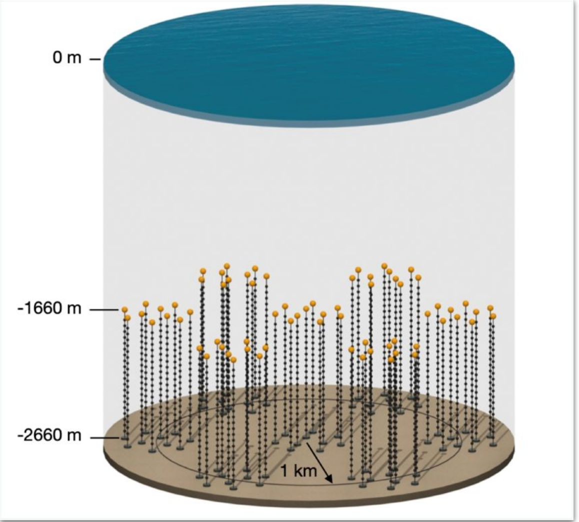
P-ONE Data Acquisition System

Jeanne Garriz
TeVPA 2026
September 1, 2026

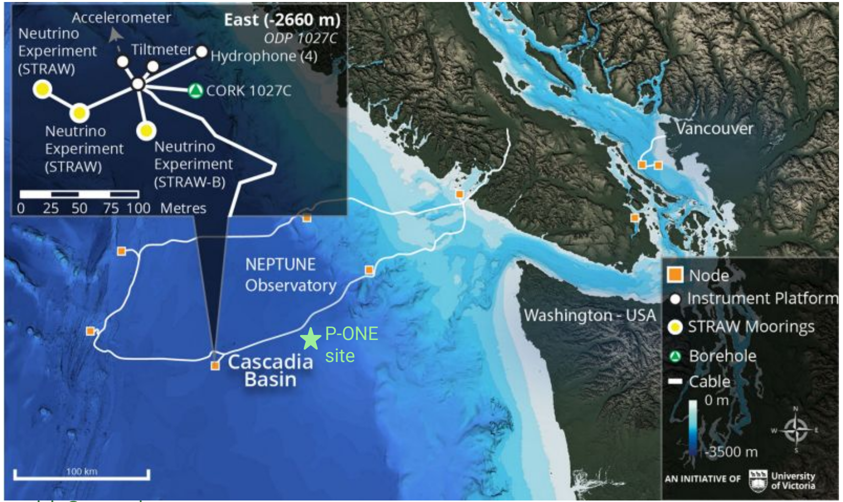
P-ONE

P-ONE

- Pacific Ocean Neutrino Experiment
- Goal: detect high energy neutrinos from astrophysical sources and make precision measurements of neutrino events
  - See talk by I. Taboada later for more info on P-ONE's goals



The P-ONE Collaboration

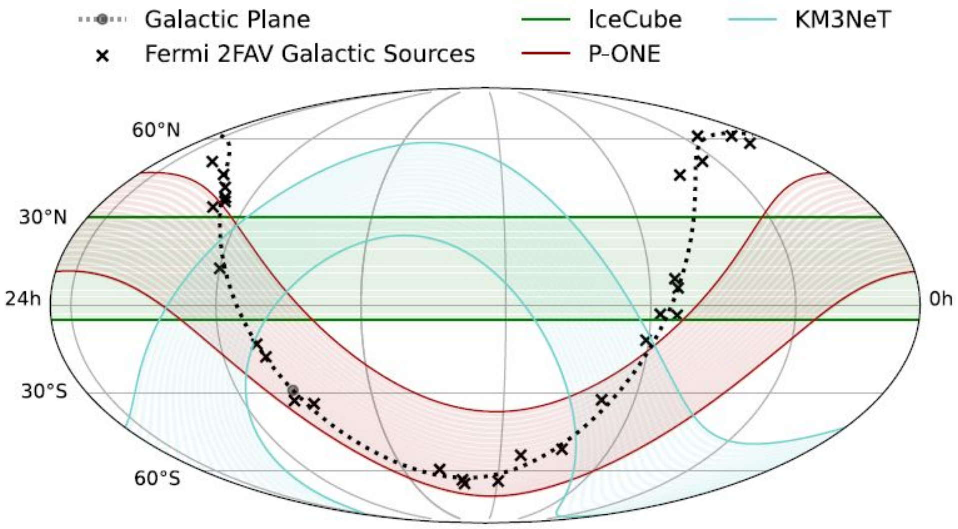


ONC

MICHIGAN STATE UNIVERSITY

Why P-ONE?

- **Location:** Better able to probe Galactic Plane
- **Water:** Longer scattering length in water over ice
- **Multi-PMT design:** More directional information
- **Unique “waveform only” design:**
    - Digital trigger cuts deadtime down to ~zero
    - Full waveforms let us tag tau events



Snapshot of regions of highest detection efficiency for different detectors. Edges of bands are where discovery potential drops by factor of 2 with respect to max value.

L. Schumacher

MICHIGAN STATE UNIVERSITY

Physics Targets and Requirements

Reconstructing neutrino interactions requires:

1. charge/energy deposited
2. time of deposited charge

Energy

Time

Physics Targets and Requirements

Reconstructing neutrino interactions requires:

1. charge/energy deposited
2. time of deposited charge

Energy

Time

How?

- Compact, high signal:noise waveforms with well known pulse shapes

Why?

- Known pulse shapes allows for waveform unfolding
- Better energy resolution than time over threshold measurement because of improved dynamic range

Physics Targets and Requirements

Reconstructing neutrino interactions requires:

1. charge/energy deposited
2. time of deposited charge

Energy

Time

How?

- Timestamp waveforms to 100 ps
- Consistent, known sampling frequency and phase drift control

Why?

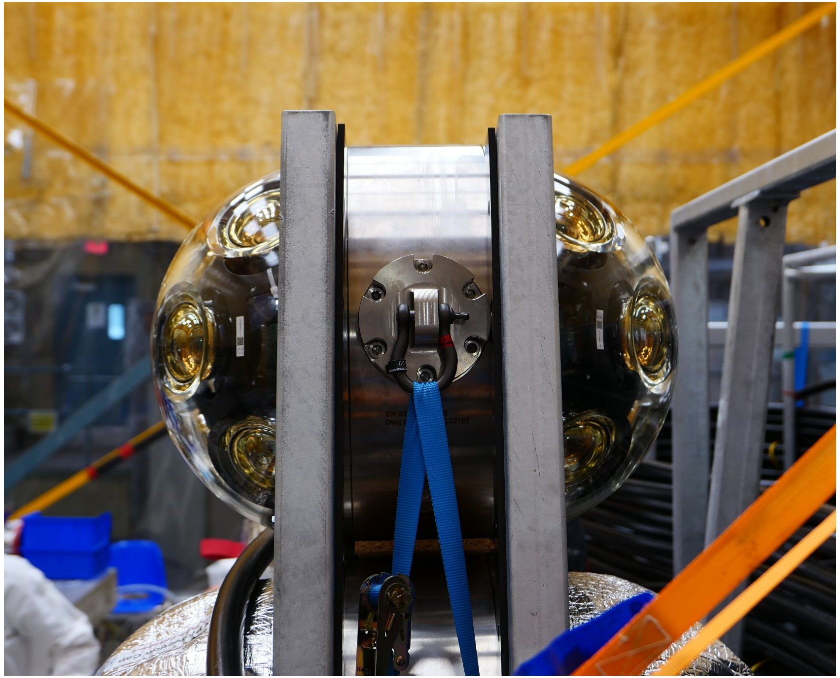
- Neutrino point source sensitivity $\propto$ angular resolution
- Reconstruction algorithms dependent on timing reconstruction
- Better flavor ID of events

