Precise clock generation for the Hyper-Kamiokande experiment

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Abstract

This document describes the time generation system designed for the Hyper-Kamiokande experiment in Japan. This next-generation long-baseline neutrino oscillation experiment detects neutrinos in a 188 kton fiducial-volume Water Cherenkov detector equipped with more than 20,000 20-inch PMTs. In order to precisely reconstruct neutrino interaction vertex in the water and provide an UTC time stamp, this system relies on a set of atomic clock and Global Navigation Satellite System antennas to produce a stable and accurate timebase for this experiment.

In this document, we will briefly introduce the HK detector, the timing and synchronization requirements, and the considered design. The development of this architecture is a joint work between LPNHE and SYRTE.

1 Introduction

Hyper-Kamiokande (HK) is a next-generation LBL-ν experiment in Japan that aims at providing exquisite constraints on CP violation in the leptonic sector along with precise measurements of the oscillation parameters using the neutrino beam produced by the J-PARC accelerator complex. The HK experimental program is very rich, covering fundamental particle physics including the measurement of proton decay or search for sterile neutrinos, multi-messenger astrophysics with the detection of core-collapse supernovae and other cosmic particle accelerators, and solar physics by measuring low-energy neutrinos produced by the Sun. The HK experiment is building on the experience accumulated over the last 2 decades with the Super-Kamiokande (SK) and Tokai-To-Kamioka (T2K) experiment in Japan. One of the major components of this program is the construction of a new large-scale water Cherenkov neutrino detector in the Kamioka mines. As depicted in Figure 1, this new far detector called Hyper-Kamiokande of 250 ktons of pure water will have a fiducial volume 8 times larger than the current Super-Kamiokande detector and will be instrumented with at least 20,000 20-inch photomultiplier tubes from Hamamatsu (R12860HQE).

To guarantee the full success of the HK experiment, key components of the far detector need to be carefully designed and produced, such as the time synchronization and clock distribution system to the photo-sensors. Indeed, the reconstruction of Cherenkov rings induced by charged particles relies on the accurate timing of the photon arrival at each detector's PMT and have to be correlated to the absolute time on Earth. When looking at the reconstruction of a single event, any timing bias between subsets of PMTs will lead to misreconstruction of the vertex position.

To guarantee the most stable and precise reference, the local timebase originates in an atomic clock and a GNSS (Global Navigation Satellite System) station working together to generate a Pulse Per Second (PPS) and a 10 MHz signals which are synthesized in the master clock generator (MCLK Gen) to produce a 125 MHz output. This frequency is then distributed over different branches and delivered to more than 1,000 electronic front-end modules that can read out up to 40,000 20-inch PMTs and about 5,000 mPMTs, as shown in Figure 2. The PPS and the 10 MHz signal, along with satellite information, reach also a computer

