Timing in the NO$\nu$A detectors with atomic clock based time transfers between Fermilab, the Soudan mine and the NO$\nu$A Far detector.

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Abstract. The NO$\nu$A experiment uses a GPS based timing system both to internally synchronize the readout of the DAQ components and to establish an absolute wall clock reference which can be used to link the Fermilab accelerator complex with the neutrino flux that crosses the NO$\nu$A detectors. We describe the methods that were used during the commissioning of the NO$\nu$A DAQ and Timing systems to establish the synchronization between the Fermilab beam and the NO$\nu$A far detector. We present how high precision atomic clocks were trained and transported between the MINOS and NO$\nu$A detectors during a Northern Minnesota blizzard to validate the absolute time offsets of the experiments and make the first observation of beam neutrinos in the NO$\nu$A far detector.

1. Overview

The NO$\nu$A experiment is a long baseline neutrino oscillation experiment designed to measure both $\nu_e$ appearance and $\nu_\mu$ disappearance, for both neutrinos and anti-neutrinos, in order to determine the neutrino mass hierarchy, improve knowledge of the neutrino mixing structure and investigate the CP violating phase $\delta_{CP}$ of the PMNS mixing matrix.

The NO$\nu$A experiment[1] uses a near/far detector setup where each of the NO$\nu$A detector has a functionally identical design, differing only in total size and location where they have been sited. The 300 ton near detector has been situated 100 m underground approximately 1km from the primary target station at a position 14 mrad off the beam. In this position it is able to measure the neutrino flux prior to oscillations and perform measurements of the beam composition and determine the energy spectra for each of the beam components. The massive 14 kt far detector is located in Ash River Minnesota, approximately 810 km from the primary target station and 14 mrads off of the primary beam axis. In this position the detector sees a neutrino flux resulting from the 120 GeV NuMI beamline that is centered around an energy of approximately 2 GeV and narrow in spread due to off-axis decay kinematics of the parent pions.

Observation of the first neutrino interaction in the NO$\nu$A detectors required that the hit information recorded by each detector and the spill information that was generated by the

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[1] Neutrinos at the Main Injector
accelerator complex be precisely correlated and that the systems that were used to perform these correlations be precisely calibrated and verified.

2. NOνA Timing System

The NOνA experiment relies on a sophisticated timing system[2] for two critical aspects of the detector’s operation and data taking, internal detector readout synchronization and site to site time alignment. Each detector is outfitted with two independent timing system “master” distribution units and two corresponding chains of “slave” timing units. The master/slave backbone provides a chain of signal repeaters which propagate timing commands, clock signals and synchronization pulses. This chain uses a loop-back topology to measure the internal delays between repeater points and between detector electronic targets that are receiving the clock and command signals. The calculated delays are then used in the repeater chain propagate the synchronization information down to the front end electronics that digitize the photodetectors attached to each detector cell, as well as the acquisition electronics that aggregate the data from the front end boards[3]. Using this chain of precision delays, each of the more than 12,000 custom electronics systems are internally synchronized to better than 16 ns of each other across the detector, as shown in Fig. 1. The combination of the timing synchronization and multi-point waveform readout of each of the detector cells then allows for the determination of an absolute “wall clock” time stamp of each signal in the detector with a single hit timing resolution of better than 20 ns over almost the full dynamic range of the readout, as shown in Fig. 2.

The correlation and alignment of timing systems between detectors sites is performed by linking each of the master timing distribution units located at each detector to a GPS antenna and receiver. The GPS receiver is then required to obtain a 3-dimensional lock to the GPS constellations that are visible at its location and from that lock produce the required reference information that is needed to drive the NOνA timing system. In particular the GPS receiver provides a stable 10 MHz reference clock which is used through a PLL to derive the 128 MHz

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2 Avalanche Photo Diodes

3 The timing system operates at a base clock frequency of 128 MHz and performs delay calibration and synchronization at a resolution of 64 MHz corresponding to a 1/4 clock cycle of the 16 MHz digitization clock that is used for the far detector readout.

4 Global Positioning System

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Figure 1. Relative errors in the calibrated offsets of each of the 168 far detector data concentrator modules (DCMs) in the NOνA readout chain.

