Time transfer techniques for the synchronisation between CERN and LNGS

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Abstract

This internal note explains the work carried out by the BE-CO-HT section at CERN in order to ensure a time transfer between CERN and Gran Sasso National Laboratory (LNGS) with a systematic uncertainty at the level of several nanoseconds, opening the way to meaningful neutrino Time Of Flight (TOF) measurements. The main contributions have been focused on the following areas:

- Study and development of a common-view scheme using geodetic GPS receivers and techniques similar to those used in the manufacturing of Universal Coordinated Time (UTC).
- Selection and calibration of GPS receivers for synchronisation applications.
- Development of techniques to measure cabling delays inside CERN and LNGS with sub-nanosecond accuracy.
- Characterisation of the delay from the BCTFI.400344 Beam Current Transformer (BCT) to a digitising oscilloscope in HCA442 (point 4 of the SPS, where the CNGS extraction line is located).
- Daily operation and support of the system on the CERN site.

The combination of these developments has resulted in an improvement in the time transfer accuracy of more than two orders of magnitude, and has enabled the measurement of neutrino TOF with very low uncertainty.

This document focuses on the techniques rather than exact results of measurement campaigns. In the interest of conciseness and clarity, these results are documented in separate dedicated reports.

1 Background

The BE-CO-HT section is in charge of – among other things – designing, developing and operating CERN's General Machine Timing (GMT) system. When we were mandated to work on CERN-LNGS synchronisation for the CNGS project in 2005, a previous team in the former SL-CO group had already proposed a GPS-based solution. This solution, however, did not have the ambition of being more accurate than $\sim 1\ \mu s$, because at the time the only requirement was being able to discriminate in LNGS events between neutrinos coming from the Sun and other sources and those coming from the CNGS beam.

Specialists in the BE-CO-HT team knew about ways to reduce the uncertainty to the ns level. In particular, many of the techniques used in the manufacturing of UTC by national metrology

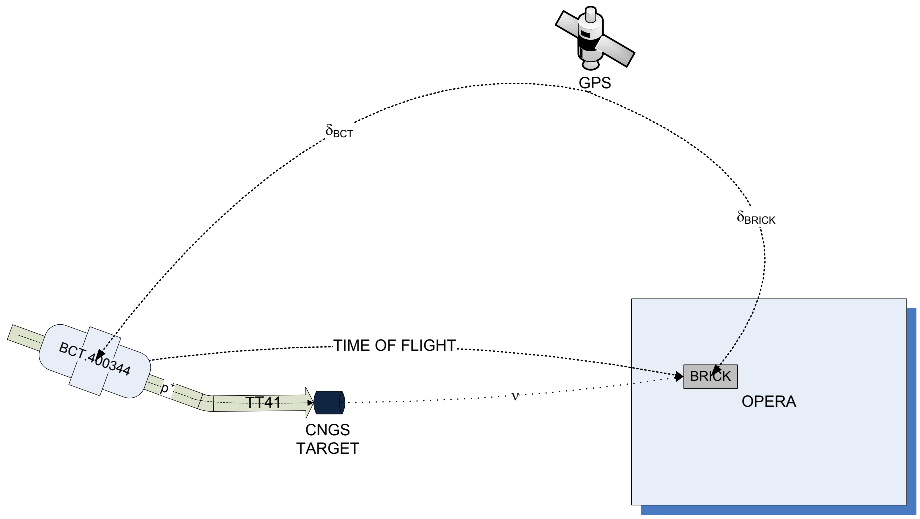

Figure 1: Time of flight measurement

labs could be used in this new context. We decided to consult with the Swiss national metrology lab (METAS) and adapt these methods to the time transfer between CERN and LNGS.

Having nanosecond accuracy between two distant GPS receivers was only part of the solution to our problem. In addition, we needed to find ways of calibrating cabling lengths in CERN and LNGS with a similar degree of accuracy, which are also described in this note.

