Report calibration NPL-PTB 2010

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GPS based link calibration between PTB and NPL

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Result for the link currently used by BIPM (executive summary)

Data from the NPL to PTB GPS link used by BIPM as backup for TWSTFT data are built on the receivers NP11 – PTBB.

The differential correction $-C_{GPS}$ to be added according to (2) to the GPS data obtained with these two fixed receivers is -0.99 ns, and the calibration uncertainty (1 σ) amounts to 1.01 ns. (see Table 5).

Details of the data evaluation and uncertainty estimation are given in the following sections. Information on the installation of the travelling receiver and on the fixed receivers at NPL and PTB, respectively, are given in Annex 1 and Annex2.

Calibration Procedure

In the relative link calibration campaign between NPL and PTB a traveling receiver (TR) was first operated at PTB together with all the fixed GPS receivers in a common-clock, very short baseline (a few meters distance between the antennas) setup for several days. Then it was shipped to NPL together with its antenna and antenna cable and operated there again for several days in a very short baseline setup together with the equipment at NPL. In order to ensure that the internal delays have not changed during the travel the measurement at PTB was repeated after the TR was shipped back to PTB.

By differencing the common-clock difference (CCD) results of both labs, the contributions of the TR cancels out and the calibration values for the links between the fixed receivers (FR) can be calculated according to

$$<\mathrm{TR@PTB} - \mathrm{FR(PTB)}> - <\mathrm{TR@NPL} - \mathrm{FR(NPL)}> = \mathrm{C}_1 - \mathrm{C}_2 = \mathrm{C}_{\mathrm{GPS}}\,, \qquad (1)$$

where <…> stands for the mean value over a certain period. The mean values are obtained by first calculating the time deviation (TDEV) of the CCD measurements. Then the averaging period is determined from the global minimum of the time deviation (TDEV) of the CCD measurement data, in order to get rid of the white phase noise. The averaged data are used to calculate the mean value of the CCD. The two CCDs at PTB are used to calculate C_1. The difference between the two CCD values obtained at PTB (dCCD) is part of the uncertainty budget which is explained later.

Only the offset of the 1 PPS signal connected to the TIC has to be measured with respect to the local UTC, the delays of the FRs are included in the calibration values. The operational link has to be corrected according to

$$[\mathrm{UTC(NPL)} - \mathrm{UTC(PTB)}]_{\mathrm{GPS}} = \mathrm{FR(NPL)} - \mathrm{FR(PTB)} - \mathrm{C}_{\mathrm{GPS}}\,. \qquad (2)$$

The calibration value for the TWSTFT link is calculated by comparing it to the calibrated GPS link

$$<[\mathrm{UTC(NPL)} - \mathrm{UTC(PTB)}]_{\mathrm{GPS}} - [\mathrm{UTC(NPL)} - \mathrm{UTC(PTB)}]_{\mathrm{TWSTFT}}> = \mathrm{C}_{\mathrm{TWSTFT}}\,. \qquad (3)$$

Equipment

The measurements were performed with the PTB calibration set-up (see Figure 1), consisting of a GTR50 receiver, a SR620 time interval counter (TIC) and a monitor/keyboard. The devices are integrated in a transportable rack. Becasue of the use of a traveling TIC for the determination of the local UTC reference points at both sites, a systematic error related to internal delay differences between different counters does not exist.

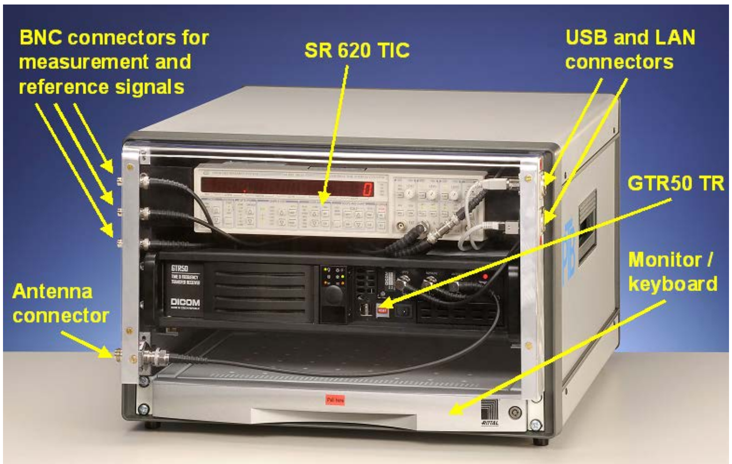

Figure 1. PTB's calibration set-up.

Table 1 lists the FRs at PTB and NPL. The nomenclature used here takes into account that one receiver produces different kinds of data.

Table 1. Receivers at PTB and NPL and their designation when providing data of different kind.

Institute	Receiver	C/A	P3	RINEX
PTB	Ashtech Z12-T	---	PT02	PTBB
	Ashtech Z12-T	---	PT03	PTBG
	AOS TTS-3	PT05	PT06	---
	Dicom GTR50	PT07	PT08	PT08
NPL	Dicom GTR50	NP11	NP11	NP11
	Time and Frequency Solutions Timetrace – GPS Common View	TFS102	---	---

Uncertainty Estimation

The overall uncertainty of the GPS link calibration is given by

$$\mathrm{U_{GPS}} = \sqrt{\mathrm{u_a^2} + \mathrm{u_b^2}}\,, \tag{4}$$

with the statistical uncertainty u_a and the systematic uncertainty u_b. The statistical uncertainty is related to the standard deviation (SD) of the averaged CCD data. At NPL the SD is directly the relevant u_a-contribution. Since CCD data were taken at PTB before and after the trip to NPL the higher SD is chosen as the relevant contribution. In case that the difference of the mean values of the two CCD measurements (dCCD) exceed the SD, the absolute value of dCCD is used as u_a (see reference [1]).
The systematic uncertainty is given by

$$\mathrm{u_b} = \sqrt{\sum_n \mathrm{u}_{\mathrm{b},n}}\,. \tag{5}$$

The contributions to the sum are listed in Table 2 and explained below.

