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Relative calibration of the GPS time link between CERN and LNGS

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Introduction

In July 2011 the GPS link between the “European Organization for Nuclear Research” (CERN) and the “Gran Sasso National Laboratory” (LNGS) was calibrated using PTB´s mobile GPS receiver set-up for relative link calibrations [1]. The precise calibration of the GPS link between the two institutes CERN and LNGS, among other measures, allows the estimation of the time of flight of neutrinos generated in the “CERN Neutrinos to Gran Sasso” (CNGS) experiment and measured with the “Oscillation Project with Emulsion Tracking Apparatus” (OPERA) detector at LNGS, if the delays of the laboratories´ internal timing systems are also calibrated.

Setup and equipment

At CERN and LNGS the 1 PPS output signal of a Septentrio PolaRx GPS receiver is provided to a measurement system called CTRI. The CTRI timestamps the 1 PPS with respect to a GPS disciplined rubidium clock which provides the timing signal for the accelerator system at CERN and the OPERA neutrino detection system at LNGS, respectively. Thus, the timing signal of the accelerator and the neutrino detector can be referenced to the PolaRx measurements, which enables a GPS comparison of the timing signals at both locations in order to measure the time of flight of the neutrinos between the two laboratories. The setup is depicted in Figure 1.

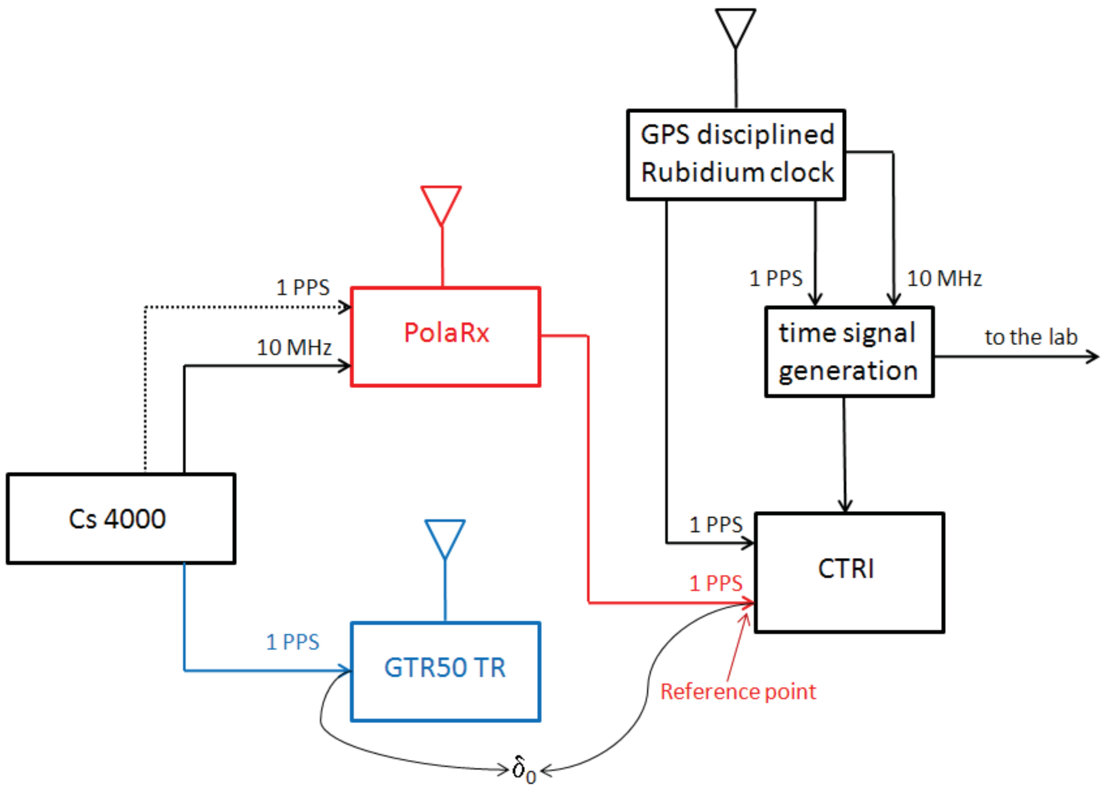

Figure 1. Schematic of the time signal generation at CERN and LNGS. The internal oscillator of the PolaRx receiver is locked to the 10 MHz signal of a commercial caesium clock Cs 4000. The dotted 1 PPS connection to the PolaRx depicts the option of synchronizing its internal timescale to the external signal, at the instant when the receiver is turned on, but this option was only realized at LNGS. The components colored in blue are the equipment that was temporarily used for the calibration, most important the travelling GTR50 receiver (GTR50 TR). The red colored components are subject of the relative calibration and cannot be changed without losing the calibration information.