The third key ingredient to increase accuracy was the decision to digitise the whole BCT waveform for each extraction at CERN. We noticed that the spill did not have a uniform distribution, and knowledge of those variations could be put to good use in a correlation experiment between CERN extractions and events in the OPERA detector in LNGS.

2 Introduction

The neutrino beam generated in the CNGS extraction line in CERN's SPS goes through the Earth's crust and gets detected in the Gran Sasso National Laboratory in Italy.

It is assumed that the neutrino beam intensity is directly proportional to the proton beam intensity colliding against the CNGS target. Therefore a superposition of all the BCT waveforms of the proton spills should resemble the neutrino event time histogram in the OPERA detector. A correlation between both curves gives an estimation of the neutrino TOF. Features in the BCT waveforms which make them depart from a flat distribution are useful for the fitting procedure – in fact they were at the origin of our decision to digitise the waveforms – and suggest that even more precision could be achieved with different types of beams in the future.

The BCTFI.400344 waveform for every extraction is stored into the BE-CO long-term measurement database. Every acquisition is time-tagged with respect to the SPS timing system. In LNGS, neutrino events are tagged by the OPERA team with respect to the time base of OPERA.

We designate by t_{GPS}^{event} the time at which an event is seen in LNGS, in the GPS time base.

Conversely, t_{GPS}^{beam} designates the time at which the proton responsible for that event crossed the BCT at CERN, measured also in the GPS time base. Then, looking at Fig. 1 we can write:

$$t_{GPS}^{beam} = t_{BCT}^{beam} + \delta_{BCT} \tag{1}$$

and

$$t_{GPS}^{event} = t_{OPERA}^{event} + \delta_{BRICK} \tag{2}$$

where

- t_{BCT}^{beam} is the time at which the proton crosses the BCT in a time base offset with respect to GPS due to cabling delays between the BCT and the GPS receiver in the CERN Control Room (CCR), and also due to fluctuations between GPS time and that of the GPS receiver in the CCR, mainly due to atmospheric perturbations.
- δ_{BCT} is the correction which must be applied to the t_{BCT}^{beam} time tag in order to take it to the common GPS time base.
- t_{OPERA}^{event} is the time of event detection in one of the bricks of OPERA, using a time base which is offset with respect to GPS by a delay induced by cables and atmospheric perturbations, as above.
- δ_{BRICK} is the correction needed to take the time tag in OPERA to the GPS time base.

The value δ_{BCT} is made of a fixed quantity representing the delay induced by internal CERN cabling, and variable corrections to compensate for the short-term noise in the GPS signal at the GPS receiver:

$$\delta_{BCT} = \delta_{BCT\_fixed} + \delta_{BCT\_variable} \tag{3}$$

In this document we show how to determine the value of δ_{BCT_fixed} and give indications on how to calculate $\delta_{BCT\_variable}$ from the logged time tags. The methods we introduced to measure cabling delays at CERN were also used later in LNGS during measurement campaigns in collaboration with the OPERA team.

Fig. 2 gives a detailed view of the calibration chain from the beam passing through the BCT until the GPS system, as implemented during the 2010 run. There are two GPS receivers:

- The Symmetricom Xli, is able to generate a stable clock locked to GPS with an accuracy of ∼100ns and a precision of ∼20ns rms. This GPS receiver provides a 10MHz and a PPS (Pulse Per Second) reference to the SPS timing system master.
- The Septentrio PolaRx2e timing GPS receiver clocked by a caesium clock (CS4000). The PolaRx2e accepts the GPS signal and the high stability CS4000 10MHz signal to generate a timebase whose offset with respect to GPS UTC can be known a posteriori with very good accuracy.

A general purpose timing receiver (CTRI) connected to the SPS timing network, time tags the PPS coming from the PolaRx2e with a precision of 1ns. This time tag is stored in the long term measurement database for the generation of a precise paper clock. A second CTRI in HCA442 time-tags the kicker pulse that sends the SPS beam towards TT40.