The uncertainties due to the instabilities of the connection to the local UTC sites ($u_{b,1}$, $u_{b,2}$) [?] are estimated from long term laboratory experience.

According to the manufacturer specifications the trigger level timing error of the TIC ($u_{b,3}$, $u_{b,4}$) is given by [2]

$$\text{Trigger level timing error} = \frac{15\ \text{mV} + 0.5\ \%\ \text{of trigger level}}{1\ \text{PPS slew rate}} \tag{6}$$

for start and stop channel, respectively. With a trigger level of 1 V at one channel and an estimated signal slew rate of 0.5 V/ns the error is 0.04 ns per channel and 0.06 ns for the measurement after adding the start and stop error in quadrature. The trigger level timing error of the TR´s internal TIC ($u_{b,5}$, $u_{b,6}$) is estimated, according to information given by the manufacturer [3], as 10 mV / (1 PPS slew rate) per channel. The error of the stop channel cancels out, because it is always provided with the signal of the receiver board.

Table 2. Systematic uncertainty contributions. Values are determined either by measurements or by estimation and rounded to the second decimal. The contributions marked with an asterisk are only applied to special measurements (see text).

Uncertainty	**Value / ns**	**Description**
$u_{b,1}$	0.10	Instability of the connection to UTC(PTB)
$u_{b,2}$	0.10	Instability of the connection to UTC(NPL)
$u_{b,3}$	0.06	TIC trigger level timing error at PTB
$u_{b,4}$	0.06	TIC trigger level timing error at USNO
$u_{b,5}$	0.02	TR trigger level timing error at PTB
$u_{b,6}$	0.02	TR trigger level timing error at NPL
$u_{b,7}$	0.10	TIC nonlinearities at PTB
$u_{b,8}$	0.10	TIC nonlinearities at NPL
$u_{b,9}$	0.01	Jitter of the TIC after 100 measurements at PTB
$u_{b,10}$	0.01	Jitter of the TIC after 100 measurements at NPL
$u_{b,11}$	0.01	Determination of the UTC reference point at PTB
$u_{b,12}$	0.10	Determination of the UTC reference point at NPL
$u_{b,13}$	0.30	Multipath
$u_{b,14}$	0.18	Antenna cable and antenna
$u_{b,15}$*	0.27	Position error at PTB
$u_{b,16}$*	0.40	Position error at NPL
$u_{b,17}$*	0.30	Uncertainty of the ambiguity estimation

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. Since the TR´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 [4]).

Although the TIC jitter (SD) is the statistical uncertainty of the TIC measurement, it becomes a systematic uncertainty in terms of the GPS measurement ($u_{b,9}$, $u_{b,10}$), because the result of the TIC measurement affects all GPS measurements in the same way. The jitter was found to be 0.01 ns at both labs.

The delay of the UTC reference connected to the traveling TIC inside the calibration set-up has to be determined by a measurement, if it is not the local UTC by definition. The uncertainty of this measurement was $u_{b,11}$ = 0.01 ns at PTB, while the NPL quoted a value of $u_{b,10}$ = 0.10 ns.

The multipath effect at both sites is accounted for by $u_{b,13}$ = 0.30 ns [5].

Since the average outside temperature could be different for the two CCD measurements at PTB and the CCD measurement at NPL, an uncertainty $u_{b,14}$ = 0.18 ns is applied, accounting for different delays of of the antenna and the antenna cable during the distinct CCD measurements. The 0.18 ns are composed of a temperature coefficient of 0.01 ns/°C, estimated from an experiment performed at ROA in 2008 [6], multiplied with a maximum anticipated temperature difference of 20°C between the CCD measurements.

For the generation of the CGGTTS data the antenna positions of the TR 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 link calibrations, 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 "true" position of the TR at PTB and NPL is estimated with the help of the RINEX data and the NRCan-PPP software [7]. The PPP method guarantees consistency. Thus the PPP position can be named "true" position. The height error coefficients at each site are evaluated by comparing P3 CGGTTS data from two receivers in a common-clock short baseline setup generated with the R2CGGTTS software [8] developed at ORB from RINEX data and then regenerating the data of one of the two receivers with virtual height shifts of ±1 m. This is exemplarily depicted for the site NPL in Figure 2.

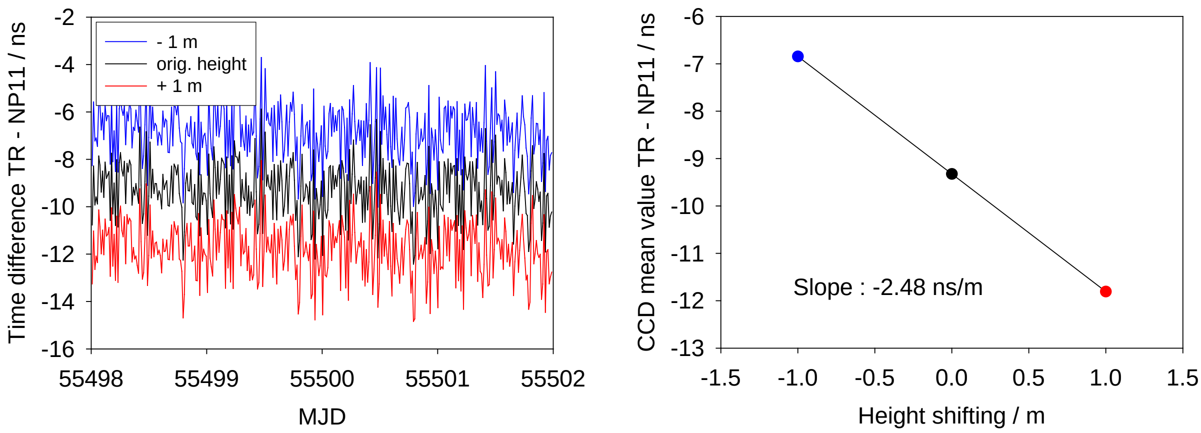

Figure 2. Determination of the position error coefficient at NPL.

