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# Relative Calibration of the Time Transfer Link between CERN and LNGS for Precise Neutrino Time of Flight Measurements

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**Abstract—The relative calibration of the GPS time link between European Organization for Nuclear Research (CERN) and Gran Sasso National Laboratory (LNGS), performed in 2011, is reviewed. "Relative" means that traveling equipment was used to calibrate the delay of the link as a whole, but no information on absolute delays of individual components was gained. The precisely calibrated GPS link was used in the framework of the measurement of the time of flight of neutrinos generated in the CERN Neutrino to Gran Sasso (CNGS) experiment and measured with the Oscillation Project with Emulsion Tracking Apparatus (OPERA) detector at LNGS.**

## I. INTRODUCTION

High-energy particle physics experiments are good examples of applications for precise timing, because numerous steering, control, and measurement sub-systems have to be in synchronization at a particle accelerator site. Due to their weak interaction with other matter, neutrinos generated at a local site can be detected at a remote site with in principle unlimited distance to the source, since the neutrino beam passes the solid Earth mostly unaffected. Such an experiment is performed in the framework of the CERN Neutrinos to Gran Sasso (CNGS) setup, where neutrinos generated at CERN whose start-time is determined with respect to the local reference time are detected in the underground Gran Sasso National Laboratory (LNGS) in Italy, 730 km away from Geneva. The Oscillation Project with Emulsion Tracking Apparatus (OPERA) at LNGS allows the time stamping of neutrino detection events with respect to the local timing system.

If the offset of the timescales between CERN and LNGS is known, the time of flight of neutrinos can be extracted from the measurement data. The remote time comparison between CERN and LNGS is done by means of a GPS link, employing precise dual frequency geodetic GPS receivers which are common in time and frequency metrology.

In July 2011, the Physikalisch-Technische Bundesanstalt (PTB) was entrusted to calibrate the GPS link using PTB's mobile GPS receiver set-up for relative link calibrations, strictly applying the rules for achieving nanosecond precision which had been developed within the timing community during the last years and verified in calibration campaigns between various National Metrology Institutes. The calibration

[*] Present address: TimeTech GmbH, Stuttgart, Germany

[#] Present address: Laboratory for High Energy Physics, University Bern, Switzerland value obtained by operating the calibration equipment in common-clock configuration in parallel with the fixed equipment at each site agrees with the result of a previously equipment calibration conducted at Swiss Federal Office of Metrology (METAS) at the one-sigma uncertainty level.

An overview and a detail description of the complete neutrino time of flight measurement experiment are given in reference [1]. This paper briefly reviews the calibration of the GPS time link between the two remote sites only, based on the more detailed calibration report [2].

## II. SIGNAL GENERATION AND REMOTE COMPARISON

At both sites, CERN and LNGS, the local time and frequency reference signals are generated from GPS disciplined oscillators. The accuracy of the 1 PPS output signals of these clocks with respect to GPS system time is on the order of several hundred nanoseconds. Then, additional Septentrio PolaRx receivers are used to precisely compare the two remote timescales (see Figure 1). The internal timing reference of the PolaRx receivers are derived from 10 MHz reference frequencies provided by commercial Cs 4000 clocks on both sites. The offset with respect to GPS system time is either arbitrarily set when the receiver is turned on (at CERN) or initially synchronized to a 1 PPS signal provided by the Cs 4000 (at LNGS).

