Data Processing and Calibration

Kurtis Nishimura
University of Hawaii
LAPPD Electronics Godparent Review
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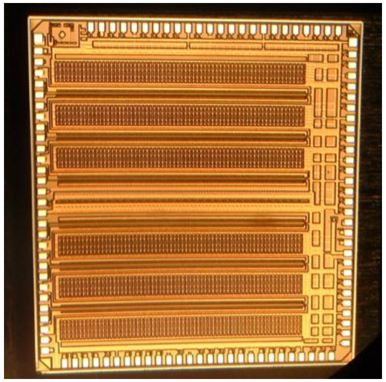
Oscilloscope on a chip?



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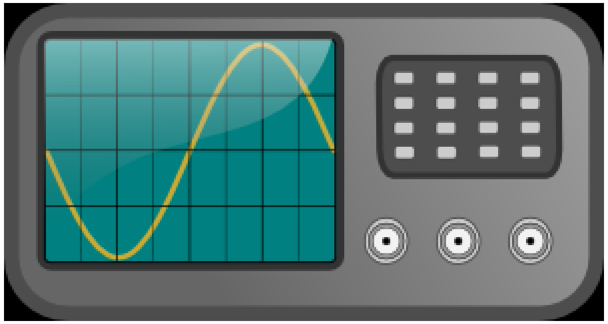
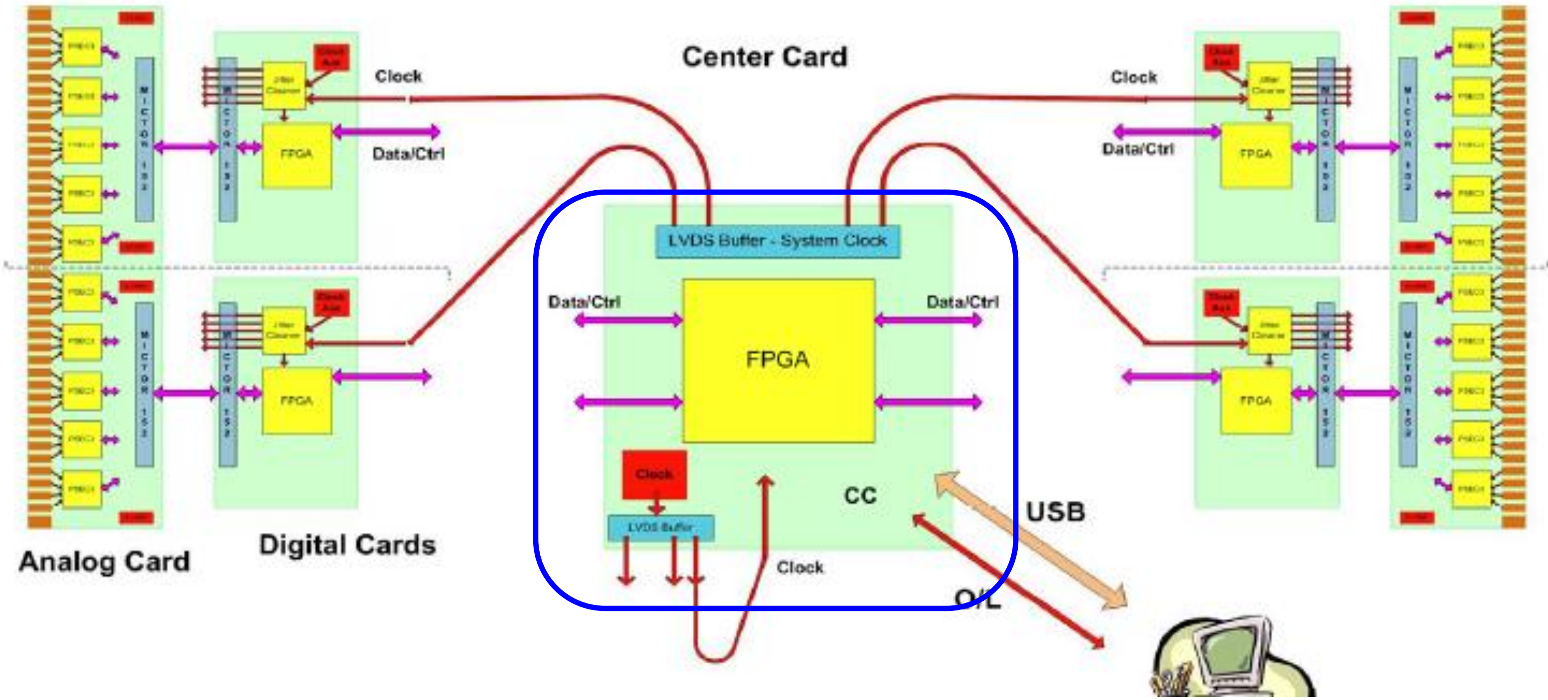


- Some fundamental differences between switched-capacitor array waveform digitizers and oscilloscopes:
  - Possible benefits:
    - **High channel densities.**
    - **Low relative cost per channel.**
    - **Low power.**
  - Potential drawbacks:
    - **Many calibrations are required to get to equivalent of a scope trace.**
- Outputs are application specific:
  - Waveforms are great for debugging, but **feature extraction** ultimately desired.
    - e.g., outputs from a tile might be **x**,**y**,**t**,**q** for each hit
    - If 3 strips read out per hit, this is the difference between 2.3 kB (full waveforms) and 16 bytes (32-bits each for **x**,**y**,**t**,**q**).

SuperModule Feature Extraction (FPGA)