Jeanne Garriz | garrizje@msu.edu

DAQ Hardware Overview

1. 16 PMTs collect light from neutrino interactions
2. PMT signals digitized by 16 channel analog to digital converter
   a. ADC samples at 208.3 MHz (4.8 ns period)
3. Full waveforms stored

- To achieve angular resolution goal of 0.05 degrees, we require **ADC synchronization at ≤100 ps level** (at 200 PEs)
- Data uplink: IP over Ethernet on fiber optics

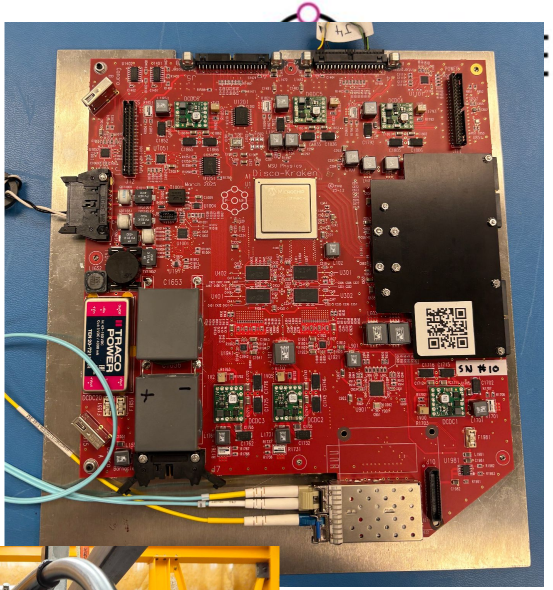


MICHIGAN STATE UNIVERSITY

Jeanne Garriz | garrizje@msu.edu

Other Module Hardware

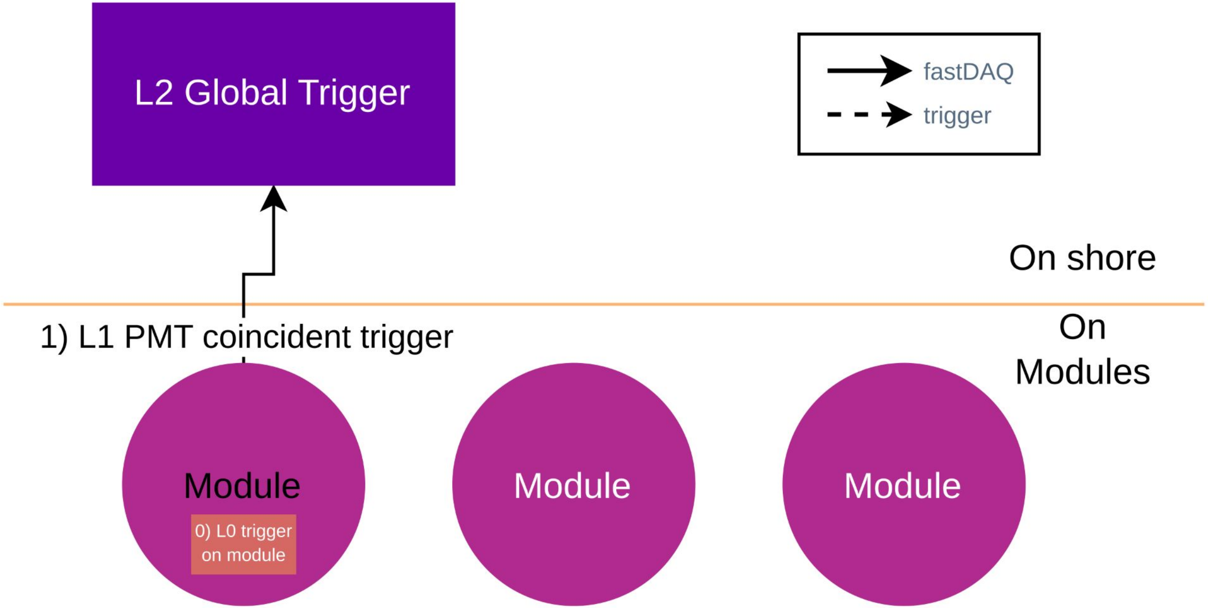
- Environmental sensors on Mainboard
- Muon In-Situ Tracker:
  - Detect muons passing through module
- Interposer:
  - Board that distributes power to PMTs, acoustic receivers, and flasher LEDs
- Calibration hardware:
  - Acoustic receiver
  - LED flashers
- Power consumption: ~11 W/module



MICHIGAN STATE UNIVERSITY

Trigger

- Push/pull architecture between modules (fastDAQ) and shore (global trigger)
- L0: on module, ADC value crossing trigger threshold
- L1: PMT coincidence logic that fastDAQ then reports to shore