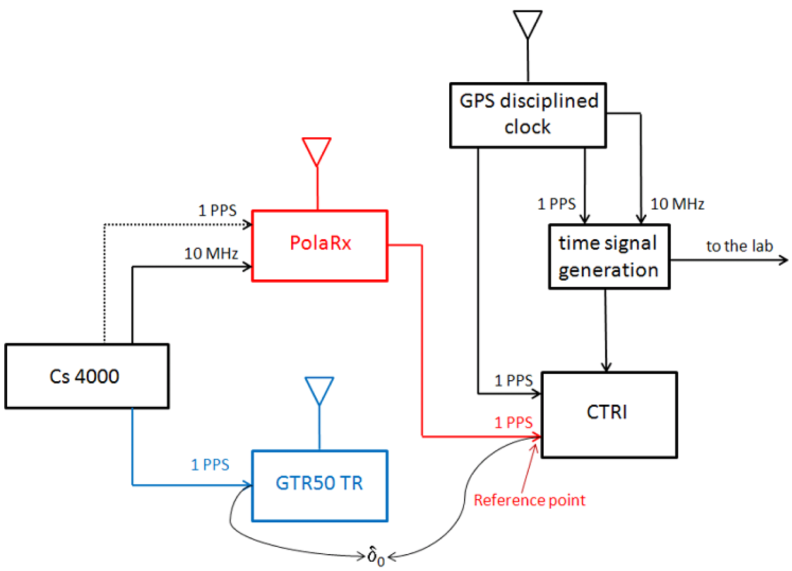


Figure 1. Scheme of time signal generation and remote comparison setup (red) at CERN and LNGS, with additional temporarily installed travelling equipment (blue).

The 1 PPS output of the PolaRx is coherently derived from the internal timing reference and compared to the 1 PPS of the GPS disciplined oscillator with a device called CTRI. The CTRI is in principle a usual time interval counter (TIC) which in addition adds timestamps to the measurement data. Thus, the local timescale can be compared to the timescale of the remote laboratory via the time references maintained in the two PolaRx receivers, which are both related to GPS system time.

The design of the time signal generation and comparison system is different from the design usually used in metrology laboratories. One of the main tasks of metrology laboratories is the realization of a timescale which is in close agreement with the international reference Universal Coordinated Time UTC. Thus, a metrology laboratory possesses an electrical reference point at which the 1 PPS signal is the local UTC realization by definition (see e.g. reference [3]). Other locally distributed 1 PPS signals are coherent to the local UTC 1 PPS. If receivers like the PolaRx are used for remote timescale comparisons, the initial synchronization is done with such a 1 PPS and an output 1 PPS is not necessary for the remote comparison. A relative link calibration is then performed by operating a traveling receiver (TR) successively in both labs for several days and calculating the time difference between the fixed and the traveling receiver, called common-clock difference (CCD). The distance between the TR's antenna and the antenna of the fixed receiver are just a few meters and errors induced by the atmosphere and solid Earth tides [4] are the same for both receivers and vanish from the CCD values.

If the TR's internal timescale is synchronized to the local UTC reference points in both laboratories, the difference of the CCDs measured in both laboratories (dCCD) is free from the delays induced by the TR, with the assumption that the TRs internal delays have not changed while it is shipped from one laboratory to the other. Then dCCD reflects the calibration value which has to be applied to the link induced by the fixed equipment's internal delays, including the delays of the 1 PPS reference signals with respect to local UTCs. More details are available in references [3], [5] and [6].

In contrast to a metrology laboratory, neither at CERN nor at LNGS has a UTC reference point been defined. However, it was decided to use the PolaRx 1 PPS output, which is connected to the CTRI as reference point for the link calibration (see Figure 1). This means that the time delay of all signals connected to laboratory equipment has to be determined with respect to this point. This is described in reference [1].

Figure 1 also shows how the TR is temporarily connected to the time signal generation systems. Since it is a GTR50 GPS time and frequency transfer receiver, only a 1 PPS reference signal, generated by the Cs 4000 clock, is needed. The GTR50 internally compares the external 1 PPS signal to a 1 PPS generated from the internal timescale which is synchronized to GPS time. The internal TIC uses a surface acoustic wave (SAW) filter as an integrator and does not use an external reference frequency [7]. The GTR50 was mounted into a small transportable rack, together with an SR620 TIC and a monitor/keyboard, as shown in Figure 2. The advantage of using a GTR50 as TR is that the receiver board and the internal TIC are inside a temperature stabilized box, inside which the temperature is stabilized to 45 °C ± 0.2 °C independent from laboratory conditions.