The black graph on the left-handed plot shows the CCD between TR and NP11 with the same positions which are used by the internal processing software. The blue and the red graph depict the CDD between the two receivers using exactly the same data, but with a height shift applied to the TR of ±1 m, respectively. The right-handed plot shows the CCD mean value with respect to the height shift. The absolute value of the slope of the line which connects the three points is used as position error coefficient e_h(NPL) = 2.48 ns/m. A similar study was performed at PTB and the coefficient was calculated to be e_h(PTB) = 2.22 ns/m. The absolute value of the difference between "true" and manually entered position of the TR is 0.16 m at PTB and 0.12 m at NPL.

The uncertainty contribution $u_{b,17}$ of 0.3 ns is applied to the PPP link calibrations, according to reference [9], where a typical phase discontinuity of 0.15 ns per receiver was found for PPP batch processing with the NRCan-PPP software [7], independent of the length of the processed batch. This adds up geometrically to 0.21 ns for a CCD comparison between a pair of receivers and to 0.3 ns for the two CCD measurements.

Results

The results of the two CCD measurements at PTB before and after the calibration trip of the TR to NPL are depicted in Figure 3. Data of the GTR50 receiver (PT07, PT08) were only available for the second CCD measurement (CCD2). The code based measurements (C/A-code, P3-code) are shown on the left plot, while the data evaluated with the precise point positioning (PPP) method are shown on the right hand side. For the PPP evaluation the NRCan-PPP [7] software was used, with the same settings as used by the BIPM, applying IGS clock and ephemeris products and the actual IGS antenna calibration file.

Since data of the PT07/PT08 receiver were only available for the second CCD measurement at PTB, a statistical uncertainty of 0.5 ns is assumed, based on a previous campaign [10].

The TDEVs of the CCD comparisons used for the white phase noise elimination at PTB before the calibration trip to NPL are shown in Figure 4, while the TDEV estimates of the CCD measurements after the trip to NPL are depicted in Figure 5.

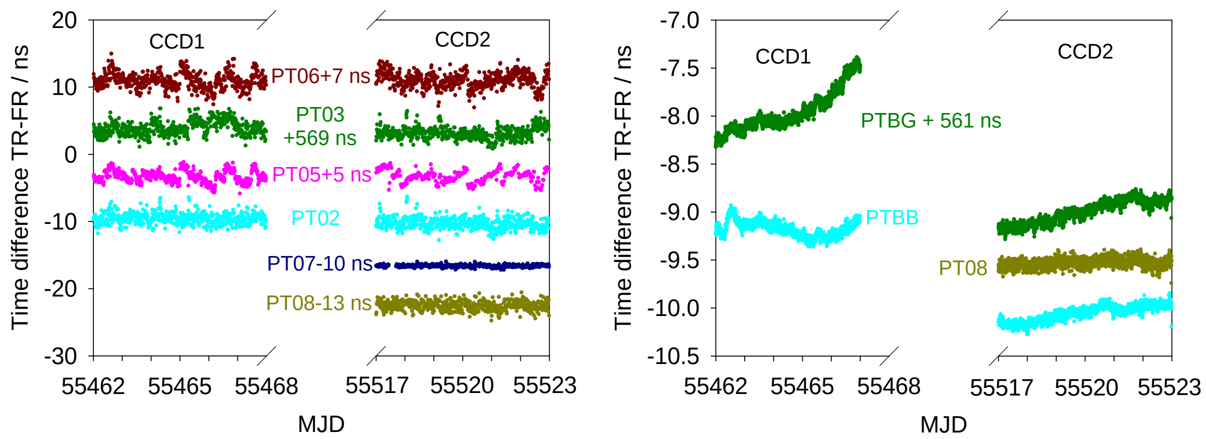

Figure 3. CCD measurements between the TR and the FRs at PTB before and after the calibration trip to NPL. For better visibility offsets are applied to some of the data. The left plot shows the code based (C/A, P3) measurements, the PPP results are depicted on the right plot.

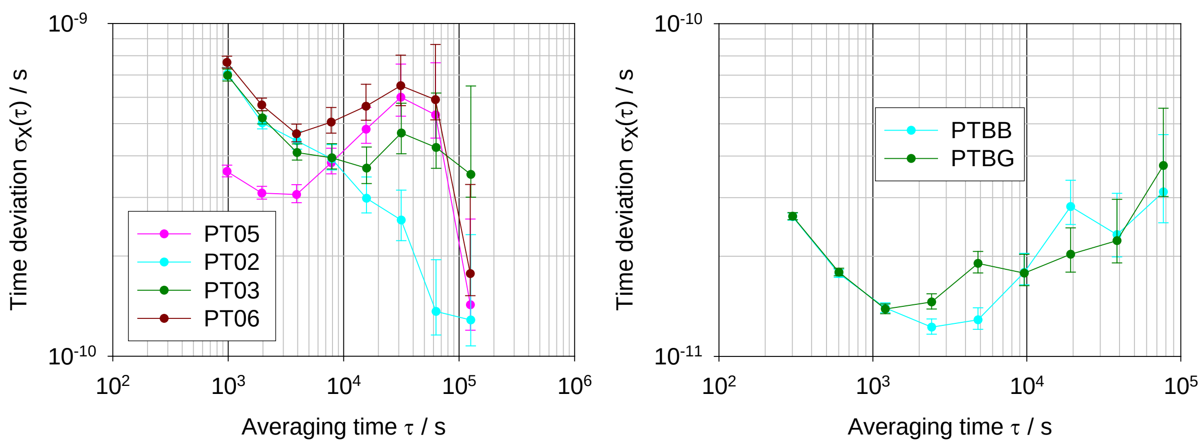

Figure 4. TDEVs of the CCD comparisons TR-FR at PTB before the trip to NPL for code based data (left plot) and PPP data (right plot).