The kicker pulse is also used to start an acquisition of the BCTFI.400344 waveform for 20us at 1GS/s, which is as well stored in the long term database. The delay between the BCT and the scope acquisition has been estimated with two different methods. One uses the CS4000 PPS injected into the BCT calibration input and the other correlates the pick-ups and BCT waveforms in HCA442.

In the following sections we describe the techniques used to calibrate the different delays depicted in Fig. 2 one by one, referring to them by the names they get in the drawing.

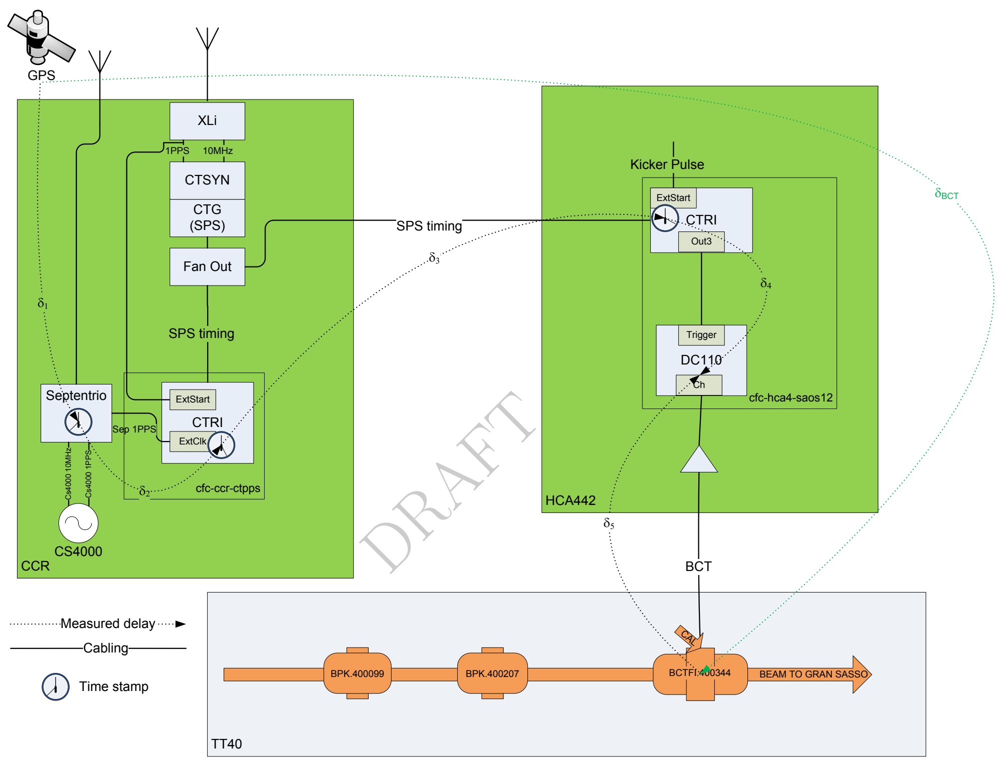

Figure 2: CERN layout

3 Corrections to align CERN's time base with GPS (δ_1)

These corrections, labelled δ_1 in Fig. 2 are meant to take time tags from the time base of the PolaRx2e receiver and that of GPS, considered common between CERN and LNGS. The $\delta_{BCT\_variable}$ in Eq. 3 is the sum of δ_1 and δ_2 (explained later).