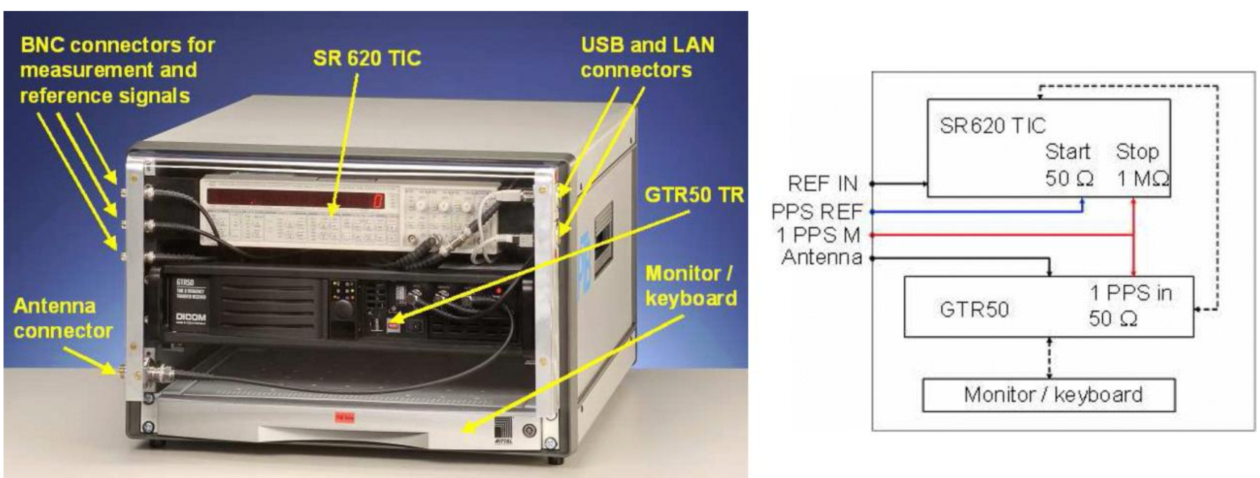


Figure 2. PTB's calibration set-up.

The SR620 TIC of this calibration set-up is used to determine the delay $\delta_0$ between the reference signal and the 1 PPS connected to the GTR50 (1 PPS M). For this task, the PolaRx 1 PPS output was disconnected from the CTRI for a short while and connected to the calibration set-up's PPS REF connector. The delays induced by the internal cabling are the same in both laboratories and cancel out in the calculation of the calibration value. The advantage of using the same TIC in both laboratories is that the systematic error is the same in both labs and thus cancels out and does not contribute to the calibration uncertainty (see [2] and [3] for a detailed explanation).

## III. DATA EVALUATION

Modern geodetic GPS receivers are capable of tracking the pseudorandom noise (PRN) code on both frequencies transmitted by the satellites, as well as the phase of the carrier frequencies [4]. The code based data are usually stored in the CGGTTS format [8], where the difference between receiver time and GPS system time is given for each tracked satellite in 16 min intervals. The time differences are calculated including the fixed receiver position, the satellite ephemeris data, and a model for the troposphere delay. A model for the ionosphere delay is not necessary if data on both frequencies are available and are combined in the so-called P3 linear combination that removes about 99 % of the ionosphere effects.

The raw GPS measurement data on code and carrier-phase are stored in the Receiver Independent Exchange Format (RINEX) [9]. Besides this observation data, the broadcasted ephemeris data are stored in an additional so-called navigation file. The observation data can be used for ultra stable timing by combining them in an algorithm called Precise Point Positioning (PPP) with satellite ephemeris from the receiver network of the International GNSS Service (IGS), in order to calculate the receiver position and the receiver clock offset with respect to the IGS network time for each observation epoch. The PPP software, which is most commonly used in the timing community, was developed at the Canadian geodetic institute National Resources of Canada (NRCan) [10]. Originally, the NRCan-PPP was developed for geodetic needs, but, for example, the Bureau international de poids et mesures (BIPM) uses this software for time comparisons within the international network operated for the realization of UTC. For timing, the observation data are usually recorded in 30 s intervals. Since PPP relies on the carrier-phase, the stability of the results is improved by a factor of about 100.

Geodetic GPS receivers like the PolaRx do not have the feature of generating CGGTTS data implemented in their firmware. In these cases, software called R2CGGTTS, developed at Royal Observatory of Belgium (ROB), is used to compute the P3 CGGTTS data from RINEX 30 s observation and navigation files [11].

Unlike the PolaRx receivers, the GTR50 which was used as the TR, is capable of generating CGGTTS data internally. This requires a priori knowledge of the antenna position. However, at both CERN and LNGS the TR’s antenna was mounted to a location which was nearby the antenna of the fixed receiver, but with unknown position coordinates. Thus, the 30 s RINEX observation data were first used to estimate the antenna position using the NRCan-PPP software. Then this position was applied to the R2CGGTTS software and P3 CGGTTS data were generated using the GTR50 RINEX observation data and - since the GTR50 does not provide navigation files - the navigation data from the PolaRx. This is possible because navigation data are independent from the exact receiver position.

