ON IMPROVED GPS-BASED CALIBRATION OF THE TIME LINKS BETWEEN METAS AND PTB

T. Feldmann[(1)], A. Bauch[(1)], D. Piester[(1)], A. Stefanov[(2)], L.-G. Bernier[(2)], C. Schlunegger[(2)], K. Liang[(1,3)]

[(1)]Physikalisch-Technische Bundesanstalt (PTB
Bundesallee 100, 38116 Braunschweig, Germany
Email: thorsten.feldmann@ptb.de

[(2)]Bundesamt für Metrologie (METAS)
Lindenweg 50, 3003 Bern-Wabern, Switzerland

[(3)]National Institute of Metrology (NIM)
No. 18, Northern 3rd Ring Eastern Road, Chaoyang Dist., Beijing, China, 100013

ABSTRACT

We report the results of a differential calibration of the time links between the Swiss Federal Office of Metrology (METAS) and the German Physikalisch-Technische Bundesanstalt (PTB) in 2009 using a travelling state-of-the-art GPS time and frequency transfer receiver. Neglecting possible long term variations of the GPS equipment, the estimated uncertainties of the calibration values are below 2 ns for all links. The results are verified by comparing them to the calibrated two-way satellite time and frequency transfer (TWSTFT) link. Thereby it appears that, vice-versa, a GPS calibration via a travelling receiver can indeed be used to calibrate a TWSTFT link with an uncertainty below 2 ns.

INTRODUCTION

In summer 2009 the time links between the Swiss Federal Office of Metrology (METAS) and the German Physikalisch-Technische Bundesanstalt (PTB) were calibrated using a travelling GPS receiver. The travelling receiver (TR) of type Dicom GTR50 [1,2] was compared to all available fixed receivers (FR) located at both labs (two at METAS, four at PTB), providing CGGTTS L3P and RINEX data. The two receivers at METAS are an Ashtech Z12-T (CH02) and a Septentrio PolaRx (CH03). At PTB the FRs are two Z12-T receivers (PT02, PT03), one AOS TTS3 (PT06), and a Dicom GTR50 (PT08). Other PTB receivers that provide L1 C/A code CGGTTS data have not been involved, because the METAS receivers do not provide this kind of data.

The P3 code links can either be operated in common-view (CV) or all-in-view (AV) mode [3,4]. We show that the usage of CV is the better choice for calculating the calibration values, independent of the mode with which the link is operated later.The carrier-phase links based on the RINEX data are calibrated utilizing the NRCan-PPP software [5] which is also used by the BIPM for precise point positioning (PPP) time transfer. Since the PPP process is done for each receiver independently before the comparison, link operation as well as calibration is de facto done in AV mode.

We estimated that the uncertainties of the achieved calibration values of the time links are below 2 ns, as it was already demonstrated in a previous study [6]. This type of GPS based link calibration can in particular be used in the case of long-distance links, for which the standard TWSTFT-based calibration [7] is technically not possible. Moreover, since the “travelling GPS receiver calibration” is much cheaper and simpler than the conventional “travelling portable TWSTFT station calibration”, it is possible to perform it more often, hence it can be used just to check a elaborate TWSTFT calibration. Furthermore, this type of link calibration is well adapted to the current structure of time links evaluated by the BIPM in the realization of UTC. It should be considered for use in regional networks, e. g., among the time laboratories collaborating in EURAMET in support of the GPS calibrations made by BIPM.

DESCRIPTION OF THE CALIBRATION PROCEDURES

The TR was first operated in PTB, together with all the fixed GPS receivers in a common-clock, very short baseline setup in order to get the so called common-clock differences (CCD). As depicted in Fig. 1, the devices are connected to the local UTC realization by 1 PPS signals with offsets d1, d2, d3, respectively, relative to the local reference point. The constant d2 stands for all offsets of the signals connected to the GPS receivers. Normally these delays are well known in a time laboratory and incorporated in the measurements, as well as receiver internal delays and antenna cable delays. However, in terms of a relative calibration these delays do not have to be taken into account, because the goal is to calibrate the entire link, including the complete chain of signal distribution, cables, devices, and antennas in both laboratories.

