Synchronization of the 14 kTon NOvA detector with the NuMI beam

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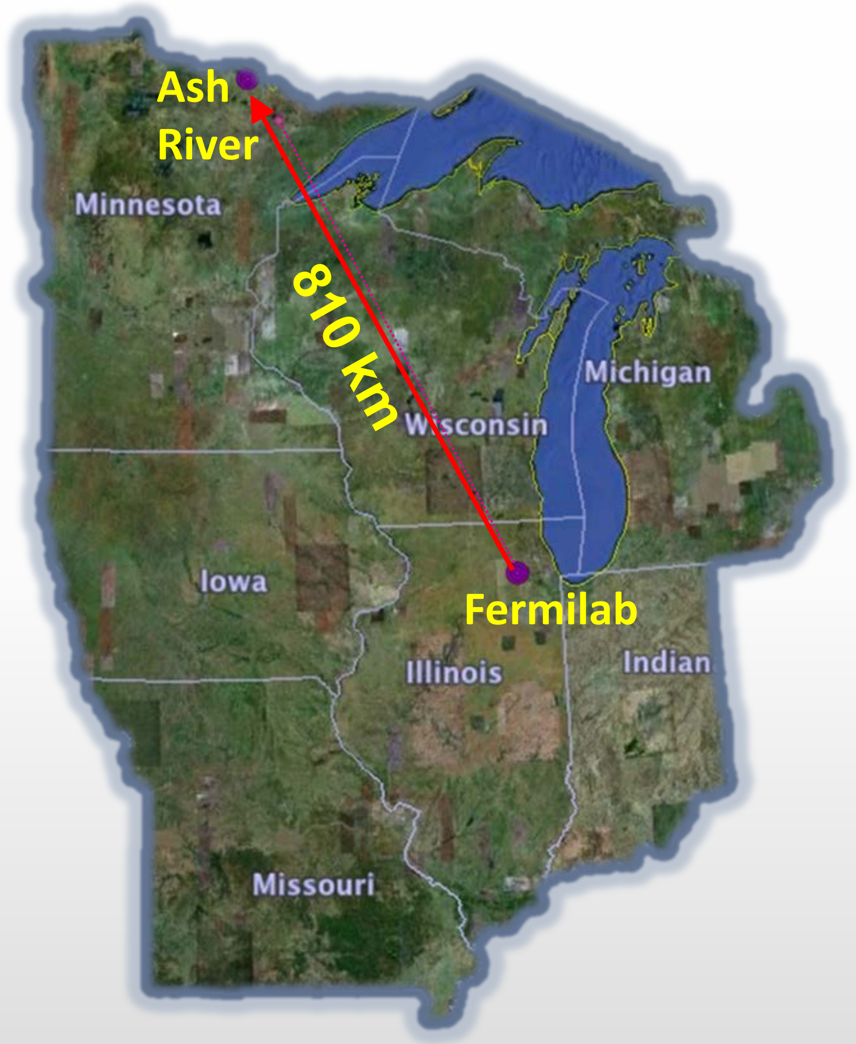
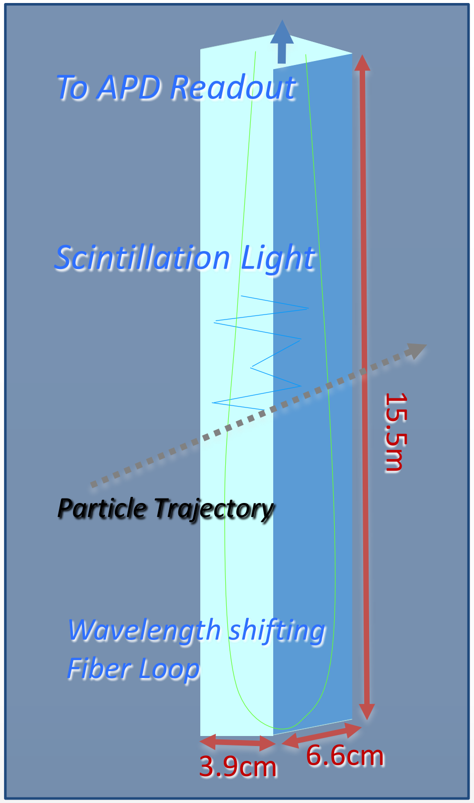
NOvA Overview

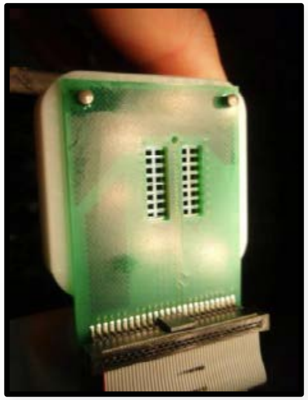
- A long-baseline neutrino oscillation experiment currently under construction and commissioning.
- NOvA uses a Near Detector at Fermilab and a Far Detector located 810 kilometers away in Ash River, MN placed 14 milliradians off-axis from the existing NuMI beam.
- The experiment will probe the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation channels to achieve a wide range of physics goals.

