABDLY_{file} - CABDLY_{ESTEC}$.

According to ESTEC: $CABDLY_{ESTEC}$ = 182.7 ns, uncertainty 0.5 ns.

As an example, in Figure 3 the single frequency differences between ES04 and PTBT are shown. Each data point represents the mean over a certain number of satellites in common view, Ntrack. The scatter among the individual observation data at each epoch are represented as Sigma in Figure 4, together with Ntrack.

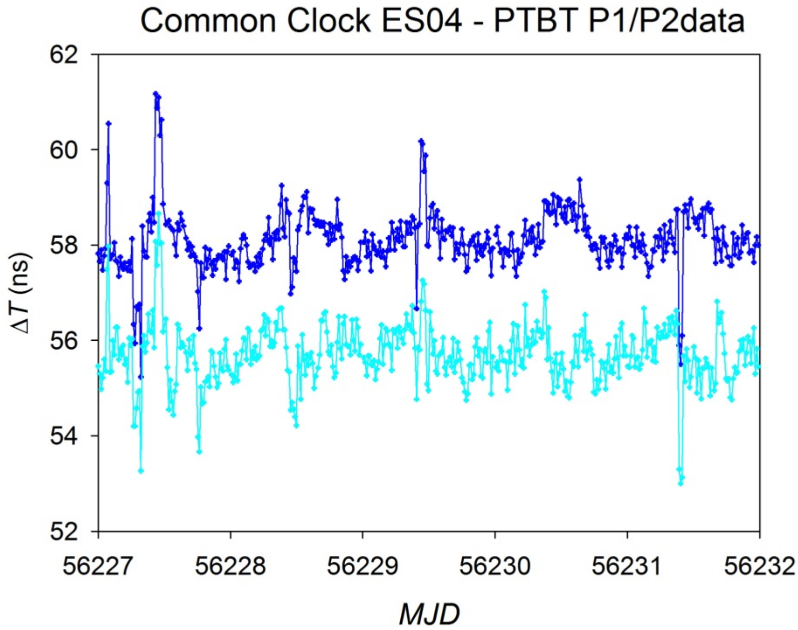


Figure 3. GPS common view comparison ES04 – PTBT for the two frequencies L1 (blue) and L2 (cyan).

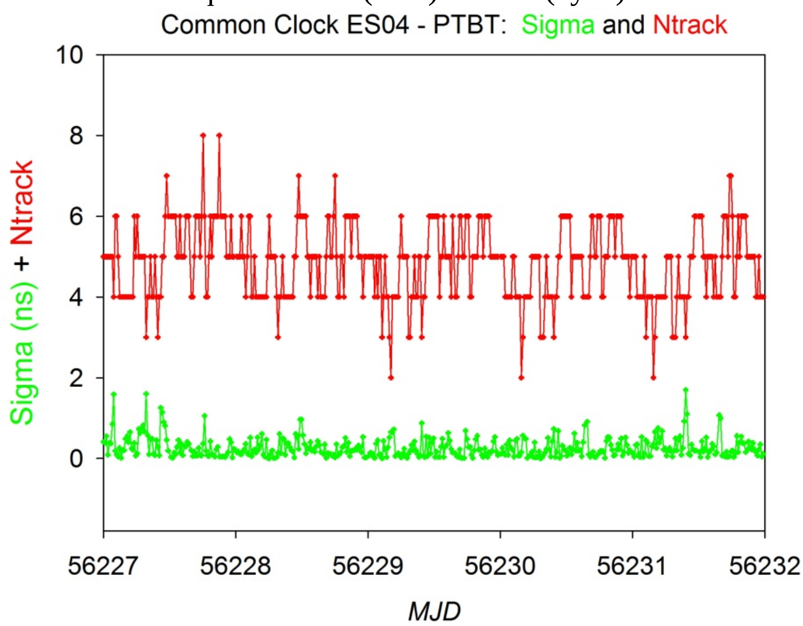


Figure 4. GPS common view comparison ES04 – PTBT, number of satellites processed in common view per 16-min track period (Ntrack, red) and standard deviation from the mean of the individual data points in nanoseconds (green).