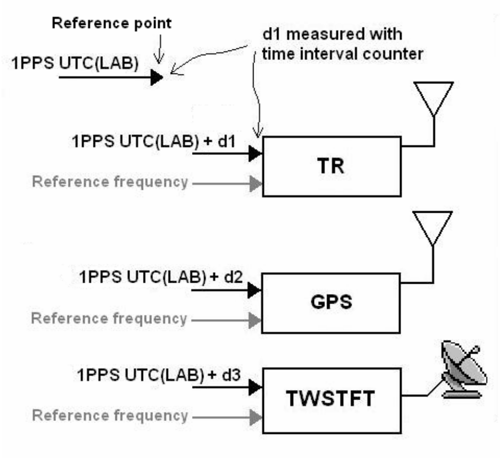

Fig. 1. Experimental setup for the common-clock measurements in METAS and PTB.

The only important value is the delay d1 of the temporary connection between the TR and the local UTC reference point in both labs. It should be measured as accurately as possible, if the TR is not directly connected to this point, which was neither the case in PTB nor in METAS.

The GTR50 1 PPS input connector can be directly considered as the TR reference point. In contrast to receivers locking their internal oscillator to an external reference frequency [8], no additional measurements are necessary. The measured d1 delay can be programmed into the GTR50´s internal processing software and is afterwards applied to all data (also to the RINEX files).

The TR was then shipped to METAS, together with its antenna and the antenna cable. The local delay d1 was measured and CCD data were taken. Finally the TR was sent back to PTB and the CCD measurement was repeated in order to ensure that the internal delays have not changed significantly during the travel.

The CCD values represent the difference of the sums of the delays in the chain antenna, antenna cable, receiver, and connection to the reference point for both receivers. By differencing the CCD results of both labs, the contributions of the TR cancel out and we get the calibration value for the links between FRs (one pair or multiple combinations). In mathematical terms it reads as follows:

$$\langle \mathrm{TR@PTB} - \mathrm{FR(PTB)} \rangle - \langle \mathrm{TR@METAS} - \mathrm{FR(METAS)} \rangle = C_1 - C_2 = C_{GPS}, \quad (1)$$

$$[\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{GPS} = \mathrm{FR(METAS)} - \mathrm{FR(PTB)} - C_{GPS}, \quad (2)$$

where $\langle ... \rangle$ stands for the mean value C_n of measurements over a certain period, UTC(CH) and UTC(PTB) are the local UTC at METAS and PTB, respectively, and C_{GPS} represents the GPS link calibration values. We note, that the sign of C_{GPS} is arbitrarily defined by (1). To calculate C_1 we used the mean of the CCD values obtained at PTB before and after the trip. The small difference between these values (dCCD) is part of the uncertainty budget, which is explained later.

PTB and METAS maintain a calibrated TWSTFT link [9]. By comparing a calibrated GPS link to the TWSTFT link, a calibration value for TWSTFT can be calculated:

$$\langle [\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{GPS} - [\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{TWSTFT} \rangle = C_{TWSTFT} \quad (3)$$

C_{TWSTF} should be close to zero and within the combined uncertainty of the calibration results. This condition can be understood as a check of the GPS calibration accuracy, or, vice versa, as a calibration of the TWSTFT link via GPS.

A second method to calibrate the TWSTFT link is to compare it to the temporary link established between a FR at PTB and the TR while it is at METAS:

$$\langle [\mathrm{TR@METAS} - \mathrm{FR(PTB)} - C_1] - [\mathrm{UTC(CH)} - \mathrm{UTC(PTB)}]_{TWSTFT} \rangle = C_{TWSTFT}. \quad (4)$$

Before we continue with the discussion of the calibration results, we briefly describe the advantage of using CV for the CCD evaluation.

AV VERSUS CV IN CALIBRATION CAMPAIGNS

A GPS P3 code time link on a European baseline, such as between METAS and PTB, can either be evaluated in common-view (CV) or in all-in-view (AV) mode. CV means that first the difference between two receivers is calculated for each satellite seen by both receivers independently at each epoch and that the mean value is calculated afterwards. In the AV mode a solution is at first independently calculated for each receiver with respect to GPS system time including all satellites tracked by each of the receivers, and differences are made based on the averages [3,4]. AV is superior to CV on intercontinental baselines and is currently (Feb. 2010) used for all the GPS-based TAI links by the BIPM. One could intuitively say that a CV link should be calibrated using CV CCD computation and an AV link using AV CCD computation, but we demonstrate in the following that CV is always preferable.

We have compared two receivers of the same type (GTR50) and two receivers of different types (GTR50 and TTS3) in CCD experiments. With identical receivers the results of CV and AV are equal in 57.23 % of the epochs, while with different receivers this is just the case in 3.36 % of all measurement epochs, as depicted in Fig. 2.