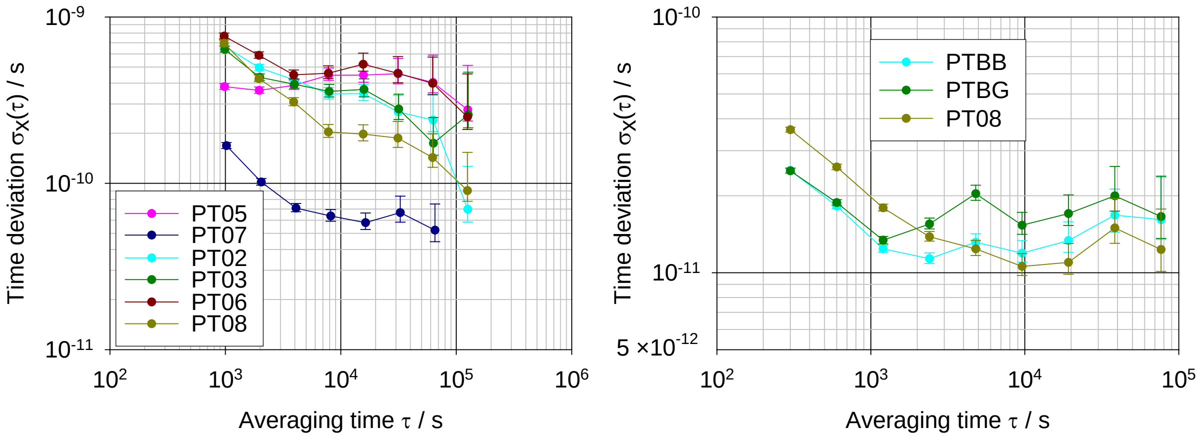

Figure 5. TDEVs of the CCD comparisons TR-FR at PTB after the trip to NPL for code based data (left plot) and PPP data (right plot).

The results of the CCD measurements at PTB are listed in Table 3. AVT1 and AVT2 are the averaging times estimated with the help of the minimum of the TDEV plots (Figure 4 and Figure 5). If the maximum of the confidence interval of an estimation point exceeds the value of the preceding estimation point, the shorter averaging time is chosen.

Table 3. Results of the CCD measurements at PTB. Values are rounded to the second decimal. The underlined value is chosen as the uncertainty $u_{a,PTB}$. The differences between CCD1 and CCD2 for the PT02/PTBB and PT03/PTBG receiver are due to changes in the PTB installations while the TR was at NPL.

Type	FR	AVT1	CCD1 / ns	AVT2	CCD2 / ns	C_1 / ns	dCCD / ns	SD1 / ns	SD2 / ns
C/A	PT05	3840 s	-8.32	1920 s	-8.28	-8.30	-0.04	0.80	0.91
	PT07	---	---	7680 s	-6.60	-6.60	---	---	0.10
P3	PT02	1/2 day	-9.51	1 day	-10.24	-9.88	0.73	0.17	0.17
	PT03	15360 s	-565.07	1/2 day	-565.81	565.44	0.74	0.77	0.47
	PT06	1 day	3.93	3840 s	4.01	3.97	-0.08	0.23	0.94
	PT08	---	---	1/2 day	-9.52	-9.52	---	---	0.19
PPP	PT08	---	---	9600 s	-9.53	-9.53	---	---	0.03
	PTBB	2400 s	-9.17	2400 s	-10.05	-9.61	0.88	0.07	0.08
	PTBG	1200 s	-560.95	1200 s	-562.00	-561.48	1.05	0.21	0.11

In contrast to the GTR50 receiver, the Ashtech Z-12 receivers at PTB do not apply the internal delays, the antenna cable delay, and the reference delay to the RINEX files. The CGGTTS P3 data are calculated from the RINEX files with the R2CGGTTS software [8] developed at ORB and the delay settings are made in this software. Thus the results of the PPP analysis of the PTBB and PTBG data are corrected by

$$D = \frac{154^2 D_{\mathrm{P1}} - 120^2 D_{\mathrm{P2}}}{9316} + D_{\mathrm{Cab}} - D_{\mathrm{Ref}}, \qquad (7)$$

where D is the total delay which has to be subtracted from the PPP calibration values. D_{P1} and D_{P2} are the internal delays on the two GPS frequencies, D_{Cab} is the antenna cable delay, and D_{ref} is the delay with respect to the UTC reference point.

The CCD measurement at NPL is depicted in Figure 6 and Figure 7. Figure 6 shows the comparison between the TR and the NP11 receiver (Left plot: C/A-code data, right plot: P3 and PPP results).