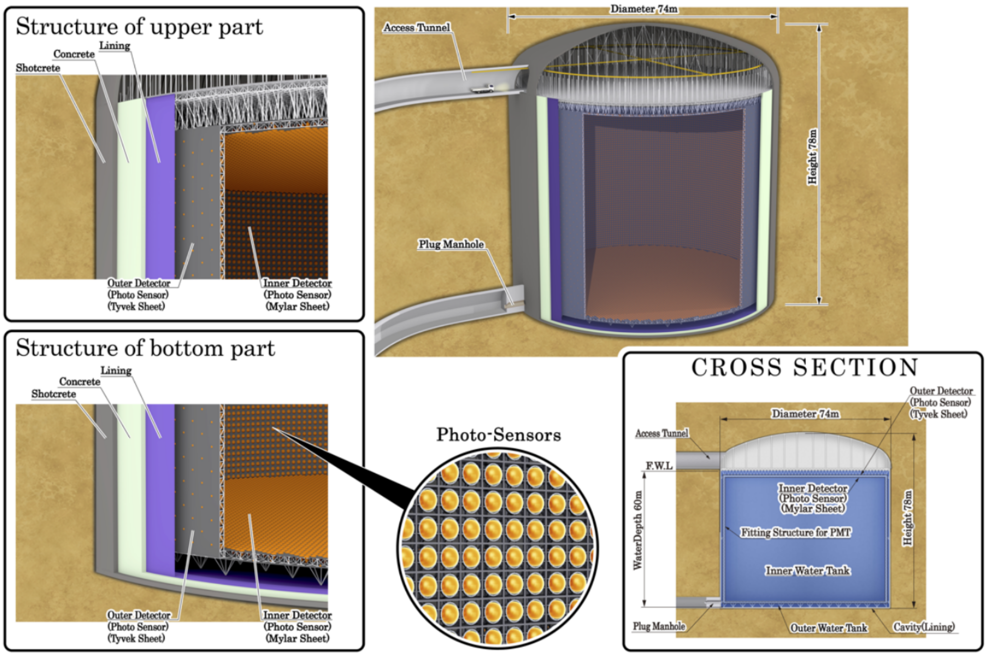

Figure 1: Layout of the Hyper-Kamiokande far detector.

infrastructure to form the UTC time synchronous with the local timebase and, from there, propagated to all the elements in the form of data packets.

For the development of such time synchronization system, the LPNHE Neutrino group is working closely with the laboratory SYstèmes de Référence Temps-Espace (SYRTE) at the Observatoire de Paris (OP). SYRTE is the designated laboratory by the French National Metrology Institute (NMI) Laboratoire National de Métrologie et d'Essais (LNE) for Time and Frequency metrology activities. Among other missions, LNE-SYRTE is operating Primary and Secondary Frequency Standards which realize the SI second definition, and generates UTC(OP), a real-time realization of the Co-ordinated Universal Time UTC, which is the basis for legal time in France.

2 Clock generation

The cadence generator technology that guarantees the best performance is the atomic clocks but, on the market, there is a vast range of instruments with different noise, stability characteristics and prices. The technologies selected for Hyper-Kamiokande are the Passive Hydrogen Maser (PHM) (microwave amplification by stimulated emission of radiation) and the Rubidium (Rb) standard which provide a 10 MHz clock and a PPS with characteristics summarized in Table 1.

technology	Passive Hydrogen Maser	Rubidium
Frequency stability	$\sim 5 \times 10^{-13}$ @ 1 s	$\sim 2 \times 10^{-11}$ @ 1 s
equivalent jitter	0.5 ps	20 ps
Frequency drift	$\sim 5 \times 10^{-15}$ @ 1 day	$\sim 1.6 \times 10^{-12}$ @ 1 day

Table 1: Passive Hydrogen Maser and Rubidium atomic clock characteristics.

As evident from the Table 1, much better performance that go up to 2 orders of magnitude is obtained with a H-maser with respect to a Rb clock, both at short and long analysis periods. A more visual comparison involving Allan Standard Deviation (ADEV) [1] can be found in Figure 3. The analysis periods for which the curves are minimal indicates an asymptotic behavior between the short term white noise modulation and the long-term frequency drifts. This is providing the period for which it is useful to consider a system to monitor

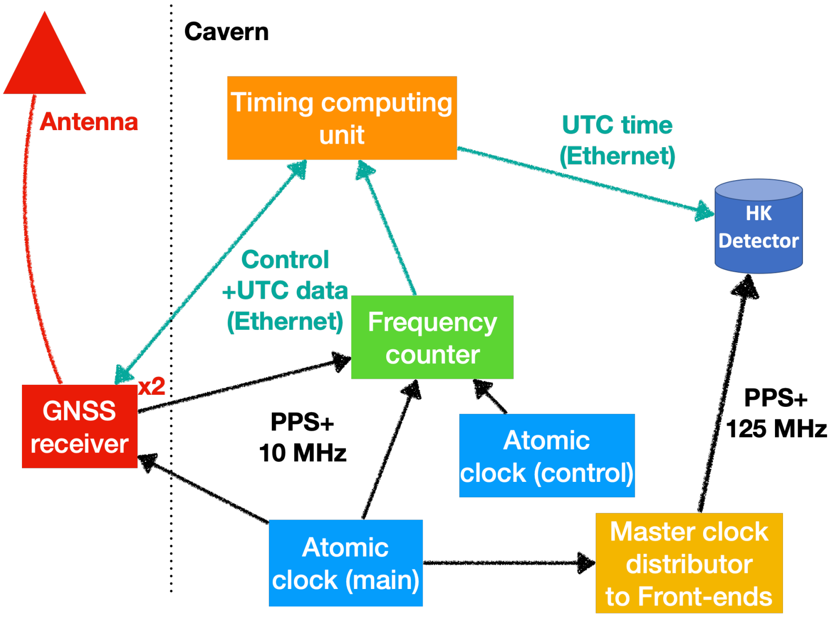

Figure 2: Detailed scheme of the clock generation section.

and correct for these drifts. The improved performances of the PHM compared with the Rb clock would allow to correct for the drift every day instead of every five hours, making the system more robust against failures.

