Comparing Timing Resolution Improvements using the Tapered-Sinc Interpolation Algorithm for Various Readout Methods

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Introduction and Motivation

- Detection imaging systems used for nonproliferation purposes require high precision timing

- *NNSA mission relevance and other applications*
  - Improving timing resolution will improve…
    - **Imaging systems that can locate orphan sources for nonproliferation and safeguards purposes**
    - Positron Emission Tomography (PET) systems to evaluate biochemical processes

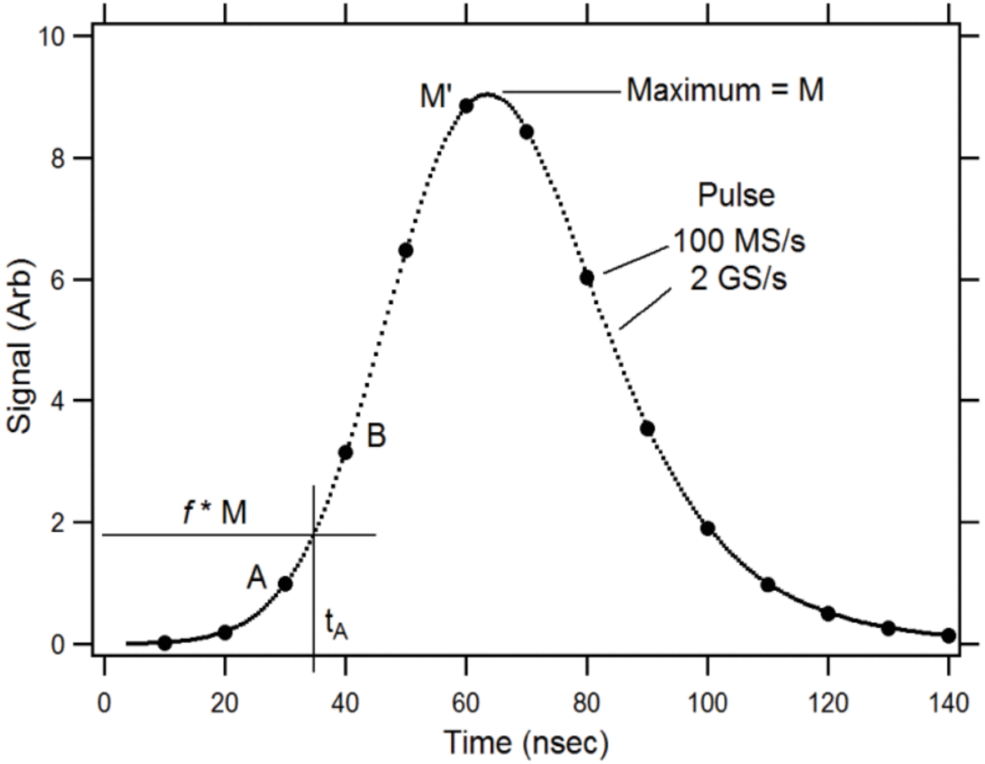
- Digitizers for data acquisition have fixed sampling rates
  - Can limit coincidence timing resolution (CTR) of fast scintillators like organic scintillators

Orphan Cs-137 source located via radiation imaging systems in Australian Outback

Photo credit: Radford, Antoinette. "How a Tiny Radioactive Capsule Was Found in Australia's Vast Outback." *BBC News*, BBC, 1 Feb. 2023.

T-Sinc Function Motivation

- Post processing interpolation algorithms can increase sampling rate of pulse, ultimately improving coincidence timing resolution (CTR)
- Fill in rising edge of pulse
- Use constant fraction discriminator (CFD) to measure CTR
  - Improve CTR via interpolation and increased sampling rate with t-sinc algorithm
- Investigate functionality on Photomultiplier Tube (PMT) vs. Silicon Photomultiplier (SiPM) readout methods



Fast pulse interpolated using t-sinc algorithm

Photo Credit: W. K. Warburton and W. Hennig, "New Algorithms for Improved Digital Pulse Arrival Timing With Sub-GSps ADCs," in IEEE Transactions on Nuclear Science, vol. 64, no. 12, pp. 2938-2950, Dec. 2017, doi: 10.1109/TNS.2017.2766074.