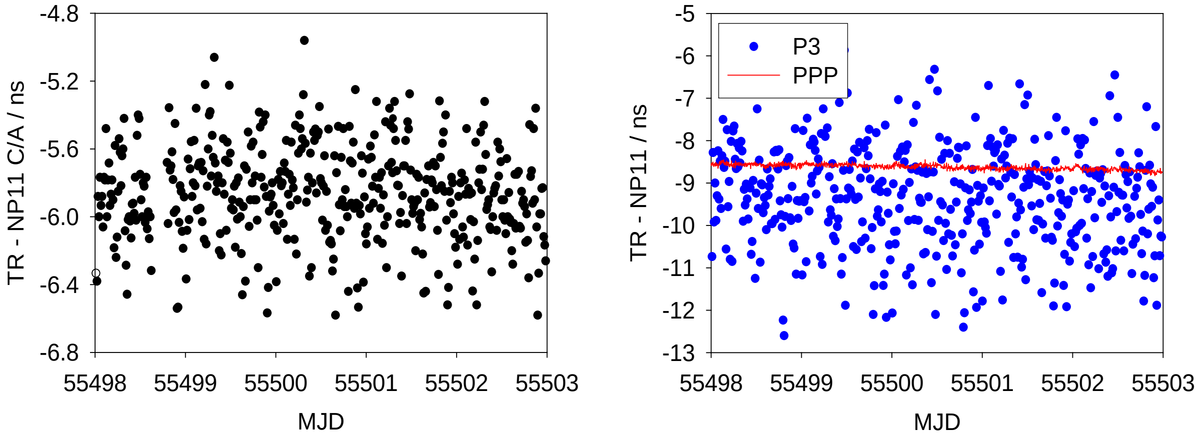

Figure 6. CCD measurement between TR and NP11 at NPL. The left picture shows the C/A-code measurement, the right picture shows P3 and PPP data.

The TF102 receiver was in operation for a too short period while the TR was at NPL. Thus it was compared to the new calibrated NP11 receiver for a period overlapping with the TR measurement for two days and then referenced to the TR. The left plot of Figure 7 shows the comparison. The square root of the geometric sum of the SDs of the TR-NP11 and the NP11-TF102 are used as statistical uncertainty of the TF102 calibration. The TDEVs of all measurements at NPL are depicted on the right plot of Figure 7.

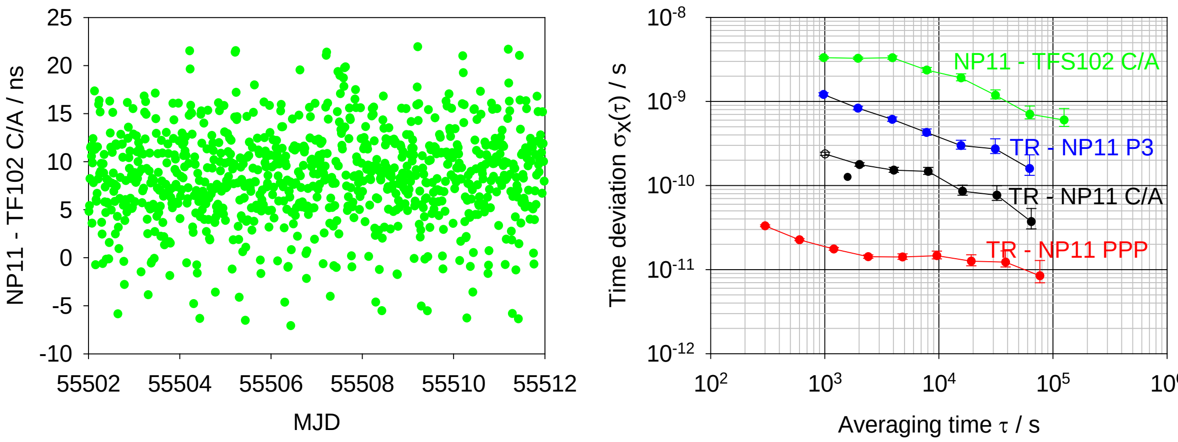

Figure 7. CCD measurement between NP11 and TF102 (left plot) and TDEVs all CCD measurements at NPL.

The NPL results, the statistical uncertainty, and the averaging times estimated from the TDEV (Figure 7) are listed in Table 4.

Table 4. Results of the CCD measurements at NPL. Values are rounded to the second decimal.

Type	FR	AVT	C_2 / ns	$U_a(C_2)$ / ns
C/A	TFS102	1 day	-14.32	0.59
	NP11	1/2 day	-5.86	0.08
P3	NP11	1/2 day	-9.34	0.23
PPP	NP11	2400 s	-8.62	0.06

The calibration values for all possible GPS links between NPL and PTB are listed in Table 5 together with the corresponding uncertainties.

Table 5. Calibration values and corresponding uncertainties for all possible GPS links. The values are rounded to the second decimal after calculation. The yellow highlighted link is used by the BIPM if no TWSTFT data are available.

Type	Link	C_{GPS} / ns	u_a / ns	u_b / ns	U / ns
C/A	TFS102-PT05	6.02	1.08	0.64	1.26
	TFS102-PT07	7.72	0.77		1.00
	NP11-PT05	-2.44	0.91		1.12
	NP11-PT07	-0.74	0.51		0.82
P3	NP11-PT02	-0.54	0.77		1.00
	NP11-PT03	-556.10	0.80		1.03
	NP11-PT06	13.31	0.97		1.16
	NP11-PT08	-0.18	0.55		0.84
PPP	NP11-PT08	-0.91	0.50	0.49	0.70
	NP11-PTBB	-0.99	0.88		1.01
	NP11-PTBG	-552.86	1.05		1.16

The difference of 3.2 ns between the P3 and PPP calibration value for the links NP11-PT03 and NP11-PTBG is significant. It is due to the unknown antenna type: In a PPP process the negligence of the IGS antenna phase center calibration file causes a general offset (see reference [1]). For the generation of the NP11 PPP data the antenna type was changed in the RINEX file header to the IGS compliant form (NOV702GG instead of Novatel GPS-702). In the meantime the receiver´s software has been corrected.