Figure 2. Single hit timing resolutions for hits in the NOνA far detector for multi-point waveform readouts as a function of the signal size measured in photoelectrons.
base clock that governs the NOνA timing system, as well as the lower frequency reference clock for digitization that is distributed to the front end electronics. The GPS system also provides an ultra stable 1 pulse per second reference signal that is align to the one second boundaries of the GPS time standard and NMEA5 data to correlate the 1 pps output with the standard. From the 10 MHz and 1 pps references, the NOνA timing system derives the “NOνA time standard” which is a 56 bit timestamp at an LSB resolution of 15.6 ns (64 MHz) and a starting epoch of January 1, 2010 at 00:00:00. The NOνA time base is align to the same one second boundaries as GPS. All of the readout electronics used in NOνA implement a timestamp counter using this time standard and record their data along with this timestamp information. This provides an absolute “wall clock” time for every hit and accelerator event that can be used to compare information taken in different locations or with different equipment.

3. Synchronizing with the Neutrino Beam
The NuMI neutrino beam provides short 10 $\mu$s wide extraction pulses at a repetition rate of approximately 1.33 s. The exact time structure and repetition rate of the beam can vary from super cycle to super cycle based on the current accelerator time line and mode of operation. As a result, the actual delivery time of the NuMI extraction pulses can not be apriori determined by the NOνA experiment based on previous extraction pulses. This means that NOνA does not implement a “predictive” trigger scheme where the time of the next spill is determined and the detector’s readout triggered, but rather uses a continuous readout of the detectors with a “buffer and hold” model that allows for asynchronous extraction of the detector readout information after the actual time window of the beam spill has been determined. Spill information is then sent to the far detector site over a wide area network connection6 where it is received and triggers the extraction of the corresponding data to disk. With the current operational parameters of the NOνA far detector, the data acquisition system can buffer in excess of 7 minutes of full detector data and the beam spill information can arrive at any time prior this expiration and cause a valid trigger event. Inherent to this scheme is the notion that the beam spill information can be precisely correlated with the time window at which the neutrinos from the beam cross the physical detectors.

The NOνA experiment uses as its beam extraction reference the time, $t_0$, the time at which the Main Injector Synchronous Beam Clock (MIBs) event number “$74$” (corresponding to the firing of the extraction kicker magnet for the NuMI beam line) is received by a master timing system located in the MINOS surface building at Fermilab. The reception of this accelerator signal and its corresponding Tevatron Clock (TCLK) signal “$A9$” are time stamped by the master timing unit in the high precision NOνA time base. Knowledge of the paths that the clock signals travel, the delays along these paths and the flight paths of the NuMI neutrinos, allowed for an a priori calculation that the neutrino flux would cross the NOνA near detector 217.6 $\mu$s after the event’s $t_0$.

The proximity of the NOνA near detector to the primary target station and it’s siting underground with 100 m of overburden, allow for the beam induced activity in the detector to be easily recognized against the low background activity rates that are seen outside the beam window. This allowed for the offset between $t_0$ and the beam crossing to be easily verified as, shown in Fig. 3, after approximately 8 hours of near detector running.

4. Neutrino Flight Path and Time
The a priori prediction for the beam crossing of the far detect was performed by calculating the neutrino flight path to the far detector. The flight path was determined through geolocation of

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5 National Marine Electronics Association
6 Pseudo-wire connection implemented on top of ESNET and commercial internet service provide networks
Figure 3. NOνA near detector beam profile as a function of the time $\Delta t$ between the trigger time $t_0$ and the time of the observed hits in the detector. Beam crossing was initially computed to occur 217.6 $\mu$s after the trigger time $t_0$. The 6 batch structure of the extracted NuMI beam is evident.

Table 1. GPS coordinates of NOνA detectors used for flight path calculations along with the vertical offset between the antena position and the physical detector position.

| Location            | Latitude       | Longitude       | Altitude (m) | z Offset (m) |
|---------------------|----------------|----------------|--------------|--------------|
| Ash River Ant-1     | 48 d 22.715780°| 92 d 49.876930 | 348          | 19.8         |
| Ash River Ant-2     | 48 d 22.715780°| 92 d 49.876930 | 348.638      | 19.8         |
| Ash River Ant-3     | 48 d 22.716416°| 92 d 49.877639 | 350.346      | 19.8         |
| Fermilab Ant-1      | 41 d 50 m 23 s | 88 d 16 m 13 s | 228          | 120          |

The detectors via three independent GPS receivers at the far detector site and two independent receivers at Fermilab. This position information is shown in table 1.