In Fig. 2, the Septentrio PolaRx2e receiver is connected to a GPS antenna on one side and to the PPS and 10 MHz signals from the CS4000 on the other. The PolaRx2e uses information from the GPS messages to generate CGGTTS files every 16 minutes. These files contain information on the time offset between the internal PolaRx2e PPS (which is nothing but the 10 MHz of the CS4000 divided down) and each one of the GPS satellites in view. The files also contain information on the estimated quality of the timing signals received from each satellite. This information can then be used to compute a smoothed (averaged) GPS time base from the noisy GPS data. It is assumed that the CS4000 is less noisy than the raw GPS signals for time spans shorter than 24 hours, so the averaging time should not exceed that value. A similar averaging can done in LNGS. In fact this smoothing procedure is not currently being used (either at CERN or in LNGS) because it is deemed unnecessary by the OPERA team, which is in charge of merging time-stamp data. The argument is that the average of the noise processes is zero and given the number of events observed, the statistical uncertainty is low enough and the extra smoothing would not bring in any substantial additional precision. The data necessary for the smoothing is anyway logged so that it can be performed at a later date if needed.

So currently the individual 16-minute CGGTTS files are being used to apply a correction which takes the time tag of a given extraction or event in the PolaRx2e time base to the GPS common time base.

Statistical fluctuations have been taken care of by the mechanism described above. That still leaves systematic delay offsets to compensate. To deal with these, we teamed up with METAS – who had recommended the PolaRx2e setup to begin with – and performed a zero-baseline calibration experiment, whereby the two PolaRx2e receivers we had bought were installed in METAS and their delay offset was measured and documented. This was in 2008. We then installed one PolaRx2e receiver in the CCR and – with the help of the OPERA team – the other one in LNGS. In 2011 we decided that an additional calibration would be useful to verify that the delay offset had stayed constant. In collaboration with the OPERA team, and following the recommendation of the METAS specialists, we contacted the German national metrology laboratory (PTB), which has experience in performing a different type of calibration consisting of travelling with a portable calibrated GPS receiver to each site and averaging measurements during several days to come up with an estimate of delay offset between the two distant GPS receivers. The two calibration campaigns showed consistent measurements, and the fact that two different methods agree within 2 ns after several years reinforces the validity of the results.

4 Septentrio PolaRx2e to CCR Reference CTRI (δ_2)

The PPS output from the PolaRx2e is tagged by a CTRI installed in front end computer cfc-ccr-ctpps and connected to the SPS timing network. This time-stamp is used as reference to translate from the SPS(CCR) time to the PolaRx2e time. The internal delay between the place inside the PolaRx2e where time-tagging is performed and its output has been calibrated but is irrelevant anyway because it is equal in the CERN and LNGS systems. The cable length between the PolaRx2e and the CTRI external clock input is also the same at CERN and LNGS.

The time tag translation between the CTRI(CCR) time base and the PolaRx2e time base is embodied by δ_2, which is calculated offline by taking the logged time tags of the PolaRx2e PPS using the CCR CTRI.

5 CCR Reference CTRI to HCA4 Reference CTRI (δ_3)

The proton spill acquisitions are time-stamped with a different CTRI installed in HCA442 and also connected to the SPS timing network. As the cabling to both CTRIs (this one and the one in CCR) remains stable the time offsets between both modules remains stable as well (to within the thermal expansion of the SPS timing network fibres, see section 8).

In order to calibrate the delay between the CTRI cards, the CS4000's PPS output was hooked to the external clock input of the CTRI in CCR and then taken to HCA442, where it was hooked to the external start input of the other CTRI. This method is only limited by the drift of the Caesium clock during the trip between the CCR and HCA442, which is estimated to be less than 1 ns.

Another method was used to cross-check the transportable Caesium method and have a means of continuously monitoring the delay induced by the GMT distribution. An additional fibre link was added in parallel to the GMT link between the CCR and HCA442. First a pulse is sent through this Faber from the CCR to HCA442 and tagged simultaneously in both places. Then the optical receiver and transmitter are exchanged and the operation is repeated in a reversed path using the same fibber. The calibration path delay should be the same in both directions as the receiver and transmitter are identical in both cases. Figures 3 and 4 describe the measurement setup. The calibration path has been left permanently configured as in Fig. 4. The time-tags in the CCR are stored in the permanent database to observe any possible drift in the transmission delays.

