INTER-LABORATORY SYNCHRONIZATION FOR THE CNGS PROJECT

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Abstract

CERN will start sending a neutrino beam to Gran Sasso National Laboratory in Italy in July 2006. This beam will cover a distance of around 730 km through the crust of the earth from an extraction line in CERN's SPS to dedicated detectors in Gran Sasso. This paper describes the technological choices made to fulfill the specification of inter-laboratory synchronization in the region of 100 ns, as well as some preliminary results. The common time standard is UTC as disseminated by the GPS system, and the techniques are similar to those used by national metrology laboratories for the manufacturing of UTC itself. In addition, real-time messages sent through the Internet allow the detectors in Gran Sasso to go into calibration mode when no beam is being sent. Data concerning the delay and determinism of this international network link is also presented.

INTRODUCTION

The CNGS (CERN Neutrinos to Gran Sasso) project aims at delivering a high intensity neutrino beam though the Earth's crust from CERN (Geneva, Switzerland) to the Gran Sasso National Laboratory (LNGS) located 120 km east of Rome in Italy. This beam will contain exclusively neutrinos of the muon type, and the detectors in LNGS will try to find tau-neutrinos resulting from the oscillation of muon-neutrinos as they travel though the 730 km straight line separating CERN and LNGS.

In order to correlate the events observed in LNGS with the beam pulses sent from CERN's SPS, both of them will be time-tagged using Universal Coordinated Time (UTC) as a reference, therefore allowing discrimination of events caused by CERN neutrinos with respect to spurious events. The local time bases in LNGS and CERN are provided by GPS Disciplined Oscillators (GPSDO), delivering Pulse-Per-Second (PPS) outputs and 10 MHz clocks to break each second in 10 million ticks. Both GPSDO devices contain Rubidium oscillators to ensure good short-term stability and rely on the numerous Cesium clocks driving the GPS constellation of satellites for their long-term stability. As a result, the quality of the 10 MHz output is excellent, with typical Allan variances [1] of 10^{-11} for an averaging time of 1 second and 10^{-12} for 100 seconds. The limiting factor to achieve good inter-lab synchronization is therefore the variance between the output times of the PPS pulses in LNGS and at CERN. This report presents the results measurement campaigns performed to quantify the systematic offset between the two PPS pulses, used to calibrate the system, and also to study the variance of these measurements to ascertain whether the specified performance (100 ns RMS) is achievable with the basic GPSDO setup, knowing that more involved techniques, such as common view and two-way satellite time transfer [2] could be implemented to improve performance if necessary.

Once each laboratory has a facility with a well controlled and characterized GPSDO, it is necessary to take that time reference from there to the place of interest, i.e. the SPS extraction point at CERN and the Opera detector in LNGS. In both cases, the fibre delay incurred has to be measured and taken into account when generating the time tags. The methods used are also presented in this report, along with results from actual measurements.

Another request from the CNGS project concerns the possibility of running calibration procedures in the Opera detector during periods of no beam from CERN. In order to synchronize these calibration runs, taking into account that the SPS is a multi-cycling machine with a multitude of operating modes decided online by operators, a fail-safe scheme using UDP packets though the Internet was put in place. We describe the scheme and comment on some preliminary results which confirm that this cheap, non-deterministic solution is indeed good enough for our purposes.

GPSDO CALIBRATION

A GPSDO is a special kind of GPS receiver designed to provide very accurate and stable timing signals. In order to do so, it works to find a very precise position fix during the first hours after power-up. This implies of course that the device should not move at all during normal operation. After many position averages (around 100000 in our case), the device goes into "timing" mode, i.e. it fixes its position and only solves the time equation. This means that a GPSDO can keep track of time with only one GPS satellite in sight (and not three as would be needed to find its position as well) but the more satellites the GPSDO sees the more accurate the timing will be.

The biggest source of errors in the generation of a stable PPS output in a GPSDO is the variable propagation time of GPS signals through their one-way trip from the satellites to the GPSDO, especially through the ionosphere and troposphere [2]. For our two relatively close locations, we assume there will be a "common mode" effect whereby the deviations from UTC of our two GPSDOs will go in the same sense and will have roughly the same values. For more local variations, typically of a faster nature, the Rubidium oscillator on each GPSDO will act as a low-pass filter, with a time constant of around 3 hours, smoothing out the short-term variations.