The flowchart depicted in Figure 3 shows the processing steps which were performed to calculate P3 code based CCDs and PPP carrier-phase CCDs. Since the P3 CGGTTS files contain the time difference with respect to GPS time for each satellite separately, a comparison between two receivers can be made in common-view (CV) or 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 over all satellites is calculated afterwards. In AV mode an average is at first independently calculated for each receiver including all satellites tracked by each of the receivers, and differences between the two receivers are made based on the averages.

In reference [6] it has been shown that that calibration values obtained with the CV method are also valid if the link between the remote sites is evaluated in AV mode. Since CCD data obtained with CV are less noisy than data obtained with AV, the CV method leads to a lower statistical calibration uncertainty.

The PPP software uses the code to estimate the initial unknown phase of the carrier frequency. However, the code based calibration values are not automatically valid for a PPP link. Amongst other contributions, which are different from PPP, the P3 calibration values include delay contributions arising from potential errors of the fixed positions used for the CGGTTS generation. If the position error is small, the noise level is not significantly increased compared to a data evaluation with an ideal position. The position error can be regarded as any other instrumental delay of the fixed equipment. If the P3 calibration value is applied to the PPP link, this could lead to a wrong offset, because the PPP software estimates time offset and position from the measurement data of at least 4 satellites from a linearized observation model using a Kalman filter.

The output of the R2CGGTTS and PPP processing of the RINEX data of both fixed receiver and TR are used to generate P3 CV and PPP AV data. The spacing of the PPP data is 5 min, since the IGS time is given in this interval. By definition, PPP is an AV process, since one time offset and position estimate including all satellites in view is calculated for each receiver at each epoch independently.