From Figures 3 and 4 we can write

CCR to HCA442:

$$t_{c1} = t_1 + A \tag{4}$$

$$t_{h1} = (t_1 + \beta) + B \tag{5}$$

HCA442 to CCR:

$$t_{c2} = (t_2 + \beta) + A \tag{6}$$

$$t_{h2} = t_2 + B \tag{7}$$

Where t_{c1} and t_{h1} are the time-tags for a pulse generated at the CCR and received at HCA442 respectively. t_{c2} and t_{h2} are the time-tags for a pulse travelling from HCA442 to the CCR. t_1 and t_2 are the generation pulse time-stamps with respect to an ideal time base. β is the calibration path transmission delay, A and B are the offsets of the timing receivers with respect to this ideal time base. We are interested in finding the time offset between the timing receiver in the CCR and that in HCA442, i.e. δ_3:

$$\delta_3 = A - B \tag{8}$$

$$t_{h1} - t_{c1} = \beta - \delta_3 \tag{9}$$

$$t_{c2} - t_{h2} = \beta + \delta_3 \tag{10}$$

$$\delta_3 = ((t_{c2} - t_{h2}) - (t_{h1} - t_{c1}))/2 \tag{11}$$

$$\beta = ((t_{c2} - t_{h2}) + (t_{h1} - t_{c1}))/2 \tag{12}$$

This method can be used for calibrating the length of any fibre or copper link, and was also used to calibrate fibre links between the GPS room in LNGS and the OPERA detector. The only necessary infrastructure is the existence of a parallel calibration fibre or cable.

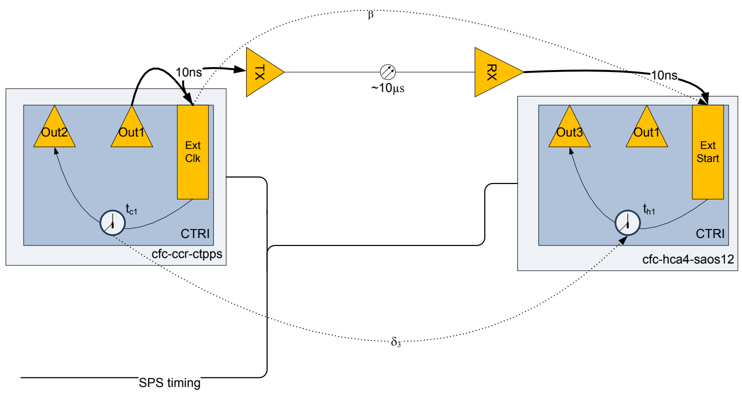

Figure 3: Fibre calibration path from CCR to HCA442.

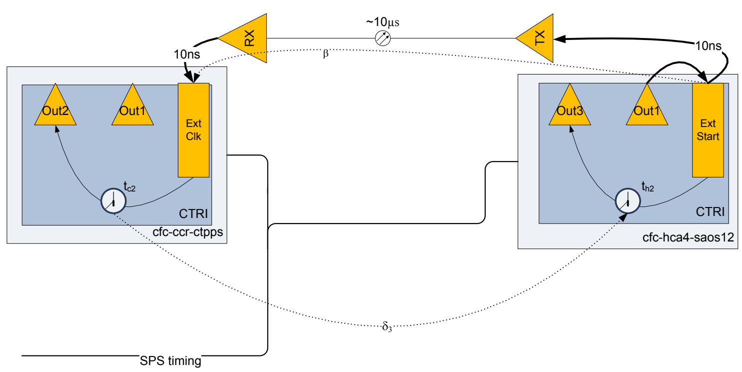

Figure 4: Fibre calibration path from HCA442 to CCR.