T-Sinc Function Background

T-Sinc is the tapered sinc function:

- $\mathrm{sinc}(x) = \sin(x)/x$
- $\mathrm{tsinc}(i) = \mathrm{sinc}(i\pi/N)\exp(-(i/T)^2)$
- $$g(j,k) = \sum_{i=0}^{L-1}(y(j-i)\mathrm{tsinc}(iN+k) + y(j+1+i)\mathrm{tsinc}((i+1)N-k))$$

N - Number of interpolated points

T - Tapering constant

L - Number of lobes

W. K. Warburton and W. Hennig, "New Algorithms for Improved Digital Pulse Arrival Timing With Sub-GSps ADCs," in IEEE Transactions on Nuclear Science, vol. 64, no. 12, pp. 2938-2950, Dec. 2017, doi: 10.1109/TNS.2017.2766074.

Coincidence Timing Resolution (CTR) Background

- CTR quantifies system resolution
  - **Readout method**
    - **Photomultiplier Tube**
    - **Silicon Photomultiplier**
- Annihilation photons from centered ^{22}Na source should theoretically hit detectors at the same time/consistent difference in time
  - Deviance implies non-zero timing resolution
  - Quantified using full-width at half maximum

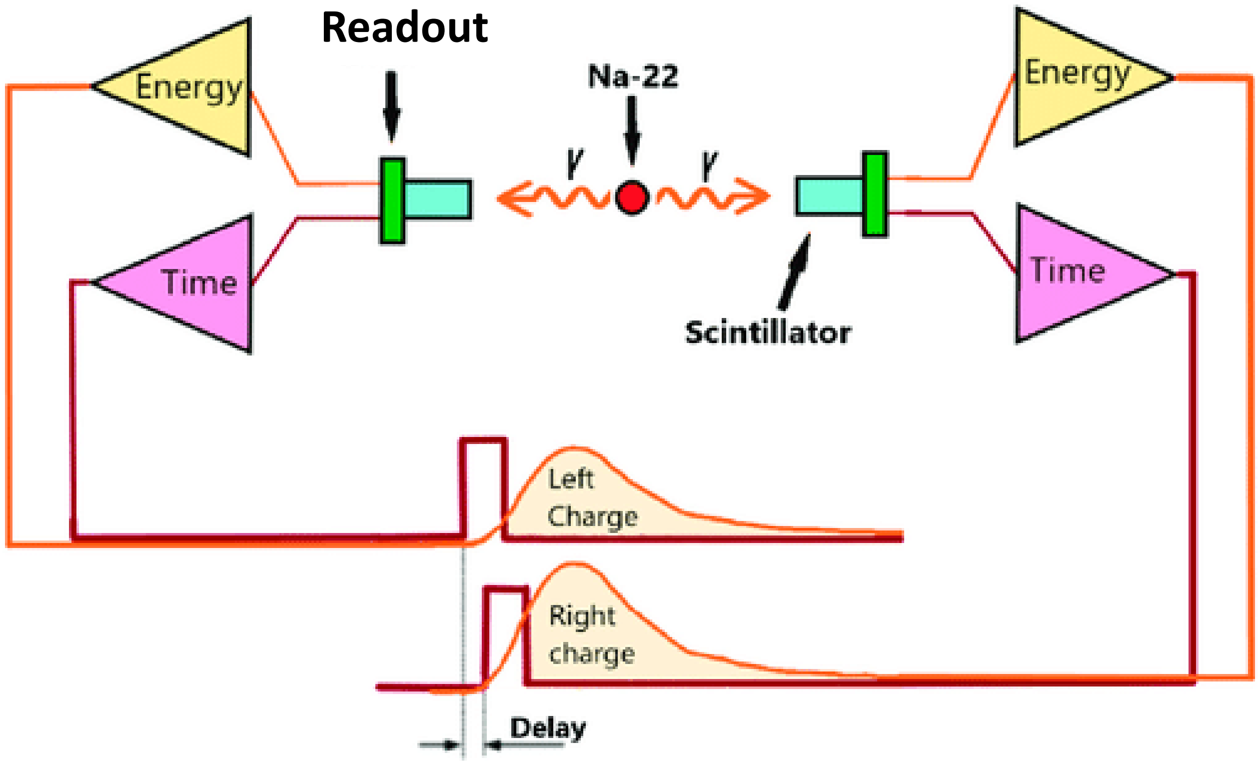


Photo Credit: Pots, Rosalinde & Gundacker, Stefan & Auffray, Etiennette. (2020). “Exploiting Cross-Luminescence in BaF2 for Ultrafast Timing Applications Using Deep-Ultraviolet Sensitive HPK Silicon Photomultipliers.” Frontiers in Physics. 8. 10.3389/fphy.2020.592875.