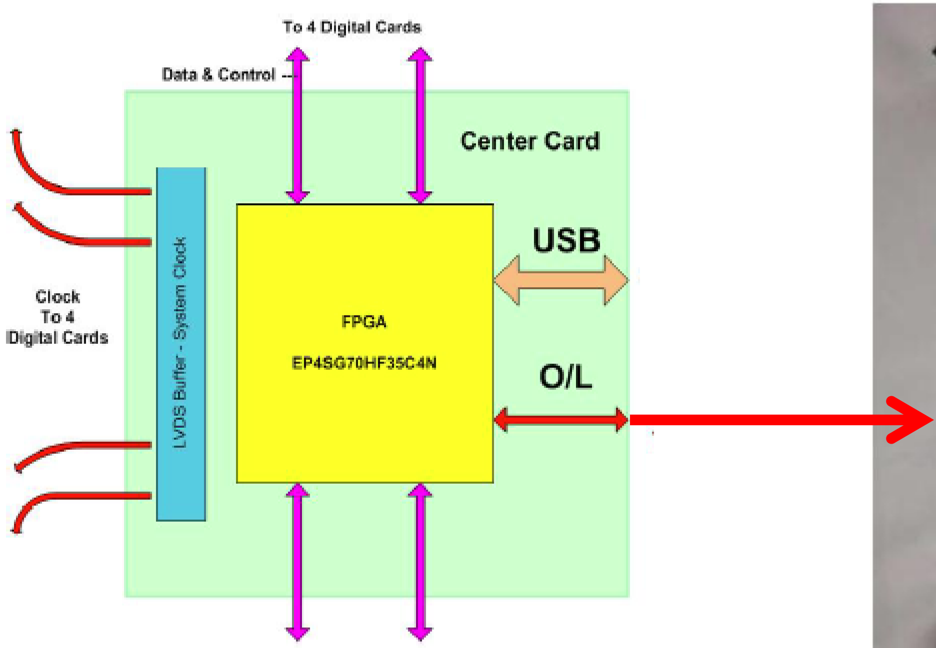


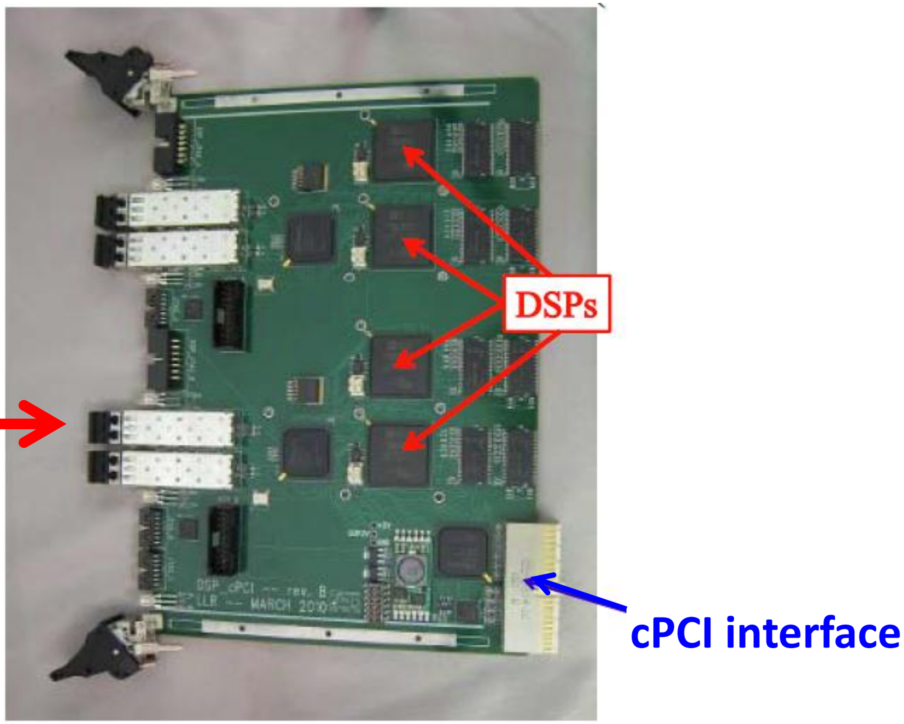
- **Baseline FPGA processing model**: the **central FPGA** performs necessary corrections and feature extraction.

➔ End user sees corrected waveforms or feature extracted data.

- Uses existing system hardware.
- Algorithms implemented in **HDL** : firmware.

Alternative Model: Calibrations in DSPs





- **DSP processing model**: raw data sent by fiberoptic to dedicated digital signal processing modules.

➔ End user sees corrected waveforms or feature extracted data.

- Extra hardware needed.
- Development ongoing in Hawaii for other projects (e.g., Belle II).
- Algorithms implementated in **C** : embedded software.

Calibrations Required

1. Voltage conversion:
   – Convert ADC counts to voltage.
2. Pedestal correction:
   – Remove cell-to-cell fixed DC patterns.
3. Time base correction:
   – Keep overall sampling rate constant (or correct for drift).
   – Correct for cell-to-cell variations in sampling rate.

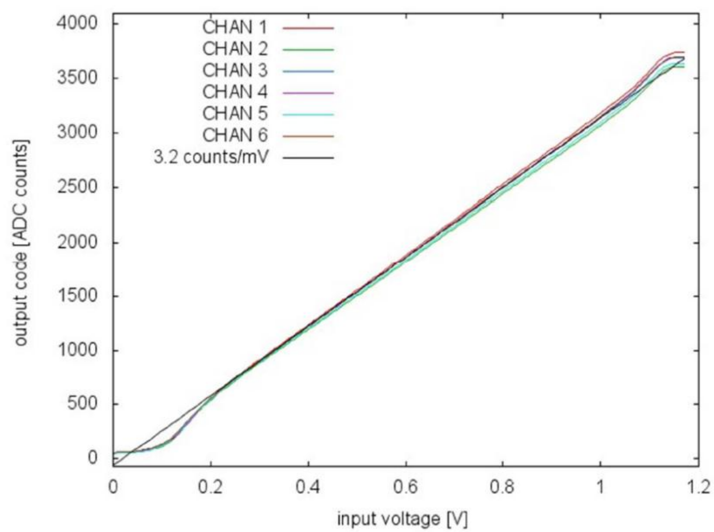
➔ Calibrations have been studied with full waveforms in <u>software</u>. Still to be implemented in firmware.

Calibrations Required

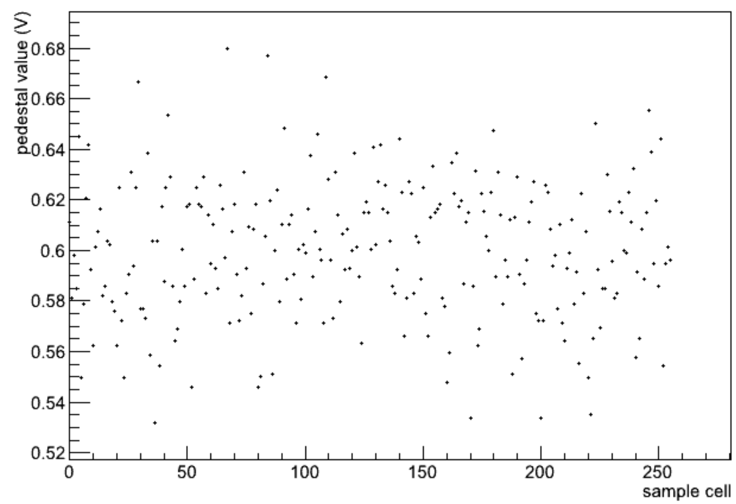
1. Voltage conversion:
   – Convert ADC counts to voltage.
2. Pedestal correction:
   – Remove cell-to-cell fixed DC patterns.