The system represented on Figure 2 depicts a set of two atomic clocks used to produce the 10 MHz clock and PPS signals. Such redundancy is necessary in order to recover from potential hardware failures on one of the two clocks and assure minimum dead time. In addition, having two clocks would allow also a continuous comparison between them to detect possible temporary malfunction or frequency drifts. Indeed, using frequency comparators on the two clocks would allow to detect whether one of the clocks is drifting in time or having sudden instabilities[1]. The candidate instrument to perform this task is the Keysight 5323A frequency counter [3] which measures the two inputs time distance periodically and saves data to a file, allowing offline timing corrections in the event reconstruction.

To mitigate the medium and long term instabilities, the atomic clock output will work in conjunction with a GNSS receiver (see Section 3) so that the time information from the satellites will be used to identify and correct the drifts by means of a continuous frequency comparison. This check will allow also a continuous comparison between the local generated time scale and the broadcast UTC parameter provided by the GNSS to know exactly the relationship between them. As evident from the scheme in Fig. 2, the 125 MHz clock will be generated from the local atomic clock source and the GNSS data will be solely used to accord it with the broadcast UTC. This is the most effective scheme for a detector like Hyper-Kamiokande because the event reconstruction relies mostly on the short term clock stability while the UTC time tagging will be used to date an interesting event and to label the neutrino interactions generated by the particles accelerated at J-PARC as explained below.

3 Synchronization with UTC

As already mentioned, the GNSS station will also be used to correlate the local timebase with the broadcast UTC by means of the information included in their data stream. To guarantee an accuracy at the level of 50 ns or better, many parameters must be taken under control and corrected, if needed. Some of them are related to the satellite ephemeris or to the satellite clock offsets against the GNSS time scale as broadcast by the GNSS navigation message, which must be corrected by using data from another source. Some other elements are relative to the receiver and concern the electromagnetic signal that reach the antenna, the potential interference and multi-paths. But the largest part is the determination, within an uncertainty consistent with the requirements, of the hardware delays of all three elements of a GNSS station, that is the antenna,

[1]Actually, a third atomic clock would be required in order to detect which one of the clocks is experiencing instabilities.

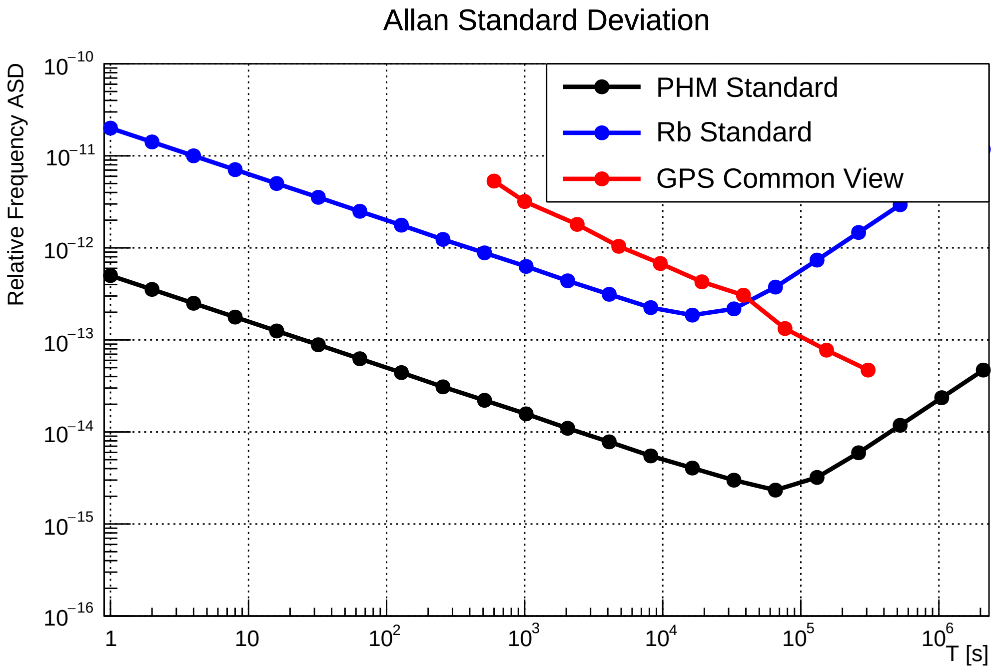

Figure 3: Relative frequency Allan Standard Deviation of the two selected clock generation systems and the GPS Single View [2].