The internal oscillator of the PolaRx is synchronized to the 10 MHz frequency of a commercial caesium clock. The offset of the internal timescale of the PolaRx with respect to the GPS time is arbitrarily set when the receiver is switched on (or initially aligned to the external 1 PPS at LNGS). All measurements of received GPS signals are made with respect to this internal time scale. Since the output 1 PPS is derived from the PolaRx internal timescale a calibration is not lost if the receiver is turned off and on.

For the relative calibration the connector of the cable which provides the PolaRx 1 PPS signal to the CTRI was chosen as the reference point at both laboratories. The travelling Dicom GTR50 time and frequency transfer receiver (TR) was operated between the MJDs 55762 to 55764 at LNGS and between 55767 to 55770 at CERN in parallel with the PolaRx receiver. To reference the measurements of the TR to the reference point, the cable was disconnected from the CTRI and the signal was measured with a time interval counter (TIC) with respect to the caesium 1 PPS connected to the TR. 300 single measurements were taken at each laboratory.

In contrast to the PolaRx, the GTR50 receiver´s GPS oscillator is synchronized to the GPS system time and the external 1 PPS input signal is compared to the internal GPS 1 PPS signal with an internal TIC. These TIC measurement results are applied to all output data (RINEX, CGGTTS) by the internal processing software.

Both TR and TIC measurements were performed with the PTB calibration set-up (see Figure 2), consisting of the GTR50 receiver, a SR620 (TIC), and a monitor/keyboard [1]. The devices are integrated in a transportable rack. The internal delays of SR620 TICs vary from unit to unit and the maximum difference between two counters is stated as 0.5 ns by the manufacturer. Since the travelling TIC was used to measure the delay δ_0 between the reference point and the caesium 1 PPS at both laboratories this systematic effect cancels out. Furthermore, also the delays induced by the cabling inside the calibration set-up cancel out.

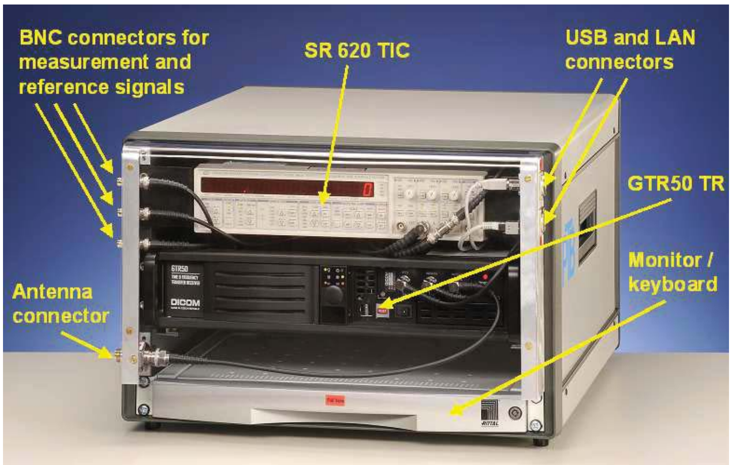

Figure 2. PTB's calibration set-up.

If the TR measurements are corrected for the δ_0 measurements the calibration value for the GPS link between the reference points at CERN and LNGS is given by differencing the GPS common-clock difference (CCD) results of both laboratories according to

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

where <…> stands for the mean value over a certain period. The time link has thus to be corrected according to

$$\mathrm{PolaRx(CERN)} - \mathrm{PolaRx(LNGS)} + C_{\mathrm{GPS}} = \mathrm{RP(CERN)} - \mathrm{RP(LNGS)} \,. \quad (2)$$

RP(CERN) and RP(LNGS) denote the reference points at CERN and LNGS, respectively.

Besides the accurate measurement of δ_0 at both laboratories also the position of the TR antenna has to be known with high precision at both sites. Then an eventual position error of the PolaRx antennas is absorbed by the calibration value (1), as well as the antenna cable delays, the receivers´ internal delays, and the delays of the cables connecting the receivers and the CTRIs.