In 2011 the setting of the delay D_{P1} of the NP11 receiver was changed from -46.7 ns at the moment of the calibration measurement to -46.95 ns. By using equation (7) and the other delays taken from the header of the calibration P3 files and a P3 file generated in June 2011, the total internal delay has changed by +0.25 ns. The calibration values of the P3 and PPP links involving the NP11 receiver have to be corrected. Since the calibration values are subtracted from the link data according to equation (2) the 0.25 ns have also to be subtracted ($C_{GPS,new}$=$C_{GPS,old}$–0.25 ns).

TWSTFT Calibration

The operational TWSTFT link between NPL and PTB is compared to the GPS link with the lowest uncertainty, which is the PPP link NP11-PT08. The GPS and the TWSTFT data are depicted on the left handed plot of Figure 8. TWSTFT data were not available during the GPS calibration campaign and during the rest of the year 2010. The TWSTFT data of this period used here were the only one found to have an acceptable noise level. The change of the delay settings of the NP11 receiver is taken into account. The data are in good agreement with the Circular T value within the 5 ns uncertainty stated by the BIPM.

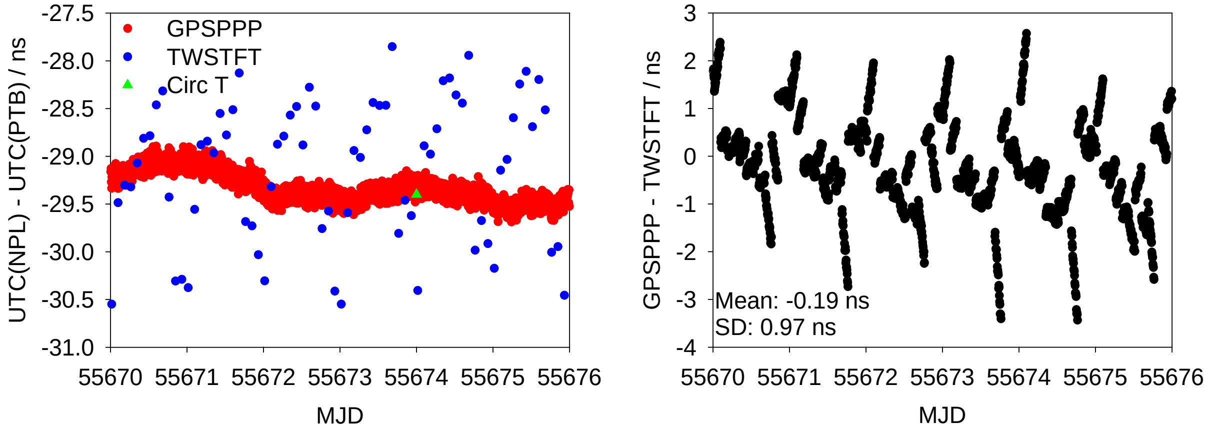

Figure 8. GPSPPP - TWSTFT

The right handed plot shows the comparison of the calibrated GPSPPP link to the TWSTFT link. The 300 s spaced GPS data were compared to values obtained by a linear interpolation between two adjacent TWSTFT measurements. It is obvious that the dominating noise type is not white phase noise. This is confirmed by calculating the TDEV, which has its minimum at the beginning (τ = 300 s). Thus the TDEV is not depicted here. The TWSTFT calibration value (3) is calculated as the mean value of the complete data set. By geometrically adding the SD of the GPS-TWSTFT comparison to the uncertainty of the NP11-PT08 GPSPPP calibration one gets

$$C_{\mathrm{TWSTFT}} = (-0.19 \pm 1.20)\ \mathrm{ns}\,. \qquad (?)$$

Summary

With PTB´s travelling calibration setup the links between NPL and PTB have been calibrated with uncertainties well below 1.5 ns. The link usually evaluated by the BIPM is the PPP link NP11-PTBB. This link should be corrected by adding 0.99 ns (see Table 5 and equation (2)).
By comparing the new calibrated link NP11-PT08 with TWSTFT data, the calibration value for TWSTFT is just -0.19 ns but with an uncertainty of 1.2 ns. Thus the TWSTFT link between PTB and NPL should not be adjusted.

Changes of the NP11 receiver´s delay settings have to be taken into account when analyzing its data.

References

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ANNEX 1

BIPM calibration information sheet

Laboratory:	PTB
Date and hour of the beginning of measurements CCD1	**2010-09-23 (00:00 UTC)**
Date and hour of the end of measurements CCD1	**2010-09-28 (24:00 UTC)**
Date and hour of the beginning of measurements CCD2:	**2010-11-17 (00:00 UTC)**
Date and hour of the end of measurements CCD2:	**2010-11-22 (24:00 UTC)**

Receiver setup information

	Local:	**Portable: PTTR**
• Maker:	Ashtech	DICOM
• Type:	Z-XII3T	GTR50
• Serial number:	RT820013901	
• Receiver internal delay (GPS) :	P1 = 304.5 ns, P2 = 318.9 ns	P1 = -28.8 ns, P2 = -22.7 ns, MC = -26.8 ns
• Receiver internal delay (GLO) :	N/A	N/A
• Antenna cable identification:	-	-
Corresponding cable delay :	301.7 ns	223.8 ns
• Delay to local UTC :	65.5 ns	73.8
• Receiver trigger level:	1 V	1 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	3844059.94 m (PTB mast P12)	3844057.85 m (PTB mast P11)
Longitude or Y m	709661.39 m	709663.12 m
Height or Z m	5023129.65 m	5023131.03 m