➔ **Straightforward to measure and apply these calibrations.**

1. Output code vs. input voltage



2. Output code vs. input voltage



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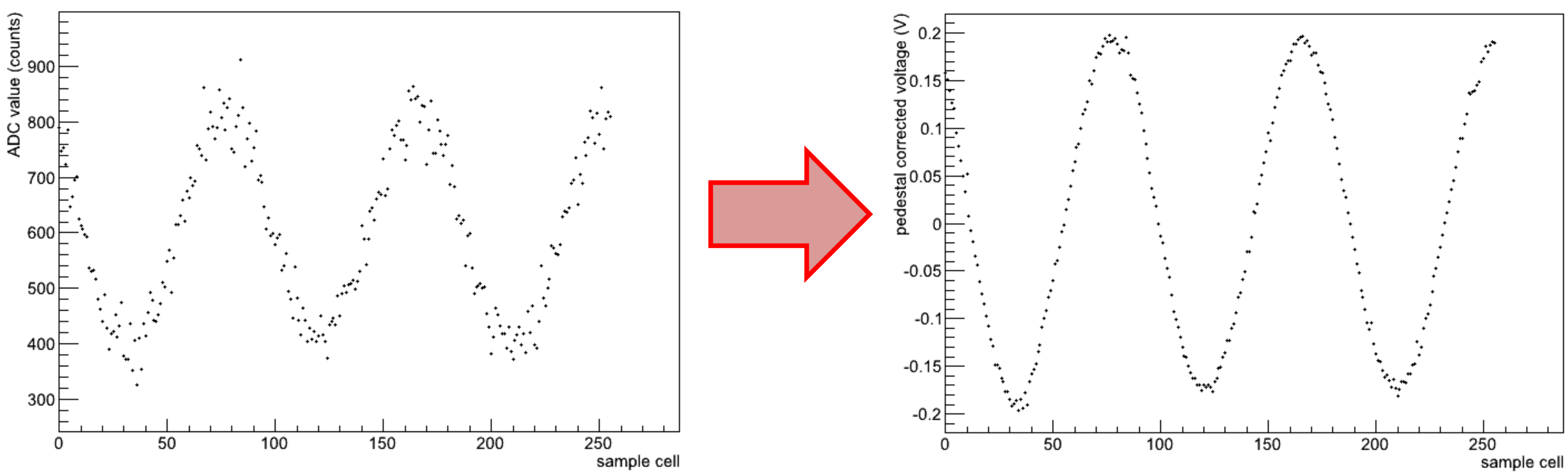
➔ **Straightforward to measure and apply these calibrations.**

➔ **For some applications, these alone are enough.**

Raw readout of 120 MHz sine input | **120 MHz input, voltage/pedestal corrected**



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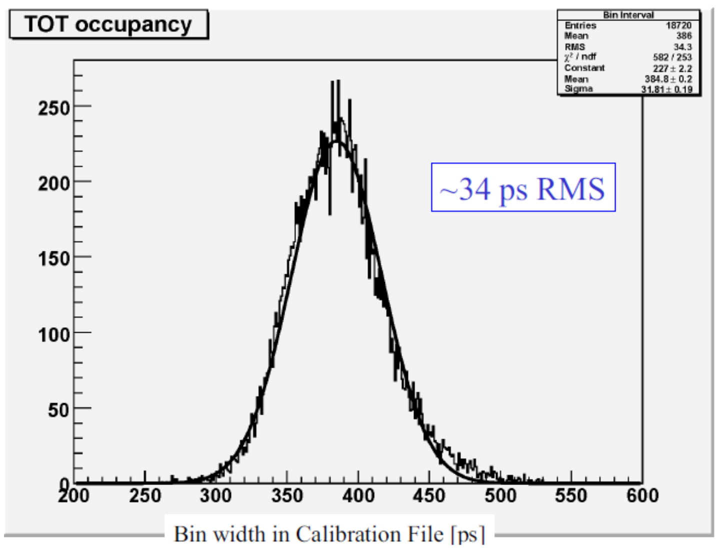
   – Keep overall sampling rate constant (or correct for drift).
   – **Correct for cell-to-cell variations in sampling rate.**

→ **Historically tricker: substantial effort has been spent here.**

***May only be required for applications where "precision" timing is required.**

Time Base Corrections

- Overall time base drift:
  - ☑ **On PSEC3, overall sampling rate is locked by DLL.**
- Still needed:
  - ❑ Precise measurement of the sampling rate.
  - ❑ Calibration of individual time delays between sample cells ($\Delta t_{i,i+1}$).



Variations are a natural consequence of delay-line sampling technique.

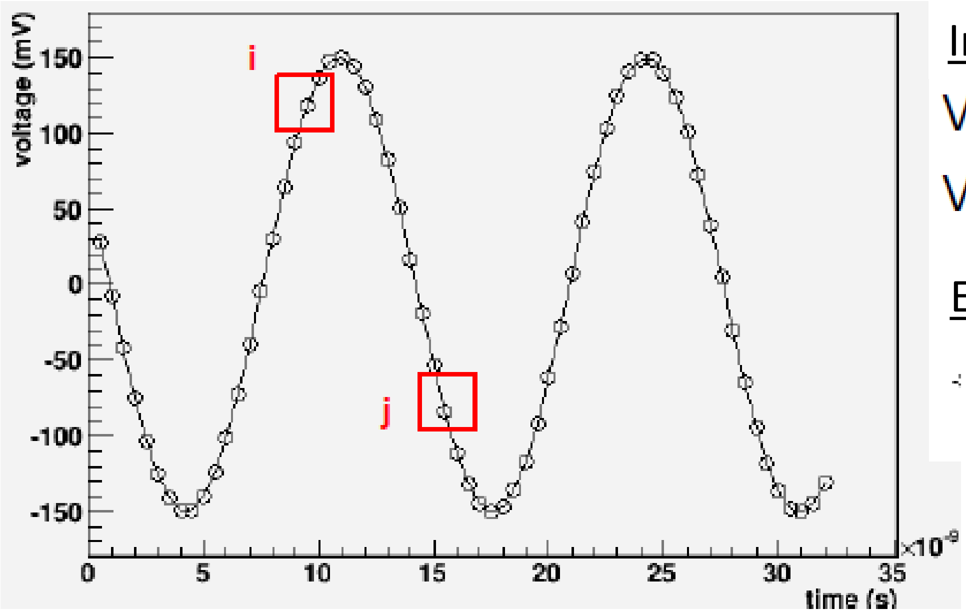
Example from LABRADOR3 ASIC: arXiv:physics/0509023

Mean sample-to-sample time: 385 ps (~2.6 GSa/s)
Measured σ of sample-to-sample time: 34 ps (~10%)

- We typically use sine wave inputs of known frequency.