Coincidence Timing Resolution Experiment Set-Up

Two experiments performed comparing different readout methods…

1. Photomultiplier tubes:

- Bare 6 mm edge organic glass scintillator (OGS)* cubes tested and coupled to 38.1 mm diameter Hamamatsu H3178-51 PMTs

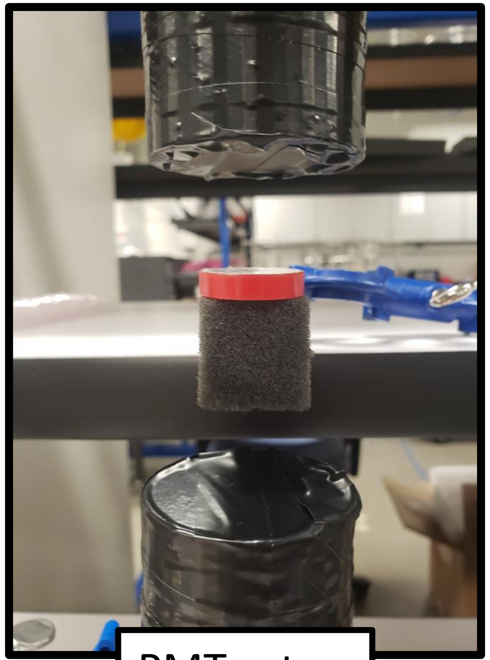
2. Silicon photomultipliers:

- Teflon wrapped 6 mm edge OGS* cubes tested
- SiPM readout on single board

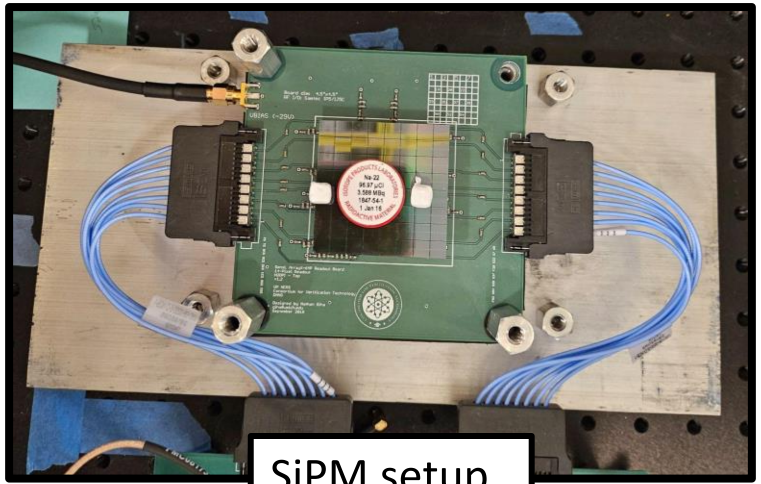
Both experiments used…

- Cs-137 source for calibration
- 2.5 GHz oscilloscope for acquisition
- Na-22 centered between detectors to measure annihilation protons

* Sandia National Laboratories



PMT setup



SiPM setup

T-Sinc Analysis Procedure

1. Using the CoMPASS data acquisition system to acquire fast pulses from 2.5 GHz oscilloscope, find the CFD time difference between Channel 1 and Channel 2 for every set of coincidence pulses.
   a. CFD fraction = 20%
   b. Threshold set at 50mV