To validate our assumption and gain some extra confidence, we decided to calibrate CERN's GPSDO both against the official source of UTC time in Switzerland (the Swiss Federal Office of Metrology, METAS, in Bern) and against the LNGS GPSDO in Gran Sasso. UTC is in fact a “paper clock” built a posteriori in the “Bureau International des Poids et Mesures” (BIPM) in Paris. Measurements of GPS signals performed using Cesium clocks all around the world are taken by BIPM, properly weighted and averaged, to come up with a table of corrections each given lab should apply to their measurements. In METAS, the time metrology team also generates a “real-time” UTC, called UTC(CH.R), whose typical RMS difference with respect to the paper clock UTC(CH) is 1.3 ns and can therefore be neglected at the scale of 100 ns of interest to us. The result for the measured time offset PPS(GPSDO)-UTC(CH.R) was (+100±50) ns, with the plus sign meaning that the PPS signal coming out of the GPSDO was ahead in time of the one coming from the UTC(CH.R) realization stand. The confidence level given by METAS is such that if we correct for the 100 ns systematic offset, we can trust that the “perfect” UTC PPS pulse would fall in the ±50 ns window around our PPS with a probability of 95%.

We could have requested a similar calibration procedure to be performed on the LNGS GPSDO, but it was felt that the ultimate test would actually consist in measuring the two GPSDOs against one another. The result of these measurements, performed over a 12 day period in March 2006 in the LNGS site, can be seen in Figure 1.

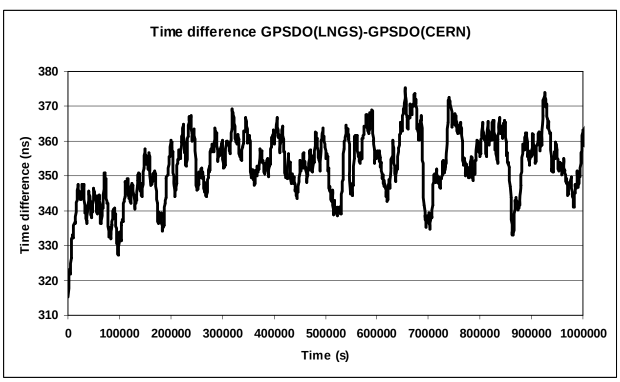

Figure 1: time difference measurements between the PPS outputs of the LNGS and CERN GPSDOs.

The average value of the data is 353 ns, meaning that the LNGS GPDO is really well ahead of UTC. The 100 ns of offset between the CERN GPSDO and UTC had already been compensated using a programmable register in the device. The excursions in the waveform are well contained within the 100 ns envelope allowed by the specifications of the CNGS project. A certain periodicity can be seen in the waveform with a period of one day. This can be explained by the fact that the GPS receiver antenna sees the same satellite configuration in the sky every 24 hours, so any systematic effects within each GPSDO will reproduce with that same period.

FIBRE DELAY CALIBRATION

The GPSDO installed at CERN is located in the CERN Control Centre (CCC), while the LNGS system runs in the network routers room in the laboratory site. In both cases these systems are far away from the places were the precise timing signals are needed (point 4 of the SPS at CERN and the Opera detector in LNGS). In both labs, dedicated electronics take the PPS and 10 MHz outputs of the GPSDO and use them to encode timing information on a fibre link. At the receiving side, another set of electronic cards uses this information to generate pulses or to time-tag external events. Since the moment of arrival of the messages is as important as the message content itself, it is very important to calibrate the delay induced by the fibre in the timing transmission.

A very simple scheme requiring only one additional fibre between the two points of interest has been used at CERN to calibrate the delay between the CCC and SPS point 4 (building BB4). One optical transmitter and one optical receiver are used in a first phase to transmit the PPS pulse through the additional link from the CCC to BB4. The PPS pulses at the two ends are then time tagged using standard CERN timing receivers. Then we take the same transmitter module to BB4 and the same receiver module to the CCC and repeat the operation using the PPS produced by the timing receiver in BB4. One can prove that the time offset between the CCC and BB4 is given by:

$$\Delta T_{BB4-CCC} = \frac{t_{RCCC} + t_{FCCC} - t_{RBB4} - t_{FBB4}}{2} \qquad (1)$$

Where t_{RCCC} is the time tag of the “return” (BB4 to CCC) pulse as seen in the CCC, t_{FCCC} is the time tag of the “forward” (CCC to BB4) pulse as seen in the CCC and so on. In the above formula, it has been assumed that the delay of the fibre link is the same in both directions, and also that it stayed stable during the 1 hour it took to take the material from the CCC to BB4 and vice-versa. This assumption has been validated by leaving the system running in the “return” configuration for some weeks, i.e. emitting the PPS pulse in BB4 and looking at only one half of the equation. Any fibre delay variation induced by temperature changes should be visible in this setup. The observed variations are in the 1-2 ns region and can be neglected for our purposes. The final result for the time offset between the CCC and BB4 as computed using this scheme is 10.584 μs, corresponding roughly to 2.1 km of fibre with a delay of 5 ns/m. More elaborate systems can be used to calibrate the fibre delay online. For example, we could have two calibrated sets consisting of a transmitter and a receiver working all the time and logging these time differences to correct the time tags offline. Online correction of the delays, which would involve active devices such as phase shifters or fibre stretchers, is not needed in our application.