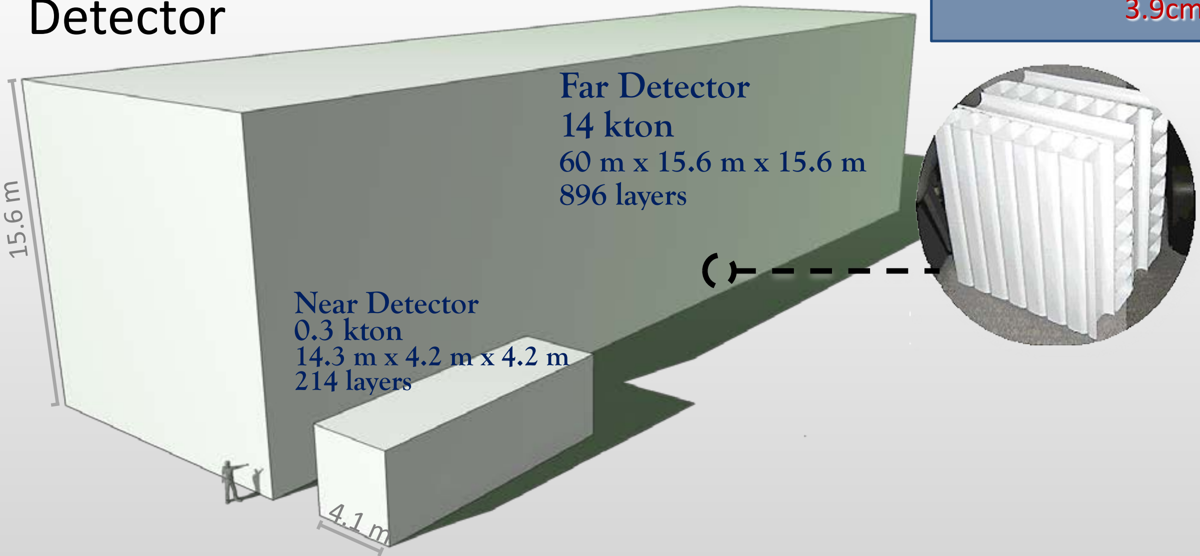


NOvA Detectors

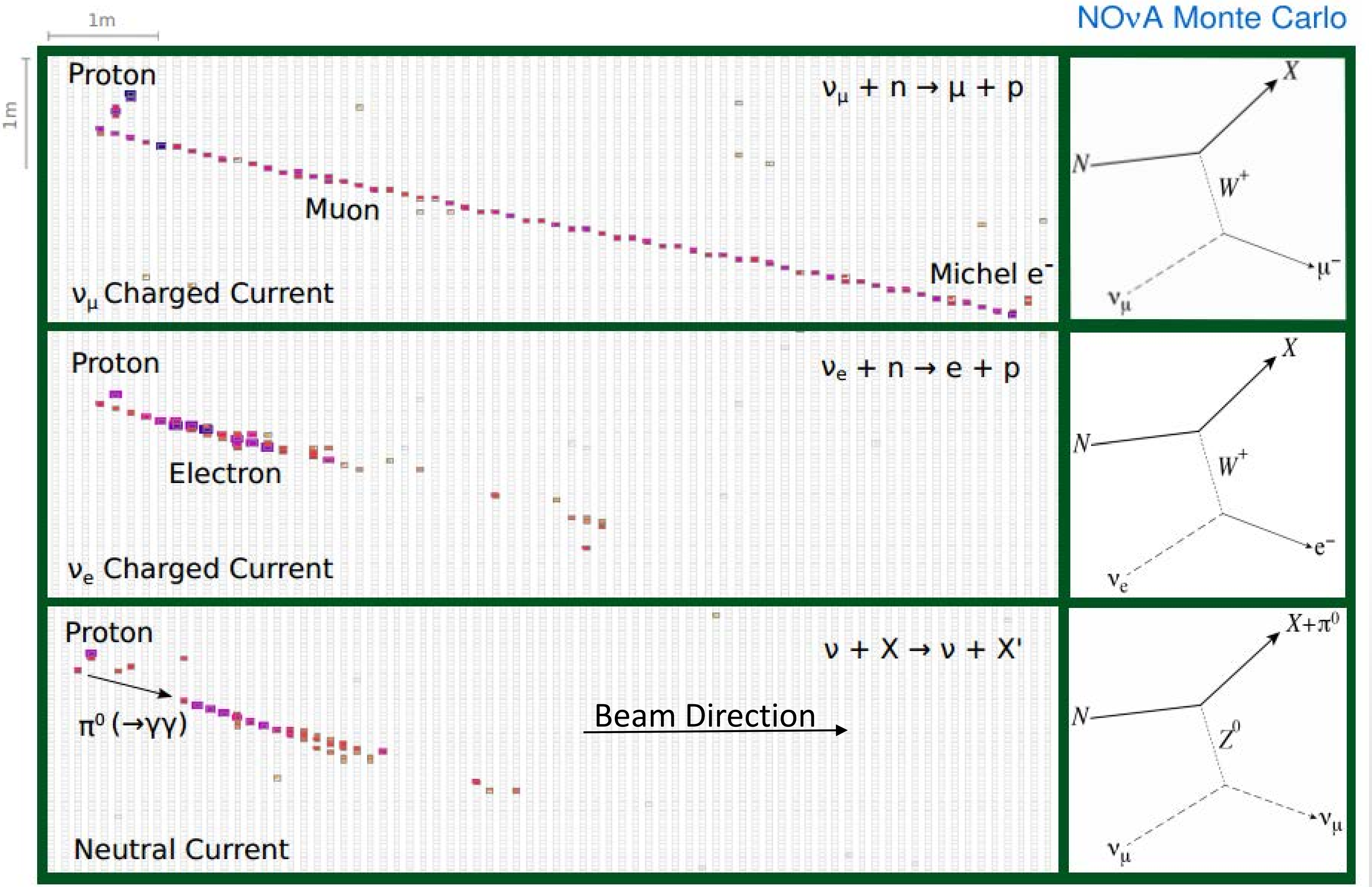
- Functionally identical, highly active Near and Far Detectors
- Composed of alternating horizontal and vertical PVC cells filled with liquid scintillator to provide 3D tracking and calorimetry
- 344,064 individual readout cells at Far Detector, 20,192 at Near Detector







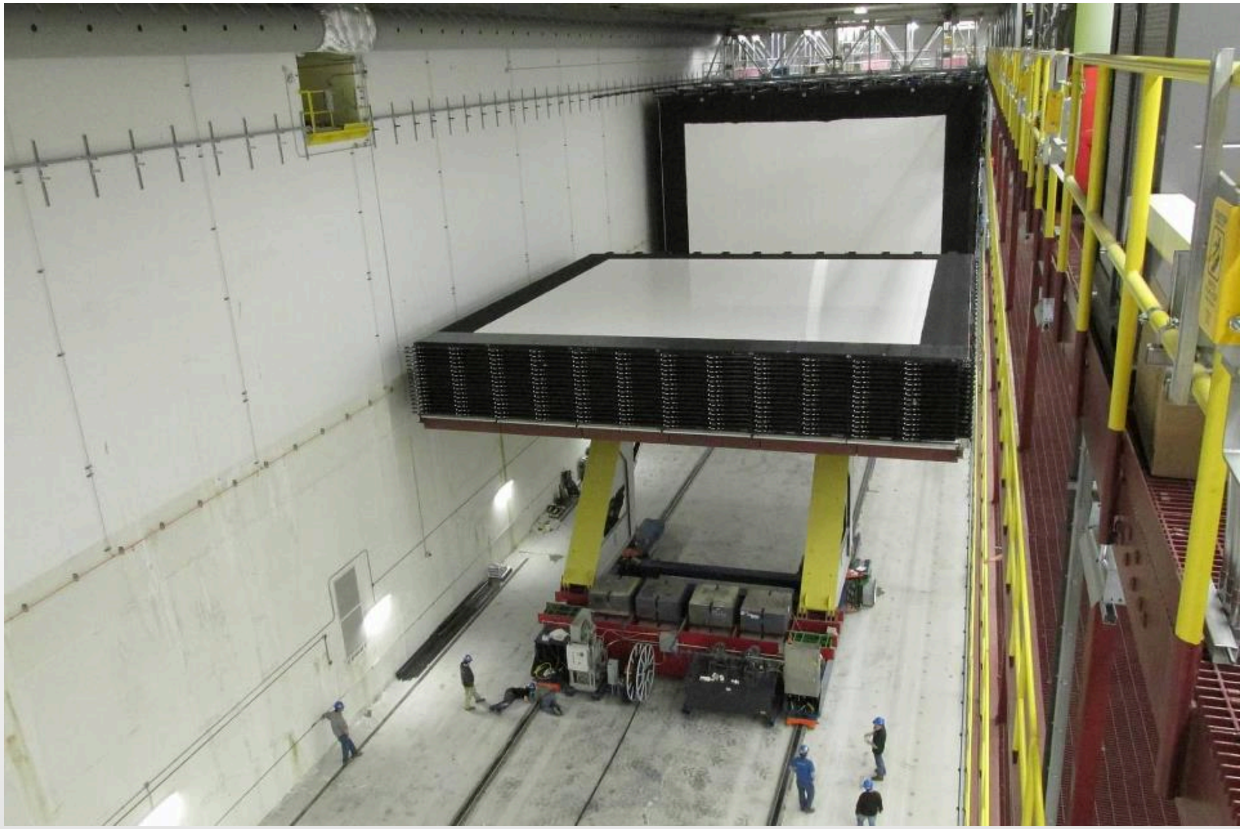
Each Avalanche photodiode (APD) reads out a 32 cell module on individual pixels. 12 modules compose a plane at the Far Detector.



Detector is finely grained and composed of low-z material to optimize separation of electrons from π^0 background. These displays show readout in only one detector view.