2. Histogram the time difference

3. Repeat the above steps with down-sampled data and interpolated data.

T-Sinc Analysis Procedure

Original Pulse

Downsampled Pulse

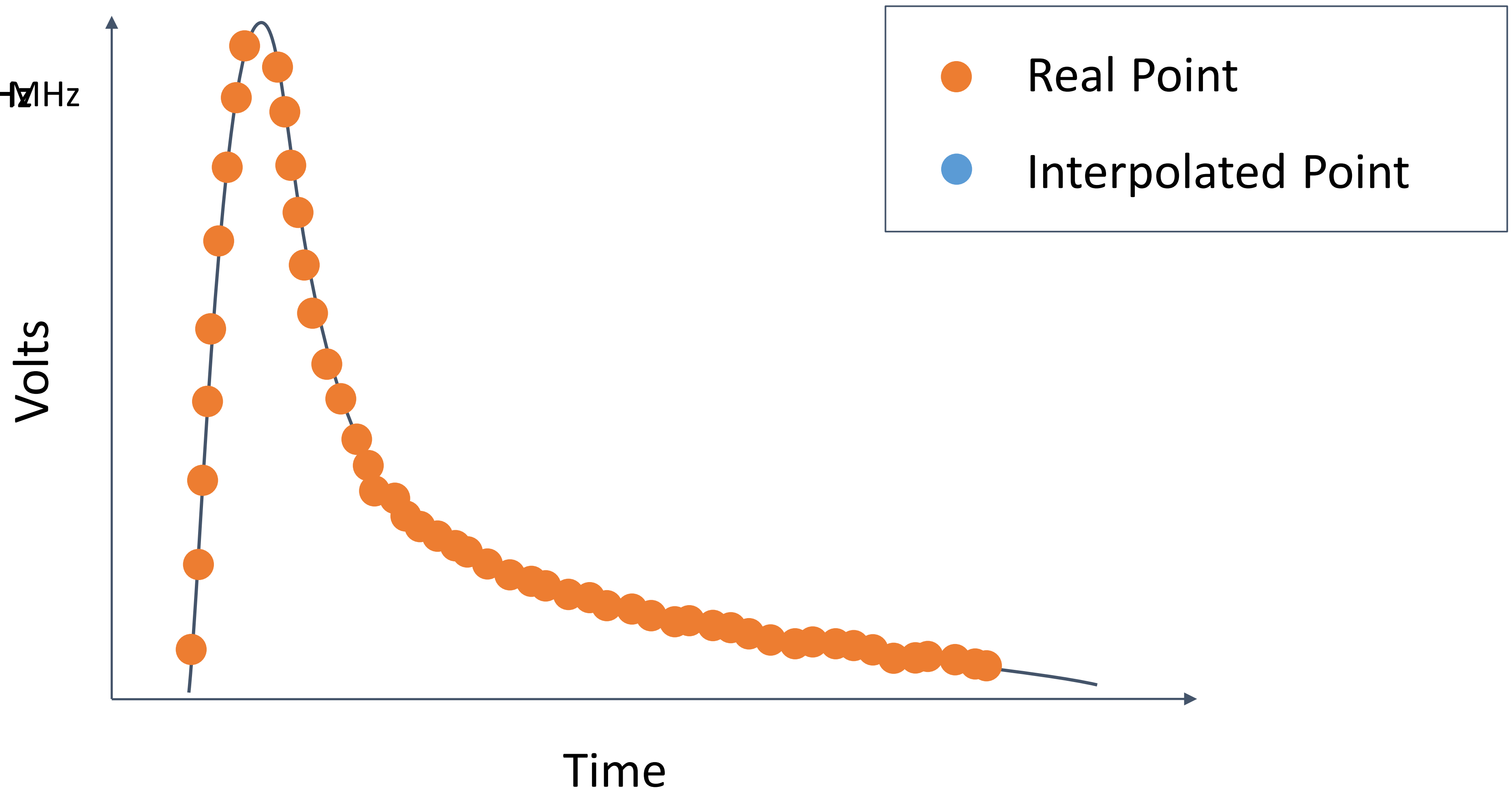
Interpolated Pulse

Sampling Frequency = 2.5 GHz

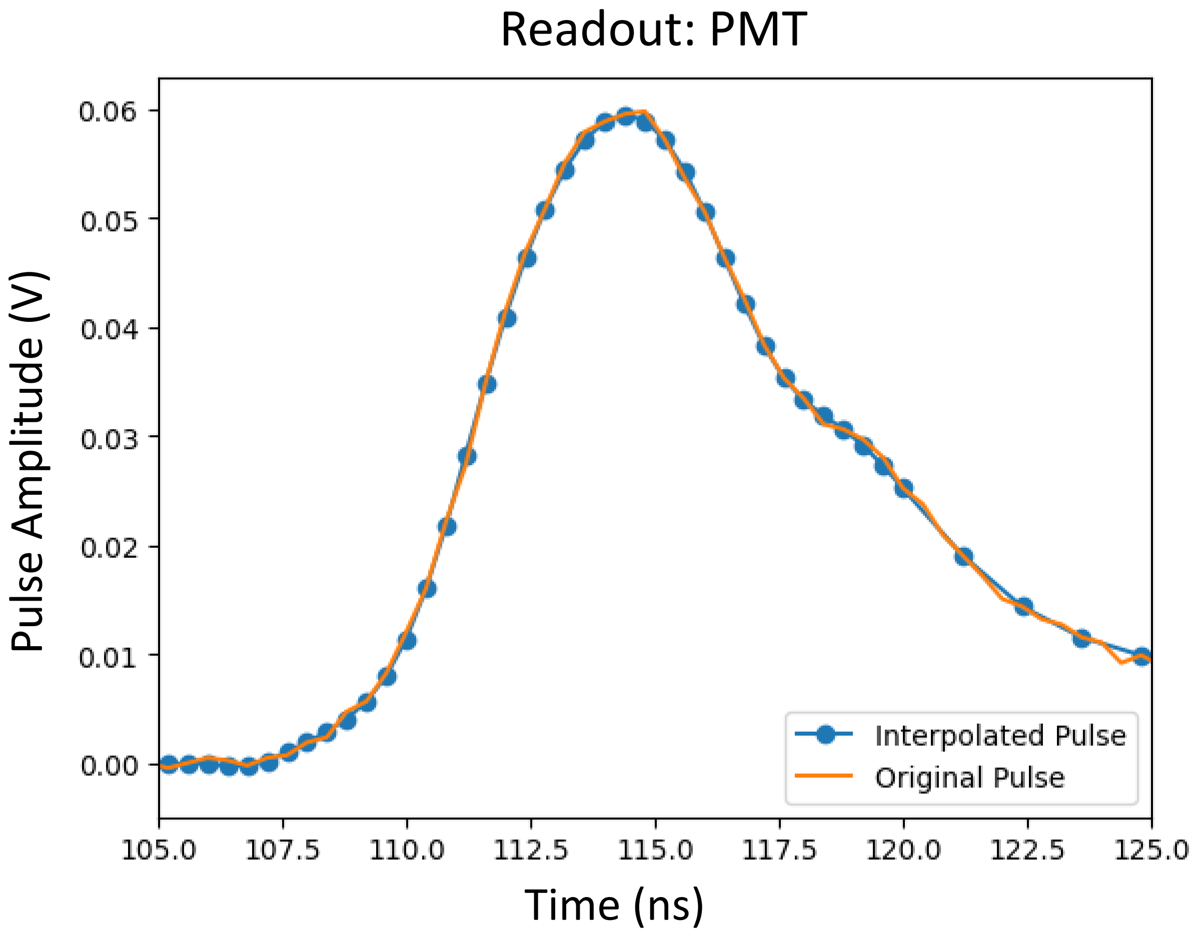
Sampling Frequency = 833 MHz

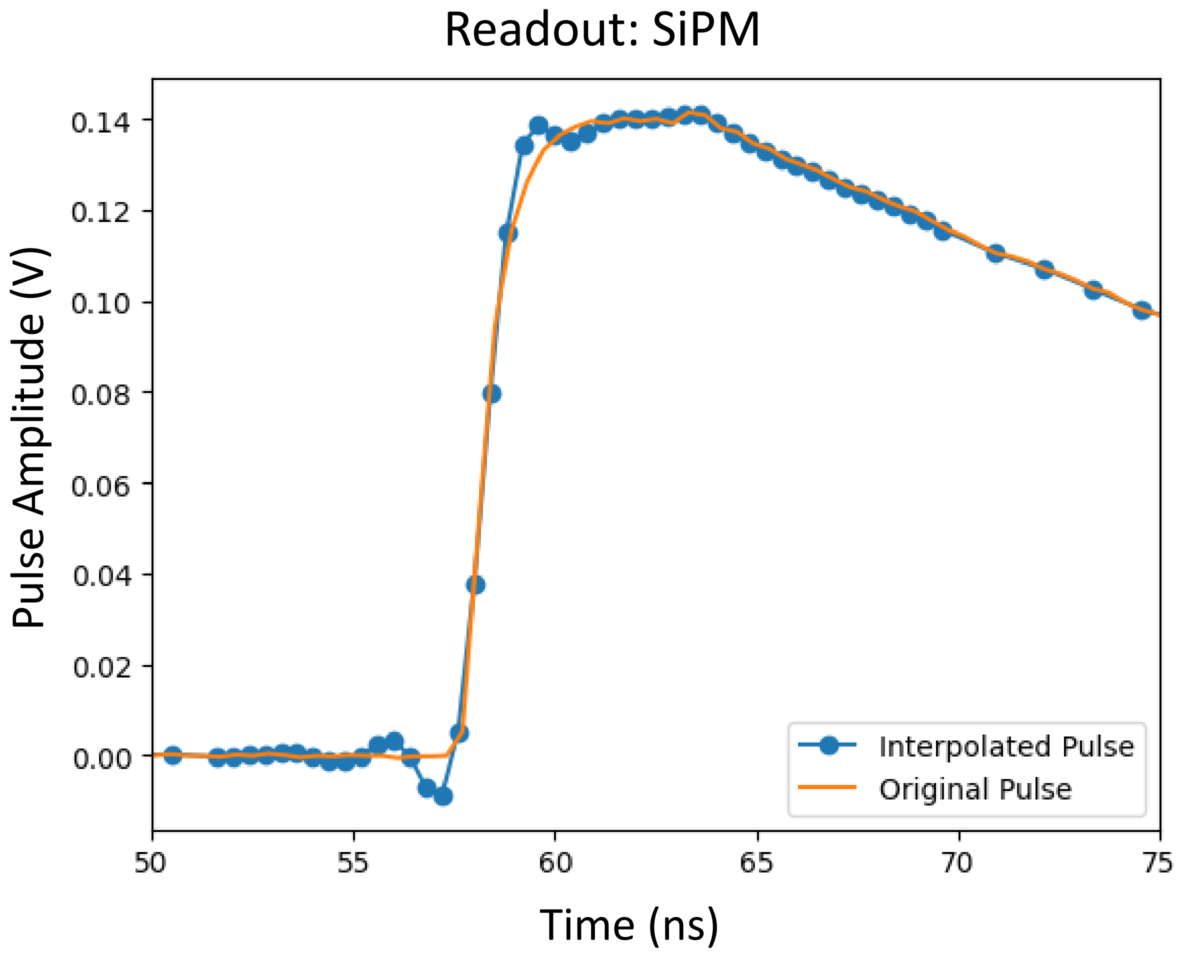
Downsampling factor $N = 3$

Upsampling factor $N = 3$



