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Relative calibration of the GPS time link between CERN and LNGS

Preliminary report

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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 set-up for relative link calibrations [1]. The precise calibration of the GPS link between the two institutes CERN and LNGS allows for the estimation of the time of flight of neutrinos generated in the "CERN Neutrinos to Gran Sasso" (CNGS) experiment and the 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.

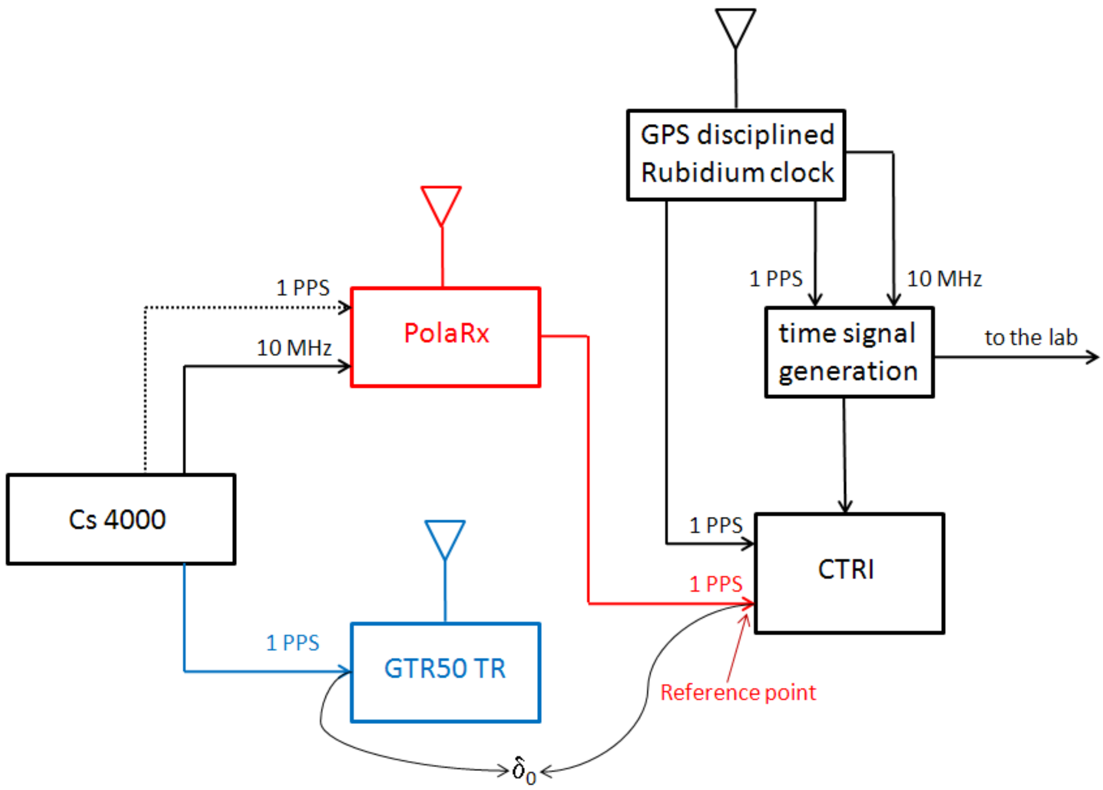

Figure 1. Schematic of the time signal generation at CERN and LNGS. The internal oscillator of the PolaRx receiver is locked to the 10 MHz signal of a commercial caesium clock Cs 4000. The dotted 1 PPS connection to the PolaRx depicts the option of synchronizing its internal timescale to the external signal, if 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, basically the travelling GTR50 receiver (GTR50 TR). The red colored components are subject of the relative calibration and may not 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). 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. A 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 measurements 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.