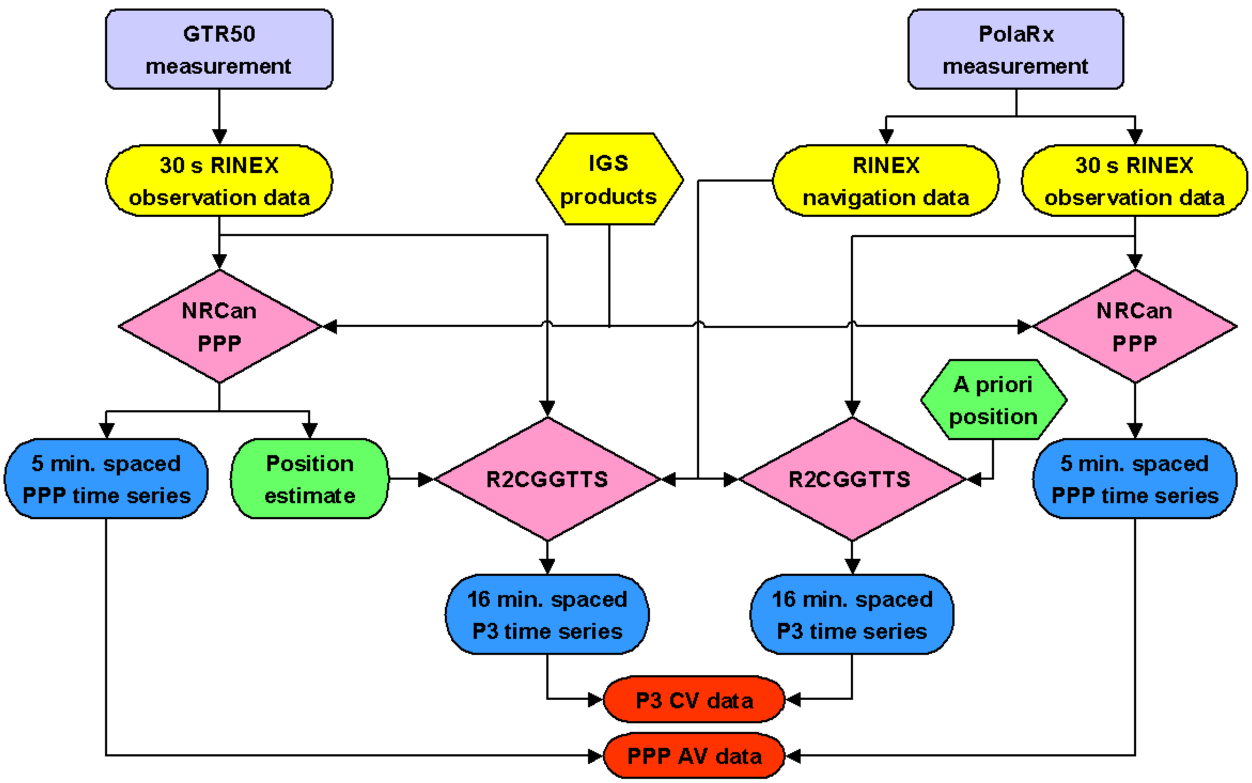


Figure 3. Common-clock data evaluation flowchart.

After recording data for both sites, the data are further processed according to Figure 4. The four time series, P3 and PPP data for CERN and LNGS, were averaged in order to calculate the standard deviation, and the outliers were removed by a 3σ filter. Then the time deviation (TDEV) of these outlier cleaned data was calculated. The minimum of the TDEV as function of averaging time is used to determine the period $\tau_W$ at which the data are dominated by white phase noise. The slope of the TDEV as function of averaging time is only negative for white phase noise and this noise type is dominant in the short term for measurement instruments and links. For more details see references [2] and [3], and [12] for an explanation of TDEV and its properties.

The mean value of pure white phase noise is zero and it does not contain any meaningful information. Thus, the data are split in blocks of length $\tau_W$. These new time series with data spacing $\tau_W$ were free from white phase noise and were averaged for the second time to get the calibration value and the standard deviation, which is the statistical uncertainty of the calibration.

The calibration values (for P3 and PPP) are calculated according to

$$\langle \text{PolaRx(LNGS)} - \text{TR@LNGS} \rangle - \langle \text{PolaRx(CERN)} - \text{TR@CERN} \rangle = C_{LNGS} - C_{CERN} = C_{GPS}, \qquad (1)$$

where <…> denotes the averaging over the data blocks of length $\tau_W$. $C_{GPS}$ equals dCCD and is the link calibration value. The link between the remote sites has then to be corrected according to

$$\text{PolaRx(CERN)} - \text{PolaRx(LNGS)} + C_{GPS} = \text{RP(CERN)} - \text{RP(LNGS)}, \qquad (2)$$

with RP the time at the reference points at CERN and LNGS, respectively.

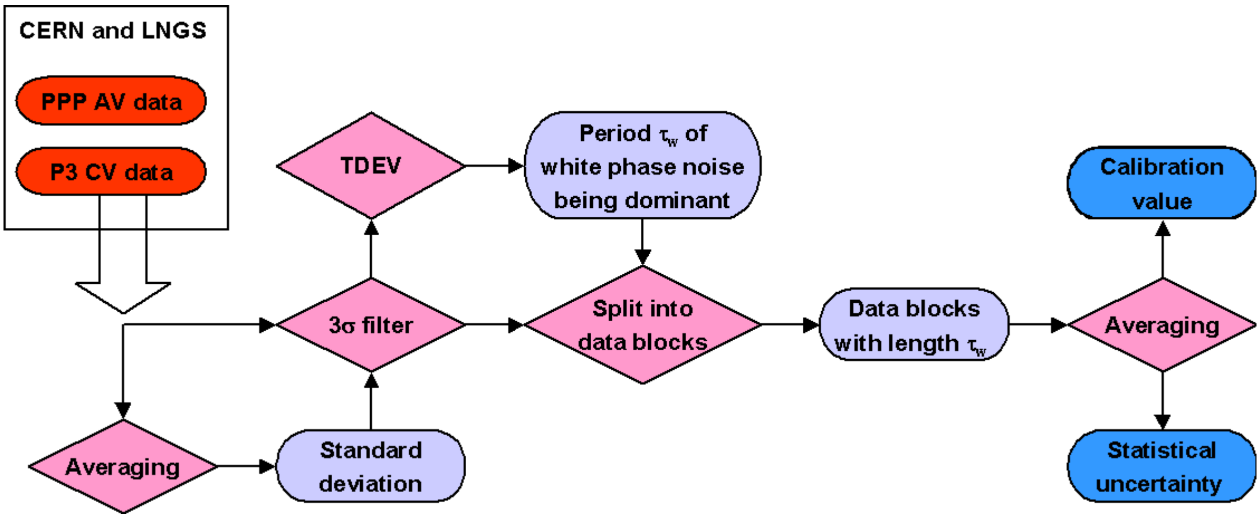


Figure 4. Calibration value calculation and uncertainty estimation flowchart.