Project Status

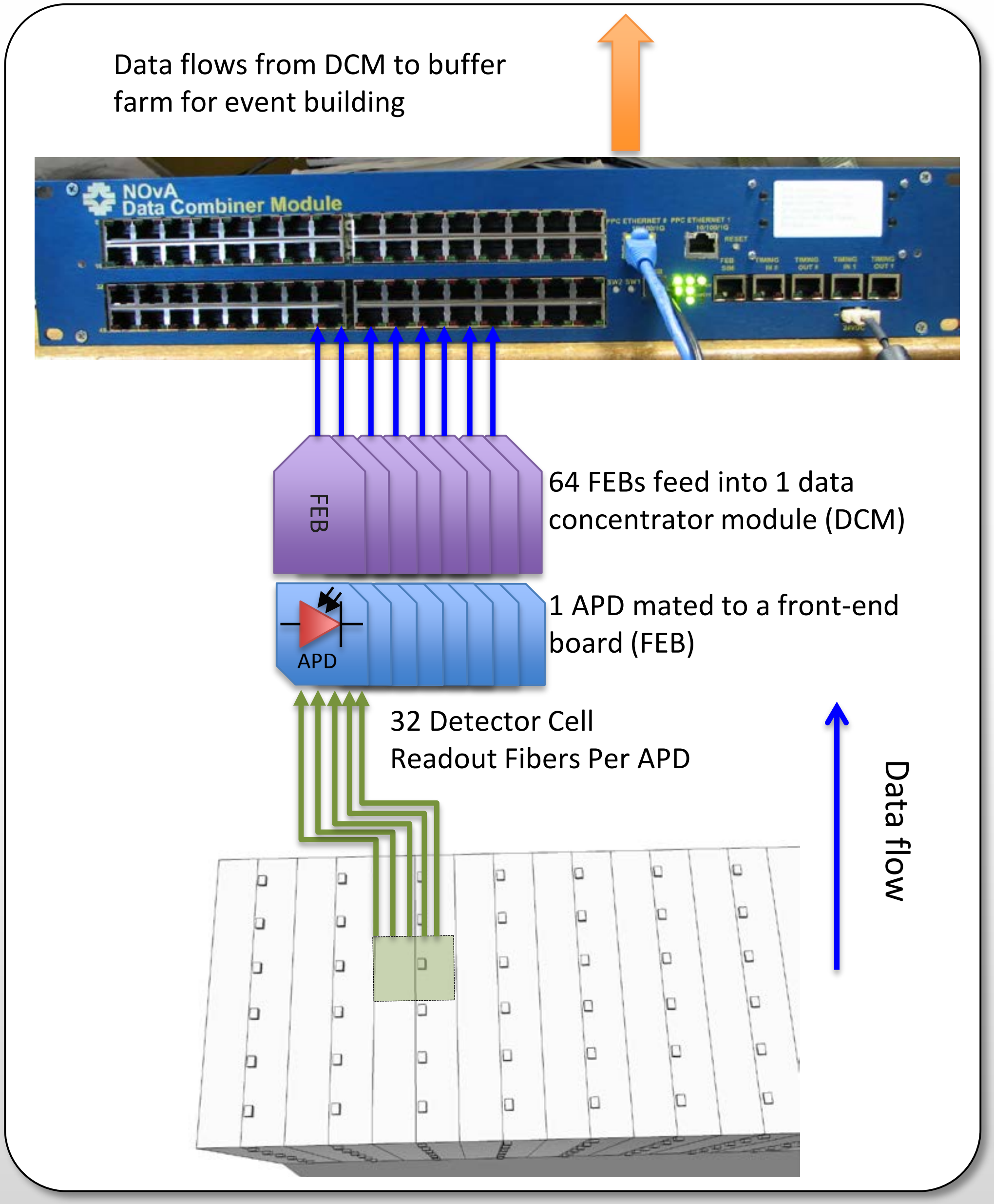
- First Far Detector block in place in September 2012. 20 of 28 completed now.
- 2 kilotons of detector are instrumented with APDs.
- Upgrades to NuMI beamline completed and operation began September 2013.
- Underground Near Detector under construction with completion early next year.



A completed detector block being moved into place at the Far Detector hall.

Data Flow

- Each kTon of detector is instrumented with 12 data concentrator modules (DCMs)
- 1-6 located on top of the detector, 7-12 on the side
- One DCM collects data from a region with 64 front-end boards (FEBs), 2048 cells



NOvA Timing Requirements

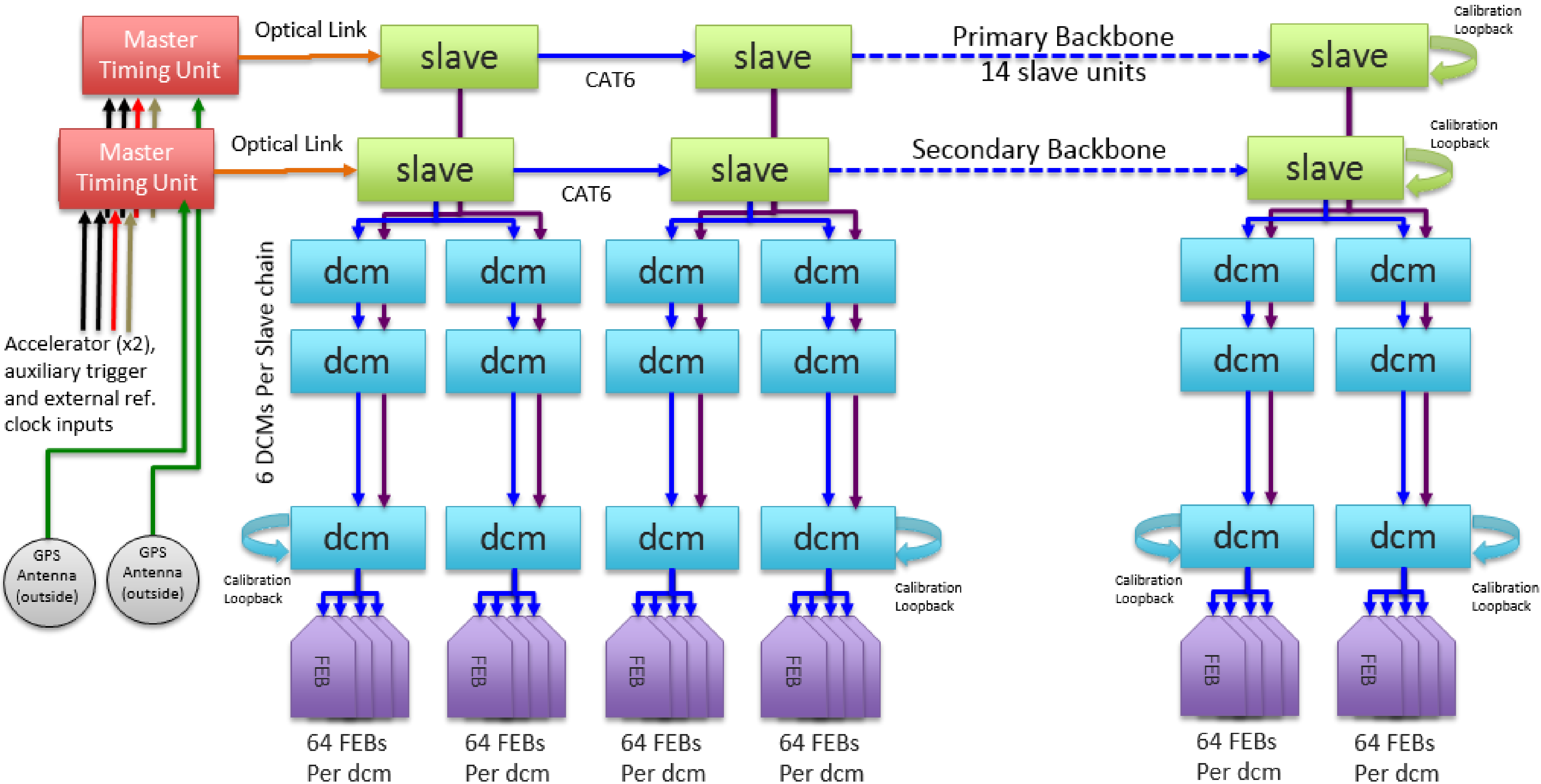
- To make the NOvA physics measurements, the arrival of the narrow 10 μs neutrino beam inside both the Near and Far Detector must be known to high precision.
- There is no way to predict the arrival of beam spill.
  - Absolute timing structure of accelerator super cycles varies depending on which experiments are running
  - No way to verify a spill until it has occurred (both the kicker fired and protons recorded on target).
- Must be able to synchronize 344,064 channels with better then 10 ns resolution to an absolute wall time.

Solution: Distributive Timing System

- Instrument every channel with a TDC.
- Globally synchronize every channel by distributing timing information from a master timing distribution unit (MTDU) connected to a GPS receiver.
- Readout the detector continuously and time stamp each hit in a deep buffer (planned operation is 20 s).
- MTDU takes accelerator inputs to time stamp beam spills.
- Pure software trigger to read events from buffer.

