A GPS calibration trip experience between ROA and PTB

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Abstract— **For a GPS calibration campaign between ROA and PTB a GTR50 time and frequency transfer receiver from ROA was chosen. The operation performance of GTR50 type receivers has been validated in long term operation during the last years. The travelling GTR50 was also tested in a sequence of shutdowns and restarts to detect time jumps and malfunctions just after the restart and during the following days of operation.**

In September 2008, the receiver was shipped to PTB and then was operated there for eleven days. One week after it had returned back at ROA, the common-view data showed only a 100 ps difference with respect to the same configuration carried out one week before the trip.

In this paper we will present the calibration results of this GPS link, and an evaluation of its type A and B uncertainty. The time transfer results were achieved by using C/A, P3 and also carrier phase PPP comparison techniques. We finally extrapolate these results in order to calibrate the two-way satellite time and frequency transfer (TWSTFT) link between ROA and PTB, using one month of data, and involving one GTR50 from ROA and one Ashtech Z-12T from PTB.

We show that a TWSTFT link can be calibrated by means of GPS time comparisons with an uncertainty below 2 ns, and that potentially even sub-nanosecond uncertainty can be achieved.

Keywords: GPS time and frequency transfer, calibration, P3, PPP, TWSTFT.

I. Introduction

GPS Time and Frequency transfer is among the most useful tools for comparison of remote clocks and represents the basis for the contributions of timing laboratories to the realization of International Atomic Time (TAI). It is one of the most accurate techniques in this field, that in the case of Precise Point Positioning (PPP) is at the same level of performance as the state-of-art technique, two-way satellite time and frequency transfer (TWSTFT). However, to provide accurate time transfer by means of GPS links, it is necessary to carry out GPS calibrations periodically to check the long term stability of the equipment.

Generally there are two types of calibration procedures: absolute and differential ones. The first is carried out by GPS signal simulators [1, 2], and although some new developments have been used during the last decade, it still is complex and not widely used. The latter has been the one used e.g. in 2004 when a TTR6-AOA GPS receiver from ROA was used for a calibration campaign between selected European Laboratories that contribute with their data to computation of TAI. After visiting VSL, PTB and OP, the receiver came back to ROA, where an unexpected delay change of more than 6 ns was detected in the closure measurement, indicating the limitations of the chosen configuration [3].

For the purpose of link calibrations, BIPM has performed a number of differential calibrations for geodetic GPS receivers of European Labs contributing to TAI [4]. ROA has resumed its activities and took an initiative to improve the calibration accuracy of its time transfer link to PTB, which is the pivot laboratory in Europe for TAI realization. In this paper, we report on the calibration trip results with a focus on the uncertainty budget evaluation.

II. The Traveling Set

The portable receiver (PR) comprises the geodetic GTR50 receiver intended for time and frequency transfer, its NovAtel antenna, (type GPS-702-GG, with pinwheel technology for multipath rejection and stable phase centre), and 48 m low loss and easy handling H155 antenna cable, nearly as flexible as the RG-58 standard, due to its small diameter.

The GTR50 receiver which is designated later as LAZ1 is basically a Linux PC in a 19¨ chassis together with one GPS board (originally it was a Javad GD and currently a Javad GGD-112T) and one time interval counter. The Javad GPS board supports both code and phase measurements. Its internal quartz oscillator is the reference for pseudo-range measurements and the source of a one Pulse Per Second (PPS) output synchronized to GPS Time. The difference between this PPS and the PPS input reference is measured with the time interval counter, that together with the receiver circuits, and the GPS, are located in a thermostated box (based on thermoelectric Peltier modules) to minimize their delay temperature dependence.

All the components of this setup were transported in a single box, which weighs less than 20 kg. The cables for frequency and PPS input were provided by PTB, as well as a keyboard and a display, to complete the local configuration.

TABLE 1. Mean ± SD values of the CCD, and the closure measurements estimated at ROA.