Antenna information

	Local:	**Portable:**
• Maker:	Ashtech	Novatel
• Type:	ASH700936E	NOV702
• Serial number:	CR15930	NAE07020087
If the antenna is temperature stabilised		
• Set temperature value :	-	-

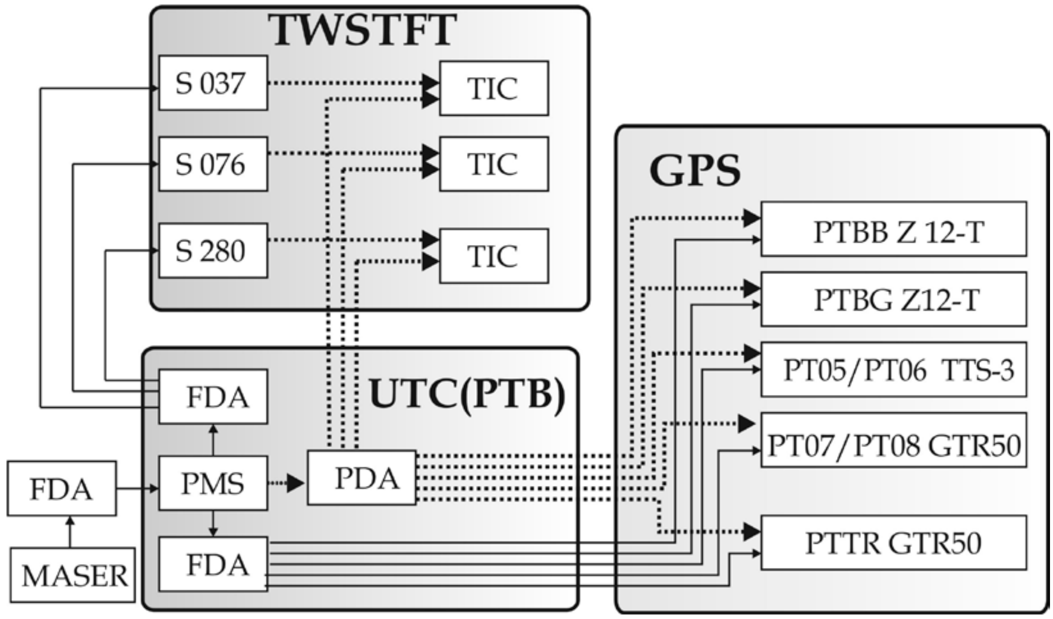
Local antenna cable information

• Maker:	Nokia
• Type:	RG214
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	20 m

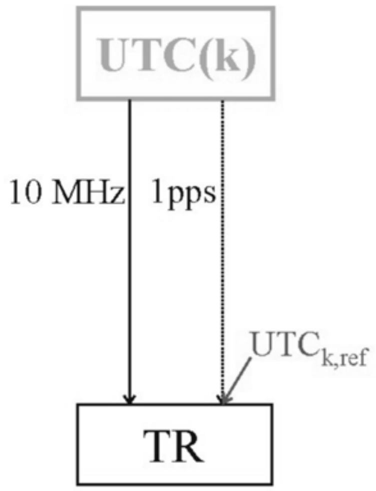
General information

• Rise time of the local UTC pulse:	< 5 ns
• **Is the laboratory air conditioned:**	Yes
• Set temperature value and uncertainty :	23,0 ± 0,5 °C
• Set humidity value and uncertainty :	Max. 50 %

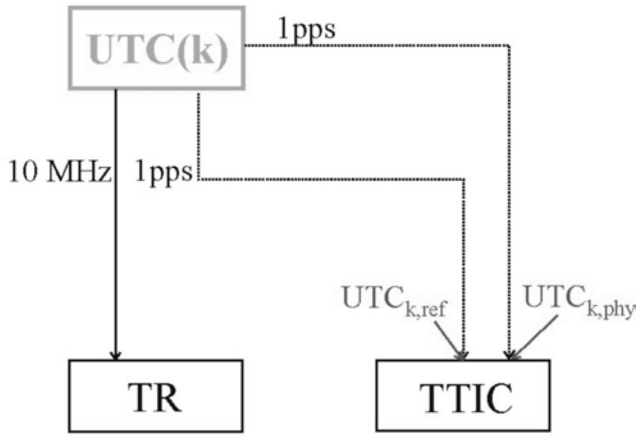
Installation of fixed and travelling receivers in PTB



Description of the Delay to local UTC(k) measurement



UTC(k) local realization of UTC
$UTC_{k,ref}$ reference 1pps for the TR (trigger level 1.0 V)
TR travelling receiver



UTC(k) local realization of UTC
$UTC_{k,phy}$ local physical 1pps representation of UTC
$UTC_{k,ref}$ reference 1pps for the TR (trigger level 1.0 V)
TR travelling receiver
TTIC travelling TIC

ANNEX 1

BIPM calibration information sheet

Laboratory:	NPL
Date and hour of the beginning of measurements:	**2010-11-02 (00:00 UTC)**
Date and hour of the end of measurements:	**2010-11-12 (00:00 UTC)**

Receiver setup information

	Local:	**Portable: PTBTR**
• Maker:	GTR50	GTR50
• Type:	DICOM	DICOM
• Serial number:	0807183	
• Receiver internal delay (GPS) :	P1 = -34.9 ns, P2 = -27.1 ns, MC = -30.8 ns	
• Receiver internal delay (GLO) :	N/A	N/A
• Antenna cable identification:	-	
Corresponding cable delay :	251.5 ns	
• Delay to local UTC :	53.6 ns	
• Receiver trigger level:	1.0 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	+3985120.38	+3844065.12 (PTB mast P2)
Longitude or Y m	-23893.87	+709658.82
Height or Z m	+4963240.36	+5023125.83