INTDLY values for the two receivers have been calculated day-wise and are listed in Table 3. Data shown in Figure 3 exhibit some systematic variations in addition to white phase noise. A stability analysis of the 5-days series of data reveals a minimum TDEV of about 0.1 ns to 0.3 ns in all cases. The value 0.3 ns is thus estimated as the contribution to the statistical uncertainty in all four cases.

Table 3. INTDLY values for receivers ES03 and ES04, in brackets the standard deviation of the typically 89 data points per day.

MJD	ES03 INTDLY(P1) (ns)	ES03 INTDLY(P2) (ns)	ES04 INTDLY(P1) (ns)	ES04 INTDLY(P2) (ns)
56227	49.7 (0.9)	47.9 (1.0)	58.0 (0.9)	55.7 (0.9)
56228	50.0 (0.5)	48.1 (0.5)	58.1 (0.5)	55.9 (0.5)
56229	50.0 (0.5)	48.1 (0.5)	58.2 (0.5)	55.8 (0.5)
56230	50.1 (0.4)	48.0 (0.4)	58.2 (0.4)	55.7 (0.5)
56231	49.9 (0.3)	48.0 (0.7)	58.1 (0.6)	55.6 (0.7)
Mean	**49.9 (0.3)**	**48.0 (0.3)**	**58.1 (0.3)**	**55.7 (0.3)**

Validation of the result

Combining RINEX files and the new INTDLY values in R2CGGTTS, new CGGTTS data files were generated and CV analysis ES03-ES04 and ES03-PT07 was performed. As the software R2CGGTTS requires a RINEX file for day *N+1* to generate a CGGTTS file for day *N* [1] the assessment covers only four days, 56227 to 56230.

Figure 5 shows the common clock results ES03-ES04, the mean value is < 0.05 ns. Figure 6 shows the time scale comparison UTC(ESTEC)-UTC(PTB) via receivers ES03 and PT07. The result agrees within the statistical uncertainty of 0.3 ns with the result obtained using PTBT and PT07 during the same days.

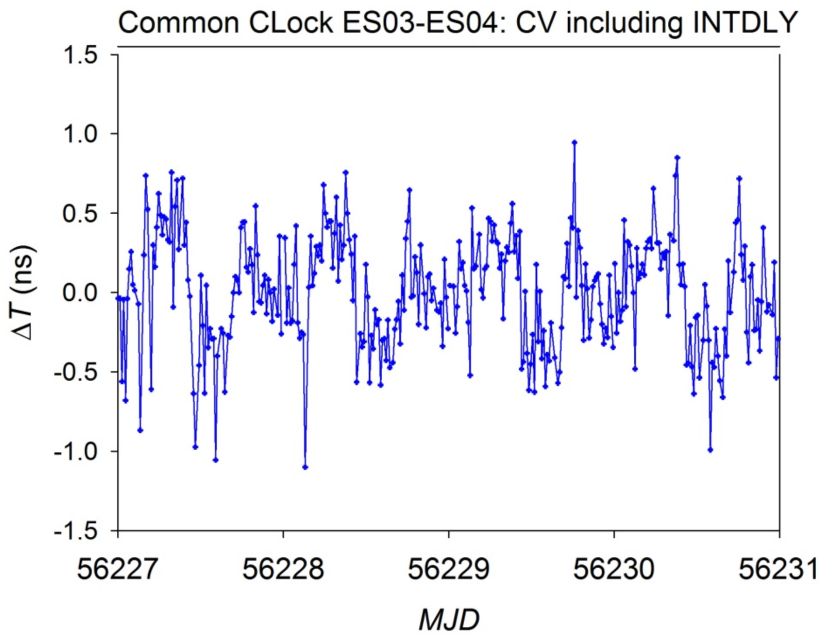


Figure 5. GPS common view comparison ES03 – ES04 with the new INT DLY values applied.