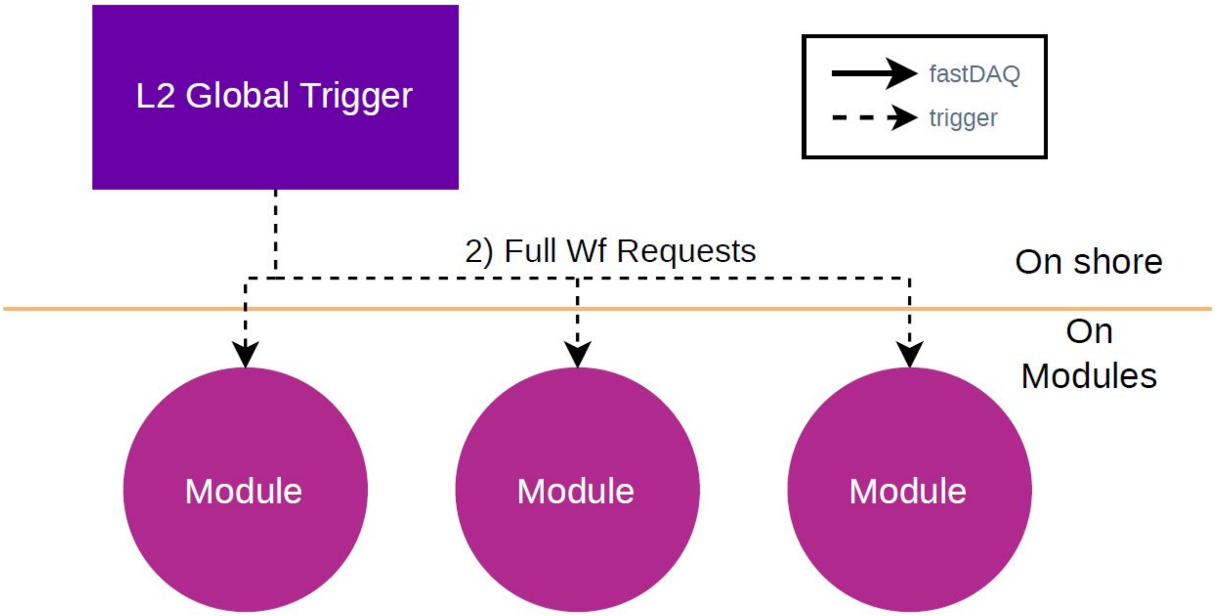


MICHIGAN STATE UNIVERSITY

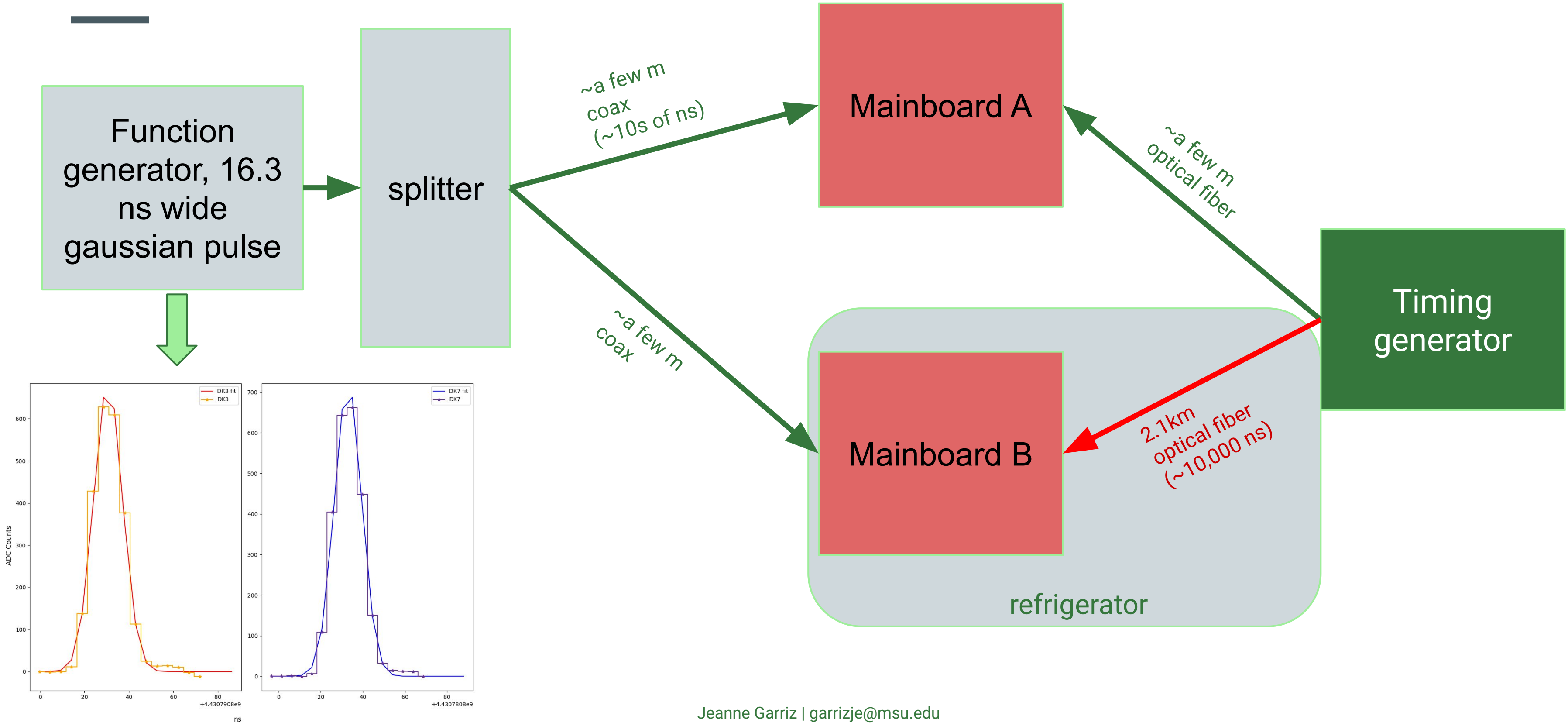
Jeanne Garriz | garrizje@msu.edu

Trigger

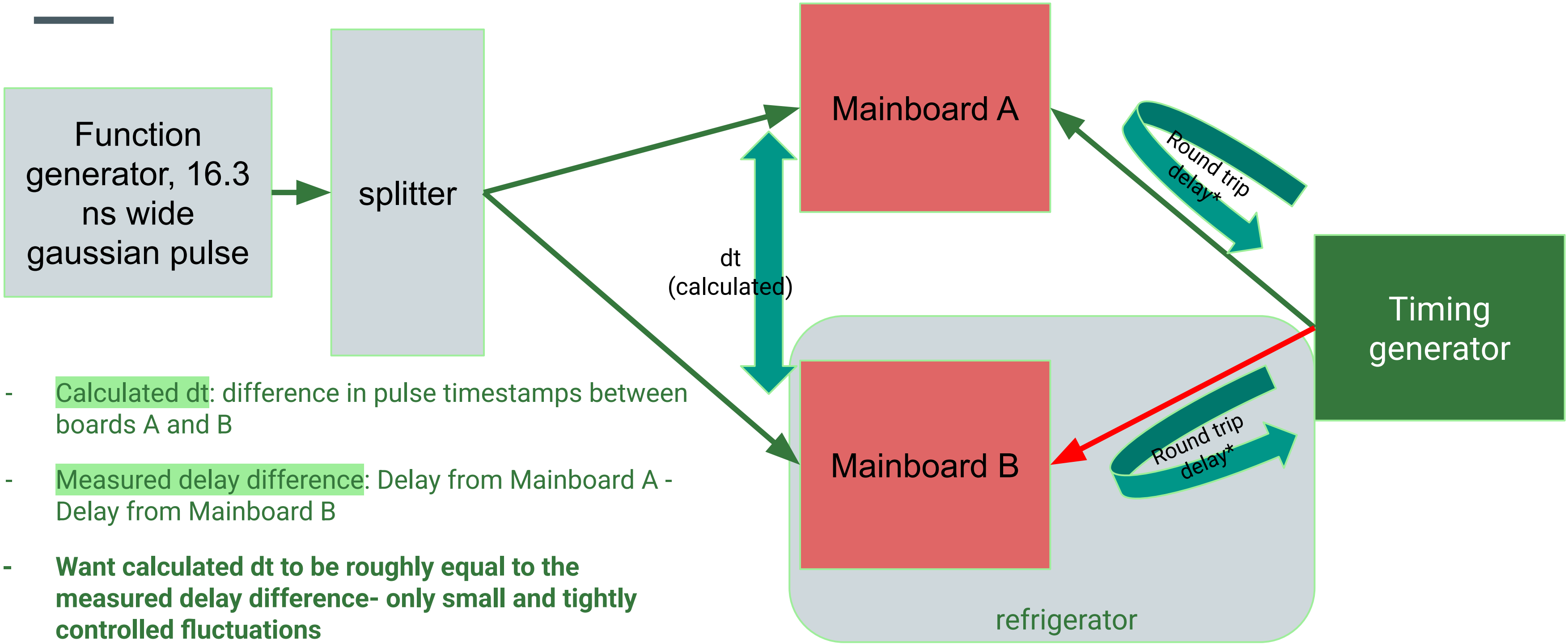
- L2: Determines what other modules might contribute to physics events from L1 triggers and sends requests to fastDAQ on modules
    - Actual algorithm still in development