## IV. Uncertainty Estimation

The overall uncertainty of the calibration is given by

$$U_{GPS} = \sqrt{u_a^{\,2} + u_b^{\,2}}\,. \qquad (3)$$

where $u_a$ is the statistical uncertainty, calculated as geometric sum of the statistical uncertainties of the averaging of the data blocks (cf. Figure 4) and $u_b$ is the systematic uncertainty, consisting of the contributions given in Table 1, which are geometrically added.

Table 1. Systematic uncertainty contributions.

| **Uncertainty** | **Value / ns** | **Description** |
|---|---|---|
| $u_{b,1}$ | 0.14 | Instability of the reference points |
| $u_{b,2}$ | 0.08 | TIC trigger level timing error |
| $u_{b,3}$ | 0.03 | TR trigger level timing error |
| $u_{b,4}$ | 0.14 | TIC nonlinearities |
| $u_{b,5}$ | 0.03 | Jitter of the TIC after 300 measurements at LNGS |
| $u_{b,6}$ | 0.05 | Jitter of the TIC after 300 measurements at CERN |
| $u_{b,7}$ | 0.30 | Multipath |
| $u_{b,8}$ | 0.18 | Antenna cable and antenna |
| $u_{b,9}$ | 0.30 | Uncertainty of the ambiguity estimation (only for PPP) |
| $u_{b,P3}$ | 0.42 | Total P3 systematic uncertainty |
| $u_{b,PPP}$ | 0.51 | Total PPP systematic uncertainty |

The values in Table 1 are either determined by measurements (e.g. $\delta_0$ measurement with SR620 TIC) or estimated. For a detailed explanation of the contributions the reader is referred to reference [2]. The PPP calibration has an extra uncertainty contribution due to the unknown initial phase of the carrier frequency.

## V. RESULTS

The results of the P3 and PPP CCD results are depicted in Figure 5. Some of the P3 data were identified as outliers and removed by the 3σ filter.

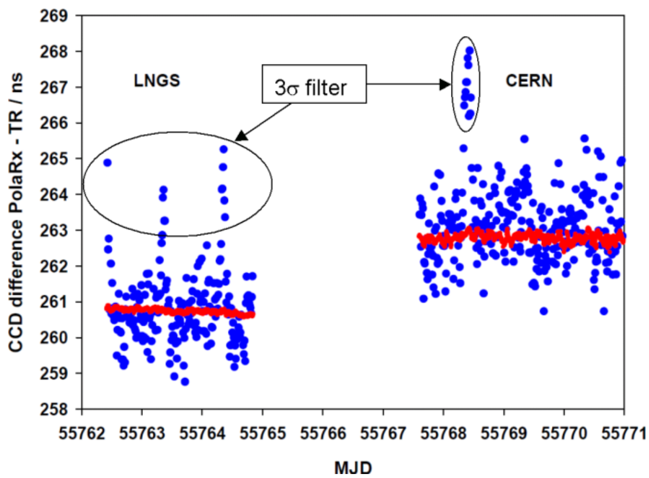


Figure 5. CCD results (blue: P3, red: PPP) at CERN and LNGS. The measurement period (x-axis) is given as Modified Julian Day (MJD).

The related TDEVs of the time series are shown in Figure 6, with the corresponding confidence intervals given as "error bars" which are calculated with the statistical methods stated in reference [12]. For the calculation of each TDEV point (except the first one) the averaging time of the preceding point is doubled. In order to avoid underestimation of the statistical uncertainty the minimum of the upper "error bars" is used to determine the time interval $\tau_W$.