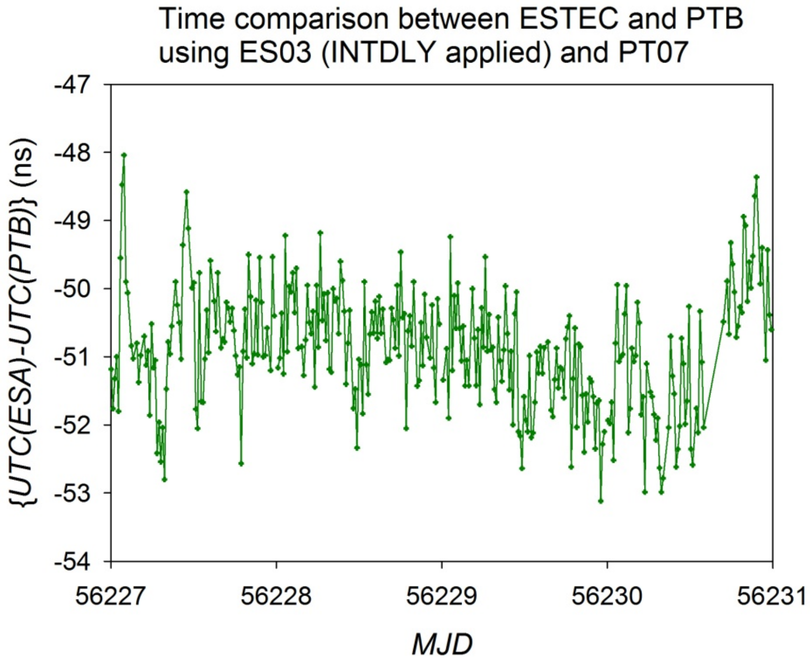


Figure 6. GPS common view comparison UTC(ESA)-UTC(PTB) via GPS P3 common view and involving receivers ES03 and PT07.

Uncertainty Estimation

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

$$\mathrm{U_{CAL}} = \sqrt{\mathrm{u_a^2 + u_b^2}}\,, \tag{3}$$

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 ESTEC (Table 3) and collected at PTB when the correct INTDLY of PTBT was determined. The systematic uncertainty is given by

$$\mathrm{u_b} = \sqrt{\sum_n \mathrm{u}_{\mathrm{b},n}}\,. \tag{4}$$

The contributions to the sum are listed in Table 4 and explained subsequently. Note that the uncertainty of the INTDLY values of PTB's fixed receiver PTBB which served as a reference is not included.

The uncertainties of the connection to the local UTC sites ($u_{b,1}$, $u_{b,2}$) [2] are estimated in part from long term laboratory experience and in part based on cable delay measurement. The value is dominated by the specified measurement uncertainty for time interval using a SR620 counter [3].

According to the manufacturer specifications the trigger level timing error of the travelling SR620 TIC ($u_{b,3}$, $u_{b,4}$) is given by [3]

$$\text{Trigger level timing error} = \frac{15\ \text{mV} + 0.5\ \%\ \text{of trigger level}}{1\ \text{PPS slew rate}} \quad (5)$$

for start and stop channel, respectively. At both labs a trigger level of 1 V at both channels was used. The 1 PPS slew rate can be estimated to be approximately 0.5 V/ns for a signal at the endpoint of a relatively short cable. This was checked by using a scope at PTB. Thus the error is 0.04 ns for the stop channel at both labs.

The trigger level timing error of the PTBT's internal TIC ($u_{b,5}$, $u_{b,6}$) is estimated, according to information given by the manufacturer [4], as 10 mV / (1 PPS slew rate) per channel. The error of the stop channel cancels out, because it is always connected to the signal of the receiver board. PTBT was connected to a signal with a high slew rate in both cases.

Table 4. Uncertainty contributions. Values are determined either by measurements or by estimation and rounded to the second decimal.

