

GNSS and atomic clock solutions for Hyper-Kamiokande experiment

The IN2P3-CEA group is elaborating a proposal for the time synchronization and clock distribution of the Hyper-Kamiokande (HK) experiment. The system is composed by two main parts: the synchronization of all the local electronics modules to a local time base and the correlation of this time base with the Coordinated Universal Time (UTC).

This document describes the possible solutions to address the creation of a very stable and precise local time base and its synchronization with UTC.

The requirements needed for this work are:

- Stability of the local time base in terms of total jitter and time drift,
- Correlation accuracy between the local time base and UTC.

At the present time, these requirements are not clearly established so only a problem analysis and a survey of possible solutions can be done. The final choice of the architecture and its components will be done when all the constraints will be established.

Here are the elements known at the present time mostly based on the different interactions had with the colleagues of the SYRTE lab in Paris.

The local time base:

The local time base has to be a very precise and very stable local oscillator. It generates a low-frequency cadence that will be used to form the 125 MHz clock distributed to all the electronics modules and help the GNSS receiver stability. The only requirement available for the moment is that the total jitter on any electronics module 125 MHz clock has to be smaller than 100 ps rms so the goal is to have a source that adds a negligible contribution to it. The natural choice would be an atomic clock that generates a cadence of 10 MHz and a Pulse Per Second (PPS). The jitter characteristics of high-end devices are in the order of 10^{-13} s (for the rubidium passives) or 10^{-14} s (for the **active Masers or Hydrogen?**) and their prices seem to be around 60 Keuros to 200 Keuros. The less expensive clocks (at 60 Keuros) could have good jitter performances but could suffer of a slow drift in the medium/long term (**10 years or less?**). This effect consists of a lack of precision that slowly develops. It is not guaranteed to be always on the same direction and is difficult to predict quantitatively. The only effective way to measure it is to have 2 atomic clocks side by side and constantly track the difference between them. A system like that is very precise and reliable but is expensive. Moreover, tracking the drift, is only needed for the correlation of the local time base to the UTC and has no impact on the local modules' synchronization. This is because all the modules will always see a clock generated by the same source hence their local time will all change by the same quantity.

Another (potentially less expensive) way to mitigate this drift is to perform periodic comparisons with another calibrated clock shipped to Japan every couple of years. This type of calibration would only correct long-term drifts. The amount of time between two calibrations should be estimated depending on the expected drift of each device.

It could be worth to explore the following points:

- Would it be possible to find cheaper atomic clocks that still satisfy the HK requirements?
- How large is the rubidium clock's drift and how fast it develops? Can it be measured only once in a while by a portable time station used to calibrate the entire system?

The generation of 125 MHz clock:

Another critical point for the local time distribution is the frequency multiplication of the clock generated by the local source up to the frequency needed for the experiment (125 MHz). In the effort of minimizing the final clock noise, one element is critical: the noise is added only when a frequency is multiplied and not when is divided. This implies that the number of multiplications has to be minimized so, a possible architecture could be to multiply the 10 MHz from the atomic clock to a high frequency (1 GHz for example) and then use it to generate the 125 MHz. The choice of 1 GHz is practical because it's easily dividable to 125 MHz (it is 8 time faster) and is commonly used in many applications so the components to generate it are easily accessible.

The multiplication from 10 MHz to 1 GHz is actually done starting from an independent 1 GHz oscillator, dividing its output to 10 MHz, comparing it to the atomic clock out and reporting the differences to the first oscillator. More details about this technique are needed.

Here are the open points:

- How the actual division and comparison between the 1 GHz and 10 MHz is done?
- How the difference is reported to 1 GHz?
- How to divide the clock by eight without adding noise?
- Is the PPS generated by the atomic clock?

The correlation with UTC:

Once the local time base is created it has to be correlated to the UTC in order to:

- Associate each acquired event with a universal time to then correlate it with other experiments;
- "Trigger" the far detector's acquisition with the particles bunch generated by the accelerator.

Each electronics board will receive the clock and the PPS plus a message from an NTP (Network Time Protocol) server for the date and time. Using the local clock, it will be able to interpolate the PPS at steps of 8 ns ($1/125$ MHz) so to have a time stamp with a resolution of 8 ns. Clearly, the accuracy of the received PPS with respect to the UTC is related to the accuracy of the generated time stamp.

This correlation is achieved using the global positioning satellites constellations. The most-known and used constellation is now the GPS but others are in development so, in the document, the generic term GNSS (Global Navigation Satellite System) is used. The concept of the global positioning is based on the time. Each user can achieve its position receiving the UTC time from 4 (if only 3 are available, it is still possible to get a position and time by assuming the device is at the sea level) or more satellites whose position is known with good accuracy. This concept can then be exploited also to get the UTC.

The time accuracy depends on different factors like the perturbations on the received signals (reflections, effect of the atmosphere, etc.), the number of satellites "seen" by the device, the knowledge of the satellite positions and others. Some of them can be corrected using

high-end equipment, some others can be eliminated manipulating the received data while some others are impossible to correct and will force the constraints relaxation.

Clearly a lower accuracy of the local PPS to the UTC will be reflected to an incertitude on the event time tagging at the far detector and “beam trigger” from the J-PARC accelerator or any other kind of trigger (including other experiments and observatories). This last aspect could be mitigated by using the common view technique. It consists in forcing the two GNSS receiving systems, at the accelerator and at the far detector, to lock on the same satellites. By means of specific software algorithms a higher synchronization accuracy can be reached.

Here are the open points related to the UTC correlation:

- Which GNSS receiver is needed? Is it worth to get the state of the art or a less expensive solution is enough?
- The far detector site orography is crucial for the system accuracy because it constrains the GNSS antenna position and the possibility to develop the common view technique. Do we know the orography?
- What are the elements that concur to the total time stamp incertitude beside the electronics (PMT Transit Time Spread etc.)?