Time Reconstruction Test Setup



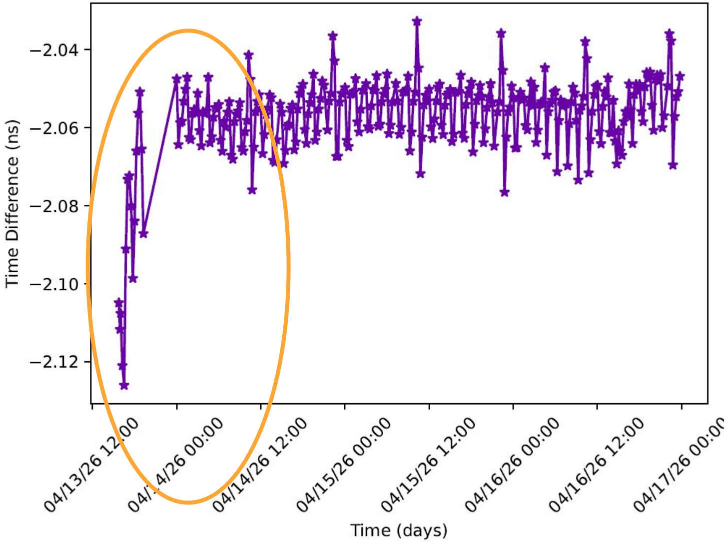
Measured Quantities

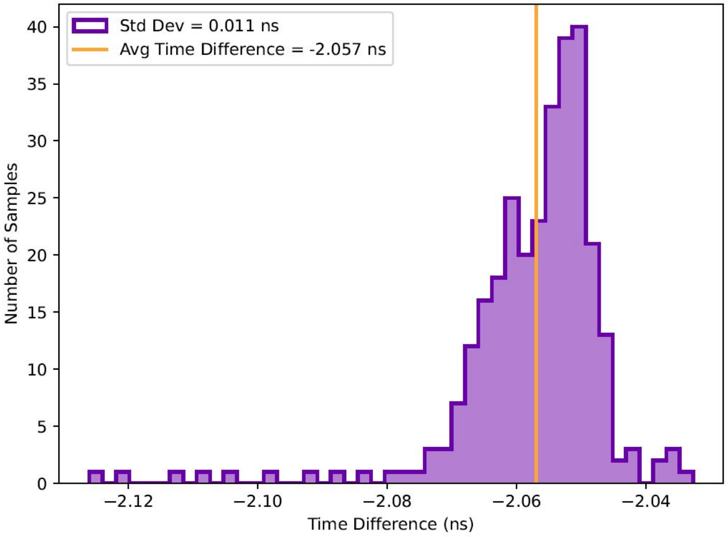


- Calculated dt: difference in pulse timestamps between boards A and B
- Measured delay difference: Delay from Mainboard A - Delay from Mainboard B
- **Want calculated dt to be roughly equal to the measured delay difference- only small and tightly controlled fluctuations**

*round trip delay/2 recorded and used for measurements

Measured Delay Difference - Calculated dt





- Including cooldown period, difference is only ~80 ps
- Standard deviation ~11 ps

MICHIGAN STATE UNIVERSITY

Jeanne Garriz | garrizje@msu.edu

Waveform Unfolding

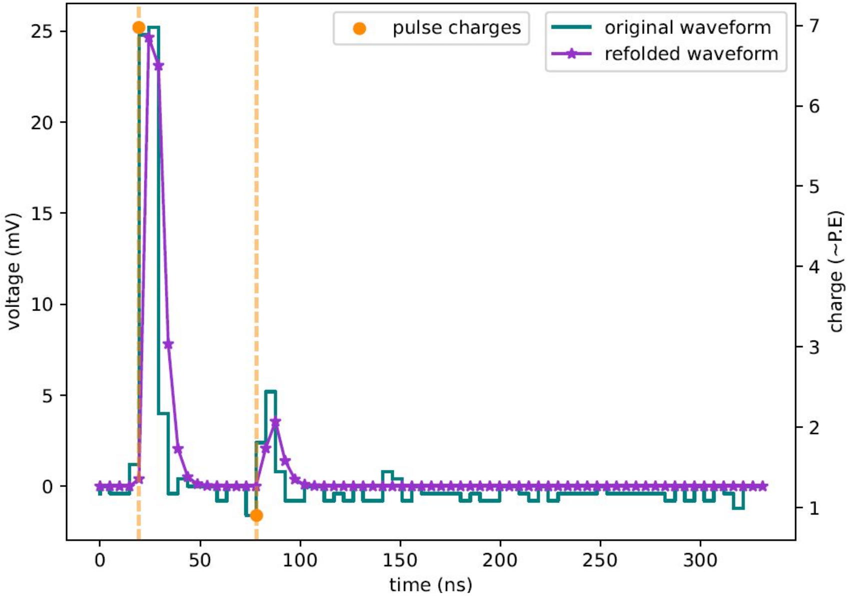
Basis matrix of SPEs

$$\mathbf{B}\vec{q} = \vec{w}$$

waveform

Charge distribution

- Number and amplitude of basis functions contributing ∝ **charge deposited** in the PMT
- Allows us to determine more precisely the time of the SPEs because we have multiple points in the waveform