Timing Calibration w/ Correlations

- Plot correlations between pairs of samples:
  - To determine Δt_{ij}, plot $V_i - V_j$ versus $V_i + V_j$



<u>Input signals given by</u>:

$V_i = A \sin(\omega t_i + \phi)$

$V_j = A \sin(\omega t_j + \phi)$

<u>Effectively rotate by 45°</u>:

- $x := V_i + V_j$
- $y := V_i - V_j$

$$\rightarrow \frac{x^2}{4A^2\cos^2(\omega\delta t/2)} + \frac{y^2}{4A^2\sin^2(\omega\delta t/2)} = 1$$

- **i and j can be adjacent (or not), but cycle ambiguities exist if > 1 period apart.**

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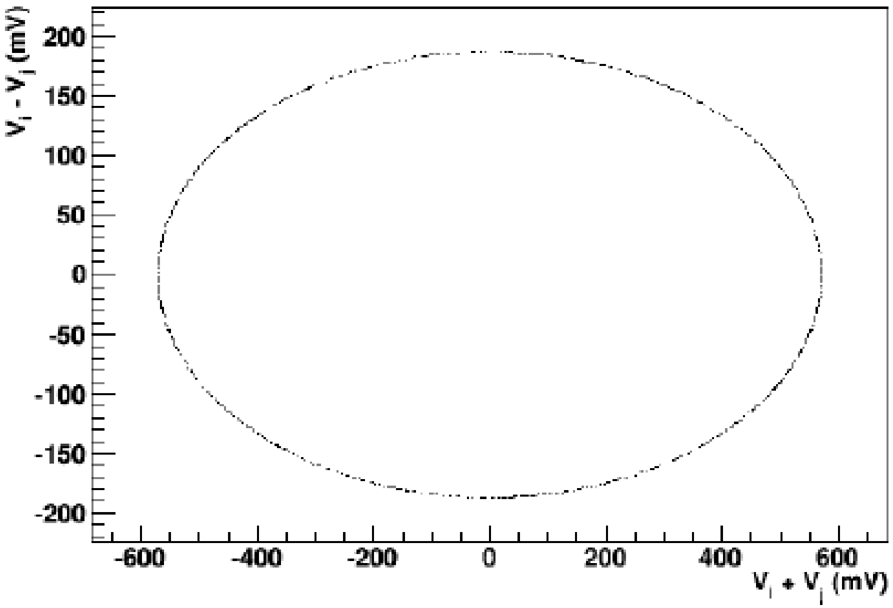

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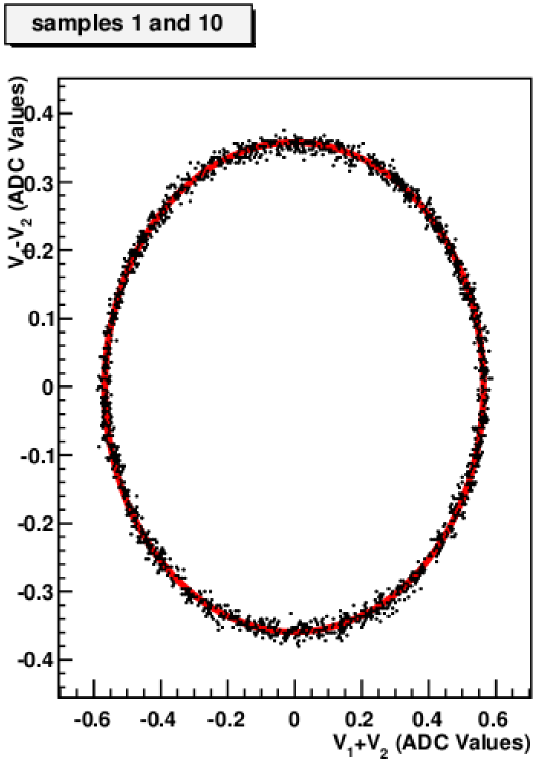
➔ $$\frac{x^2}{4A^2\cos^2(\omega\delta t/2)} + \frac{y^2}{4A^2\sin^2(\omega\delta t/2)} = 1$$

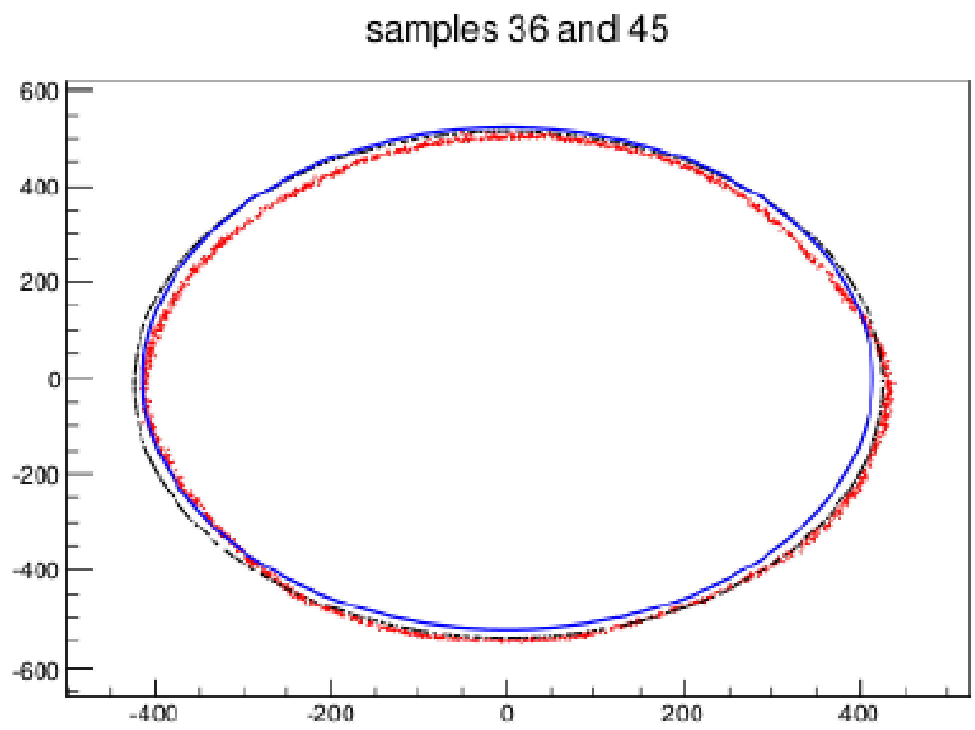
- **i and j can be adjacent (or not), but cycle ambiguities exist if > 1 period apart.**
- **Technique was presented at TIPP 2011 & paper to appear in Physics Procedia.**