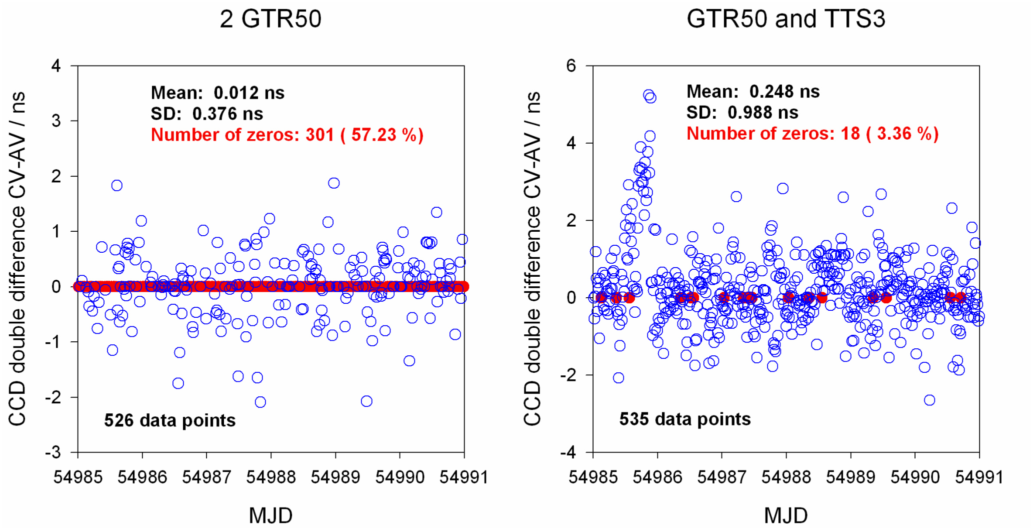

Fig. 2. CCD double differences CV-AV of two identical receivers (2 GTR50) and two receiver of different types (GTR50 and TTS3), each equipped with its own antenna, but connected to the same clock.

For the interpretation of this result we define the measurement of one satellite performed by one single receiver R at a certain epoch as

$$R_n(k) = UTC(L) + \Delta(k) - GPST + \varepsilon_n(k) + \delta_n, \tag{5}$$

with the satellite number n, the receiver number k=1,2, the local UTC realization UTC(L), a receiver R specific offset $\Delta(k)$, the GPS time GPST, a noise contribution $\varepsilon_n(k)$ and a satellite specific offset δ_n to the ideal GPS time. If we number all satellites tracked by both receivers at the same time arbitrarily with consecutive integers and define N(1,2) as the number of all these satellites, we can write for a CV CCD comparison (CCC):

$$CCC = \frac{1}{N(1,2)}\sum_{n=1}^{N(1,2)}\left[R_n(1) - R_n(2)\right] = \Delta(1) - \Delta(2) + \frac{1}{N(1,2)}\sum_{n=1}^{N(1,2)}\left[\varepsilon_n(1) - \varepsilon_n(2)\right] = C_1 + E_{CV} \tag{6}$$

The difference between the receiver offsets $\Delta(1) - \Delta(2)$ is our calibration value C_1 defined by (1), and E_{CV} is the total noise. All other contributions cancel. Using N(1) as the number of satellites seen by GPS(1) and N(2) as the number of satellites seen by GPS(2), an AV CCD comparison (ACC) reads

$$ACC = \frac{1}{N(1)}\sum_{n=1}^{N(1)} R_n(1) - \frac{1}{N(2)}\sum_{m=1}^{N(2)} R_m(1) = C_1 + \frac{1}{N(1)}\sum_{n=1}^{N(1)}\left[\delta_n + \varepsilon_n(1)\right] - \frac{1}{N(2)}\sum_{m=1}^{N(2)}\left[\delta_m + \varepsilon_m(2)\right] \tag{7}$$

Both receivers are tracking a number of satellites in parallel, while some satellites are only tracked by one of the receivers. By numbering the satellites in an appropriate way, we can rewrite (7) as

$$ACC = C_1 + \underbrace{\frac{1}{N(1,2)}\sum_{n=1}^{N(1,2)}\left[\varepsilon_n(1)-\varepsilon_n(2)\right]}_{E_{CV}} + \frac{1}{\tilde{N}(1)}\sum_{m=1}^{\tilde{N}(1)}\left[\delta_m+\varepsilon_m(1)\right] - \frac{1}{\tilde{N}(2)}\sum_{q=1}^{\tilde{N}(2)}\left[\delta_q+\varepsilon_q(2)\right] \quad (8)$$

with $\tilde{N}(1)$ and $\tilde{N}(2)$ the number of satellites tracked only by R(1) or R(2), respectively. This is (6) with additional contributions.