Waveform Unfolding

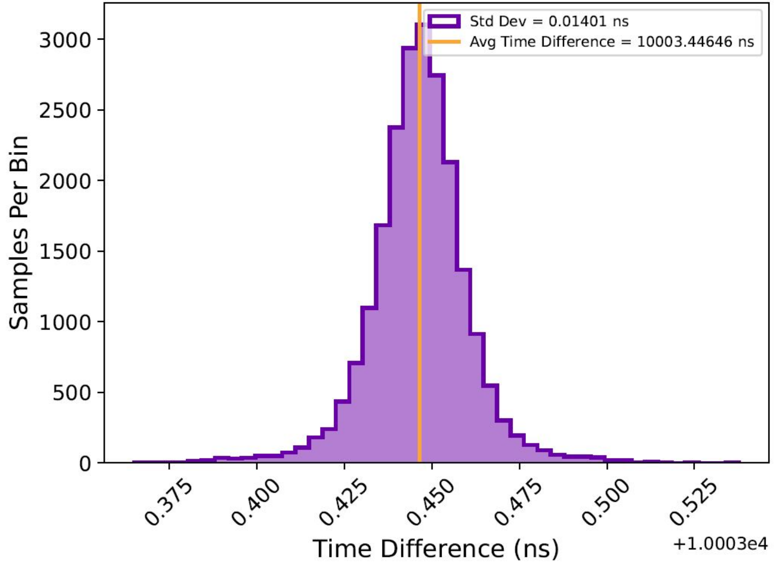
Basis matrix of SPEs

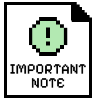
$$\mathbf{B}\vec{q} = \vec{w}$$

waveform

Charge distribution

- Proof of concept: trigger timestamps for previous setup calculated using waveform unfolding
    - Gives better than sampling rate resolution





10,000 ns difference due to one board being connected to timing generator using 2.1km fiber

Conclusions

- P-ONE's unique waveform-only architecture will give it advantages in timing and energy reconstruction
- Timing synchronization between boards and timing generator exceeds requirements
    - Over multiple days, max variation is ~80 ps with a spread of 11 ps (including cooldown period)
    - Consistent sampling frequency and deterministic phase verified with time sync measurements
- Waveform unfolding works to reconstruct charge deposited and achieve sub sample frequency precision
- There is A Lot more to the DAQ system for P-ONE > full paper will be on the arxiv sometime soon…stay tuned

Questions?

Backup

MICHIGAN STATE UNIVERSITY

100 ps Requirement

- Sources of uncertainty in timing include PMT TTS, timing reconstruction from waveform digitization, OM time sync uncertainty, light propagation time spread, uncertainty in mean PMT transit time, and uncertainty in OM position
- N = number of photons, with 200 PE being dynamic range requirement

$$\sigma_t = \frac{\sigma_{\mathrm{digi}}}{N} \oplus \underbrace{\boxed{\frac{\sigma_{\mathrm{tts}} \oplus \sigma_{\mathrm{prop}}}{\sqrt{N}}}}_{\text{irreducible}} \oplus \left(\sigma_{\mathrm{sync}} \oplus \sigma_{\mathrm{tt}} \oplus \frac{\sigma_{\mathrm{geo}}}{(c/n_g)}\right)$$

Keep reducible uncertainty much less than irreducible for small N

$$\sigma_{\mathrm{digi}} \ll \sigma_{\mathrm{tts}} \oplus \sigma_{\mathrm{prop}}$$

For N = 200

$$\sigma_{\mathrm{sync}} \oplus \sigma_{\mathrm{tt}} \oplus \frac{\sigma_{\mathrm{geo}}}{(c/n_g)} \ll \frac{\sigma_{\mathrm{tts}} \oplus \sigma_{\mathrm{prop}}}{\sqrt{200}}$$

$$\boxed{\sigma_{\mathrm{digi}} \ll 1.3\,\mathrm{ns}}$$

To satisfy both regimes, where σ_{tts} = 1.3 ns

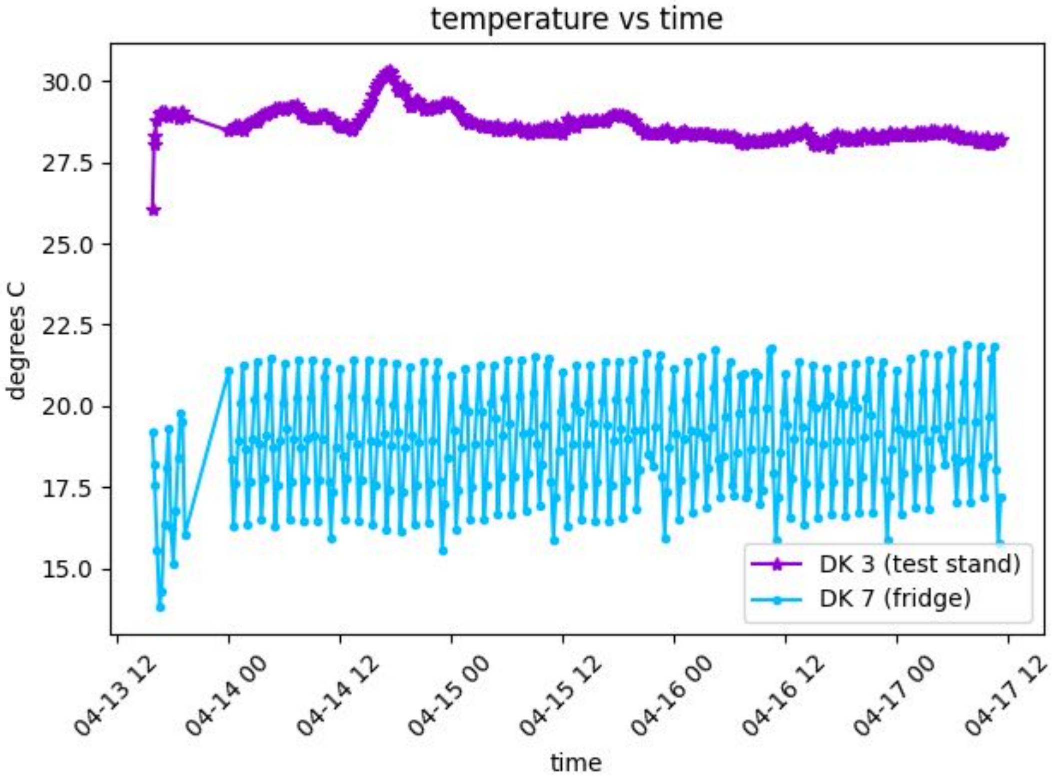
$$\boxed{\sigma_{\mathrm{sync}} \oplus \sigma_{\mathrm{tt}} \oplus \frac{\sigma_{\mathrm{geo}}}{(c/n_g)} \ll 0.1\,\mathrm{ns}}$$

Slow Control Software

- Collects all non-PMT data and controls overall detector operation
- Interface for all calibration sensors, detector/run control, and online database entry
- Uses JSON Remote Procedure Call (RPC) protocol- client requests function be run on remote server
    - Tuber- C++ server and Python client used to access instrumentation control
- Modules run slow control server on boot up