Successes and Failures

Oscilloscope Data and Fit



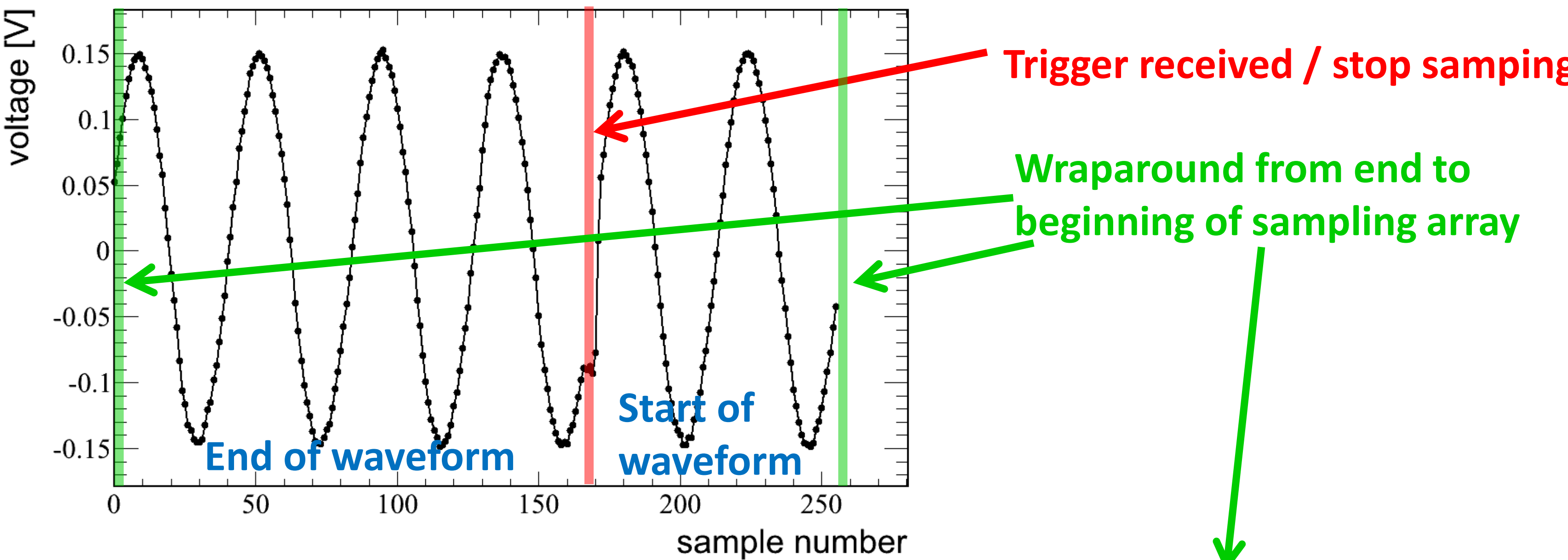
PSEC-4 Data and Fit



This procedure worked reasonably well on PSEC-3, but...
...PSEC-4 response is not well described by the ellipse.
Possible causes? Nonlinearities, correlated noise, other non-idealities?

➔ Fell back to a simpler "brute-force" technique. This may be revisited, as these features might provide insights into PSEC performance.

Another Method: Zero Crossings

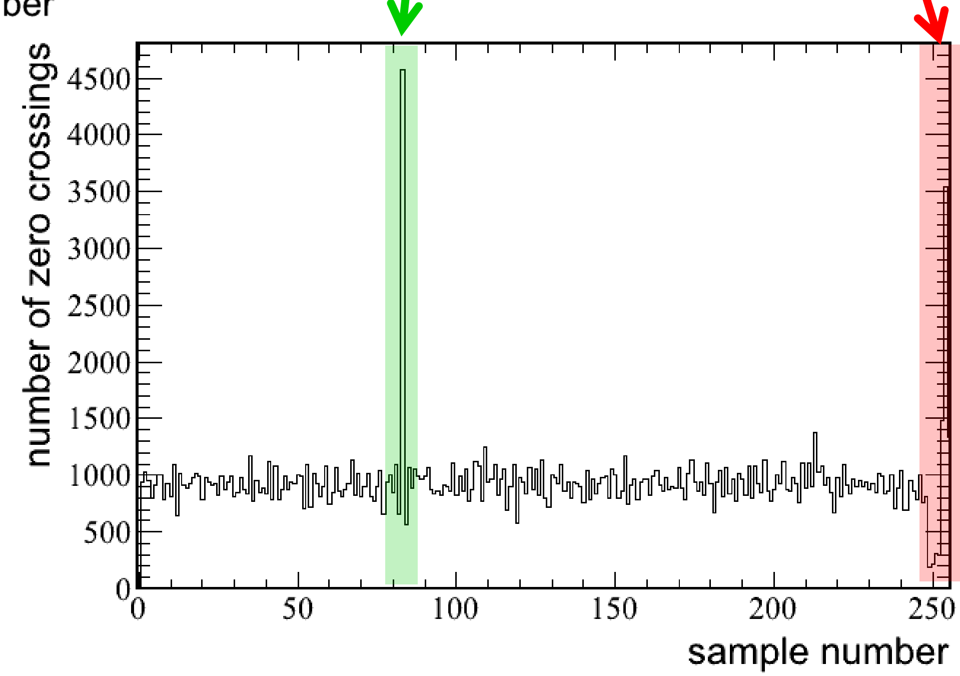


Measure occupancy of zero crossings between each pair of samples.