Uncertainty	Value (ns)	Description
u_a	0.45	Common clock measurement uncertainty 0.3 ns × sqr(2).
$u_{b,1}$	0.50	Connection to UTC(PTB)
$u_{b,2}$	0.50	Connection to UTC(ESA)
$u_{b,3}$	0.04	TIC trigger level timing error at PTB
$u_{b,4}$	0.04	TIC trigger level timing error at ESTEC
$u_{b,5}$	0.02	TR trigger level timing error at PTB
$u_{b,6}$	0.02	TR trigger level timing error at ESTEC
$u_{b,7}$	0.1	TIC nonlinearities at PTB
$u_{b,8}$	0.1	TIC nonlinearities at ESTEC
$u_{b,9}$	0.05	Jitter of the TIC measurement at PTB
$u_{b,10}$	0.05	Jitter of the TIC measurement at ESTEC
$u_{b,11}$	0.30	Multipath
$u_{b,12}$	0.8	PTBT antenna cable and antenna
$u_{b,13}$	0.5	ESTEC cable delay
$u_{b,14}$	0.25	Position error at PTB
$u_{b,15}$	0.25	Position error at ESTEC
$u_{b,16}$	2.4	Common-Clock difference

The uncertainty contributions $u_{b,7}$ and $u_{b,8}$ are related to imperfections in the TIC in conjunction with the relationship between the zero-crossings of the external reference frequency and the 1 PPS signals. This "nonlinearity" is probably caused by the internal interpolation process. By connecting the traveling TIC to 5 MHz and 10 MHz generated by different clocks (masers, commercial caesium clocks), respectively, 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. In case of distorted signals this effect can be at the order of a nanosecond. Since the PTBT´s internal TIC uses a surface acoustic wave (SAW) filter as interpolator, its nonlinearity effect can be neglected, because it is of the order of a few picoseconds (see reference [5]).

Although the TIC jitter (SD) is the statistical uncertainty of the TIC measurements, it becomes a systematic uncertainty in terms of the GPS measurements ($u_{b,9}$, $u_{b,10}$), because the results of the TIC measurements affect all GPS measurements in the same way.

Based on an estimate in [6] an uncertainty contribution due to potential multipath disturbance is added as $u_{b,11}$. Measurement of antenna cable delays is usually done with an uncertainty of 0.5 ns, in case of PTBT two measurements were involved (standard cable and cable #2 at ESTEC). Note that this contribution $u_{B,12}$ is zero in case that the same cable is used at all sites. The term $u_{b,13}$ was reported by ESTEC.

For the generation of the CGGTTS data the PTBT antenna position is manually entered into the processing software in ITRF coordinates before the CCD measurements. These positions could differ from the "true" positions in a different way in each laboratory. This is taken into account by the contributions $u_{b,15}$ and $u_{b,16}$ in case of the code based delay calibration, because the position has an effect on the total delay. Since these effect is dominant in the height and linear for position errors up to 30 m [1], the absolute deviation of the manually entered position from the "true" position is multiplied with a coefficient which reflects the effect of the height error at each laboratory. The two uncertainty contributions, $u_{b,14}$ and $u_{b,15}$ correspond to antenna height errors of 10 cm and are based on studies published in [1].

The final uncertainty contribution, $u_{b,16}$, reflects the apparent change in PTBT operation conditions during the campaign. The combined uncertainty u_{CAL} is thus 2.8 ns (to be understood as 1-σ value).

References

[1] P. Defraigne, G. Petit, 2004, *"Time Transfer to TAI using geodetic receivers,"* **Metrologia, Vol. 40,** 184-188

[2] T. Feldmann, A. Bauch, D. Piester, M. Rost, E. Goldberg, S. Mitchell, B. Fonville, 2010, *"Advanced GPS-based Time Link Calibration with PTB´s new GPS Calibration Setup,"* Proc. 42nd PTTI, Novemberr 15-18, 2010, Reston VA, USA, 509-526

[3] *"SR620 Operating Manual and Programming Reference,"* SRS

[4] P. Panek, Dicom CZ and UFE, private communication

[5] I. Prochazka, P. Panek,, 2009, *"Nonlinear effects in the time measurement device based on surface acoustic wave filter excitation,"* **Rev. Sci. Instrum, Vol. 80,** 076102