CCD	*P1/ns*	*P2/ns*	*P3/ns*	*C/A/ns*	*PPP/ns*	*Data P3/PPP*
LAZ1-ROAG (before the trip)	1.03 ± 0.27	1.04 ± 0.34	1.03 ± 0.95	-3.01 ± 0.25	1.29 ± 0.12	400/1150
LAZ1-ROAG (After the trip)	0.91 ± 0.37	0.96 ± 0.27	1.04 ± 0.98	-3.09 ± 0.28	1.25 ± 0.15	525/156
Closure Meas.	0.12	0.08	-0.01	0.08	0.04	

TABLE 2. Mean ± SD values of the CCD estimated at PTB. The receiver types are: ROAG, LAZ1 and PTB07 (GTR50), PTBB (ASHTECH Z-XII3T), PTBG (ASHTECH Z12T), PTB05 (TTS-3) and PTB04 (TTS-2).

CCD	*P1/ns*	*P2/ns*	*P3/ns*	*C/A/ns*	*PPP/ns*	*Data P3/PPP*
LAZ1 – PTBB	-1.05 ± 0.27	-0.62 ± 0.28	-1.70 ± 0.71		-1.62 ± 0.13	966/3020
LAZ1 – PTBG	-544.05 ± 0.27	-565.45 ± 0.25	-510.93 ± 0.72		-510.72 ± 0.11	990/3100
PTBB – PTBG	-542.98 ± 0.24	-564.84 ± 0.26	-509.19 ± 0.64		-509.10 ± 0.11	930/3170
LAZ1 – PTB05			12.04 ± 1.08	-2.11 ± 0.79		960
LAZ1 – PTB04			-0.27 ± 1.28*	-0.84 ± 1.07		620
LAZ1 – PTB07 (Only 5 days)	-2.46 ± 0.21	-2.27 ± 0.24	-2.74 ± 0.66	-1.46 ± 0.18	-2.60 ± 0.05	438

*based on CCD P3-C/A including application of the measured ionospheric delay provided by IGS and the P1-C1 differential code bias (DCB).

III. Calibration Trip

To accomplish this differential GPS calibration, we started the measurement at ROA six days before the PR was shipped. The GPS units involved in the calibration were disposed in a common clock set-up, with UTC(ROA) as reference, physically realized by one high-performance Caesium Frequency Standard (type 5071A). This time reference is also connected to the TWSTFT link to PTB.

The PR was shipped to PTB on 7th October 2008, arriving three days later. The local staff made the installation with the new configuration, antenna position and UTC(PTB) as time reference. After that, the PR was operated during eleven days. Finally the equipment was shipped back to ROA, to carry out the closure measurements with the initial set-up. These measurement results are very important in order to validate the results and because of their impact in the uncertainty budget based on the differences obtained. Table 1 shows these results stated as mean value ± standard deviation (SD) of individual CGGTTS common-view (CV) values, averaged at each standard epoch, with respect to the mean value over several days.

The final link calibration value is calculated by simple difference of common clock difference (CCD) results obtained in both laboratories (Lab1-PR and Lab2-PR). It is assumed that this value will remain constant until any change or event happens in any of the two installations and can thus be taken into account in calculation of the time scale differences between ROA and PTB.

IV. Results

The CCD differences shown in a detailed example in "Fig.1" and summarized in "Fig. 2" and in Table 2 were determined with the CV C/A and P3 [5] techniques. The latter has been used by BIPM since 2003 to compute time links after applying different corrections (precise IGS ephemerides, clocks and solid Earth tides). The P3 software was developed to provide CGGTTS files from code pseudo-ranges collected with geodetic receivers and filed initially in the RINEX format. The software should follow the CCTF approved procedures.