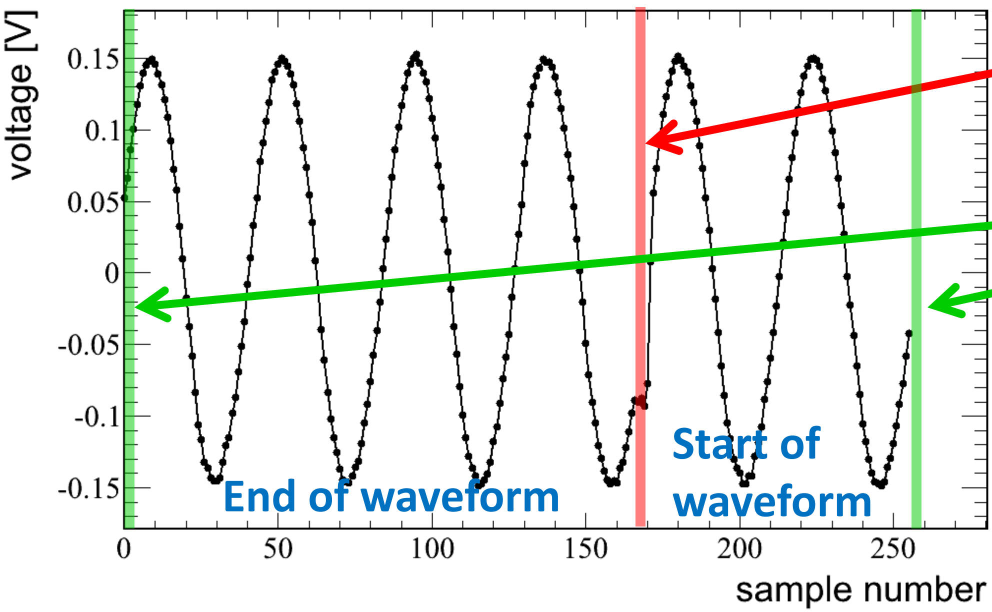
Longer delay between samples ➔ more zero crossings.

Shorter delay between samples ➔ fewer zero crossings.

Occupancy ∝ Δt



Another Method: Zero Crossings



Trigger received / stop samping

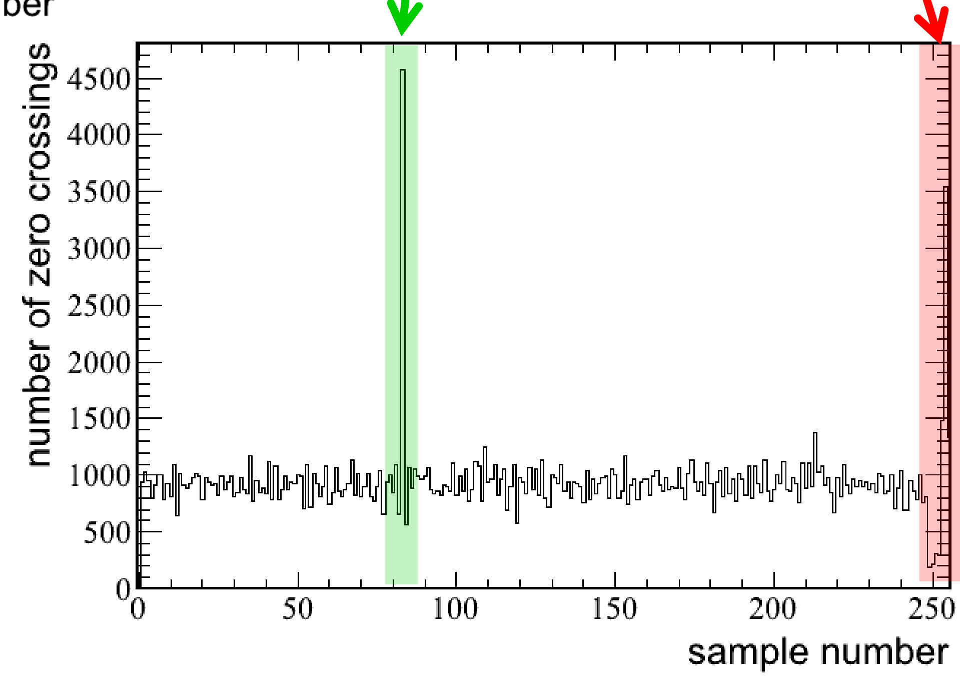
Wraparound from end to beginning of sampling array

Measure occupancy of zero crossings between each pair of samples.

Longer delay between samples ➔ more zero crossings.

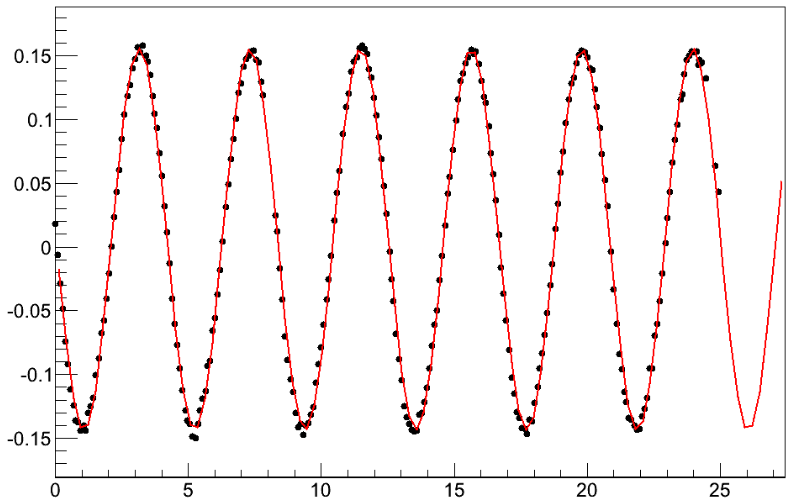
Shorter delay between samples ➔ fewer zero crossings.