[6] W. Lewandowski, C. Thomas, 1991, *"GPS Time transfers,"* **Proc. IEEE, Vol. 79, No. 7,** 991-1000

ANNEX 1

BIPM calibration information sheet

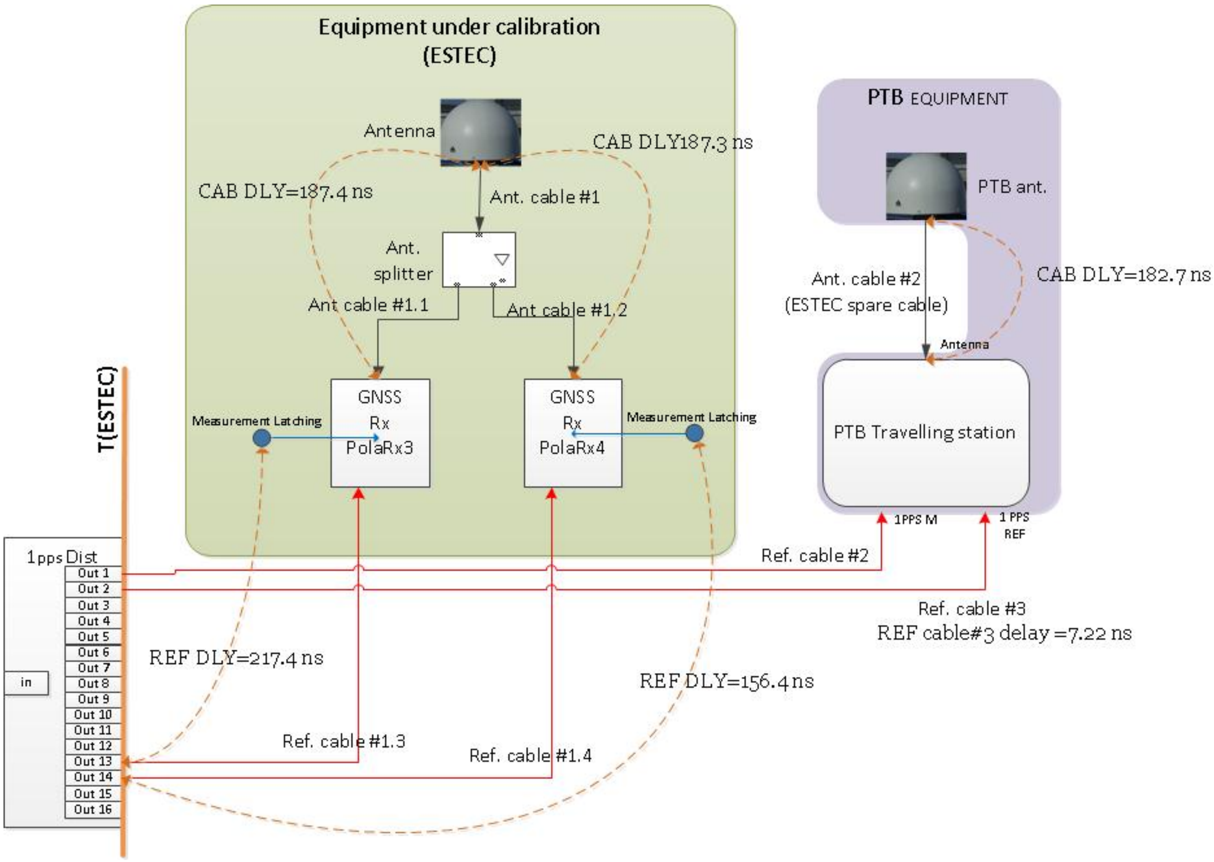
	Laboratory:	ESTEC
	Date and hour of the beginning of measurements:	**2012-10-27 (00:00:00 UTC) MJD 56227**
	Date and hour of the end of measurements:	**2012-10-31 (23:59:30 UTC) MJD 56231**