NOvA Timing Chain

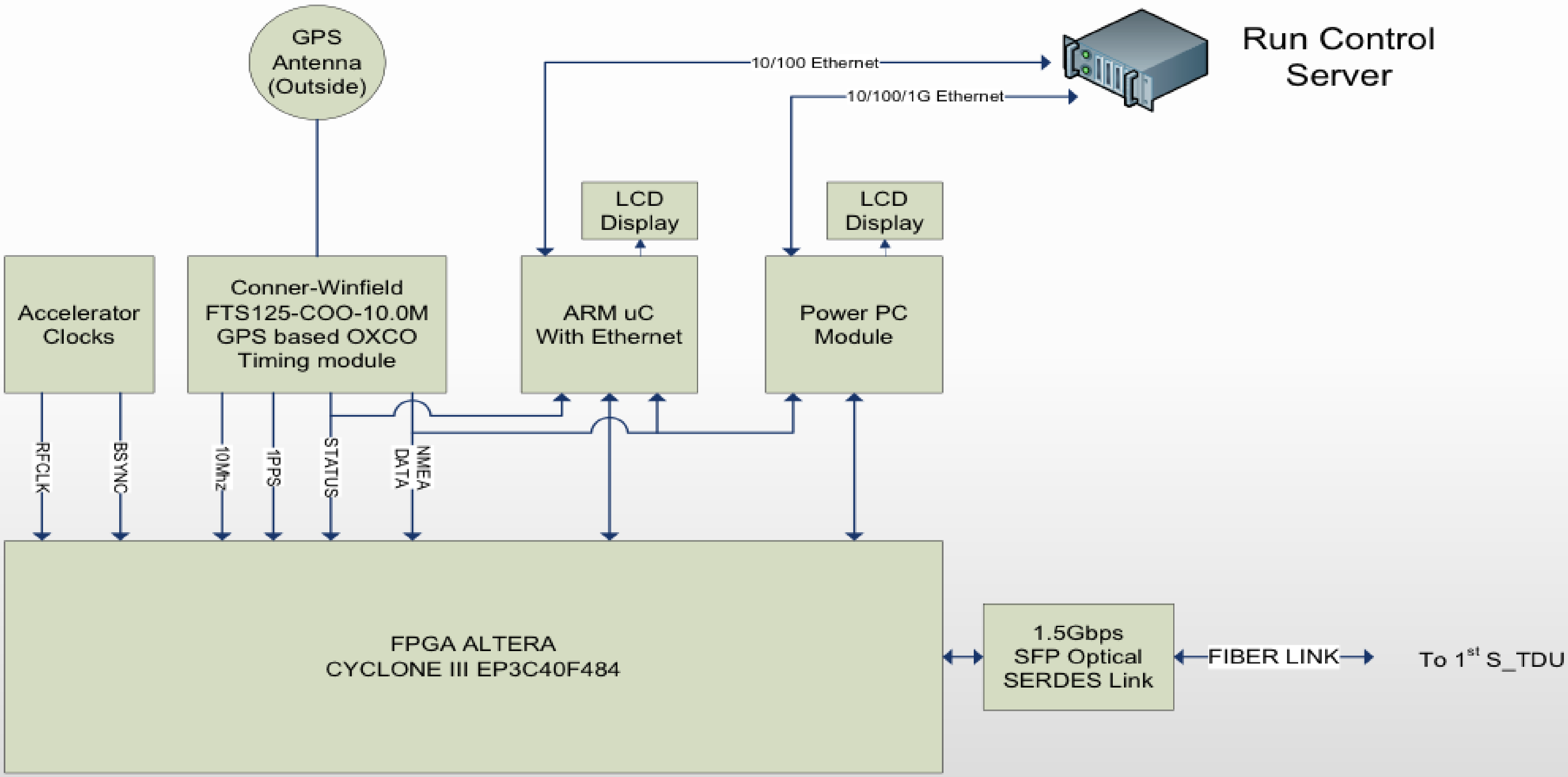
Schematic is for Far Detector layout, Near Detector is a scaled down version



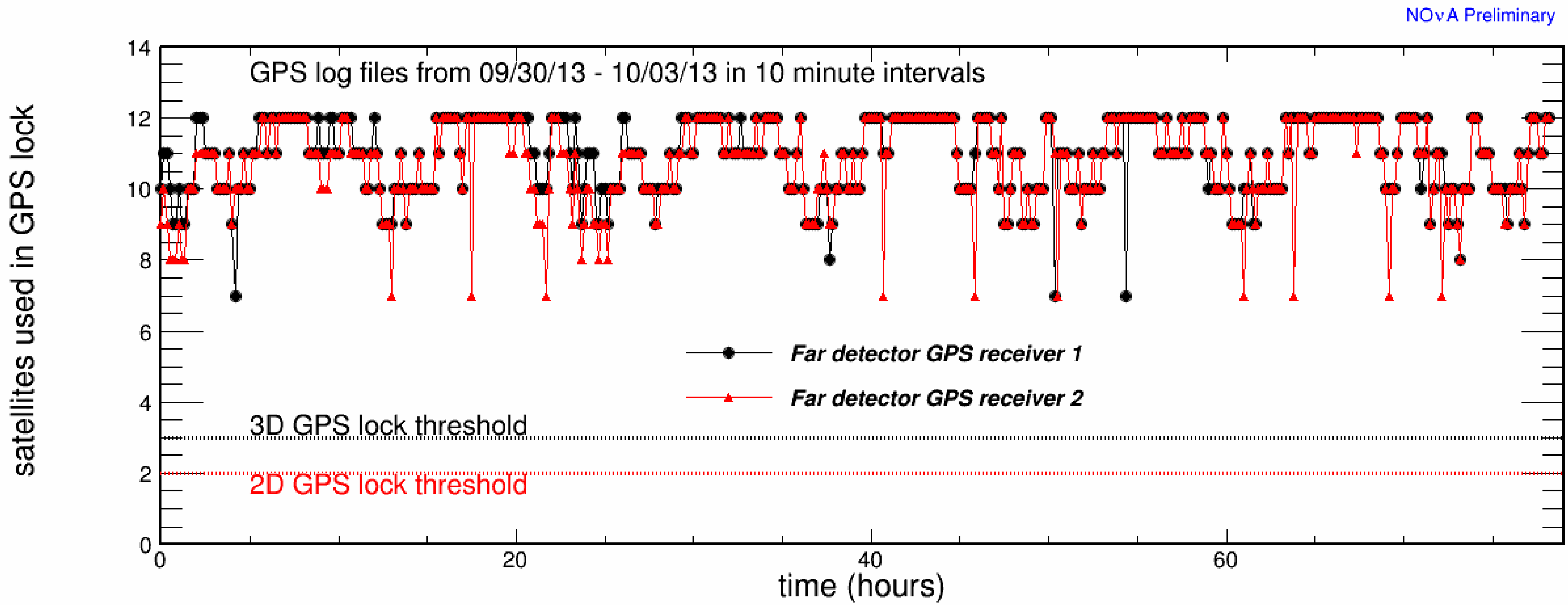
Master Timing Distribution Unit

- A GPS receiver drives a10 MHz reference clock and provides a 1 Hz reference pulse for synchronization
- Distributes synchronization and timing commands down branches to every front-end board (FEB) connected to an APD.
- The reference clock is in a phase lock loop to provide the 64 MHz signal that increments the time stamp counter on each electronic component
  - Signal digitization is time stamped from this register at 16 MHz (far Detector) or 64 MHz (Near Detector)
- 56 bit time stamp providing 64 MHz resolution, but can be expanded up to 1.024 GHz, starting at 00:00:00 January 1, 2010
- This design keeps the entire detector in sync with a universal time independent of detector location.