6 HCA4 Reference CTRI to Scope Channel (δ_4)

The pulse from the extraction kicker is converted to a suitable logic level and fed to the external start input of the CTRI in HCA442. This input pulse is time-tagged in the CTRI. In addition, the CTRI is programmed to generate an output upon reception of this external pulse. This output pulse is fed to the trigger input of the oscilloscope digitising the BCT waveform. For evaluating the delay between the kicker pulse at the input of the CTRI (which is precisely time-tagged) and the trigger pulse at the input of the oscilloscope, we conducted ad-hoc experiments with a locally generated pulse.

7 Scope channel to BCT (δ_5)

An absolute delay calibration of BCTFI.400344 and the cable taking its signal to HCA442 is difficult to implement due to the relative complexity of the BCT. In general the delay will depend on the beam position and the coil characteristics. Lab measurements show discrepancies in the order of 10ns, depending on the measurement setup. On the other hand, as suggested by the BI group, beam pick-ups are easy to model as the voltage induced on them is mainly capacitive. Cable delays between HCA442 and the pick-ups can be easily measured using reflectometry at the 1ns level. The position between the accelerator elements is known at the cm level. Nevertheless, the alignment of the bunches between the pick-ups and the BCT is not obvious for the CNGS beam. With the data taken for calibration there is a possible error of +/-10ns (2 bunches). It is much easier to do this calibration with LHC bunches, which are separated by 50ns during the present run, giving enough time to distinguish them. The delay between the beam and the BCTFI.400344 acquisition system was calculated by measuring the time of flight between the BCT and pick-ups BPK.400099 and BPK.4000207, and using the precise measurements of the pickup cable delays.

7.1 Pick-up cable delays

The pick-up cable delays were calibrated using reflectometry. A fast pulse was sent from HCA442 towards the pick-ups in the absence of beam. Then we sensed the reflection after a full round trip.

From figures 5 and 6 we can deduce the cable delays from BPK.400207 and BPK.400099 to HCA442.

The calculation of the transmission delay between BCTFI.400344 and the acquisition scope can now be deduced from the time of flight between one of the pick-ups and the BCT. Figure 8 shows the data taken without delay correction. Figure 9 shows a zoom of the BCT and pick-up signals corrected with 403ns for BPK.400207 and 589ns for BPK.400099.

The crosstalk experiment (Fig. 7) allowed us to double-check the reflectometry measurements and verify that the pickups are indeed simple capacitive coupling devices.

8 Additional considerations

The temperature dependence of delay in optical fibres is estimated at 40 $ps/km/°C$ which for the case of the fibre between the CCR and HCA442, and taking a worst case temperature variation between Summer and Winter of 30$°C$ would give us an additional uncertainty of ±2.5 ns. However, as explained in section 5 we are logging the real delay variations in the link and these measurements suggest that the yearly variation should be well below 1 ns.

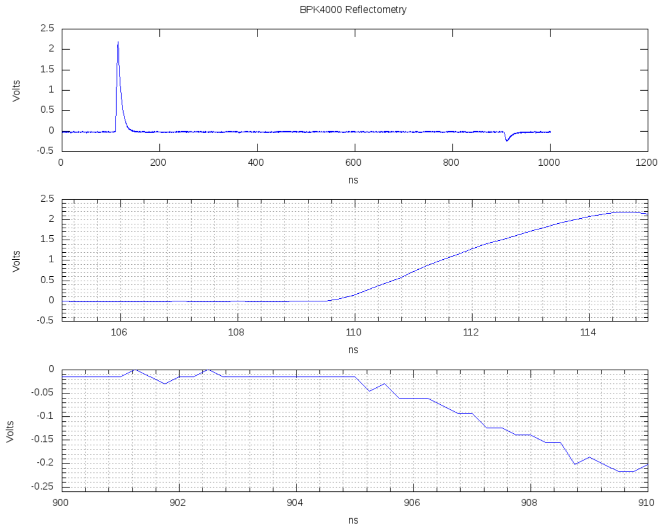

Figure 5: BPK.4000 reflectometry. The lower figures show a zoom of the rising edge of the incident pulse and of the falling edge of the reflection.