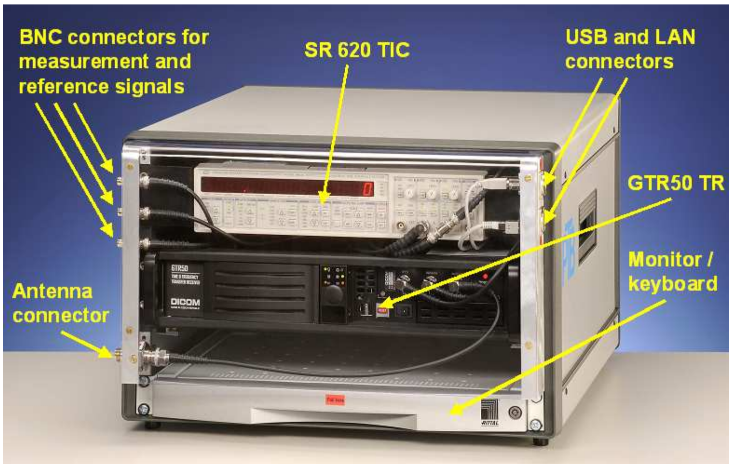

Figure 2. PTB’s calibration set-up.

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

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

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

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

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 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 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 used as an approximation to guarantee proper receiver operation. Thus the positions of the TR antenna have 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 are also generated by the R2CGGTTS software. 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 in the middle of 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 method. 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 has been estimated to be 0.1 ns from long term timing laboratory experience at each site. For both sites this geometrically adds to $u_{b,1}$ = 0.1 ns.

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

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

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. The contributions marked with an asterisk are only applied to special measurements (see text).

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
$u_{b,10}$	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 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 results of the CCD measurements at LNGS and CERN are depicted in Figure 3. The internal delays of the PolaRx receivers were absolutely calibrated by the Swiss “Federal Office of Metrology” before the relative calibration 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 this receiver subsequently according to

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

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 on 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 is 159.661 ns at LNGS and 161.08 ns at CERN.

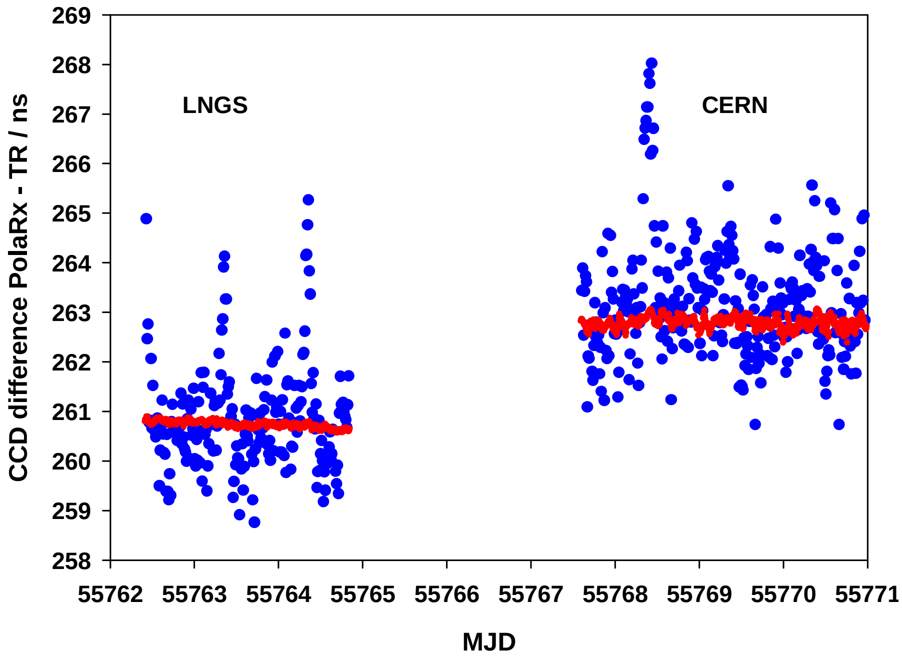

Figure 3. CCD results (blue: P3, red: PPP) at LNGS and CERN.

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 TDEV of the data is 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 is estimated in order to remove the white phase noise. The last step is 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 reference [?] for more details).