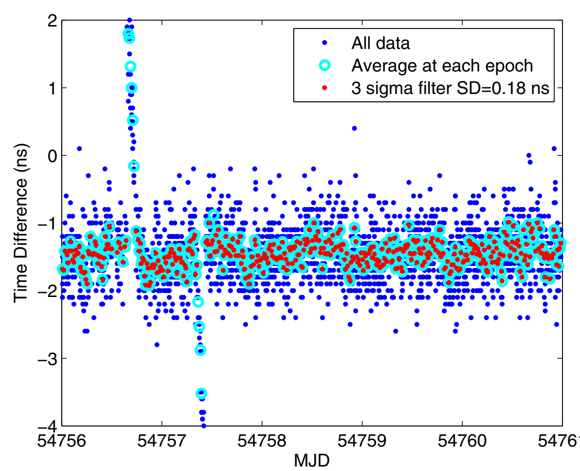

Figure 1. CV CCGGTTS C/A code data showing the difference of LAZ1-PTB07 receivers.

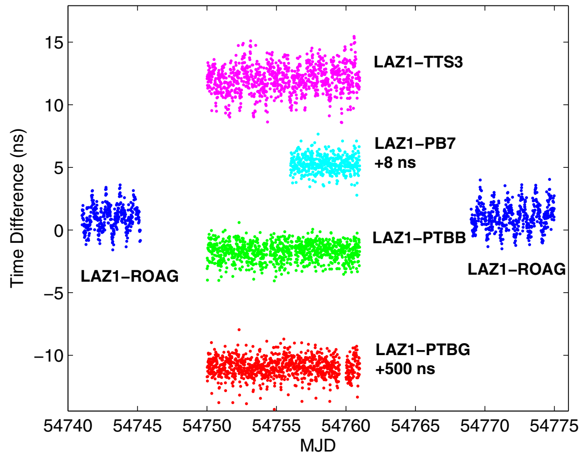

Figure 2. P3 CCD of GPS receivers participating in the calibration.

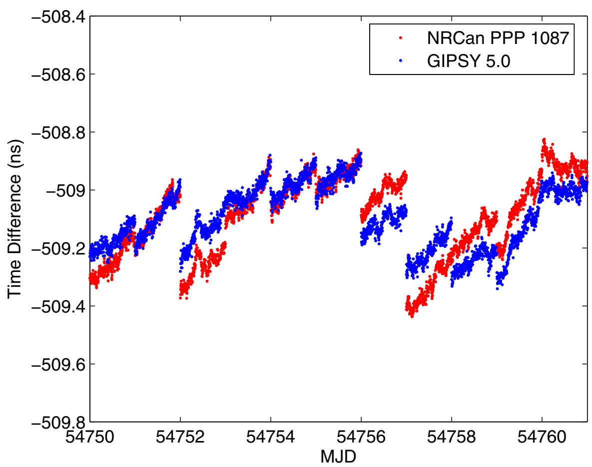

Figure 3. CCD of PTBB-PTBG pair obtained by NRCan and GIPSY.

We used the so called "Pascal Defraigne program" [5] and also a ROA-authored MATLAB version, in which the CCD is obtained by simple differences of pseudo-ranges, only corrected for the geometric effect of receivers' and satellites' positions.

The difference between the results obtained with the ROA P3 MATLAB routine using every 30 s data and the strict CCTF conventions - for each scheduled track it uses 26 30-s data points which are within the 13-minute tracks - was smaller than 0.1 ns in all cases.

The CCD has also been established with PPP technique. In this technique the RINEX files from each station are processed using dual frequency phase and code measurements together with precise ephemerides and clocks, solving the local position, troposphere and the clocks differences with respect to a reference time scale. Finally the time link between the two stations can then be obtained by simple difference of clock results from each station.

For this purpose we have used two different PPP software packages. First we used GIPSY 5.0 provided by the Jet Propulsion Laboratory, California Institute of Technology, released last summer, which includes new models for troposphere mapping function, Earth orientation models and the capability to model second order ionosphere effects. Then we used the NRCan 1087 software, provided by the Geodetic Survey Division (GSD) of Natural Resources, Canada, which uses updated models for station displacements and troposphere mapping functions. In both analyses we have tried to use the same correction models and the same IGS absolute antenna phase center offsets (atx file). The last one also implied modifying the rinex header for GTR50 with the proper antenna type (NOV702GG), automatically read from here by the NRCan software. "Fig. 3" shows the results of PTBB-PTBG obtained with both software packages processing each day separately. The largest difference is comprised in a 200 ps interval, and the final mean value over 11 days is practically the same.