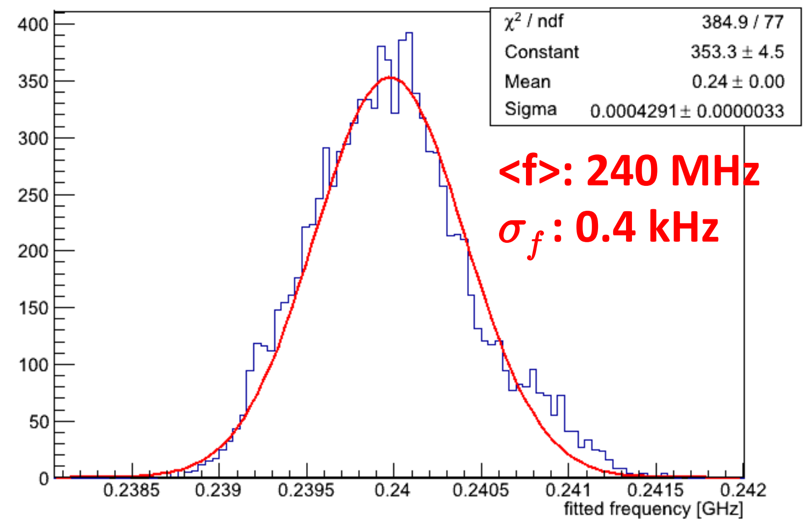
Occupancy $\propto \Delta t$



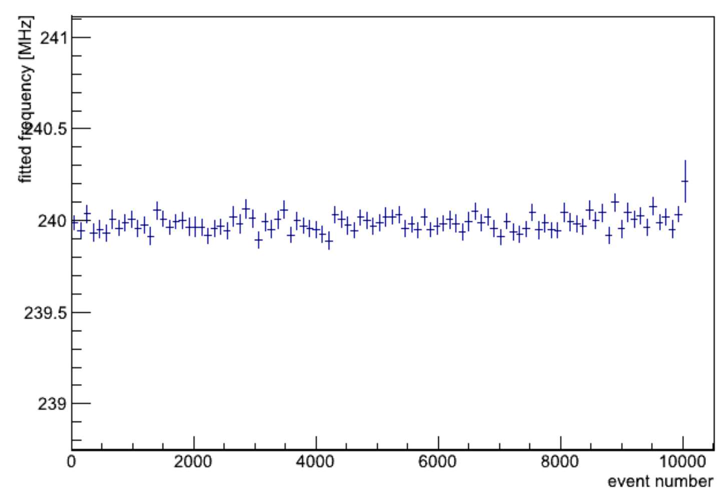
Zero Crossing Validation

- Apply Δt values (from first 10,000 events) and fit sine waves (from second 10,000 events):





- No obvious event number dependence.
- Good fit quality.
- Period in = period fitted.

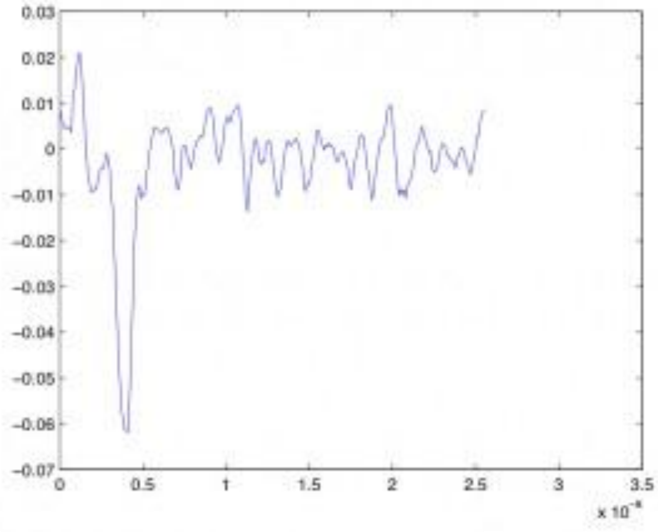


➔ Offline calibration procedures are in good shape...

Feature Extraction

- Extract features from raw waveforms.
- Examples:
  - Pulse height measurements.
  - Pulse timing.
    - e.g., fixed-threshold, CFD.
  - Pulse location (x,y).
    - e.g., charge centroid.
  - Digital filtering?
    - Requires some resampling gymnastics if FFTs are involved.
- Exact requirements depend on application.

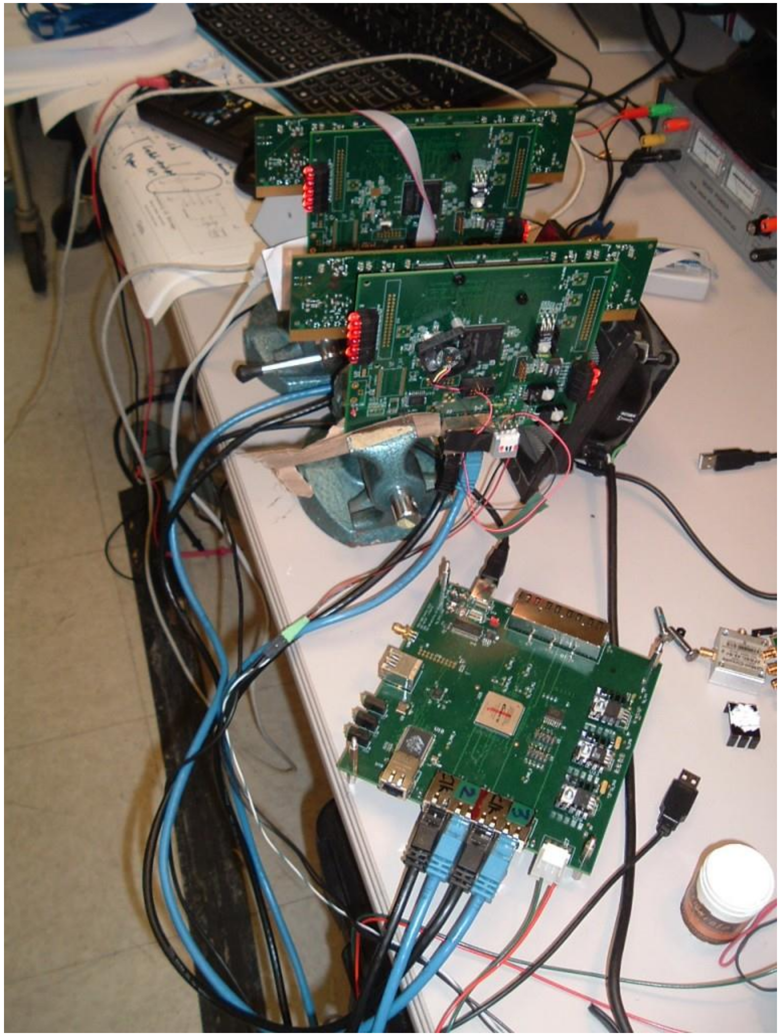
Example laser pulse with PSEC-4 evaluation board



Status and Next Steps

- Baseline calibration techniques are available in software.
  - Code in TRAC repository: https://lappd-trac.uchicago.edu/
- With SuperModule electronics operational, we can begin moving toward integrated system:
  - **We will soon need firmware/embedded software for**:
    - **Application of calibration constants.**
    - **Feature extraction.**

  *****Details and complexity may vary by application.



BACKUP

Pedestals

- Straightforward, except…
  - If ADC is nonlinear… for a given cell i:
    - $V_i^{ped} \neq (1/N) \sum ADC_i$
    - $V_i^{ped} = (1/N) \sum LUT(ADC_i)$
      - Where LUT is the lookup table from ADC counts to voltage.
      - In worst case, this LUT can vary significantly from cell-to-cell.
  - Other possible artifacts:
    - If distribution of noise is bimodal or multimodal, the mean is not the right measure of the most likely voltage for the cell.
  - Temperature dependence:
    - The pedestals may drift with temperature or other environmental variables.