Data evaluation

The data output format of the PolaRx receivers are RINEX observation and navigation data. These data are used to generate ionosphere-free code-based, so called P3 CGGTTS data with the R2CGGTTS software [2] developed at the "Royal Observatory of Belgium" (ORB). In contrast to the PolaRx, the GTR50 directly provides the P3 data which are generated by the internal processing software, but it needs the precise antenna position before the measurement is started. Since the position of the temporary antenna mounts at LNGS and CERN were unknown the position of the PolaRx receivers were initially used as an approximation to guarantee proper receiver operation. Thus the positions of the TR antenna later had to be precisely estimated using the Precise Point Positioning (PPP) software developed at the Canadian geodetic institute "Natural Resources of Canada" (NRCan) [3]. Then P3 files have also been generated by the R2CGGTTS software, including the new correct position. Since the GTR50 does not provide navigation files the PolaRx navigation files were used for this task. This is possible because the navigation data would be the same for two receivers in such very short baselines.

The 16 min spaced P3 data are evaluated in the common-view (CV) mode, which 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. The CERN is located near Geneva in Switzerland and LNGS is located near Rome in Italy. On this European baseline the time comparison can be done in the common-view (CV) mode. However, the link could also be evaluated in the all-in-view (AV) mode, which means that 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. In reference [4] it has been demonstrated that the calibration value obtained with the CV method in terms of a relative calibration is also valid if the link is evaluated in AV mode.

The results of the P3 CV calibration are verified by using the PPP time transfer . It is an AV process by definition, because the PPP software estimates the antenna position and the receiver clock offset at each epoch independently for each receiver. As input data for the satellite clocks and orbits rapid products of the "International GNSS Service" (IGS) were used. Since the clock data are 5 min spaced, also the PPP results are given in 5 min intervals.

Uncertainty Estimation

The overall uncertainty of the GPS link calibration is given by

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

with the statistical uncertainty u_a and the systematic uncertainty u_b. The statistical uncertainty is related to the noise of the CCD measurements. It is the geometric sum of the contributions of the LNGS and the CERN measurement. The systematic uncertainty is given by

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

The contributions to the sum are listed in Table 1 and explained below.

The uncertainty due to the instability of the reference point is accounted for by 0.1 ns at each site. This value is estimated from long term laboratory experience at PTB. It was observed that the delay between two 1 PPS signals which are derived from the same source but passed through different distribution equipment can vary by ± 100 ps in the long term. For both sites this geometrically adds to $u_{b,1}$ = 0.14 ns.

According to the manufacturer specifications the trigger level timing error of the SR620 TIC is given by [5]

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

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. For both sites this leads to $u_{b,2}$ = 0.08 ns. The trigger level timing error of the TR´s internal TIC $u_{b,3}$ is estimated according to information given by the manufacturer [6] 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 1. Systematic uncertainty contributions. Values are determined either by measurements or by estimation and rounded to the second decimal.

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 uncertainty contribution $u_{b,4}$ is 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. Here also both laboratories have to be taken into account. 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 [7]).

Although the TIC jitter (SD) is the statistical uncertainty of the TIC measurement, it becomes a systematic uncertainty in terms of the GPS measurement ($u_{b,5}$, $u_{b,6}$), because the result of the TIC measurement affects all GPS measurements in the same way.

The multipath effect at both sites is accounted for by $u_{b,7}$ = 0.30 ns according to the referenc [8].

Since the average outside temperature could be different for the two CCD measurements at LNGS and CERN, an uncertainty $u_{b,8}$ = 0.18 ns is applied, accounting for different delays 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 the "Royal Spanish Naval Observatory" (ROA) in 2008 [9], multiplied with a maximum anticipated temperature difference of 20°C between the CCD measurements.

The uncertainty contribution $u_{b,10}$ of 0.3 ns is applied to the PPP link calibrations, according to reference [10], where a typical phase discontinuity of 0.15 ns per receiver was found for PPP batch processing with the NRCan-PPP software, 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 internal delays of the PolaRx receivers had been absolutely calibrated by the Swiss "Federal Office of Metrology" (METAS) before the installation of the receivers and the cabling at LNGS and CERN was measured by the laboratories´ staff. In contrast to the GTR50 the PolaRx receiver does not apply internal delay values to the RINEX data. Thus this delays have to be applied to the PPP results of each receiver subsequently according to

$$D = \frac{154^2 D_{P1} - 120^2 D_{P2}}{9316} + D_{Cab} - D_{Ref}, \quad (6)$$

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 for the two GPS frequencies, D_{Cab} is the antenna cable delay, and D_{Ref} is the delay associated to the laboratory cabling. The total delay D is 159.66 ns at LNGS and 161.08 ns at CERN, i.e. the two set-ups are almost identically. The values are part of the P3 CGGTTS file header. The results of the CCD measurements at LNGS and CERN are depicted in Figure 3.