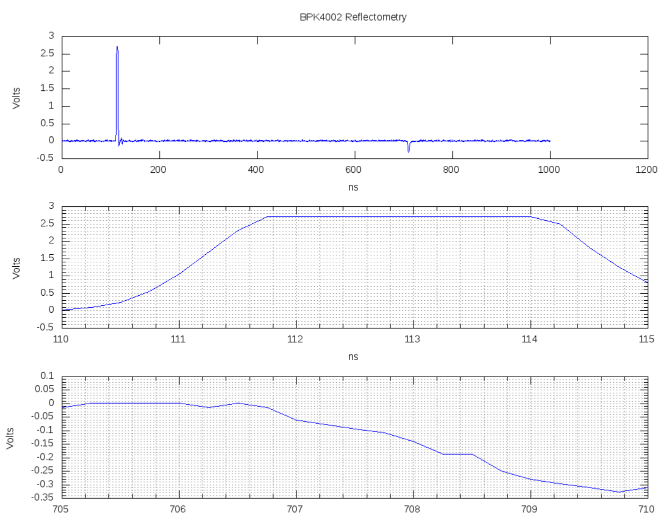

Figure 6: BPK.4002 reflectometry.

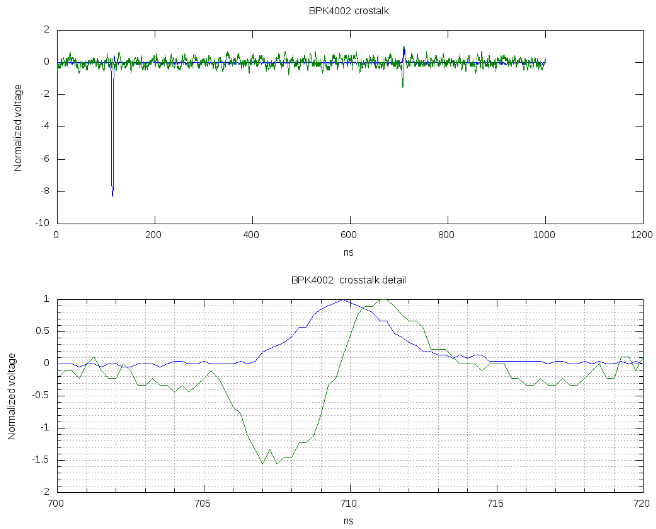

Figure 7: BPK.4002 crosstalk. Sending a pulse through one of the pickup cables and observing the signal coupled in the pickup on another cable.

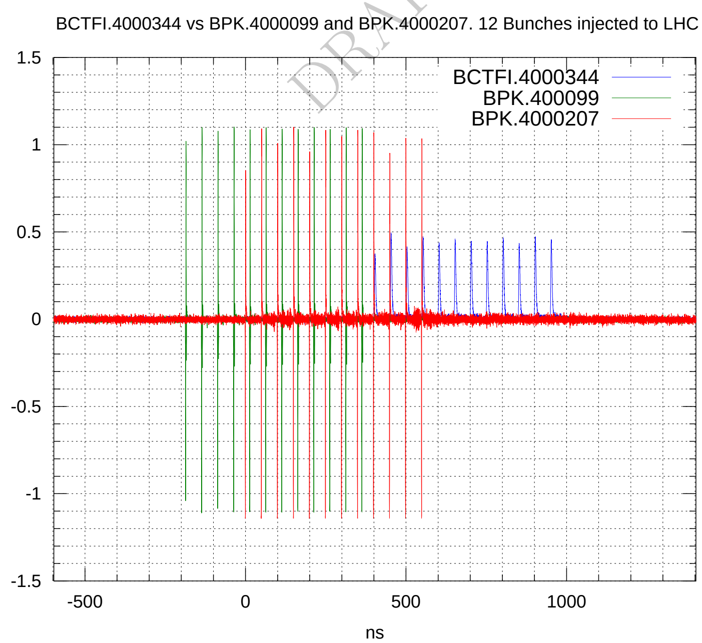

Figure 8: 12 LHC injection bunches.