We conclude that an AV CCD is a CV CCD with additional noise and offset contributions. In nearly 60% of all measurements, two identical receivers track exactly the same satellites, according to Fig. 2. Achieving nearly 100% would only be possible, if the two receivers were connected to the same antenna using a signal splitter. The other satellites add additional measurements to the solution and can slightly shift the mean value. In the operation of very long baseline links in AV mode the advantage of using many satellites, in particular at high elevation, is larger than these negative effect [3,4], but in the framework of a calibration campaign they just increase the noise level, and thus the uncertainty. We propose to use always the CV method for a link calibration. Nevertheless, we have calculated calibration values utilizing both methods.

UNCERTAINTY ESTIMATION

The uncertainty of the GPS link calibration consists of statistical and systematic uncertainties u_a and u_b, respectively:

$$U = \sqrt{u_a^2 + u_b^2} = \sqrt{u_{a,1}^2 + u_{a,2}^2 + u_{b,1}^2 + u_{b,2}^2 + u_{b,3}^2 + u_{b,4}^2 + u_{b,5}^2} \quad (9)$$

The two parts of the statistical uncertainty $u_{a,1}$ and $u_{a,2}$ of the CCD experiment in METAS and PTB are conservatively estimated to be the standard deviation (SD). We use the higher SD value of the two CCD experiments in PTB as $u_{a,2}$. Table 1 summarizes all uncertainty contributions.

Table 1. Uncertainty contributions to the GPS link calibration. If values are determined by measurements, ranges are given. The red labelled contributions are only applied to some special measurements, blue labelled contributions are only applied if the TWSTFT link is calibrated (see text for details).

Uncertainty		Value	Description
$u_{a,1}$		0.058 ns to 0.783 ns	SD of the CCD at METAS SD of the comparison GPS - TWSTFT
$u_{a,2}$		0.107 ns to 1.415 ns	SD of the CCD at PTB
$u_{b,1} = \sqrt{u_{a,J}^2 + u_{b,S}^2 + u_{b,C}^2}$		0.512 ns	Connection of the TR to UTC(CH)
	$u_{a,J}$	0.05 ns	Jitter of the TIC after 20 measurements
	$u_{b,S}$	0.5 ns	Systematic uncertainty of the TIC
	$u_{b,C}$	0.1 ns	Instability of the connection to local UTC
$u_{b,2} = u_{b,1}$		0.512 ns	Connection of the TR to UTC(PTB)
$u_{b,3} = \sqrt{u_{b,A}^2 + u_{b,CCD}^2 + u_{b,D}^2}$		> 0.2 ns	Instability of the receivers
	$u_{b,A}$	0.2 ns	Antenna cable
	$u_{a,CCD}$	0.701 ns to 0.006 ns	Difference of both CCD´s at PTB
	$u_{b,D}$	1 ns or $\sqrt{2}$ ns	Drift of the Z12-T receicer
$u_{b,4} = \sqrt{u_{b,M}^2 + u_{b,I}^2 + u_{b,T}^2}$		≥ 0.3 ns	Propagation [10]
	$u_{b,M}$	0.3 ns	Multipath
	$u_{b,I}$	0.3 ns	Ionosphere
	$u_{b,T}$	0.7 ns	Troposphere
$u_{b,5}$		0.8 ns	Uncertainty of the ambiguity estimation [11]

The systematic uncertainty $u_{b,1/2}$ of the local UTC connection to the TR is assumed to be the same in METAS and in PTB. In both laboratories a Stanford Research SR620 time interval counter (TIC) was used to measure the 1 PPS signal connected to the TR with respect to the UTC reference point. In both cases we noted a jitter $u_{a,J}$ of 5 ps after averaging over 20 single measurements. The systematic uncertainty $u_{b,S}$ of the TIC is taken from the manufacturer specifications.

We estimated the instability of the connection to the local UTC signal $u_{b,C}$, 100 ps, from long lasting laboratory experience, noting that the environmental conditions in the METAS and PTB measurement rooms are equivalent.