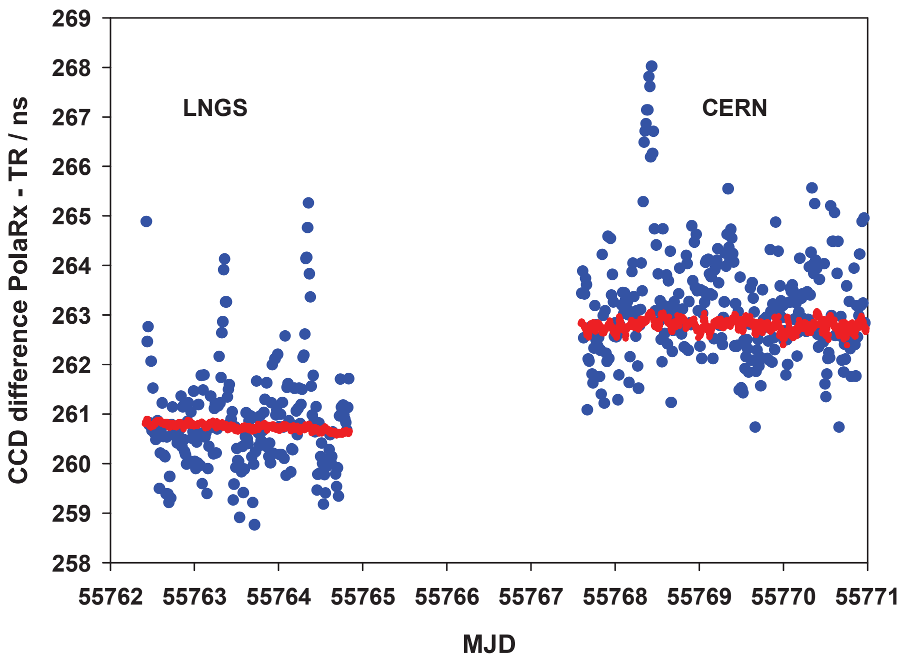

Figure 3. CCD results (blue: P3, red: PPP) at LNGS and CERN. The measurement period (x-axis) is given as Modified Julian Day

In a first step the standard deviation of the P3 data was calculated. Then the outliers were removed by a 3σ filter. In the next step the time deviation (TDEV) [11] of the data was calculated with the average of the individual data spacing as global data spacing interval. From the minimum in the double logarithmic diagram (Figure 4) an averaging time for the individual data points was estimated in order to remove the white phase noise. The last step was to average the individual CCD data, to calculate the mean value, and to calculate the SD of these averaged data around the mean, which is considered as the statistical uncertainty contribution (see also reference [1]). This is necessary, because the standard error can only be used if the measurements are independent, i.e. in case of white phase noise (TDEV with negative slope).

The TDEV points in Figure 4 are plotted together with the corresponding confidence intervals given as "error bars" which are calculated with the statistical methods stated in reference [11]. In order to avoid underestimation of the statistical uncertainty the minimum of the upper "error bar" is used to determine the averaging time. For the calculation of each TDEV point (except the first one) the averaging time of the preceding point is doubled.