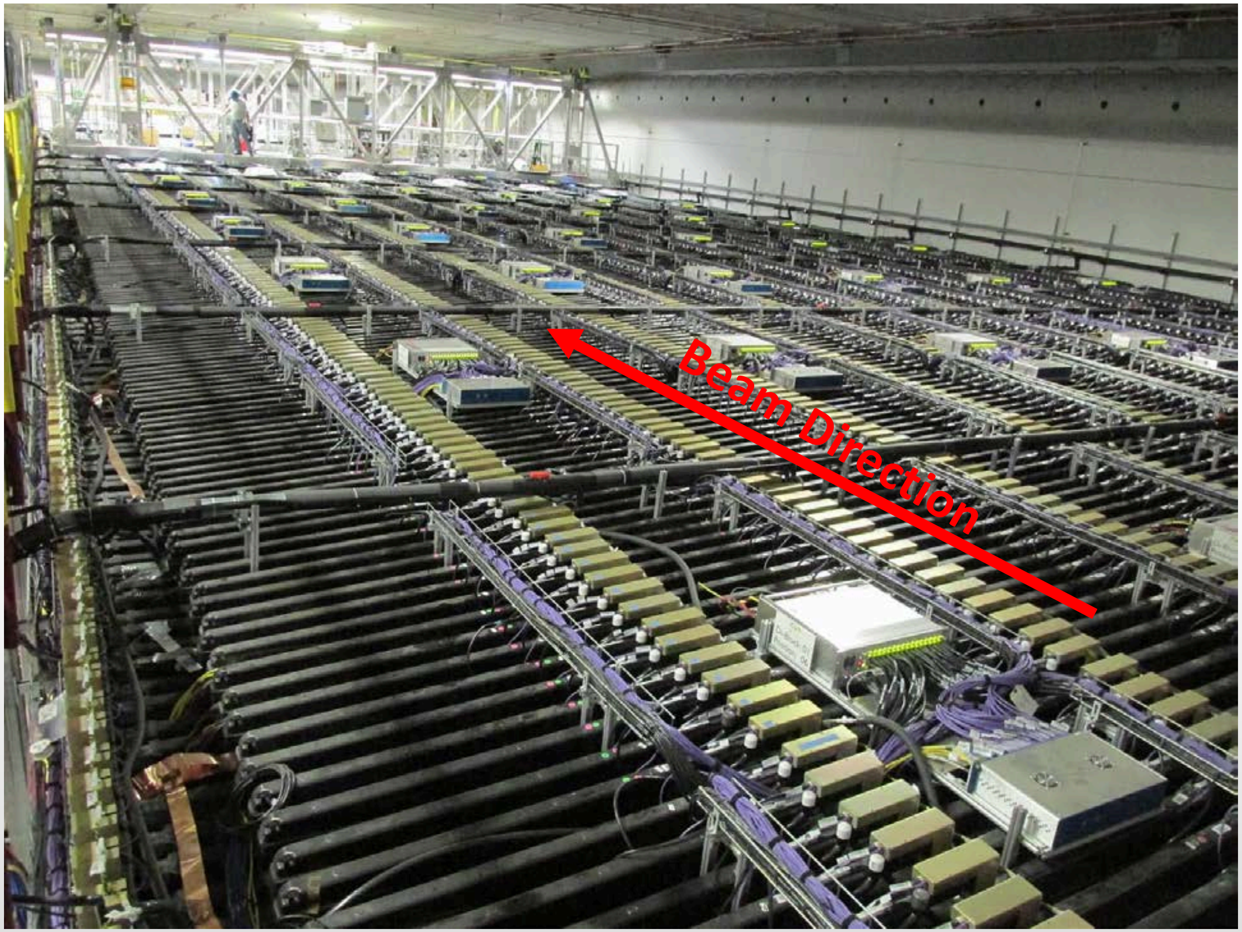
MTDU Schematic



GPS Satellite Lock Stability



Far Detector Electronics



Vertical planes instrumented with FEBs and DCMs.

Master TDUs and test stand located in control room.

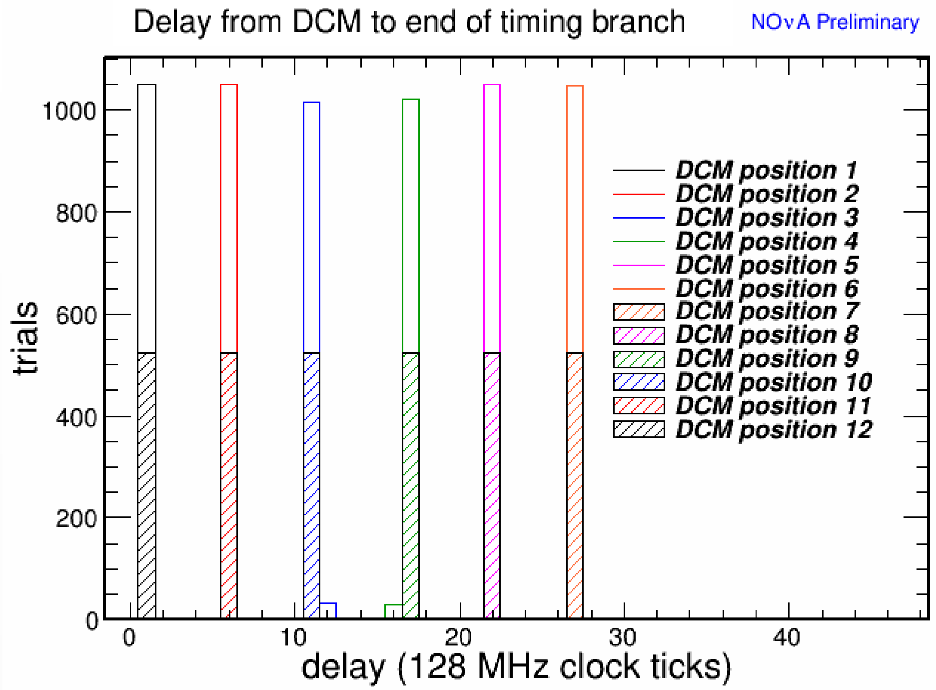
Timing System Calibration

- System requires precise calibration of the delay from the MTDU to each component of the chain.
  - MTDU sends out a sync pulse, when each TDU and DCM gets the sync a counter is cleared and started
  - The end of each branch has a loopback connector, when sync returns the unit stops counting, measuring the delay.
  - Calibration done at 128 MHz to provide better precision than the digitization clocks.
  - Delays can be regularly calculated to monitor system and track seasonal variations.

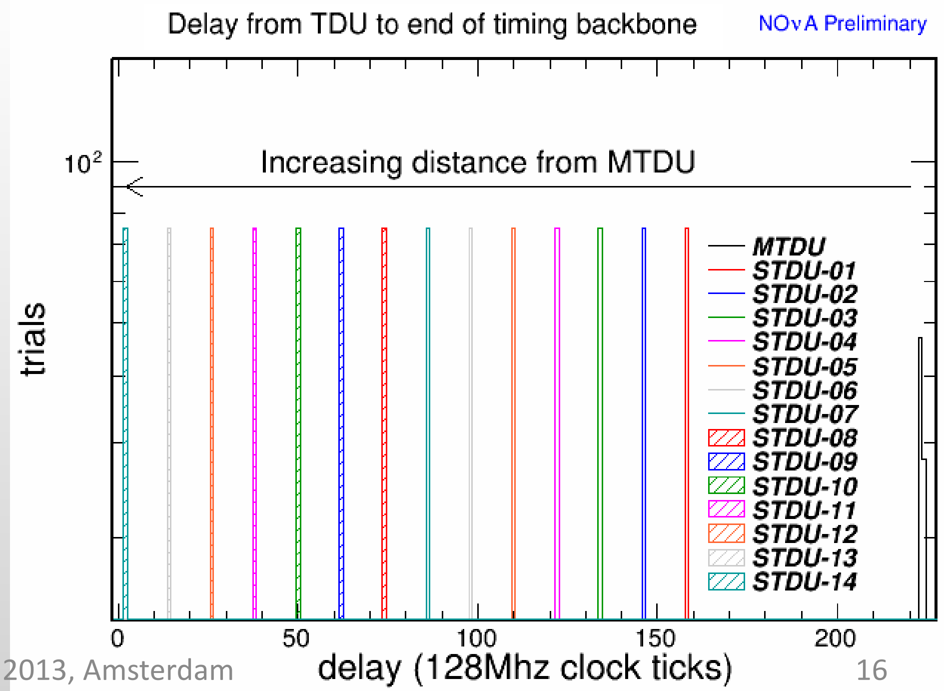
Timing System Synchronization

- To globally synchronize the clocks NOvA uses the scheme "At the tone the time will be…"
  - When a sync is requested the MTDU finds the next 1 second boundary far enough away for the command to arrive at each component.
  - This time is loaded into preset registers throughout the chain.
  - Sync stored in a buffer register that delays command by the calibrated value for that unit.
  - With proper calibration all syncs will exit buffers and begin counting from the preset time simultaneously.
- Syncs can be performed routinely during a run without disruption since readout does not require starting/stopping any gates and only uses the time stamp.