This information was then used to compute the distance between the locations under the WGS84 Earth model with the parameters:

\[
R_a = 6378137 \text{ m} \tag{1}
\]
\[
R_b = 6356752.31424518 \text{ m} \tag{2}
\]
\[
\epsilon_a = \sqrt{R_a^2 - R_b^2} / R_a \tag{3}
\]
\[
\epsilon_b = \sqrt{R_a^2 - R_b^2} / R_a \tag{4}
\]

and the prescription for transforming from the GPS reported ($\theta$, $\phi$, $A$) coordinates into the Earth centered fixed (ECF) coordinates $(p_x, p_y, p_z)$. 

\[ R_{\text{curv}}(\theta) = \frac{a}{\sqrt{1 - \epsilon^2 \sin^2 \theta}} \quad (5) \]
\[ p_x = (R_{\text{curv}}(\theta) + A) \cos \theta \cos \phi \quad (6) \]
\[ p_y = (R_{\text{curv}}(\theta) + A) \cos \theta \sin \phi \quad (7) \]
\[ p_z = \frac{R_b^2}{R_a^2} (R_{\text{curv}}(\theta) + A) \sin \theta \quad (8) \]

In the case of the path length between the FNAL and Ash River timing stations the path length is taken by comparing the distance between the ECF coordinates of far detector and the NO\(\nu\)A/Minos service building position (offset to the beam depth and detector cavern).

\[ \Delta L = \sqrt{\sum_i \left((p_i - \Delta p_i) - (p_i' - \Delta p_i')\right)^2} \quad (9) \]
\[ = 809,606 \text{ m} \quad (10) \]

The time of flight is then computed assuming the propagation of the beam at the speed of light

\[ \Delta t = \Delta L/c \quad (11) \]
\[ = 2700.56 \mu s \quad (12) \]

The resulting calculations yielded a neutrino flight path of 809,606 m between the detectors and a resulting time delta of 2700.56 \(\mu\)s between the beam crossings.

5. Atomic Clock Time Transfer, Soudan to Ash River

Verification of the beam crossing for the NO\(\nu\)A near detector was easy due to the low overall rates of activity that come from being underground and the high rate of neutrino induced activity during a beam spill. In contrast, verifying the time of the beam crossing for the NO\(\nu\)A far detector is extremely challenging due to the extremely high rate of cosmic ray activity that the detector sees due to its location on the surface and the extremely low rate of neutrino interactions being 14 mrad off the primary beam axis and being 810 km from the beam source at the 1\textsuperscript{st} oscillation maximum for the \(\nu_\mu\) to \(\nu_\tau\) transition. These combine to give an estimated rate for neutrino interactions in the far detector of approximately 0.1 neutrino interactions per kiloton per day (or approximately 1.4 neutrinos interactions per day for the full 14 kt far detector), as compared to the 180 kHz of cosmic ray activity. This made the approach of verifying the detector timing through measuring a rate excess in the predicted beam window impractical and risky due to the potential loss of data if the predictions were incorrect or if the timing systems at each site had an unaccounted for systematic shift in their time base.

Instead of using direct detection, NO\(\nu\)A used the Minos experiment as an intermediate point and performed at “time transfer” between the Soudan lab (Minos) and the Ash River lab (NO\(\nu\)A) to verify that the timing systems at all the sites were correctly aligned. This transfer was possible because the NO\(\nu\)A timing system that time stamps the beam at Fermilab could be directly compared to the Minos clock system and near detector also at Fermilab. From there, the time offset between the Minos near and Minos far detectors were known through direct observation of the neutrino beam at Soudan.

The timing system used at Soudan is based on cesium time standard, with a measured phase and drift relation to a GPS based time standard also established at Soudan. Carrying this time
Figure 4. Comparative measurement the 1pps outputs of both the TDU and Rb clock through a high precision time interval counter. The result is the phase difference between the clocks including all electronic delays that are propagated to the NO\(\nu\)A detector during synchronization. Measurement provides verification that the NO\(\nu\)A master clock phase is locked to the GPS receivers 1 s boundaries.

Figure 5. 1pps output of the trained Rb clock is fed into the TDU and time stamped by the FPGA circuitry of the TDU. Measurement determines the time difference between the timestamp of the input pulse and the GPS 1 second boundary times. Method removes delays associated with generating the TDUs 1pps outputs and associated 1 second boundary aligned synchronization reference pulse.

from Soudan to Ash River and then measuring its phase relation to the NO\(\nu\)A timing system would allow for a verification that the NO\(\nu\)A timing system was synchronized with the systems at Fermilab and that the predicted offset of the beam crossing with relation to the trigger time \(t_0\) was correct.