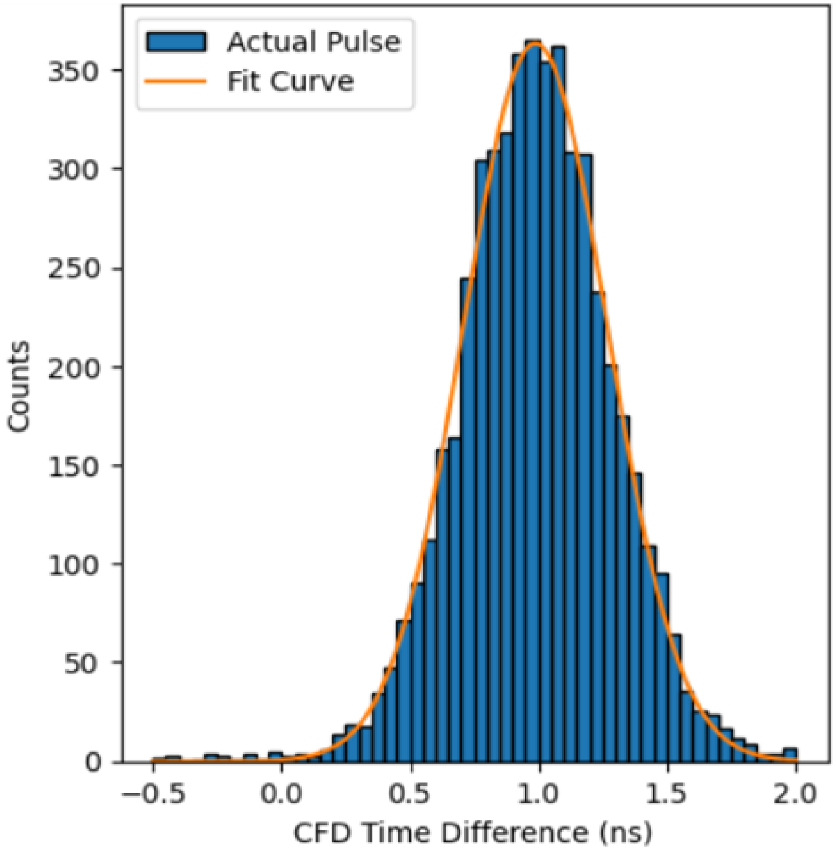
Example Reconstructed Pulses





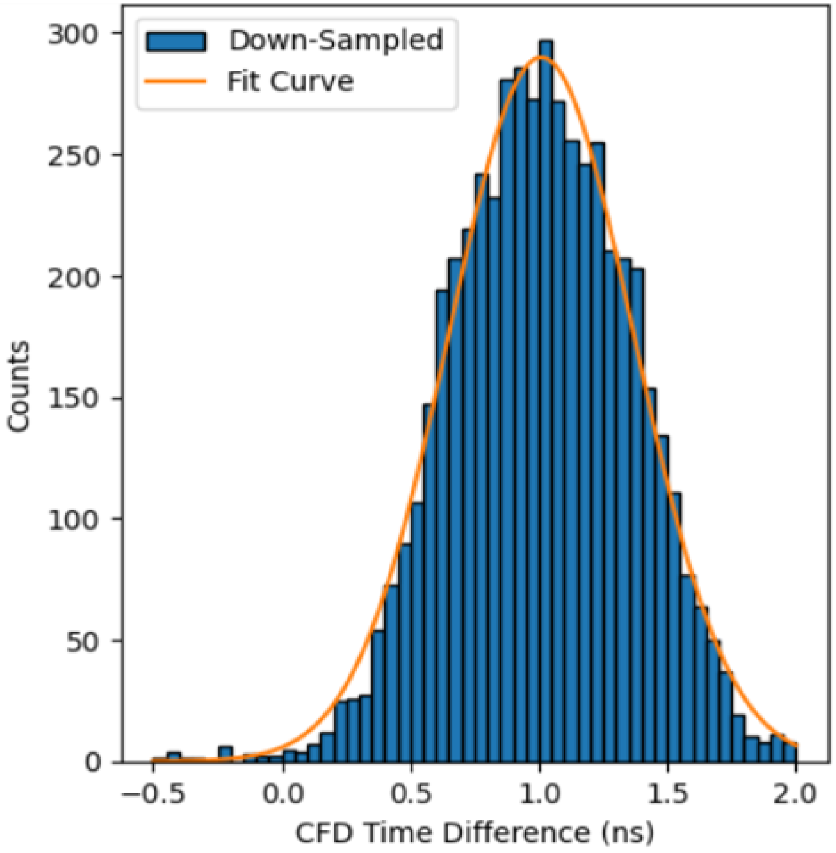
T-Sinc Function on PMT Data *N* = 5

Actual Pulse



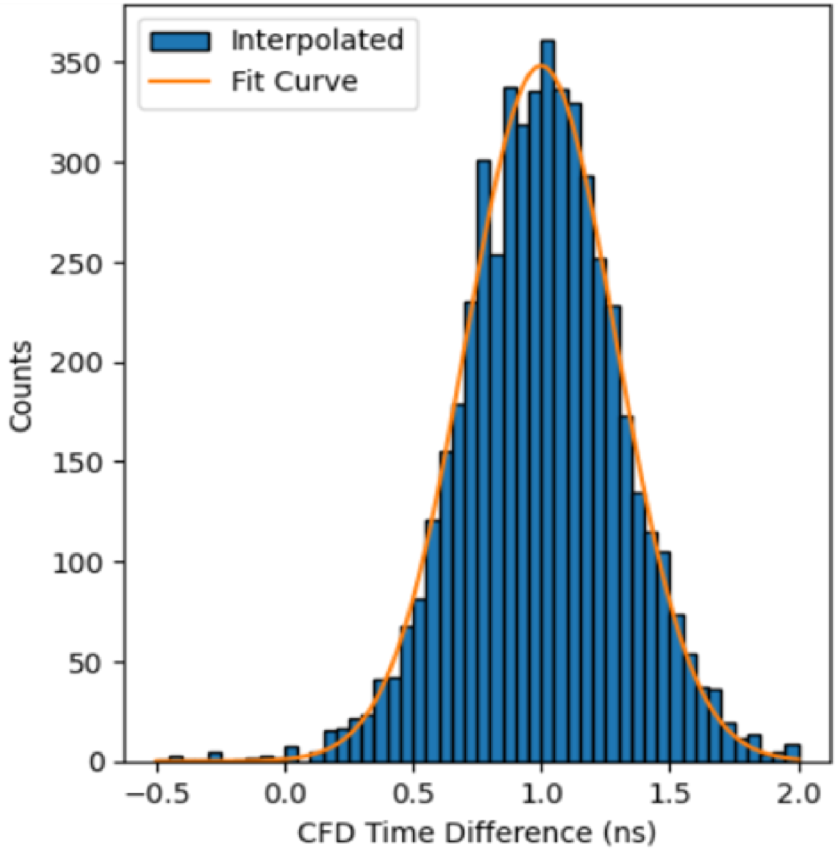
FWHM = 0.660 ns

Down-Sampled Pulse



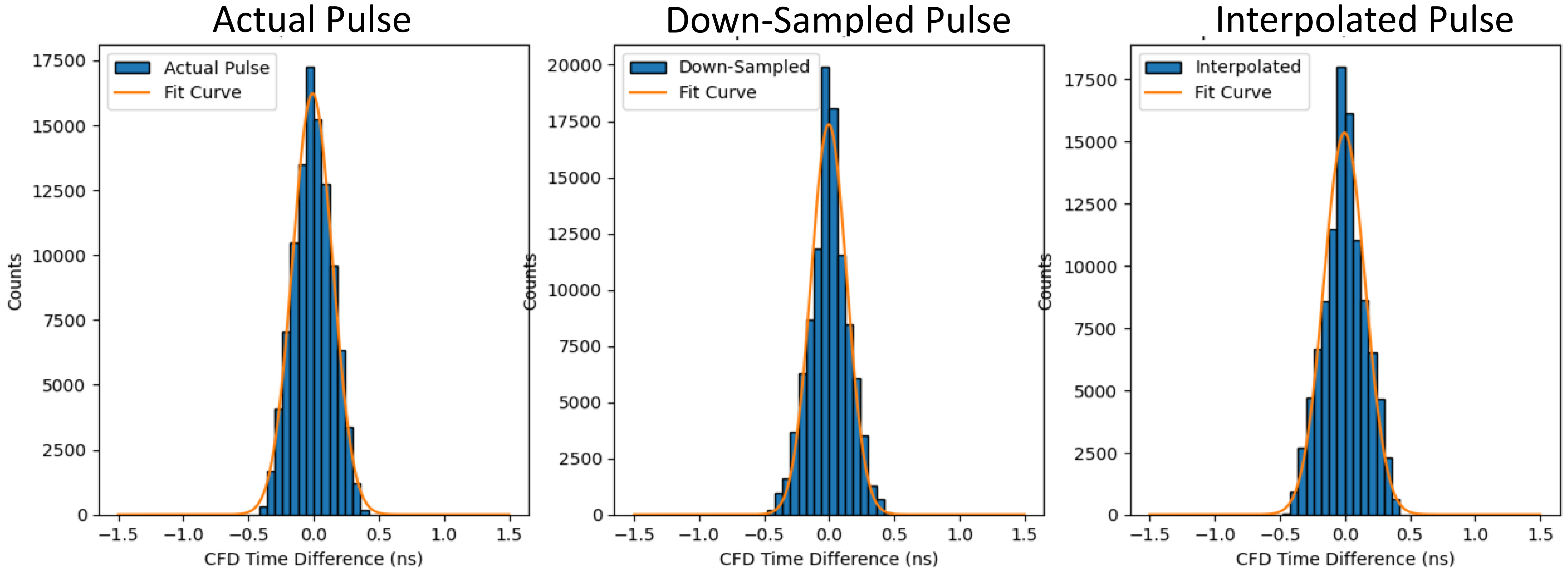
FWHM = 0.848 ns

Interpolated Pulse



FWHM = 0.688 ns

T-Sinc Function on SiPM Data *N* = 3



FWHM = 0.362 ns

FWHM = 0.324 ns

FWHM = 0.374 ns

Results Summarized

	3.81 cm Diameter PMT	Single Board SiPM
Actual pulse FWHM (ground truth) (ns)	0.66	0.36
Down-sampled pulse FWHM (ns)	0.85	0.32
Interpolated pulse FWHM (ns)	0.69	0.37
Actual and interpolated FWHM percent difference (%)	4.5	2.8
Down-sampled and interpolated FWHM percent difference (%)	**23**	**1.6**

Conclusion and Impacts

- T-sinc improves coincidence timing resolution by 20% on photomultiplier tube readout with organic glass cubes
  - Does not have the same impact on silicon photomultiplier data
    - Perhaps due to differing pulse shape of SiPM pulses

- The t-sinc algorithm gives the potential of a **higher sampling frequency** while using low frequency readout methods
  - Impacts experiments that require high precision timing such as coincidence timing resolution

- Improved sampling rate in post processing can improve **radiation imaging systems** for **safeguarding purposes** in line with NNSA mission

Next Steps

- Investigate t-sinc parameters
  - *N* - Number of interpolated points
  - *T* - Tapering constant
  - *L* - Number of lobes

- Investigate other post-processing methods
  - Step function

- Investigate other equipment
  - Various diameter PMTs
  - Various data acquisition systems

Acknowledgements

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