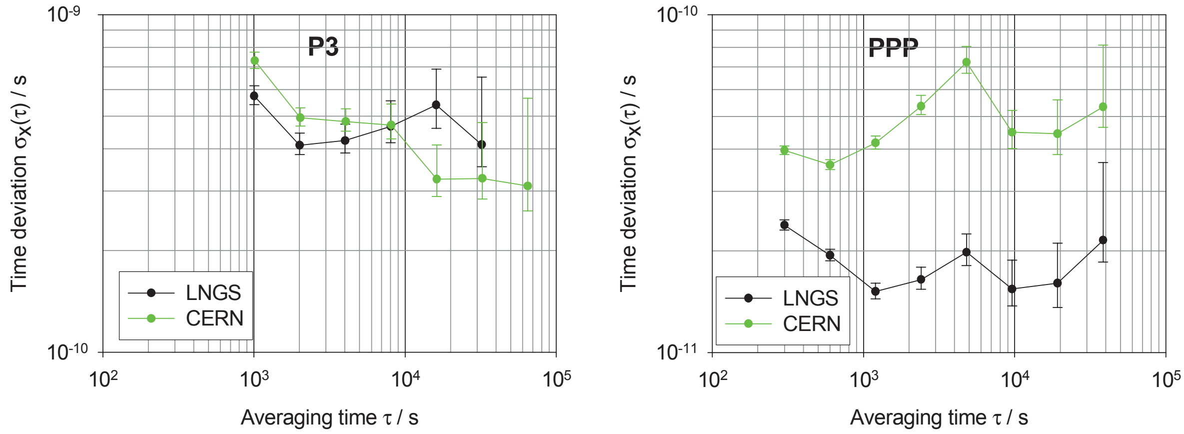

Figure 4. Time deviation (TDEV) of the CCD measurements.

In Table 3 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 4 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.

Table 3. Results of the CCD measurements at CERN and LNGS

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 of the calibration is

$$\mathbf{C_{GPS,P3} = -2.31\ ns \pm 0.90\ ns}$$

and

$$\mathbf{C_{GPS,PPP} = -2.04\ ns \pm 0.62\ ns.}$$

Closure measurement

To verify that the internal delays of the travelling equipment has 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 5.

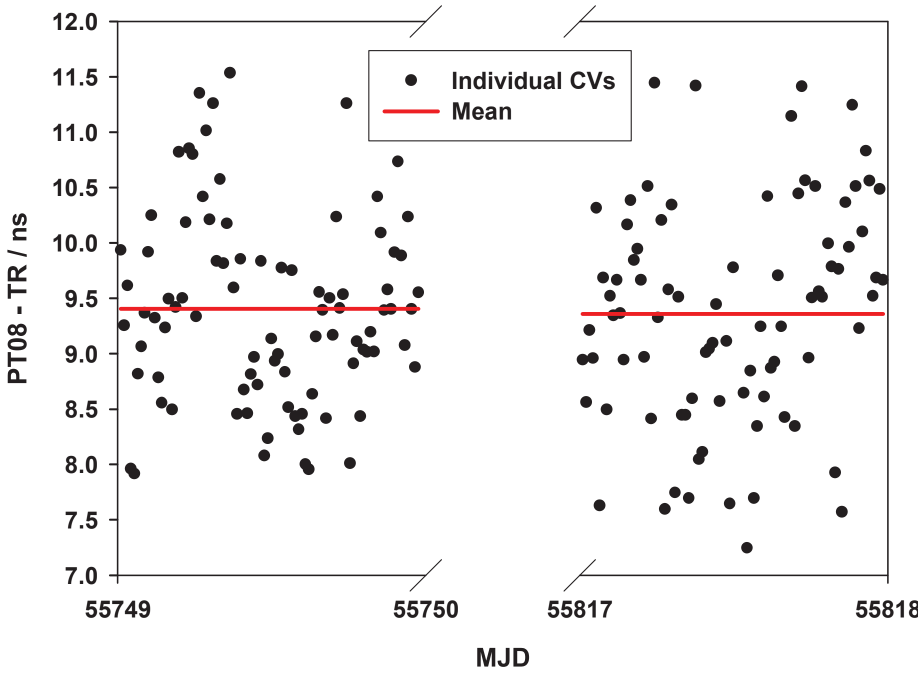

Figure 5. Closure measurements at PTB

The first CCD yields 9.40 ns and the second one 9.36 (The results are not nearby zero, because the internal cabling of the calibration set-up is not taken into account). The difference between the two measurements is 0.04 ns. Thus it has been proven that the internal delays of the calibration set-up have not significantly changed during the 68 days including the period of the calibration campaign. Since the difference of 0.04 ns is far below the statistical uncertainty of the CCD measurements at CERN and LNGS given in Table 3 as SD, it has not to be taken into account in the uncertainty budget.

Summary

The result of the relative calibration between CERN and LNGS is a correction of -2.31 ns which has to be applied to the GPS P3 time transfer results.

The results of the calibration were verified with the PPP method, which serves as a crosscheck since antenna positions and clock offsets are estimated independently for each receiver before an AV time comparison. The PPP result agrees with the P3 result within the combined uncertainty.

Two P3 CCD measurements at PTB before and after the calibration campaign have ensured that the internal delays of the calibration set-up have not significantly changed.

References

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