- DMC 6 and 7 are closest to STDU
- Statitstics are summed over first 8 kilotons of detector
- Results identical for second timing chain
- Consistent calibration within 1 clock tick (7.8125 ns)



- Delays between STDUs are evenly spaced by 12 clock ticks
- Delay for each unit is known within one clock tick
- Second timing chain produced identical results
- Full TDU backbone is operational at the Far Detector

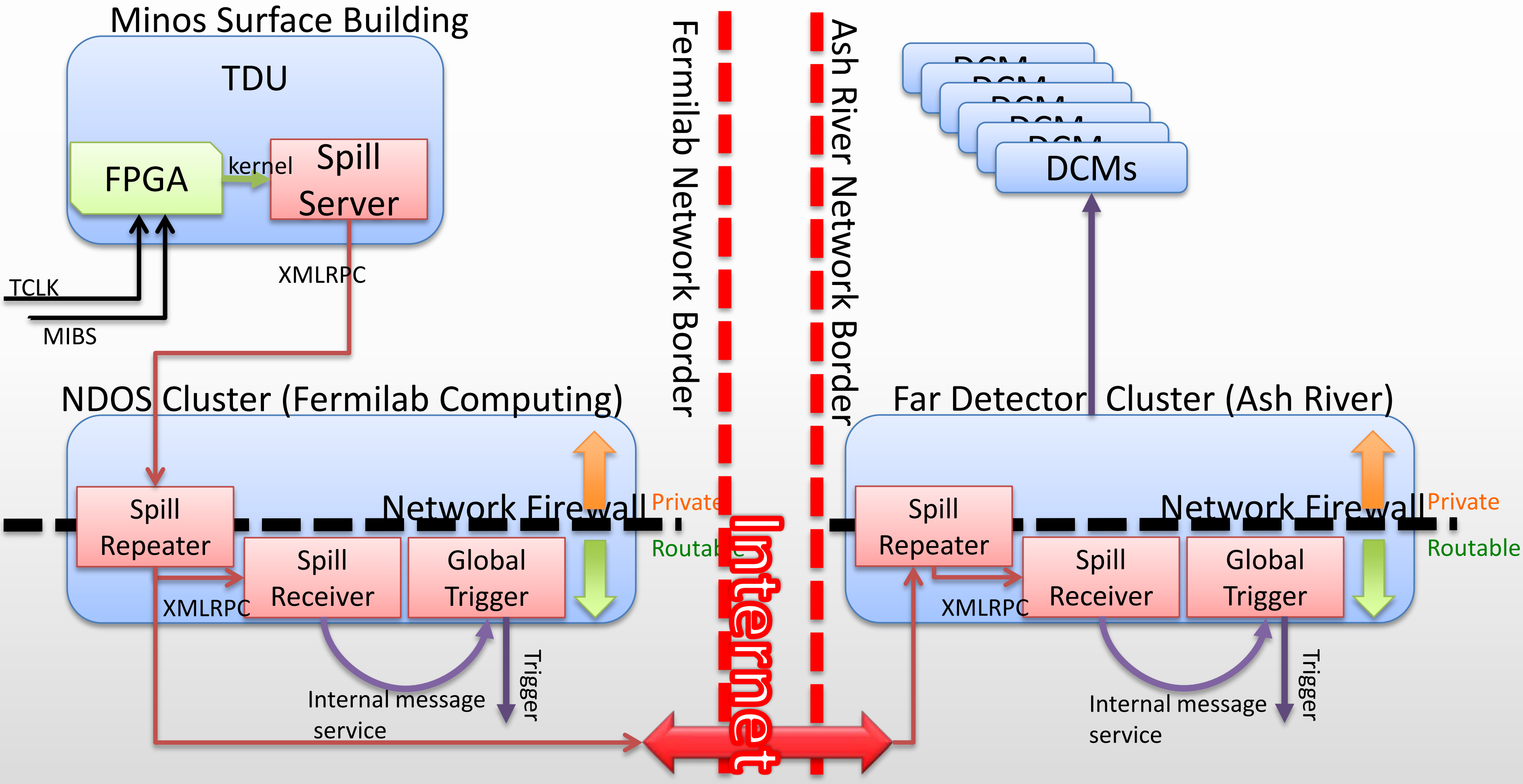


Broadcasting Beam Spills

- The MTDUs at Fermilab take in inputs from the Accelerator to time stamp events
  - Provides NuMI beam extraction events, stable 1 Hz reference pulses, and other events such as the super cycle reset.
  - Full 64 MHz precision used, in the NOvA time epoch
- Spill messages are relayed from the TDU to the near and far computing clusters where the GlobalTrigger application will initiate readout from the data buffer in the selected time window.
- Spill server backbone is always broadcasting, with up to 10 independent runs on each detector listening.