Although the clock solution is obtained with the combined code/carrier phase data analysis, for each day the evolution obtained from carrier phases has to be determined using the code information, and this is the reason why CCD of P3 and PPP must be very close (see Table 2).

V. Uncertainty Evaluation

The overall uncertainty of the calibration value is estimated from the following expression:

$$U = \sqrt{u_{A,1}^2 + u_{A,2}^2 + u_{B,1}^2 + u_{B,2}^2 + u_{B,3}^2 + u_{B,4}^2}\ ,$$

where $u_{A,1}$ reflects the statistical uncertainty of the determination of the CCD, and $u_{A,2}$ reflects the statistical uncertainty of the measurements at the remote site. In order not to underestimate the resulting uncertainty we have directly used the SD of Tables 1, 2. Nevertheless it would be also possible to estimate both by means of standard deviation of mean (SDOM), since the CCD measurements are independent and random, with predominant white phase noise and its final result is the mean value of differences of the same quantity. We have concluded that it is effectively white noise due to results of "Fig. 6", where we have applied the chi-square goodness-of-fit test. The p-value represents the probability, under the assumption that the data are normally distributed, of getting a Chi-square value as large as obtained or larger. This test is normally selected at p=5% of significance level, and all data represented show a probability larger than 40%, so we have no reason to reject our expected distribution.

The systematic uncertainty $u_{B,1}$ represents the local uncertainty of the 1PPS delay, connected to each pair of receivers, based on the specifications of the un-calibrated time interval counter (TIC) in use, with a contribution of 0.5 ns for each receiver. We have also to point out that in the case of the ASHTECH receivers, the internal reference is derived from an externally provided 20 MHz signal, and to measure the offset between the internal reference and the 1PPS signal input we have to make use of an oscilloscope [6], with its added uncertainty. The same is applied to $u_{B,2}$ in remote station, as well as the personal bias effect in the measurement method and procedure.

TABLE 3. Uncertainty values in ns estimated for GPS link calibration, getting involved ROAG, PTBB, and LAZ1 receivers.

Method	*U*	$u_{A,1}$	$u_{A,2}$	$u_{B,1}$	$u_{B,2}$	$u_{B,3}$	$u_{B,4}$
P3	1.5	0.95	0.71	0.5	0.6	0.4	0.01
PPP	0.8	0.13	0.15	0.5	0.6	0.2	0.04

In $u_{B,3}$ we have included the instability of connection to the local UTC, and the environmental effects, like humidity and especially the temperature, that can raise a linear correlation coefficient of 0.04 ns/ºC, in case of CV and P3 analysis [7]. The last term included ($u_{B,4}$) refers to the closure measurements.

The uncertainty estimation results are summarized in Table 3, and the overall values were in all cases in the range 0.8 to 1.5 ns. These values are substantially lower than the type-B uncertainty attributed to GPS links in the BIPM Circular T. Here 5 ns are stated for this type of calibration, based largely on repeated calibrations of individual operational receivers, and 3 ns for GPS links calibrated using a portable TWSTFT station [8].

VI. TWSTFT LINK CALIBRATION

Once the GPS link has been calibrated we make use of this information to calibrate another independent link between ROA and PTB. We are referring to the TWSTFT link, noting that such links have usually been calibrated with a portable station of the same technique with associated lower uncertainty. Nevertheless the differential calibration through GPS link is still unavoidable for some intercontinental links, like the ones established between NICT, NIST and PTB [9] (see also [10]).