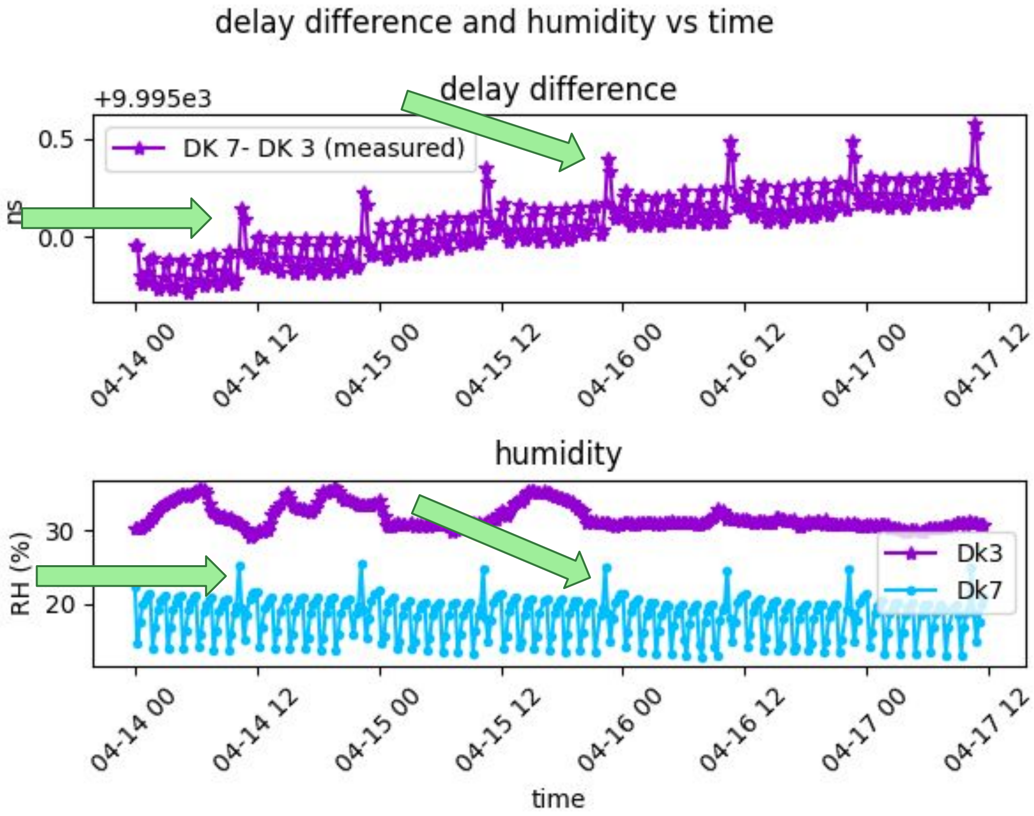
Temperature vs Time

- Temperature cycle of refrigerator visible
- Temperature was of the sensor *on the board* (not ambient temperature inside refrigerator)



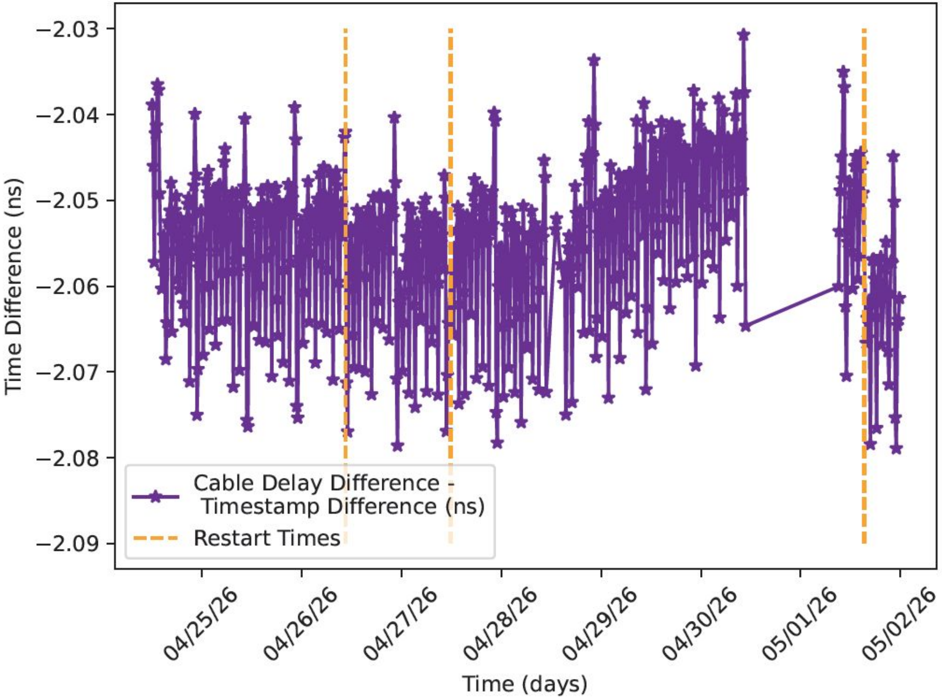
Humidity vs Time

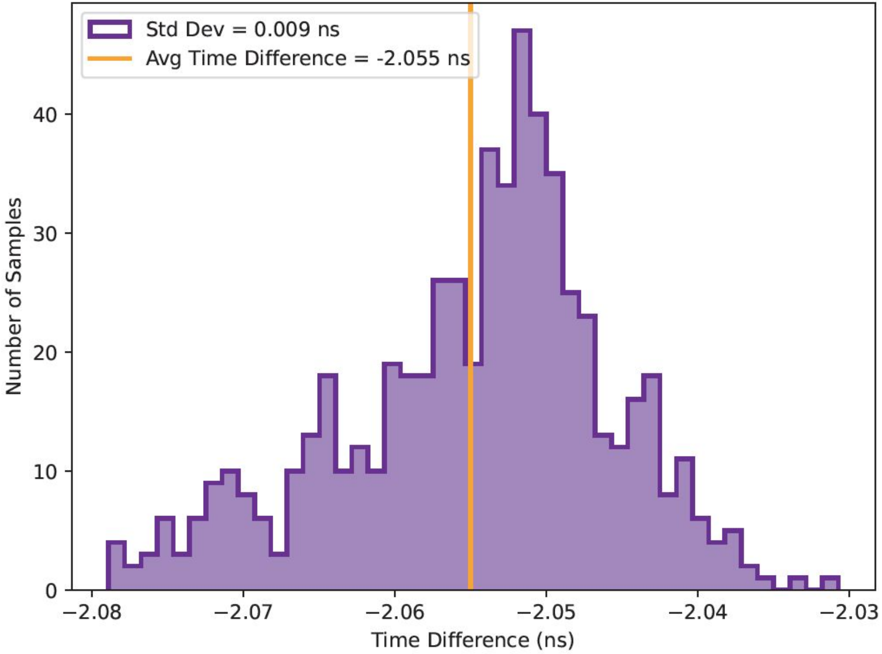
- Humidity cycling also seen (assumed to be refrigerator defrost cycle)
- Correlates very well with difference in measured delays