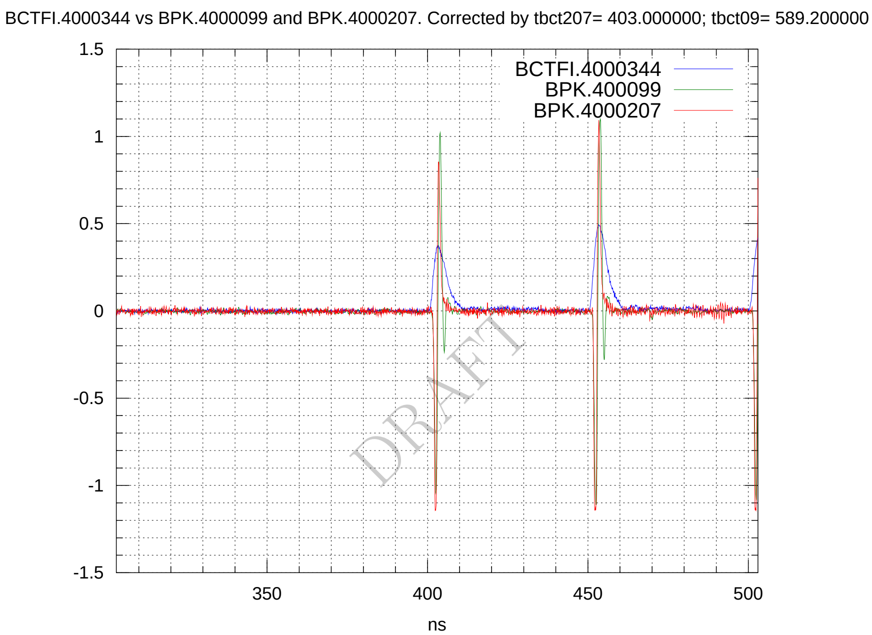

Figure 9: First LHC injection bunches with delay correction.

9 Final result

When we get a time tag in the CTRI of HCA442 (t_{BCT}^{beam} in Eq. 1), it is logged in the long-term measurement database and is the starting point for a good estimation of the exact time corresponding to the beginning of the logged BCT waveform (t_{GPS}^{beam}). There are a number of steps to follow in order to take that time tag to the common GPS time base:

- Compensate for cabling delays in order to take the time tag to the time base of the CTRI card in the CCR. This correction is essentially what is meant by δ_{BCT_fixed} in Eq. 3.
- Take the tag from the CTRI CCR time base to the PolaRx2e (in fact CS4000) time base thanks to the time tags of the PolaRx2e PPS in the CCR CTRI and then take the tag from the PolaRx2e time base to the common GPS time base using the periodic observations contained in the CGGTTS files. These two corrections are essentially what is meant by $\delta_{BCT\_variable}$ in Eq. 3.

10 Further work

In the future, there is a number of things we can do to improve the uncertainty of the measurements:

- Use a system like White Rabbit which automatically calibrates cable delays, all year round so we can get rid of thermal effects.
- Ask BE-OP to send beam to LNGS using another scheme with more intensity variations, or longer spacing between bunches, to make correlation simpler and more robust.
- Improve the GPS time transfer uncertainty with the help of our colleagues in the Swiss and German metrology labs.
- Select better sources of beam intensity waveforms if possible.

11 Acknowledgements

We would like to acknowledge Dario Autiero and Giulia Brunetti of the OPERA team, for the many years of discussions and fruitful close collaboration on the timing calibration works at CERN and LNGS. Also for the opportunity to use these technical developments in a very exciting Physics experiment and their willingness (and patience) to explain the larger picture to us.

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