In order to evaluate the instability of the receivers $u_{b,3}$, we have estimated the uncertainty due to the antenna cable $u_{b,A}$ to be 200 ps. Phase variations of the order of magnitude of 100 ps have been observed by sending a 10 MHz frequency through a 50 m cable loop on the roof of PTB´s clock hall and measuring the input versus the output with a high resolution phase comparator. Assuming a typical antenna cable length of about 50 m for each receiver, we get $\sqrt{2}\times 100$ ps for each pair TR – FR. Although the test cable was neither specified as antenna cable nor for outdoor use, we allow for 200 ps uncertainty to avoid underestimation. The difference of the two CCD experiments at PTB before and after the travel (dCCD) is an uncertainty contribution $u_{a,CCD}$, because it may be related to delay changes. It is different for each pair TR - FR and each analysis method (AV, CV, PPP). The red labelled contribution $u_{b,D}$ due to the drift of the Z12-T receiver is only applied in the case of PPP comparison, because the phase measurement shows long term drifts. It is estimated from a 80-day longterm CCD measurement between a GTR50 and a Z12-T. If the link is established by two Z12-T receivers, this uncertainty contribution has to be applied twice.

In the case of a GPS link calibration, the propagation of the signals is only affected by multipath effects [9], because in a quasi zero baseline setup, in which the CCDs are measured, the atmospherical and site dependent effects cancel.

An additional uncertainty contribution $u_{b,5}$ of 0.8 ns is applied to all PPP calibrations (red labelled), because the initial phase of the carrier frequency is a priori unknown and has to be estimated by the PPP software from the P3 code [10].

The uncertainty of the TWSTFT link calibration according to (3) is estimated by geometrically adding the SD of (3) to the calibration uncertainty of the GPS link. If the TWSTFT link is calibrated by comparing it to the temporary link established by the TR at METAS and a FR in PTB, according to (4), we have to take into account only the CCD experiment at PTB and $u_{a,1}$ becomes directly the SD of (4) (blue labelled in Table 1.) Moreover, this situation leads to uncertainties related to atmospherical effects (blue labelled extra contributions to $u_{b,4,}$ which are the main error source on European baselines, because the TR reference point is transported away from the FR in PTB. Since we have used the C/A code here, we have explicitly to take into account the ionosphere.

TIME SCHEDULE AND RESULTS

The TR was operated at PTB in June 2009 for 6 days within the interval MJD 54985 – 54991. Then, after the TR was used for another purpose, it was shipped to METAS and operated in July 2009 for ten days between MJD 55016 and MJD 55026. After this, it was immediately sent back, so that the second operation at PTB was done between MJD 55034 and MJD 55042. In June and July 2009 lightning conductors were mounted nearby the antennas at PTB, as visible in Fig. 3. These installations affected the measurements by multipath effects, which resulted in unstable carrier-phase measurements and noisy code based data. Thus, the lightning conductors have been removed at the end of July. At PTB the tracking of satellites with low elevation angles is limited by the surrounding trees. In general, the roof of the METAS building is a better place for GPS measurements, due to free sight to all directions.

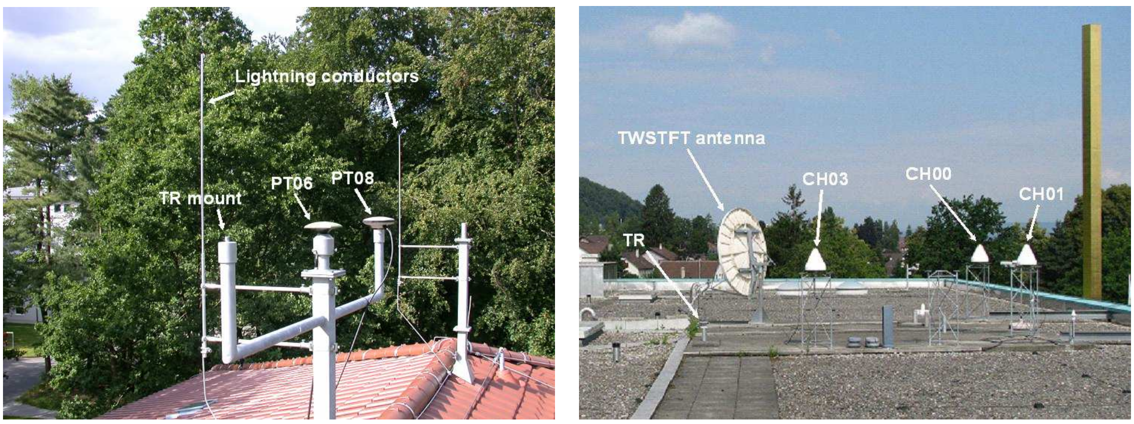

Fig. 3. Antenna sites at PTB (left picture) and at METAS (right picture). The TR antenna was not mounted at PTB site when the photo was taken. CH00 did not collect data during the calibration campaign.