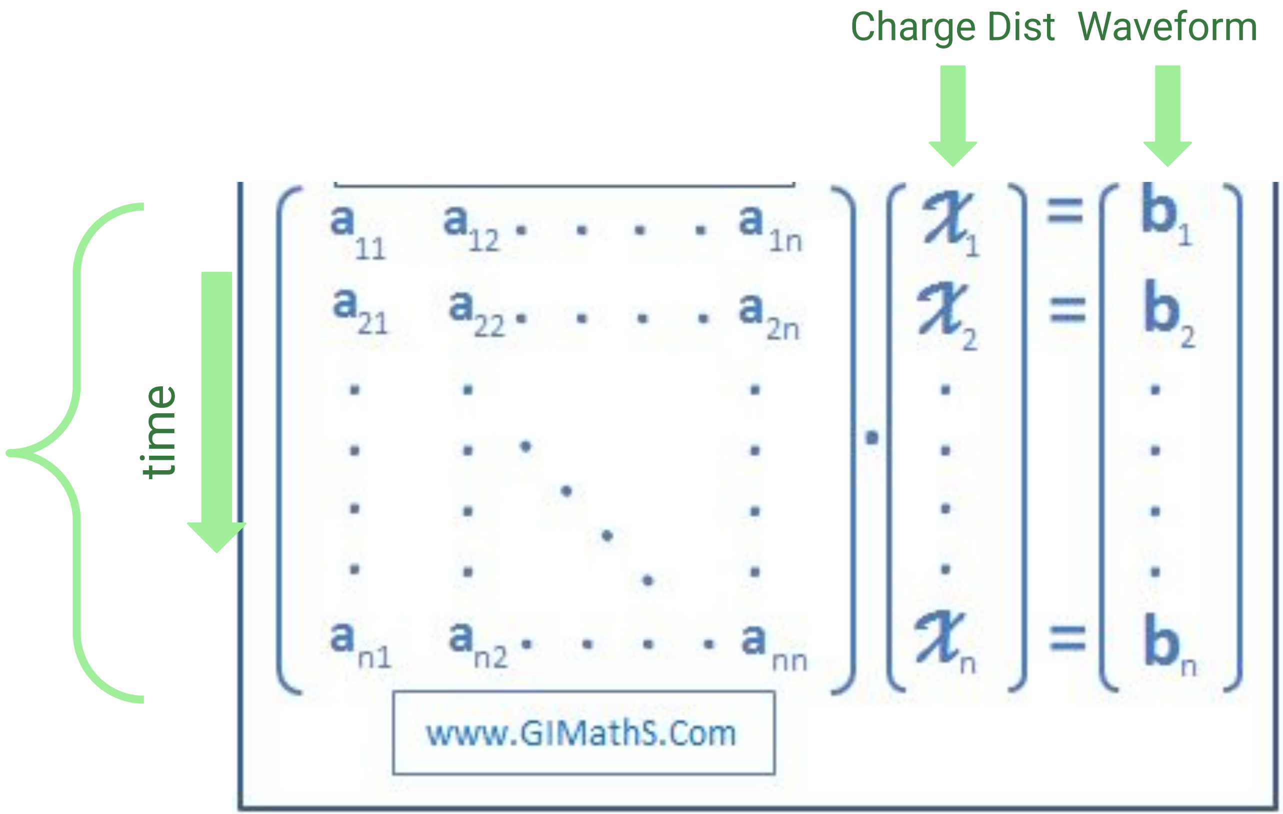
MICHIGAN STATE UNIVERSITY

Measured Delay Difference - Calculated dt (longer timescale, including restarts)





Waveform Unfolding Linear Algebra

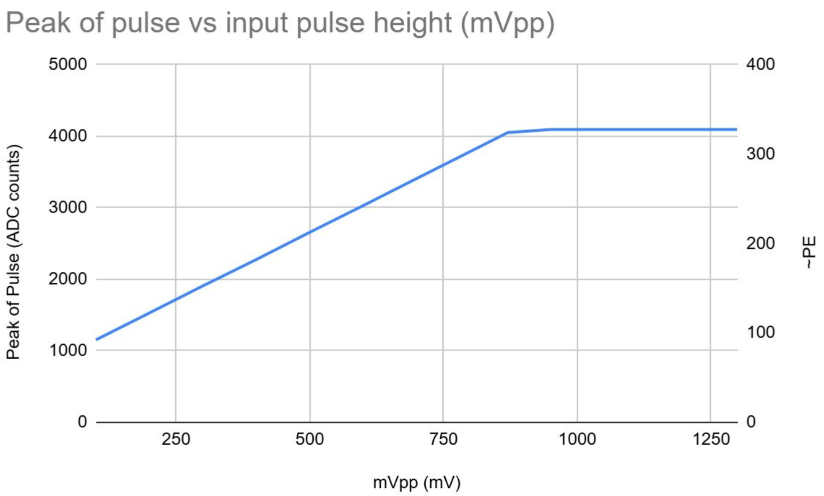


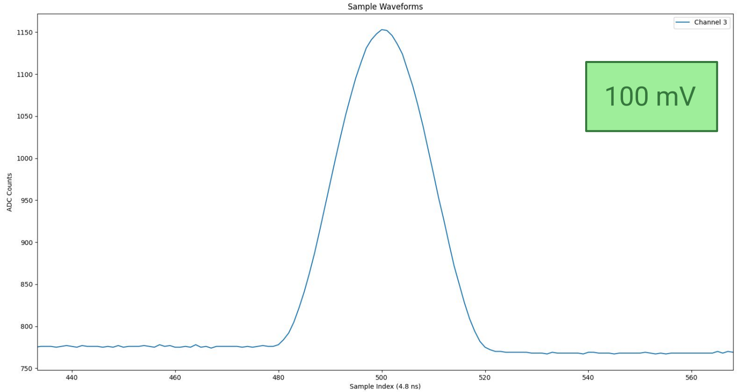
$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix}$$

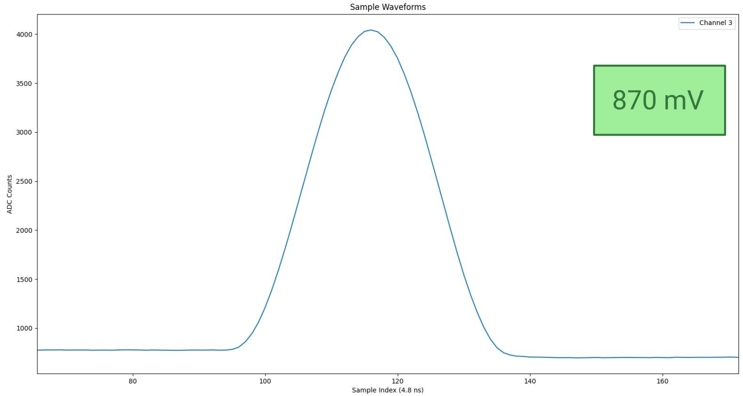
MICHIGAN STATE UNIVERSITY

ADC Linearity Study

- Test pulse from function generator: one cycle of negative unipolar 5 MHz sine wave followed by 50us of zero output
- Saturates ADC ~950 mVpp and stays flat at 4095 counts until 1200 mVpp