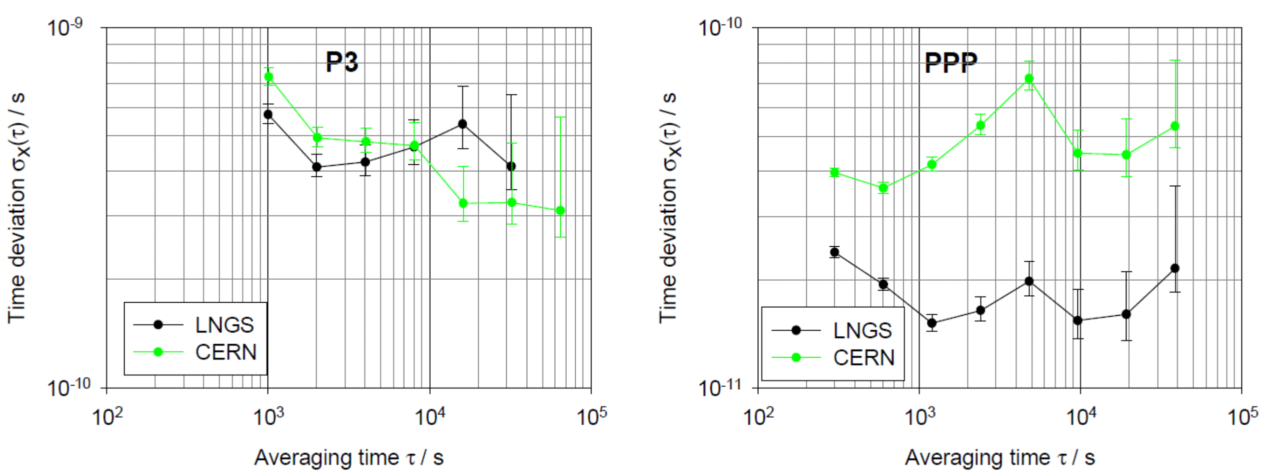


Figure 6. Time Deviation (TDEV) of the CCD data.

In Table 2 the results of the CCD measurements at LNGS and CERN are listed for P3 CV data evaluation and for the PPP method. The number of individual data used for the first averaging determined from

Figure 6 is given. The CCD value is the mean value of the averaged data and represents the calibration values $C_{LNGS}$ and $C_{CERN}$, respectively. SD denotes the standards deviation of the averaged data around the mean, which is used as the statistical uncertainty. The number of averaged data (# of averaged data) multiplied by the data spacing $\tau_0$ is equivalent to $\tau_W$. For example, a number of two averaged data means splitting the P3 data in blocks of 32 min duration and the PPP in blocks of 10 min, respectively.

Table 2. Averaging intervals, CCDs, and related standard deviation (SD).

| Lab | Type of data evaluation | Total duration of data taking | # of averaged data | CCD / ns | SD / ns |
|---|---|---|---|---|---|
| LNGS | P3 | 2.4 days | 2 | 260.74 | 0.79 |
| | PPP | 2.4 days | 4 | 260.74 | 0.34 |
| CERN | P3 | 3.4 days | 16 | 263.05 | 0.06 |
| | PPP | 3.4 days | 2 | 262.78 | 0.11 |

The result for the calibration values is

- P3: $C_{GPS,P3}$ = -2.31 ns; $U_{GPS,P3}$ = 0.90 ns,
- PPP: $C_{GPS,PPP}$ = -2.04 ns; $U_{GPS,PPP}$ = 0.62 ns.

The calibration values for PPP and P3 are in agreement at the 300 ps level (cf. Table 1: ambiguity). The total uncertainty is well below 1 ns in both P3 and PPP cases.

The P3 calibration value reflects the difference between the described link calibration and a previous calibration of the instrumental delays performed at METAS [1]. This discrepancy can be explained by long term delay variations inside any of the two receivers involved between the two calibrations. Such variations were frequently observed. Another possible reason is the inaccuracy of the fixed receivers' positions, which were used in the R2CGGTTS software. In contrast to the link calibration, in the METAS calibration the receivers were shipped to METAS and the internal delays were measured by comparing the receivers to the METAS receiver used for time transfer to UTC. This method obviously does not take into account the position errors at CERN and LNGS. In the link calibration method the position error is absorbed by the calibration value, since it appears like any other instrumental delay, as already mentioned above.