Antenna information

	Local:	**Portable:**
• Maker:	Novatel	
• Type:	NOV702	
• Serial number:	NAE08220006	
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

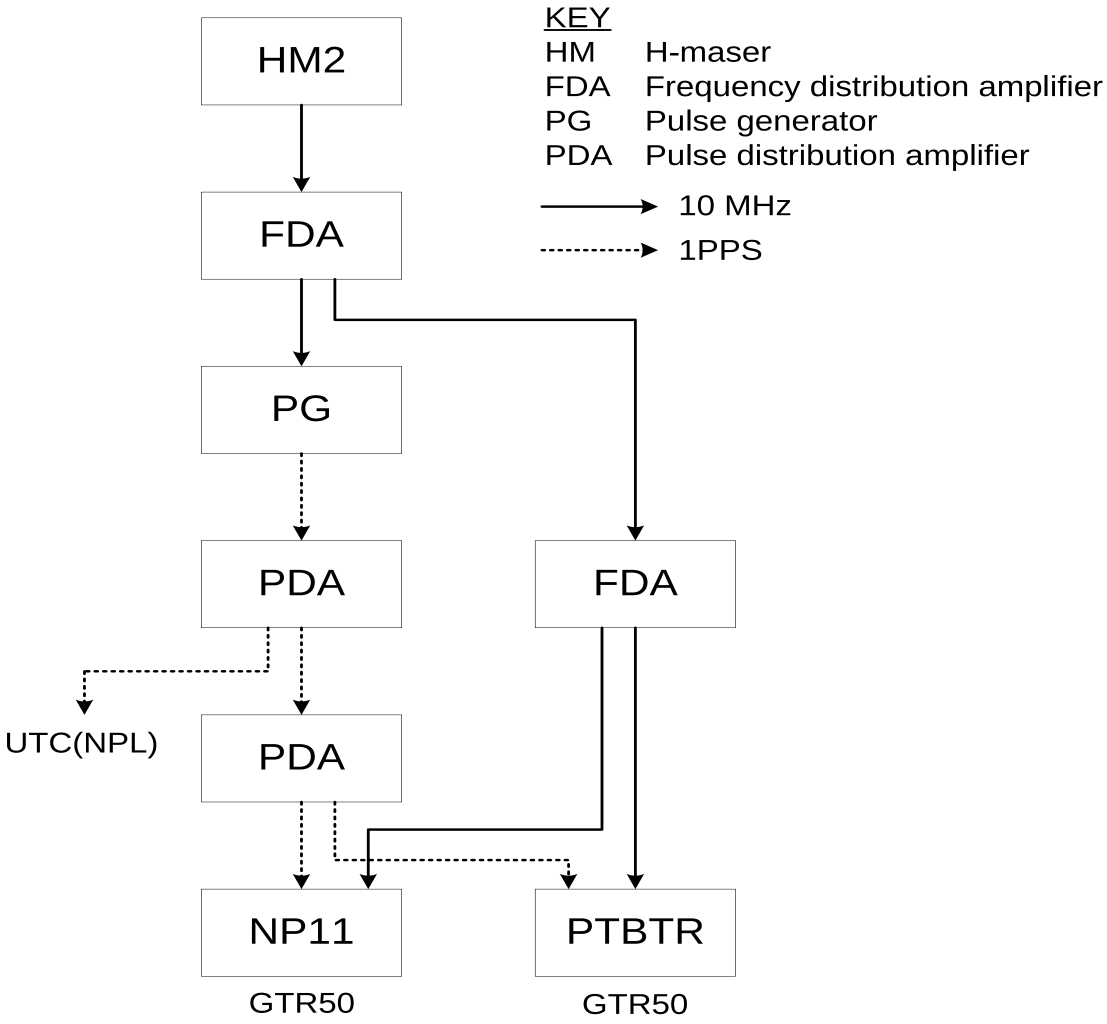
• Maker:	Andrew Corp.
• Type:	Heliax FSJ1-50A
• Is it a phase stabilised cable:	Yes
• Length of cable outside the building :	Approx. 5 m (+60 m in roof space that does not have temperature control)

General information

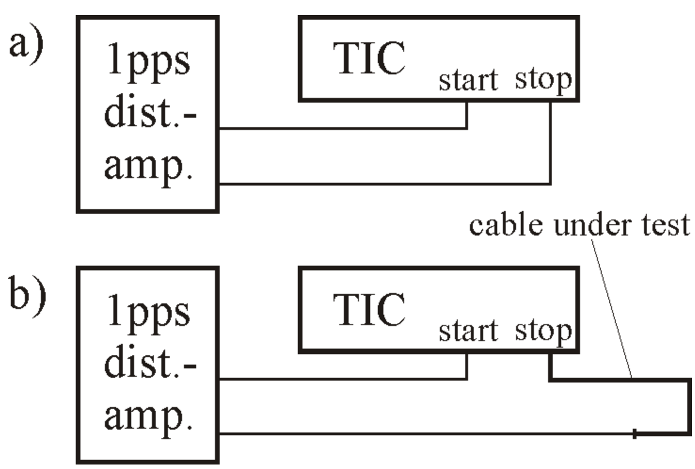
• Rise time of the local UTC pulse:	< 5 ns
• **Is the laboratory air conditioned:**	yes
• Set temperature value and uncertainty :	22.0 ± 1.0 °C
• Set humidity value and uncertainty :	Not measured during the calibration

Plot of the experiment set-up:

Link to the local UTC of both receivers and Antenna positions



Description of the local method of cable delay measurement:



cable delay = measurement b) – measurement a)