the cable between the antenna and the main unit, and the receiver main unit. To improve the first kind of uncertainty, the current common GNSS processing technique [4] includes the use of products provided by the International GNSS Service (IGS), based on data collected from a network of numerous GNSS geodetic Earth stations located all over the world, OP being part of it correction's algorithms will be implemented on the received data by means of a computer infrastructure that elaborates information coming from the UTC consortium. The uncertainty related to the hardware delays of the local equipment can be mitigated by performing an accurate calibration of the receiver, the associated antenna and the connection cable. There are two techniques to achieve such a calibration. Either an absolute calibration of each element separately, which requires instruments like a Vector Network Analyzer and a GNSS signal simulator, which might prove very expensive and not easy to operate for such a purpose [5] or a station relative calibration against another station included in the UTC network, by using a traveling GNSS station visiting both HK fixed stations. LNE-SYRTE is one leading laboratory in this second domain [6], and is part of the UTC network relatively calibrated every two years by BIPM (Bureau International des Poids et Mesures), the institution that computes UTC monthly.

To reduce the data post-processing and to reach the best possible uncertainty, a crucial role is played by the GNSS receiver, and its antenna position which is a non-trivial aspect in Hyper-Kamiokande. The far detector's electronics will be hosted in a cavern where the satellites signal cannot be received and the atomic clocks will also be placed there in order to minimize the local timebase uncertainty. The GNSS equipment will be placed at the cavern's entrance several kilometers away, in a position that maximizes the signal reception characteristics, and the signals exchanged by the two elements have to travel over a very long optical fibre without loosing their synchronicity characteristics. To build this link, the same technologies proposed for the time distribution module (described below) will be used.

The events generated by the particles packets sent by the J-PARC accelerator must be identified and separated from the noise and astrophysical events. A specific acquisition's window must be opened for each event; however a direct "trigger" signal cannot be sent due to the distance between the accelerator and the far detector. The most effective solution to this problem is the so-called "common view" technique where the two sites are both equipped with a GNSS receiver locked on the same satellites at the same epoch. The effectiveness of this method is related to the number of satellites "seen" by both sides at the same time allowing for a computation of a mean value averaging out outliers [7]. This could be a limiting factor in this case since the far detector's receiver will be installed in a valley surrounded by mountains that narrow the antenna "field of view". To mitigate these limitations multi-constellation receivers will be used so that the number of the available sources will be not limited only to the American GPS (Global Positioning System) but will also include also the European Galileo, and the Japanese QZSS (Quasi-Zenith Satellite System), even if the data processing for the last two constellations remains to be developed today.

A data collection campaign will be performed, with a portable GNSS station, at the far detector site well ahead of the detector deployment. This test will be useful to establish the best final antenna position and to check the number of common satellites available between both the near and far detectors sites. The data collected will determine also the entity of the post-processing needed to achieve the experimental requirements. The portable equipment, made of the same elements installed at the far detector site, will also be helpful during the regular data acquisition to check the resident infrastructure and measure the relationship to UTC. This experiment would also be a preparation for the future relative calibration campaigns, which could be organized every 5 years or so later on, depending on the uncertainty obtained and on the long term stability of such an implementation.

An R&D study has already started in order to define the off-the-shelf equipment to be used in HK and the Septentrio PolaRx5 multi-frequency multi-constellation timing/reference receiver associated with a multi-frequency B3E6 choke ring antenna have been selected [8, 9].

The same reliability considerations described for the atomic clocks are valid also of the GNSS equipments so a minimum set of 2 receivers and 2 antennas will be installed at the Hyper-Kamiokande far detector site and continuously monitored to guarantee that at least 1 functional set will be operational at any time.

4 Conclusions

The development of an accurate and stable timebase for the HK far detector involves the understanding on the performances of several key components, such as high-quality atomic clocks and GNSS receivers. The SYRTE laboratory at the Observatoire de Paris is one of the world-leaders in time and frequency metrology, with which the LPNHE is working closely to produce an accurate design that could be useful at IN2P3 for other (astro)particle physics experiments.

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