In Fig. 4. the results of the P3 code CCD measurements at PTB before and after the calibration trip are depicted, analyzed with CV as well as with AV. The PT03 reference point is not measured with respect to the UTC(PTB) reference point and is arbitrarily determined by the cable lengths. No significant difference of the results before and after the trip to METAS are visible.

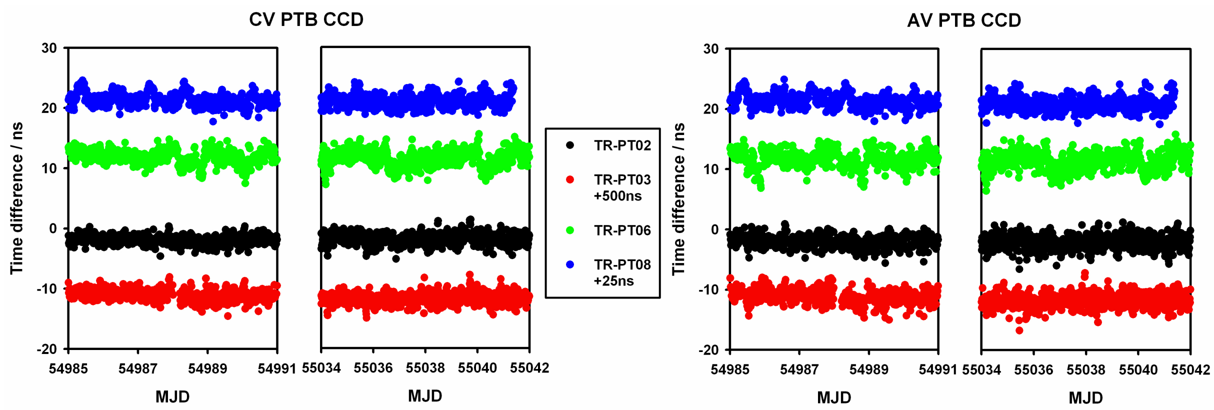

Fig 4. P3 code CCD results at PTB before and after the calibration trip to METAS, evaluated in CV and AV mode.

Fig. 5 shows the PPP CCD results at PTB. The comparison TR-PT06 is shown in a separated plot, because the noise level is at the same level as that of the code. This might be due to the receiver software. Due to problems with the antenna, PT08 data are not available on MJD 54985 and on MJD 55042. Furthermore this data look more unstable than expected from a comparison of two GTR50 [1,2,12], which is probably caused by the lightning conductors.

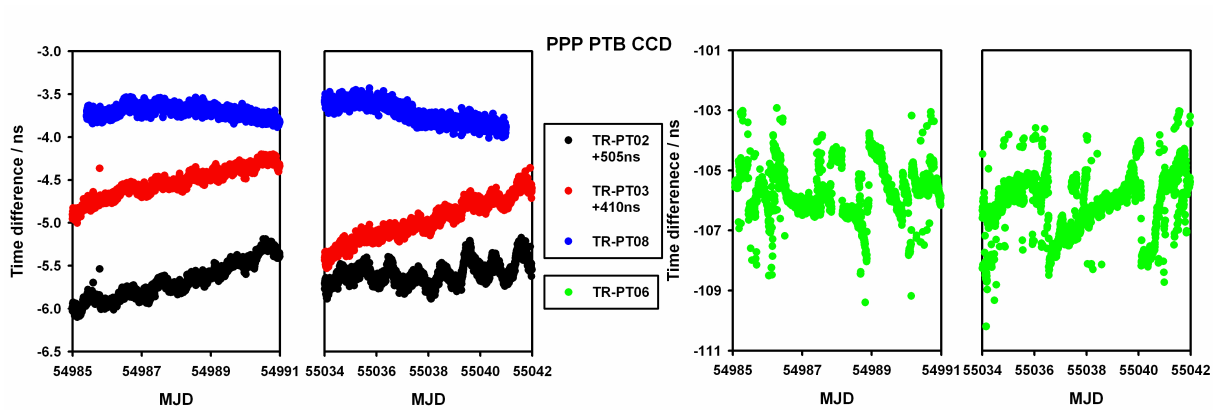

Fig. 5. PPP CCD results at PTB before and after the calibration trip to METAS, evaluated with NRCan-PPP [2].