	Receiver setup information		
	Local	**Local:**	**Portable: PTBT**
• Maker	Septentrio	Septentrio	DICOM
• Type	PolaRx3	PolaRx4	GTR50
• Serial number	2001059 (ES03)	3001286 (ES04)	0708522
• Receiver internal delay (GPS); initial values according to header information	INT DLY(P1) = 0 INT DLY(P2) = 0	INT DLY(P1) = 0 INT DLY(P2) = 0	INT DLY(P1) = -28.8 ns INT DLY(P2) = -22.7 ns
• Receiver internal delay (GLO)	N/A	N/A	N/A
• Antenna cable identification	#1/Splitter/#1.1	#1/Splitter/#1.2	at ESTEC: ESTEC spare #2
• Corresponding cable delay	187.4 ns	187.3 ns	182.7 ns at ESTEC
• Delay to local UTC	217.4 ns	156.4 ns	4.7 ns
• Receiver trigger level	1.0 V	1.0 V	1.0 V
• Coordinates reference frame	ITRF	ITRF	ITRF
Latitude or X m	+3904171.68 m	+3904171.68 m	+3904171.88 m
Longitude or Y m	+301744.41 m	+301744.41 m	+301744.85 m
Height or Z m	+5017777.48 m	+5017777.48 m	+5017777.45 m

	Antenna information		
	Local:	**Local:**	**Portable:**
• Maker:	Novatel	Novatel	Novatel
• Type:	NOV750.R4	NOV750.R4	GPS-702-GG
• Serial number:	1019003	1019003	1017577
	If the antenna is temperature stabilised		
• Set temperature value :		---	---

	Local antenna cable information	
	• Maker:	
	• Type:	
	• Is it a phase stabilised cable:	

Installation of receivers at ESTEC



All value and designations provided by ESTEC

ANNEX 2

BIPM calibration information sheet

	Laboratory:	PTB
	Date and hour of the beginning of measurements: CC1	**2012-09-05 MJD 56174**
	Date and hour of the end of measurements: CC1	**2012-09-08 56178 (5 days)**
	Date and hour of the beginning of measurements: CC2	**2012-12-06 MJD 56267**
	Date and hour of the end of measurements: CC1	**2012-12-12 56273 (7 days)**

	Receiver setup information		
	Local: PTBB	**Local: PT07**	**Portable: PTBT**
• Maker	Ashtech	DICOM	DICOM
• Type	Z-XII3T	GTR50	GTR50
• Serial number	RT820013901	0806091	0708522
• Receiver internal delay (GPS) Initial values according to header information	INT DLY(P1) = 304.5 ns, INT DLY(P2) = 318.9 ns	INT DLY(P1) = -36.0 ns INT DLY(P2) = -24.0 ns	INT DLY(P1) = -28.8 ns INT DLY(P2) = -22.7 ns
• Receiver internal delay (GLO)	N/A	N/A	N/A
• Antenna cable identification	-		
• Corresponding cable delay	301.7 ns	211.4 ns	223.8 ns
• Delay to local UTC :	75.3 ns	44.1 ns	73.9 ns (CC1) 29.5 ns (CC2)
• Receiver trigger level	1.0 V	1.0 V	1.0 V
• Coordinates reference frame	ITRF	ITRF	ITRF
Latitude or X m	3844060.0 m (PTB mast P2)	+3844056.75 m	+3844065.12 m
Longitude or Y m	709661.27 m	+709664.09 m	+709658.82 m
Height or Z m	5023129.51 m	+5023131.73 m	+5023125.83 m

	Antenna information		
	Local:	**Local:**	**Portable:**
• Maker:	Ashtech		Novatel
• Type:	ASH700936E	GPS-702-GG	GPS-702-GG
• Serial number:	CR15930	07020087	01017577

	If the antenna is temperature stabilised		
• Set temperature value :		---	---

	Local antenna cable information	
	• Maker:	
	• Type:	
	• Is it a phase stabilised cable:	