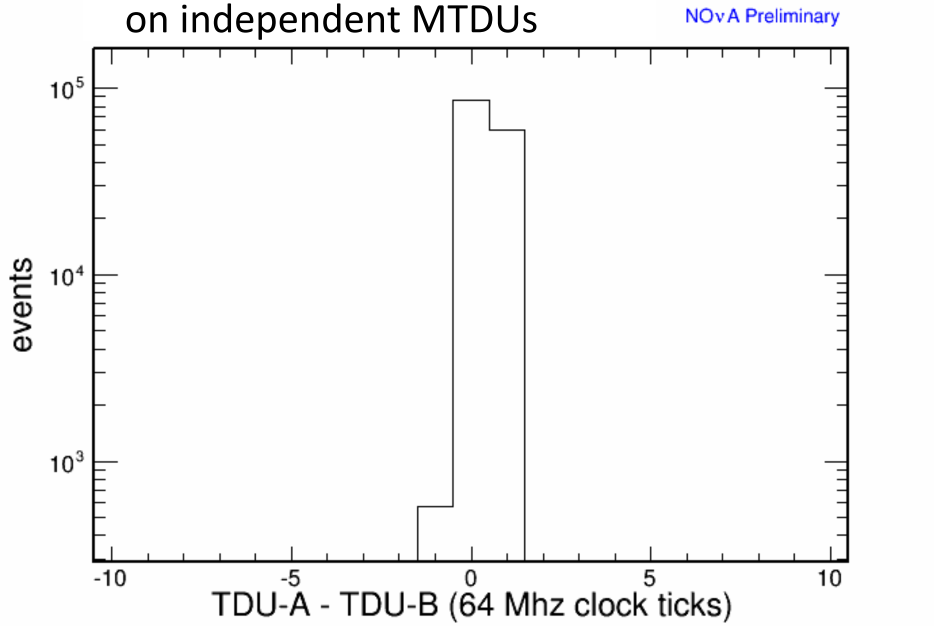
Spill Server Schematic

TCLK = Tevatron clock
MIBS = Main Injector Beam Synchronous clock

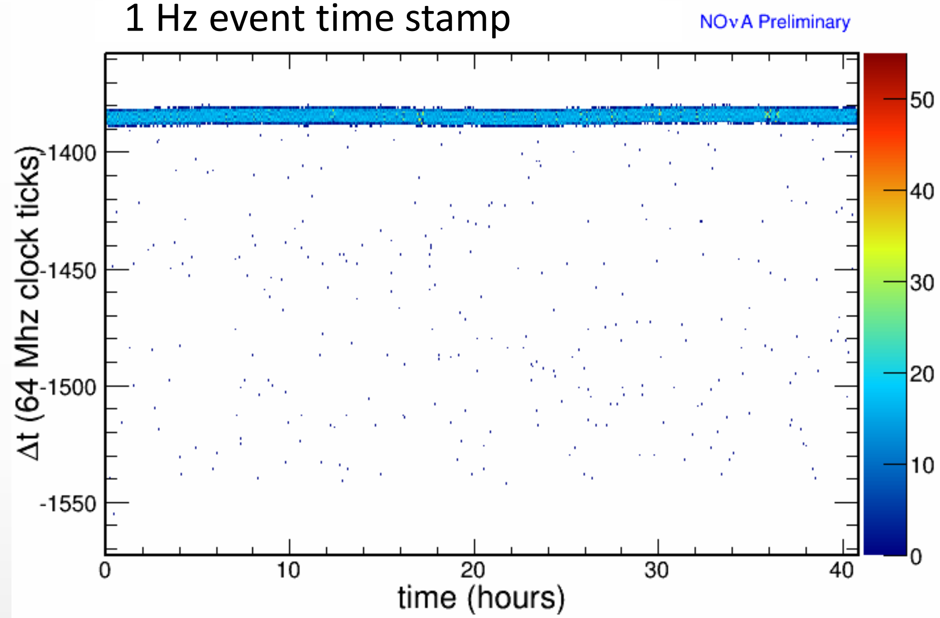


Spill Server Performance

Difference in 1 Hz time stamps on independent MTDUs



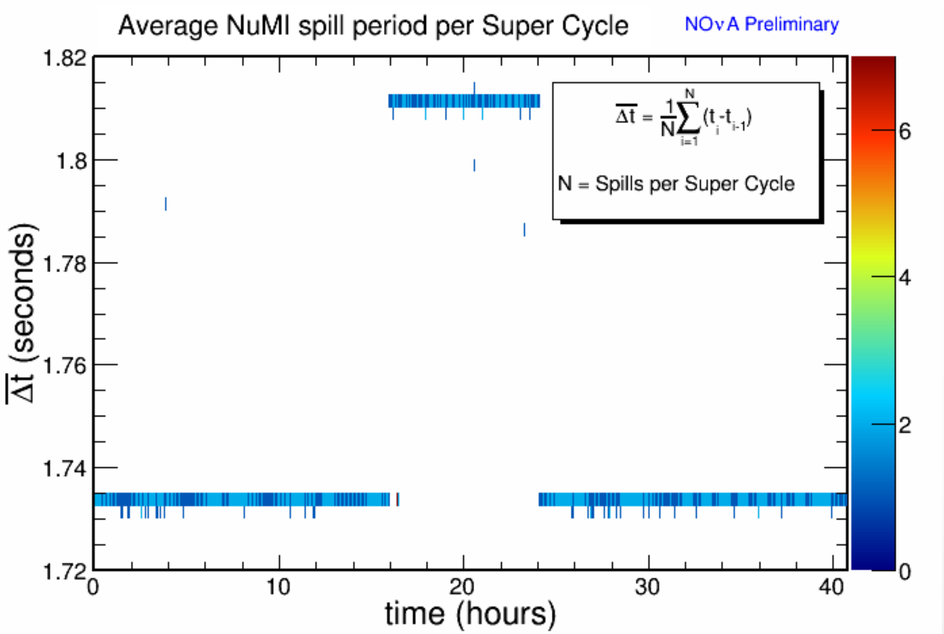
1 second NOvA time boundary – 1 Hz event time stamp

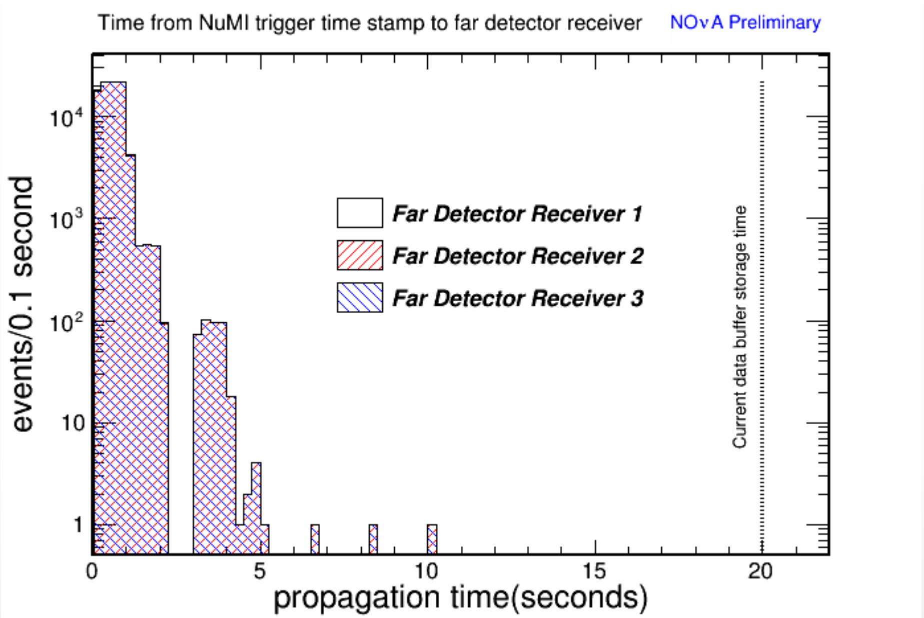


- Independent MTDUs time stamped the reference 1 Hz event agreeing within one clock tick.
- Running the spill server in pairs provides a check if a unit drifts.

- 1 Hz reference pulse has known offset from NOvA one second boundaries
- Measure of distance from the event source to the MTDU
- Signal has a low priority in the accelerator queue and can be artificially delayed

Spill Server Performance





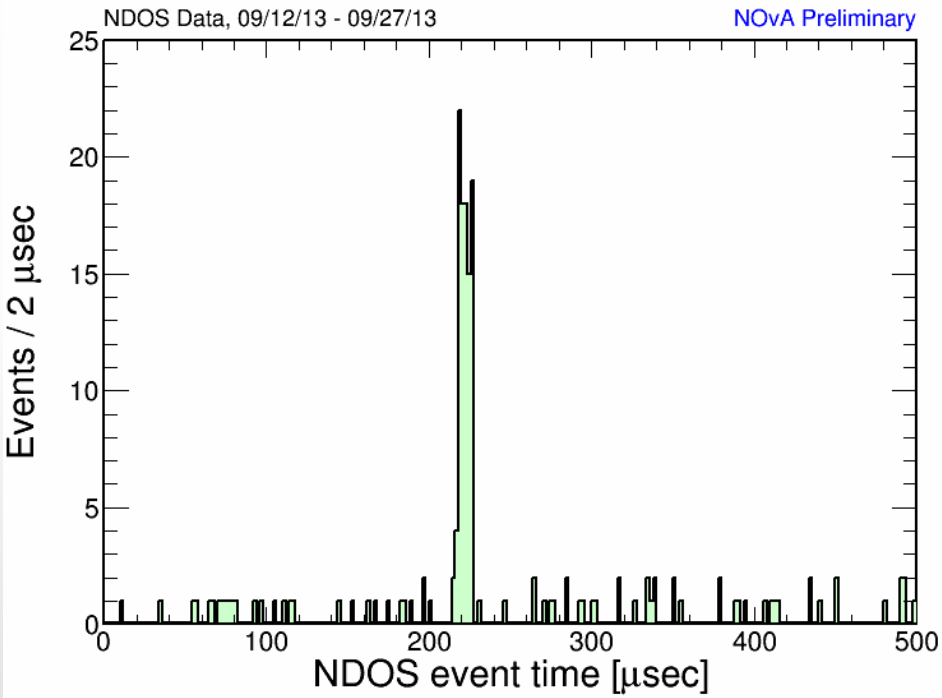
- Track average NuMI spill time per Super Cycle
- Frequency varies depending on which experiments are running

- Time from the arrival of a Beam spill on the MTDU to reception at a spill receiver at the far detector
- With 3 receivers running the propagation time was less then 10 seconds
- Spill messages were lost at a rate of less than 0.2%

Timing in the NuMI Beam

- Prototype Near Detector On the Surface (NDOS) constructed in 2010 has remained in use to time in the beam while the Near Detector is constructed.
- Beam returned in September 2013 and is undergoing commissioning.
- Statistics high enough to see evidence of the beam in an 8-12 hour window to monitor the timing system.
- Efforts are underway to search for a timing peak at the Far Detector.

- Position of detectors measured by GPS so the NDOS spill window can be transferred to the Far detector with appropriate delay.



Peak of neutrino events selected in a window from 217.0 to 227.8 µs in the 500 µs readout window. Cosmic background rejected based on fiducial, activity and direction cuts.