The CCD results at METAS are shown in Fig. 6. At MJD 55021 the CH01 receiver has not generated a daily RINEX file. Data were rebuilt from hourly files, but it was not possible to reconstruct the corresponding P3 file. Here, as well as in Fig. 5, the Z12-T receivers´ phase drifts are clearly visible.

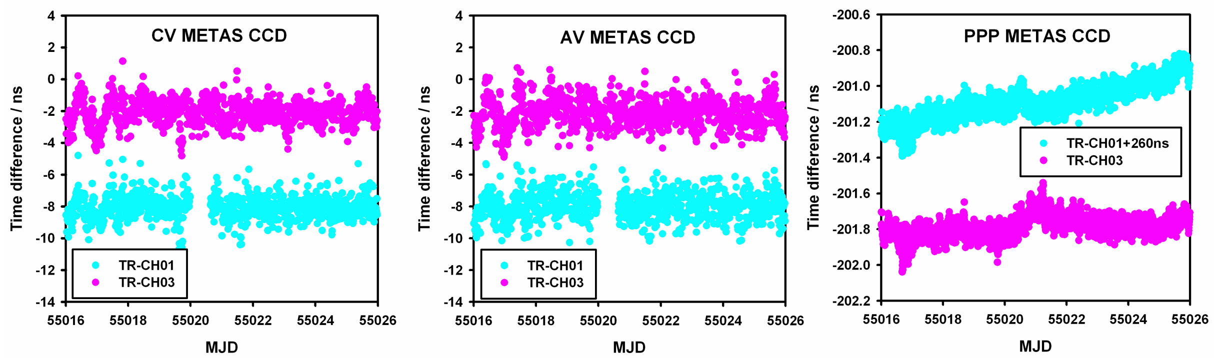

Fig. 6. CCD results at METAS.

The calibration values and the uncertainties are summarized in Table 2. As expected, the uncertainties for AV are always slightly higher than for CV. In the PPP case the uncertainties are dominated by additional systematic effects (red labelled contributions in Table 1), which leads in general to an overall uncertainty at the same level as with P3 code.

In order to check our results, we have compared the now calibrated P3 link with the lowest overall uncertainty to the calibrated TWSTFT link for one month (left plot in Fig. 7). From the mean value and the SD of 0.898 ns we get $C_{TWSTFT} = -1.204$ ns ± 1.683 ns. Additionally, we have used a temporary C/A code CV link between a fixed GTR50 (PT07) at PTB and the TR at METAS.

Table 2. Calibration values and corresponding uncertainties for the GPS links

Mode	Link	C_1 / ns	dCCD / ns	C_2 / ns	C_{GPS} / ns	u_a / ns	u_b / ns	U / ns
CV	CH01-PT02	-1.913	0.006	-8.076	6.163	1.170	0.809	1.423
	CH01-PT03	-511.410	0.701		-503.334	1.193	1.070	1.603
	CH01-PT06	11.710	0.460		19.786	1.517	0.931	1.780
	CH01-PT08	-3.849	0.413		4.227	1.316	0.908	1.599
	CH03-PT02	-1.913	0.006	-2.108	0.195	1.188	0.809	1.437
	CH03-PT03	-511.410	0.701		-509.302	1.211	1.070	1.616
	CH03-PT06	11.710	0.460		13.818	1.531	0.931	1.792
	CH03-PT08	-3.849	0.413		-1.741	1.332	0.908	1.612
AV	CH01-PT02	-2.083	0.013	-7.994	5.911	1.400	0.809	1.617
	CH01-PT03	-511.468	0.624		-503.474	1.412	1.022	1.743
	CH01-PT06	11.559	0.267		19.533	1.650	0.852	1.857
	CH01-PT08	-3.858	0.407		4.136	1.410	0.906	1.676
	CH03-PT02	-2.083	0.013	-2,112	0.029	1.423	0.809	1.637
	CH03-PT03	-511.468	0.624		-509.356	1.434	1.022	1.761
	CH03-PT06	11.559	0.267		13.671	1.670	0.852	1.875
	CH03-PT08	-3.858	0.407		-1,746	1.433	0.906	1.695
PPP	CH01-PT02	-523.703	0.039	-461.090	-62.613	0.234	1.815	1.830
	CH01-PT03	-426.862	0.657		34.228	0.223	1.930	1.943
	CH01-PT06	-105.900	0.458		355.190	0.998	1.582	1.870
	CH01-PT08	-3.911	0.416		457.179	0.145	1.571	1.578
	CH03-PT02	-523.703	0.039	-201.787	-321.916	0.220	1.515	1.531
	CH03-PT03	-426.862	0.657		-225.075	0.208	1.651	1.664
	CH03-PT06	-105.900	0.458		95.887	0.995	1.226	1.579
	CH03-PT08	-3.911	0.416		197.876	0.121	1.211	1.217