As an example the impact of a wrong position is depicted in Figure 7. A receiver at USNO is compared to a receiver at PTB and the height of the USNO receiver is manipulated. If the error is below the 10 m level, the noise does not significantly increase, but the offset is directly proportional to the error (see also reference [3] for further explanations).

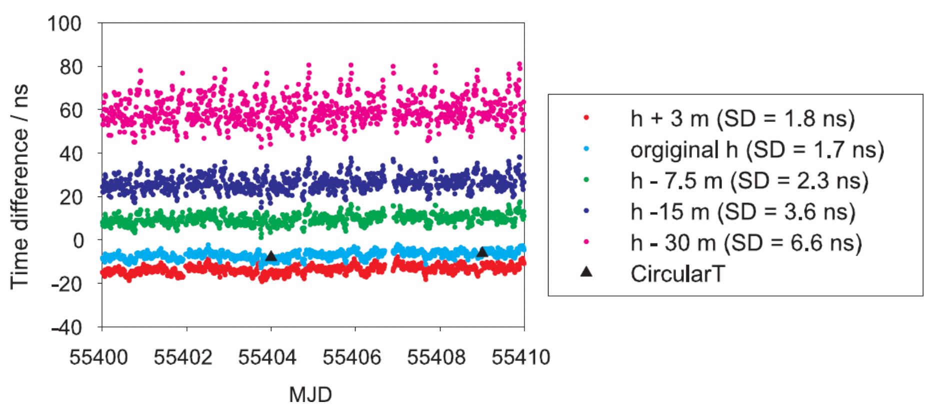


Figure 7. Impact of position error on time transfer.

## VI. CLOSURE VERIFICATION

To verify that the internal delays of the traveling equipment have not changed during the calibration campaign, the calibration set-up was operated at PTB before and after the trip to LNGS and CERN. With the internal TIC the 1 PPS of the calibration set-up was referenced to UTC(PTB). The P3 data of one day before (MJD 55749) and one day after the calibration campaign were compared to the data of a fixed GTR50 receiver (PT08, as designated by the International Bureau of Weights and Measures) at PTB using the CV method. The delay of the 1 PPS signal connected to PT08 is referenced to UTC(PTB) and the internal delays as well as the cable delay was calibrated by the manufacturer. The individual P3 common-views of the two CCD measurements at PTB and the mean values are depicted in Figure 8.

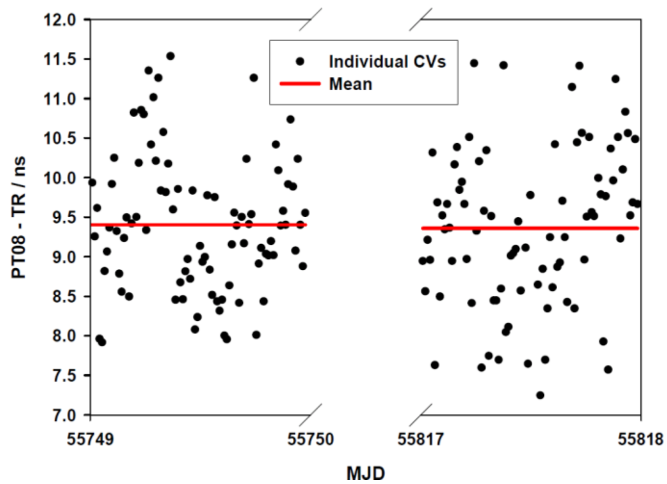


Figure 8. Closure measurements at PTB.

The differences between the two measurements are just on the order of a few ps. Since the PPP software estimates the phase ambiguity with the help of the code, a verification for PPP is not necessary.

## VII. CONCLUSION

The result of the calibration of the GPS time link between CERN and LNGS using PTB's traveling calibration set-up is in agreement with a previous equipment calibration within 2 ns. This discrepancy can be either explained by long term delay variations and by errors in the receiver positions at CERN and LNGS, which are absorbed by the link calibration, but not accounted for by an equipment calibration.

A closure measurement performed before and after the calibration set-up was shipped to CERN and LNGS shows that the internal delays of the traveling equipment have not significantly changed during the travel.

For more details on relative link calibrations using traveling equipment, the reader is referred to references [3], [5], and [6]. Additional information related to the estimation of the uncertainty can be found in the official PTB calibration report [2].

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