The result of the calibration is

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

and

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

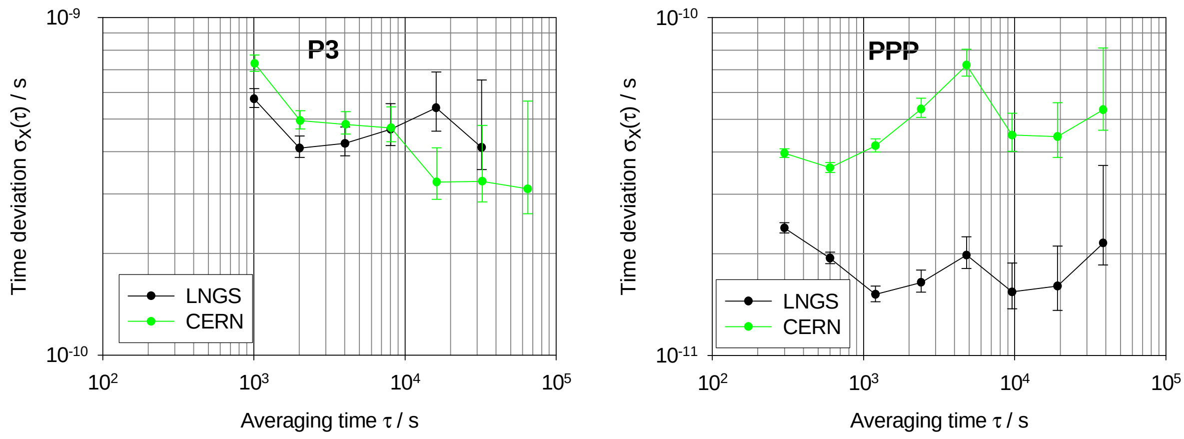

Figure 4. Time deviation of the CCD measurements.

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

Lab	**Type**	**# of averaged data**	**CCD / ns**	**SD / ns**
LNGS	P3	2	260.74	0.79
	PPP	4	260.74	0.34
CERN	P3	16	263.05	0.06
	PPP	2	262.78	0.11

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 time transfer results.

This analysis has to be verified by a closure measurement before and after the calibration campaign at PTB. Before the set-up was sent to CERN the TR was measuring data referenced to UTC(PTB). This measurement will be repeated as soon as possible.

References

[1] T. Feldmann, A. Bauch, D. Piester, M. Rost, E. Goldberg, S. Mitchell, B. Fonville, 2010, *“Advanced GPS-based Time Link Calibration with PTB´s new GPS Calibration Setup,”* Proc. 42nd PTTI, Novemberr 15-18, 2010, Reston VA, USA, 509-526

[2] P. Defraigne, G. Petit, 2004, *"Time Transfer to TAI using geodetic receivers,"* **Metrologia, Vol. 40,** 184-188

[3] J. Kouba, P. Heroux, 2002, *“Precise Point Positioning Using IGS Orbit and Clock Products,”* **GPS Solutions, Vol 5, No. 2,** 12-28

[4] T. Feldmann, A. Bauch, D. Piester, A. Stefanov, L.-G. Bernier, C. Schlunegger, K. Liang, 2010, *"On improved GPS based link calibration of the time links between METAS and PTB,"* Proc. 24th EFTF, April 13-16, 2010, Noordwijk, NL

[5] *"SR620 Operating Manual and Programming Reference,"* SRS

[6] P. Panek, Dicom CZ and UFE, private communication

[7] I. Prochazka, P. Panek,, 2009, *"Nonlinear effects in the time measurement device based on surface acoustic wave filter excitation,"* **Rev. Sci. Instrum, Vol. 80,** 076102

[8] W. Lewandowski, C. Thomas, 1991, *"GPS Time transfers,"* **Proc. IEEE, Vol. 79, No. 7,** 991-1000

[9] H. Esteban, J. Palacio, F.J. Galindo, J. Garate, 2008, *"GPS receiver performance test at ROA,"* Proc. 40th PTTI, December 01-04, 2008, Reston VA, USA, 349-360

[10] G. Petit, 2009, *"The TAIPPP pilot experiment,"* Proc. EFTF – IEEE IFCS Joint Conference, April 20-24, 2009, Besançon, France, 116-119