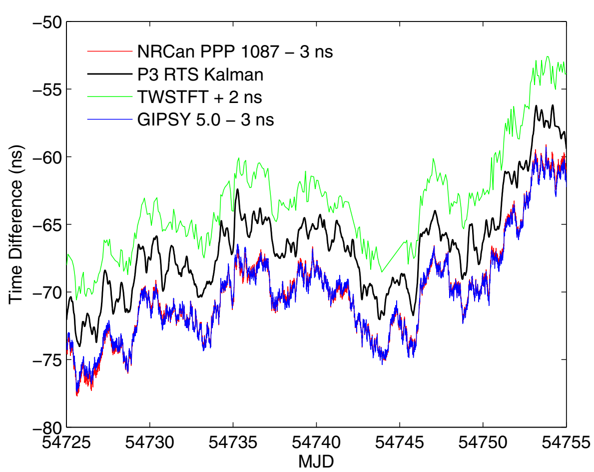

Figure 4. ROA-PTB results from TWSTFT, PPP and P3.

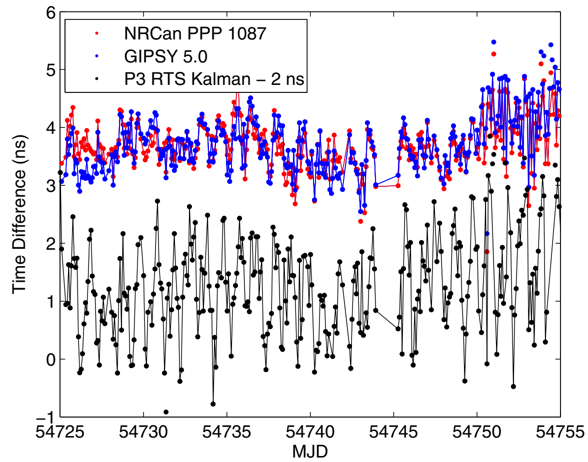

Figure 5. TWSTFT-GPS differences of ROA-PTB link.

We have initially derived the differences between the GPS and TWSTFT links, shown in "Fig. 4", using P3 technique with ROAG and PTBB receivers, applying a RTS Kalman filter to smooth the noisy data [11]. Next we have used the NRCan software to process a 30-days batch of RINEX files in the backward smoothed mode. Finally we also used the GIPSY software, which has provided a close solution to NRCan in the daily processing mode. Each data point in "Fig. 5" is the result of the exact difference of a TWSTFT value and the interpolation at that moment of PPP values (computed every 5 minutes) or P3 values (computed about every 16 minutes).

The resulting values were:

TWSTFT-P3 = 3.22 ± 0.76 ns
TWSTFT-GIPSY = 3.71 ± 0.46 ns
TWSTFT-NRCan = 3.69 ± 0.40 ns

We still have to apply the GPS link correction of the two participating GPS receivers, derived from Table 1 and 2, respectively: P3 (+1.0 +1.7 = 2.7 ns), GIPSY and NRCan (+1.3 +1.6 = 2.9 ns). As the final result, the ROA-PTB TWSTFT link would need to be corrected by -0.8 ns in case of PPP values and -0.5 for P3, but beyond these results the really important aspect is the uncertainty involved in this calculation which is estimated from the following expression:

$$U = \sqrt{u_A^2 + u_{B,1}^2 + u_{B,2}^2} \ ,$$

where u_A reflects the statistical uncertainty of TWSTFT-GPS differences, estimated by SD value and following a similar reasoning as stated for GPS link type A uncertainty. In $u_{B,1}$ we have included the instability of connection to the local UTC, the station components instabilities and environmental effects. In this connection we can see in "Fig. 7" the diurnal fluctuations of the differences between TWSTFT and PPP of the ROA-PTB link, together with the external temperature at ROA. It might be that the diurnals are due to thermal effects in the TWSTFT system, and even though the GPS could produce this effect by itself, the phase data inserted in PPP processing reduce it considerably. Nevertheless the proper ratio of both systems noise contribution must be more closely studied.

TABLE 4. Range of uncertainty values in ns estimated for the TWSTFT link calibration using a GPS link in differential mode.