The CCD measurements yield a mean value $C_{1\ C/A\ CV}$ = –1.636 ns with a SD = 0.383 ns and a difference between the two CCD experiments dCCD = 0.095 ns. The comparison of this link to TWSTFT for this period has a SD = 0.651 ns, and the calibration value becomes C_{TWSTFT} = –1.166 ns ± 1.335 ns. Both results agree with each other at the 0.1 ns level, and, noting the TWSTFT uncertainty of 1 ns [13], within the combined uncertainties.

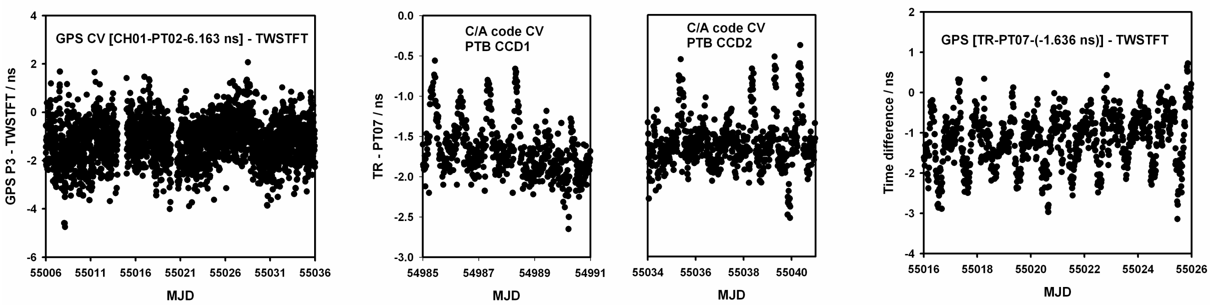

Fig 7. TWSTFT link calibration by comparing it to a calibrated P3 link (left), by comparing to the temporary C/A code GPS link established with the TR (right), and the corresponding CCD results at PTB (middle).

It is also interesting to compare the differential calibration value C_{GPS} between the most recently calibrated receivers at PTB and METAS. PT02 has been calibrated by the BIPM in April 2008 [14] and CH03 has been calibrated in August 2008 [15]. The differential calibration value C_{GPS} for CH03–PTB02 is 0.195 ns in CV mode and 0.029 ns in AV mode. This shows that the calibration constants used for the computation of CGGTTS file are correctly set.

CONCLUSION AND OUTLOOK

We have calibrated the links between METAS and PTB using a state-of-the-art time and frequency transfer receiver as the travelling receiver. Neglecting possible long term delay changes of the GPS equipment, all links can be calibrated with an uncertainty below 2 ns. By comparing our results to the calibrated TWSTFT link, we have demonstrated, that GPS could be considered as a cost effective method to calibrate TWSTFT links with an uncertainty below 2 ns. We plan to verify our results in calibration campaigns involving PTB and the United States Naval Observatory (USNO), the National Institute of Information and Communications Technology (NICT), and the National Institute of Metrology (NIM), Beijing, in the near future.

In order to reduce the statistical uncertainty, we have started building a travelling calibration station, based on a GTR50 receiver together with a SR620 TIC. If a travelling TIC is shipped together with the TR, and the reference 1 PPS is measured versus local UTC using exactly this device at both participating laboratories, it should be possible to reduce the uncertainty contribution of the connection of the TR to the local UTC.

The usage of multi system receivers, that can track both GPS and GLONASS signals, could become more and more popular in the future. A detailed study is needed, which points out whether a GLONASS link can be calibrated the same way as a GPS link or calibration values have to be calculated for each satellite separately due to the different frequencies.

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