Comparing Time Between Detectors

- At Fermilab accelerator reference pulses can be used to monitor clock stability
- For the far detector will build an independent GPS receiver and antennae to transfer between detector sites
- Will provide 1 Hz reference pulses to be time stamped by TDUs at each location
- This provides a way to monitor any systematic time offsets between detector locations
- Calibration modules will rotate between detector sites every few months

Conclusions

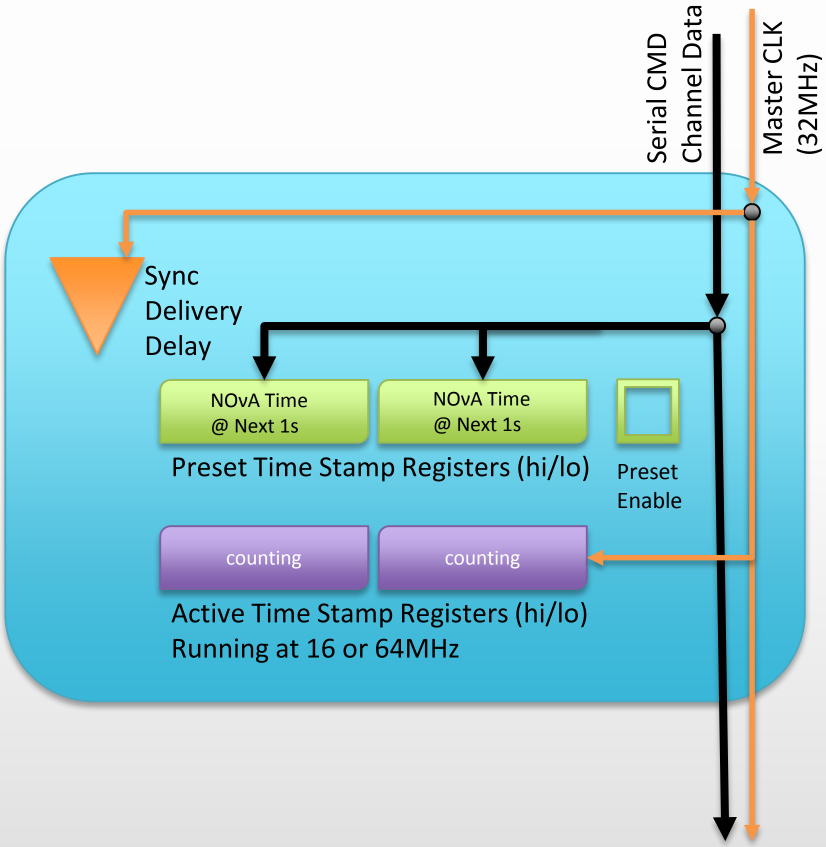
- The NOvA timing system is in production mode, with GPS receivers and TDUs fully deployed while detector construction continues
- The system has met the design criteria by the system delays within 10 ns.
- The spill server has demonstrated the ability to time stamp accelerator spills and deliver messages to the trigger systems at both detectors within the buffer storage time limits

Step 1

Use GPS to determine the 64bit NOvA time at the next 1s boundary (64MHz precision)

Send this time over the serial command channel.

The timing circuit loads the bytes into the “time stamp preset” registers.



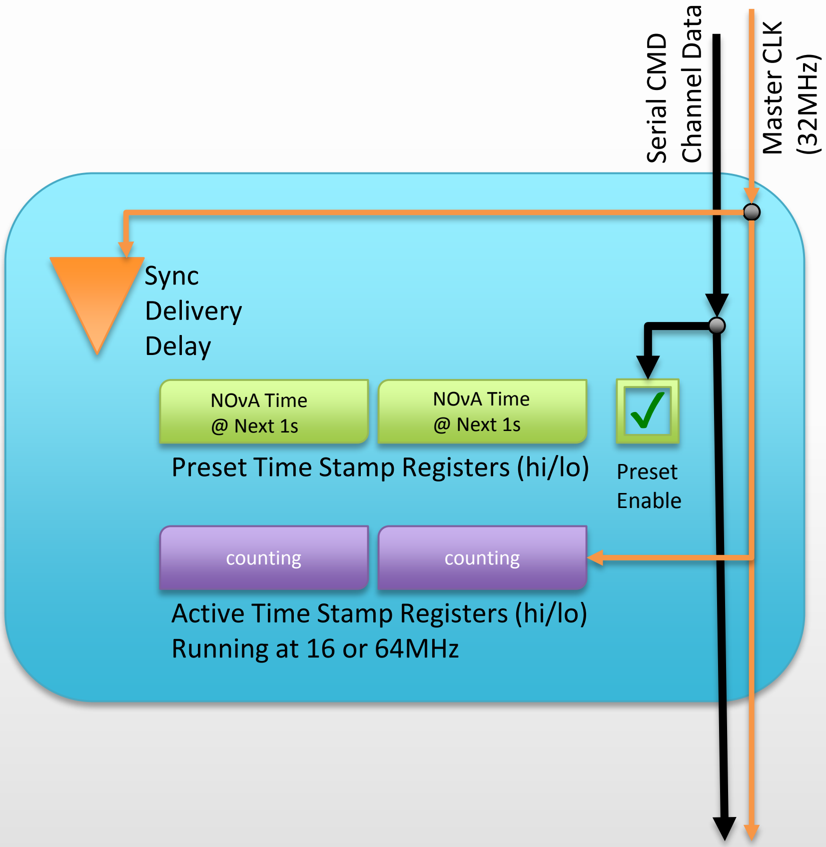
Step 2

Use the serial command channel to set the “Preset Enabled `Arm`” register.

This `arm`s the system to react when it receives the next sync pulse.

Having a specific Arm function allows the sync line to be used for different purposes like:

- Self Delay Calibration
- Timing Fiducially Diagnostics
- External Sync. Verification



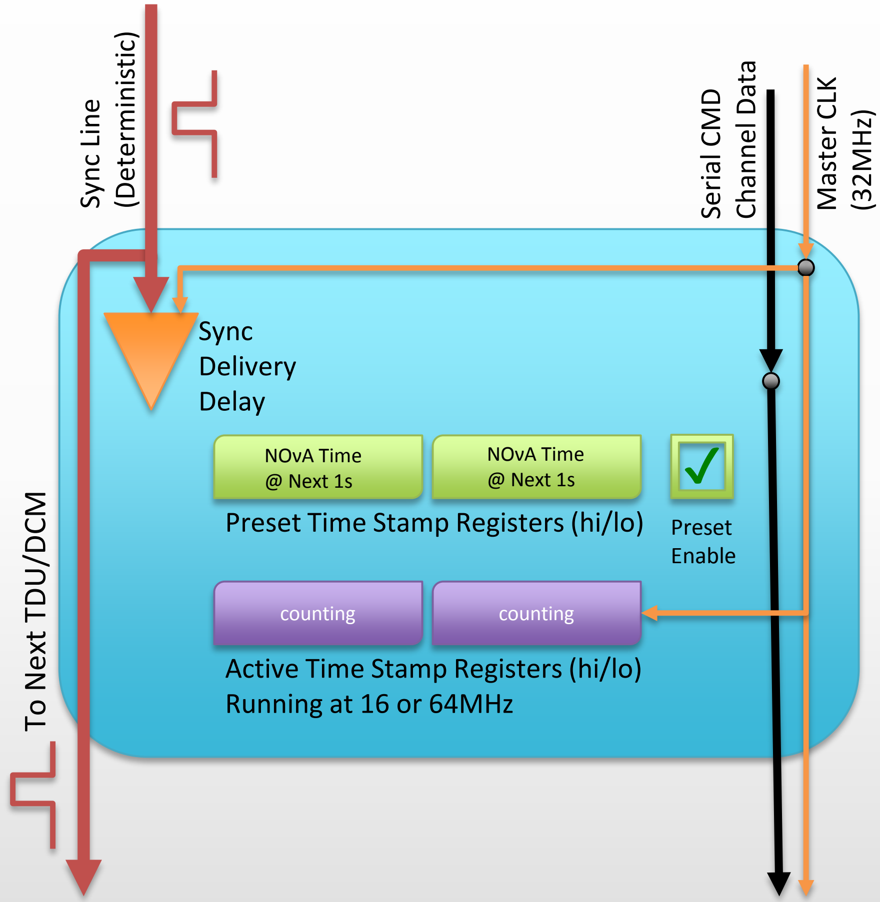
Step 3

Send a pulse on the dedicated SYNC line at a predetermined time BEFORE the next 1s boundary.

The pulse is buffered and retransmitted at each unit.

Each unit is calibrated to know its offset from its upstream and downstream partners in the chain.

The pulse is not actually delivered to the circuit until a calibrated number of master clock cycles have elapsed on this unit.



Step 4

Upon reception of the delayed sync, the values of the preset register are latched into the active time stamp registers.

The ARM register is cleared and the system continues counting on the next master clock cycle with the synchronized time.