Method	*U*	u_A	$u_{B,1}$	$u_{B,2}$
P3	1.7	0.76	0.4	1.5
PPP	1	0.46	0.3	0.8

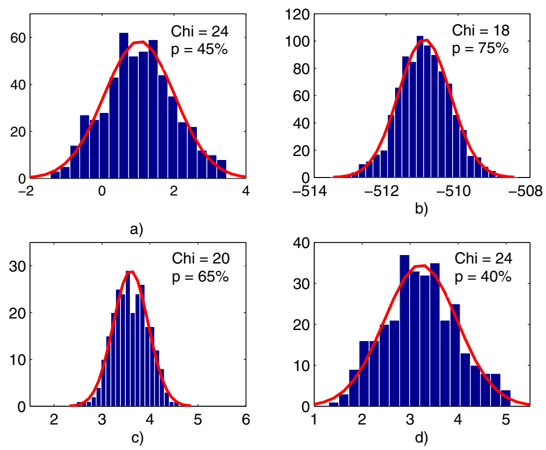

Figure 6. Histogram and chi-square goodness-of-fit test (p-value) calculated with 23 degrees of freedom, for following data combination: a) P3 LAZ1-ROAG b) P3 LAZ1-PTBG c) TWSTFT-GPS PPP d) TWSTFT-GPS P3. Horizontal axis: time difference in ns, vertical axis: frequency of data per bin.

In $u_{B,2}$ we have included the calculated uncertainty of the GPS link, and the final uncertainty for the GPS-calibrated TWSTFT link is summarized in Table 4.

VII. Conclusion

In this paper we have summarized the GPS calibration trip experience between ROA and PTB, using a portable GTR50 receiver. The uncertainty estimate is very promising since it indicates the possibility of 1-ns accuracy of GPS links. This needs to be consolidated in the long term with future calibrations.

We have found a very good agreement between TWSTFT and PPP, with similar short term variations for booth techniques, which are substantially below that attainable for smoothed P3 solutions.

Although the TWSTFT has a considerably lower uncertainty than GPS, which has been demonstrated by the repeated calibration of European TWSTFT, the good results

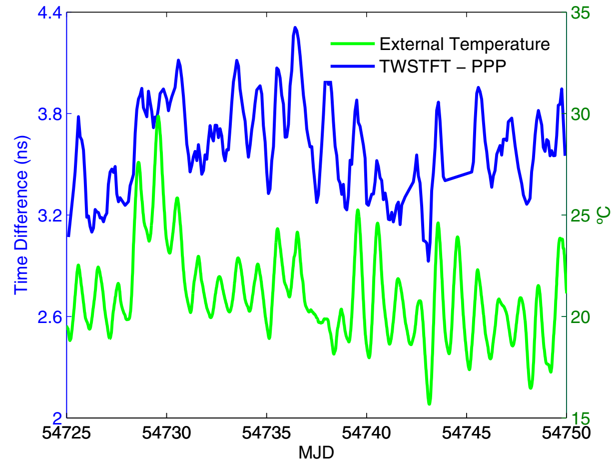

Figure 7. ROA-PTB links differences conveniently smoothed to highlight their relation with external temperature at ROA.

found in this calibration have made the estimation of TWSTFT link delays feasible with an uncertainty lower than 1.7 ns. It seems reasonable to accept this result for the TWSTFT link instead of the traditional 5-ns uncertainty, since it relies on GPS closure measurements made in rapid sequence during the routine TWSTFT analysis overlapped with the GPS calibration period. The use of the PPP processing and analysis makes the 1 ns level for link calibrations relying on GPS data feasible. We plan to repeat such a calibration exercise in order to confirm the validity of the present results.

It is worth to demonstrate in future a TWSTFT calibration using a portable TWSTFT station and to perform, at the same time, a GPS calibration as reported here. This could demonstrate that a TWSTFT link can be calibrated with a slightly higher uncertainty than shown in [8], but with a significantly lower cost for the participating stations when relying on GPS equipment only.

VIII. Acknowledgment

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