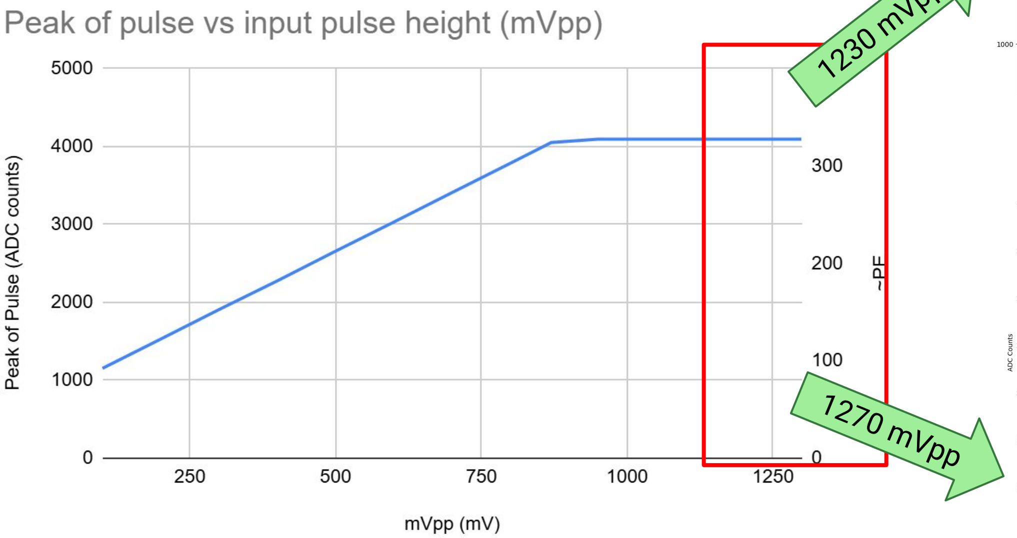


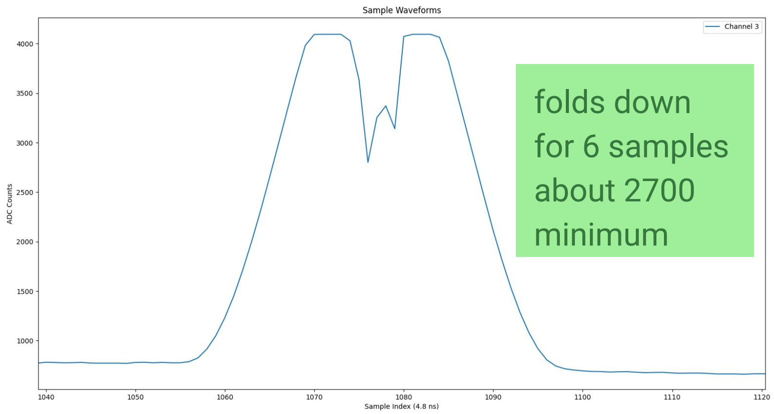


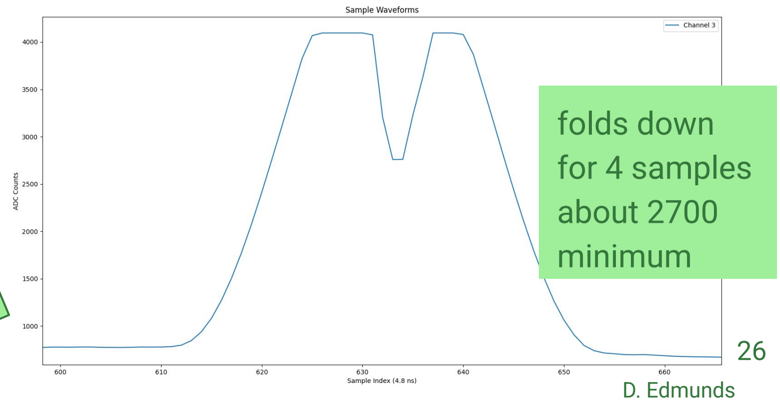


ADC Linearity Study

- **After** 1200 mVpp, the ADC output dips down from 4095 for a few samples
- Makes it hard to distinguish between an actual double pulse event and a saturated pulse
- However, is linear well above ~200 PE, which was requirement

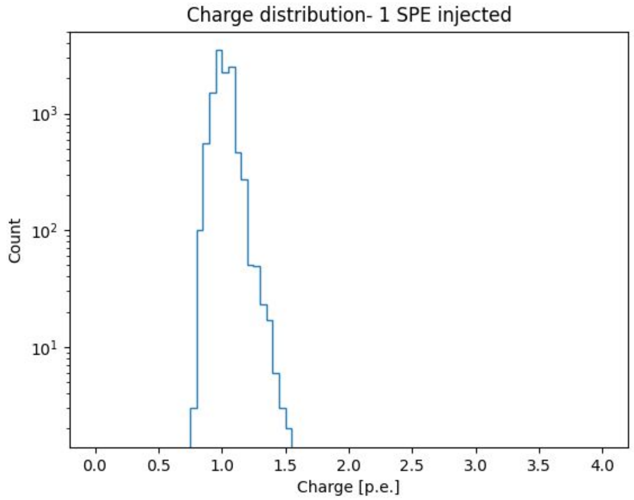


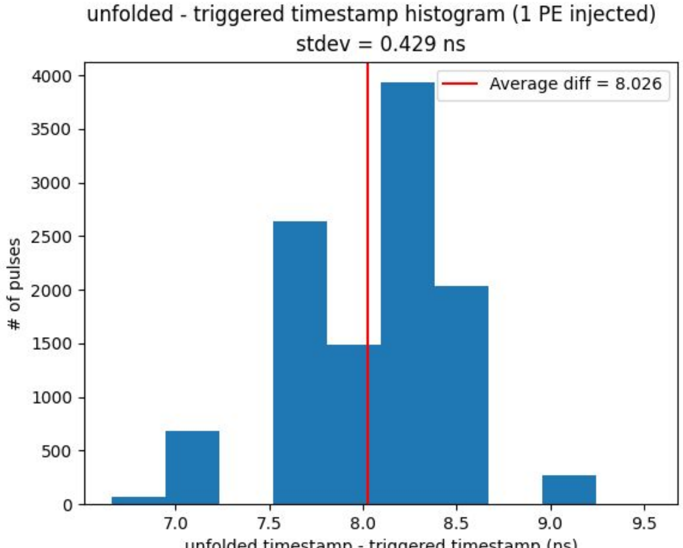




Unfolding Simulation

- Software in progress to perform unfolding on both real and simulated pulses
- Single PE simulation is able to well reconstruct SPEs
    - Recovers timing and charge





MICHIGAN STATE UNIVERSITY