SOFTWARE SYNCHRONIZATION WITH UDP PACKETS

The Opera detector in LNGS needs short calibration runs for several electronic subsystems as frequently as possible. It was agreed to have a fail-safe mechanism to inform Opera through the Internet that it can run the calibration procedure safely whenever CERN is not sending any beam to LNGS. By fail-safe we mean that the loss of packets in the network should never result in loss of useful data acquisition.

The SPS is a multi-cycling synchrotron with several users, including LNGS, the North Experimental Area and LHC. A simplified view of the multi-cycling mechanism would include different cycles meant for different destinations grouped in an entity called the super-cycle, which is run cyclically until operators decide to introduce changes. The real situation is a bit more complicated, with interlock bits driving asynchronous jumps from one normal cycle to a spare cycle online. In any event, all cycle changes occur at boundaries of the 1.2 second basic heart beat that drives all CERN accelerators. The proposed solution for the Opera calibration runs consists in sending a structure through the network at the beginning of every basic period to inform Opera of what’s going on in the SPS. Typically, this structure contains the UTC time for the start of the basic period, the UTC time at which the packet was sent (for sanity checks on the receiving side), the number of basic periods for the current cycle and the current destination for the beam.

In Opera, a task can listen to the UDP packets coming from CERN and find out for example that the coming 9 basic periods (i.e. 10.8 seconds) will be used in the SPS to generate beam for the North Area, so it is safe to go ahead and run the calibration, switching automatically back to data taking after this time is elapsed.

In order to validate the concept, we tested the round trip delay of UDP packets between CERN and LNGS. As can be seen in figure 2, none of the packets makes it in less than 25 ms, and from then on the distribution presents a maximum at 26 ms and then decreases getting to negligible levels after the 50 ms region. Of the 14400 packets sent for the test, 2 were lost and 1 actually showed a round trip delay of a full second, showing that the implementation of a fail-safe mechanism over this physical layer is absolutely necessary.

Another important aspect to be taken into consideration is how to get the current UTC time within the receiving task for sanity checking purposes. The most common approach is to issue a UNIX system call that relies on the presence of a Network Time Protocol (NTP) server nearby. An NTP server typically contains a GPS receiver and an Ethernet board, and provides time-of-day services to a set of computers in the network. If a network node is very far away (in terms of network connections) from its closest NTP server, there is a risk that the network packets coming from the NTP server will take a lot of time to reach that node, and insane results will appear within our sanity check routine with no reason. The CERN site is well stocked with NTP servers, but the same is not true in LNGS. The optimal solution is to equip the GPSDO used for PPS and 10 MHz outputs with a special add-on card implementing NTP server functionality. In this case, there is no risk of incoherent results and there is the additional bonus of physical proximity between the NTP server and its client.

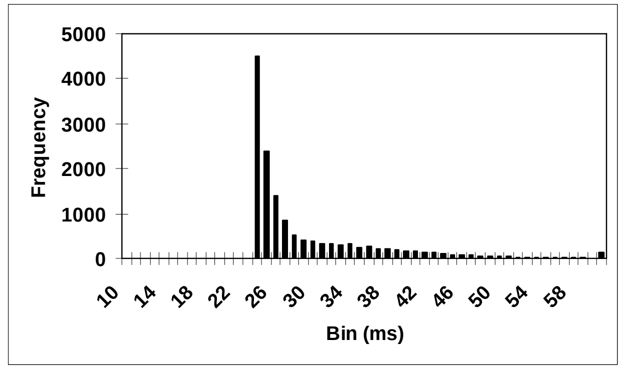

Figure 2: Histogram showing typical round trip delay times for UDP packets between CERN and LNGS.

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REFERENCES

[1] J. Levine, “Introduction to time and frequency metrology”, Review of Scientific Instruments, volume 70, number 6, June 1999.

[2] J. Levine, “Time and frequency distribution using satellites”, Reports on Progress in Physics, 65 (2002) 1119-1164.