The transfer was performed by training a SRS FS725 rubidium clock to the master HP 5071A cesium clock for Minos. This training was initiated approximately 72 hours prior to the transfer and both stabilized the rubidium clock’s frequency and phase alignment to match the cesium standard. A rubidium clock was chosen for these measurements due to its portability and short term drift characteristics.

At the start of the time transfer the phase difference between the Minos cesium clock’s 1 pps and the Soudan GPS reference’s 1 pps were measured using an Agilent S3220A time interval counter. This phase difference was verified to be the same as the difference between the rubidium clock and the GPS reference. The rubidium clock was then transport 75 miles between Soudan and Ash River by automobile. The clock was kept continuously powered during the transport through an uninterruptible power supply with a battery capacity sufficient to power the clock during the drive.

Upon arriving at the Ash River lab the phase between the rubidium clock and each of the active NO\(\nu\)A timing system masters were measured using the time interval counter, as shown in Fig. 4, to determine offset and drift:

\[
\Delta t = (T_{NO\nu A} - RB_{Minos} + \delta_{drift})
\]  

(13)

Then as shown in Fig. 5, the 1 pps output of the rubidium clock was input into the master timing units and timestamped against the GPS derived NO\(\nu\)A time base. This was used to separately verify the offset to the GPS 1 second boundary and remove internal delays related to generation and propagation of the NO\(\nu\)A 1 pps reference pulses via:

\[
\Delta t' = (t_{NO\nu A(Rb pps)} - t_{GPS(1s)})
\]  

(14)

The combination of the methods shown in Fig. 4 and Fig. 5 allow for a full determination of the alignment phases of the NO\(\nu\)A timing distribution units (TDUs) with GPS at each site and in comparison to the Soudan lab. It also determines the systematic uncertainties associated
with the time stamping of the accelerator signals and with the continuous monitoring system that is used by NO\(\nu\)A to detect problems or errors in the operation of the timing chains.

After measurements of the phase offsets for all six TDUs at Ash River, the rubidium clock was again driven back to Soudan while remaining under continuous power. Upon arriving at Soudan, the phase between the rubidium clock and the cesium master and GPS reference at Soudan were again measured. These measurements were able to determine the total amount by which the rubidium clock had drifted during the course of time transfer when it was in transit and undisciplined by an external source. The drift was assumed to be linear over the course of the measurements with a slope of 0.01 ps/s. This drift rate was then used to correct the phase differences measured in the different NO\(\nu\)A timing system. The results of these drift corrected measurements are shown in Fig. 6.

From these measurements it was determined that the site-to-site phase difference between the NO\(\nu\)A timing system and the Soudan based timing systems was less than 16 ns and hence synchronized also with the NO\(\nu\)A timing system located at Fermilab.

6. Conclusions and Validation Through Neutrino Observation

The NO\(\nu\)A detector was determined to be fully timed in and aligned with the NuMI neutrino beam in February of 2014 after the verification of the absolute alignment of the NO\(\nu\)A far detector timing system with the timing system used at Fermilab to timestamp the beam spills. The detector entered physics operation in March of 2014 has accumulated a total exposure of \(2.4 \times 10^{21}\) PoT kt over the course of 12 months, as shown in Fig. 7.

This amount of exposure, when combined with full reconstruction and selection of candidate neutrino topologies in the far detector has demonstrated a clear excess of activity in the time region corresponding to the calculated time of the beam crossing at the far detector. This excess, shown in Fig. 8, is clear evidence that the NO\(\nu\)A detector has been correctly synchronized with the NuMI beam and that an absolute time reference has been established in a site-to-site manner for the NO\(\nu\)A detectors.
Figure 7. Integrated exposure of for the NOνA far detector for the period extending from March 2014-March 2015.

Figure 8. Observed time profile of candidate neutrino events observed at the NOA Far detector from March 2014-March 2015. The 6.5 σ excess seen in the spectrum corresponds to the time interval, corrected for ν flight times, electronic and signal propagation delays, of the predicted far detector beam crossing. Absolute scale suppressed.

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References
[1] Ayres D et al. 2007 The NOνA technical design report Tech. rep. FERMILAB-DESIGN-2007-01
[2] Norman A et al. 2012 J.Phys.Conf.Ser. 396 012034
[3] Niner E et al. 2014 J.Phys.Conf.Ser. 513 012028