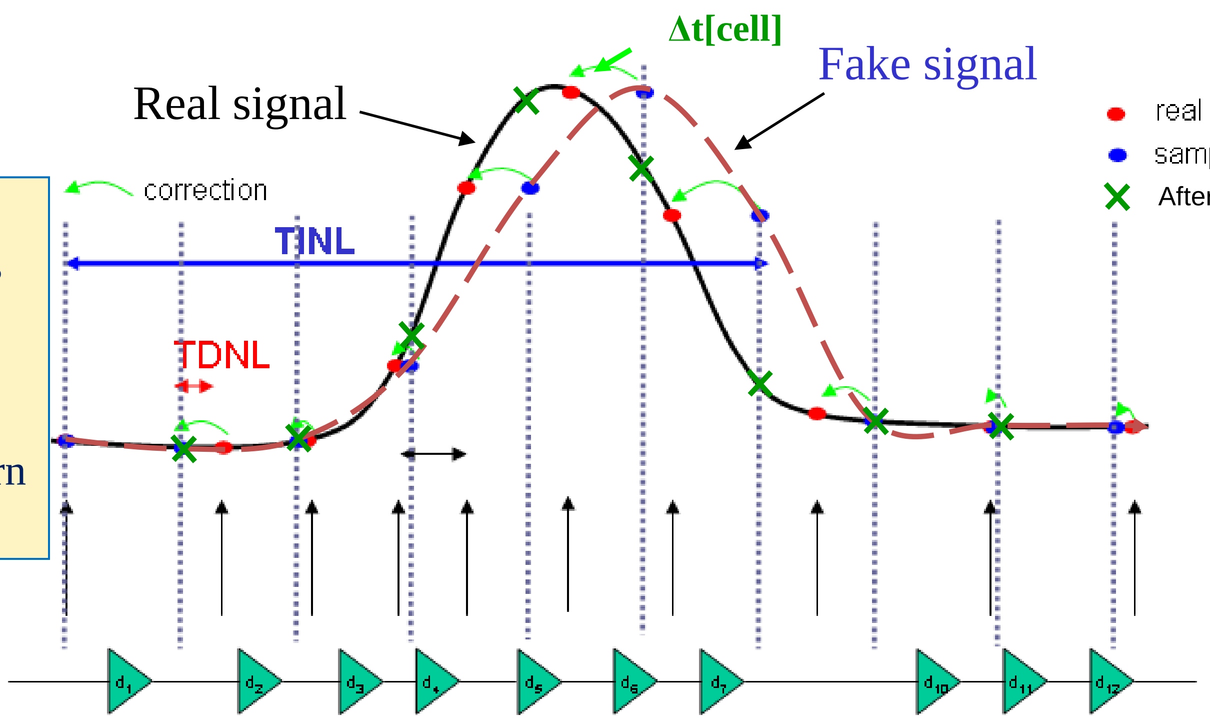
Time Non_Linearities

- Dispersion of single delays => time DNL
- **Cumulative effect** => **time INL**. Gets worse with delay line length.
- **Systematic & fixed effect** => non equidistant samples => Time Base Distortion

If we can measure it => we can correct it !

But calibration and even more correction have to remain "reasonable".

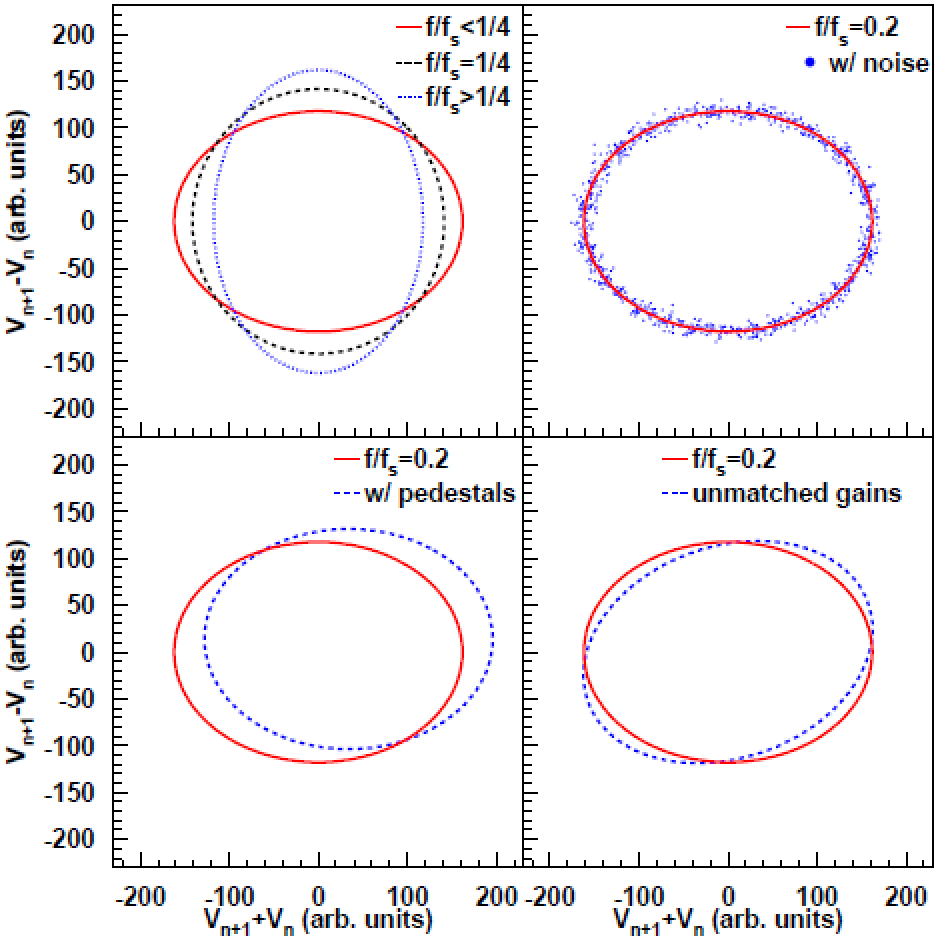
In a Matrix system, DNL is mainly due to signal splitting into lines => modulo 16 pattern if 16 lines



Remark:
same type of problem occurs
with interleaved ADCs

Timing Calibration w/ Correlations

- Ellipse features:



1) Different Δt (for known sampling frequency) give different major/minor radii.
2) Noise makes ellipse "fuzzy"
3) Nonzero pedestals shift origin
4) Difference in gain between two cells causes a rotation.

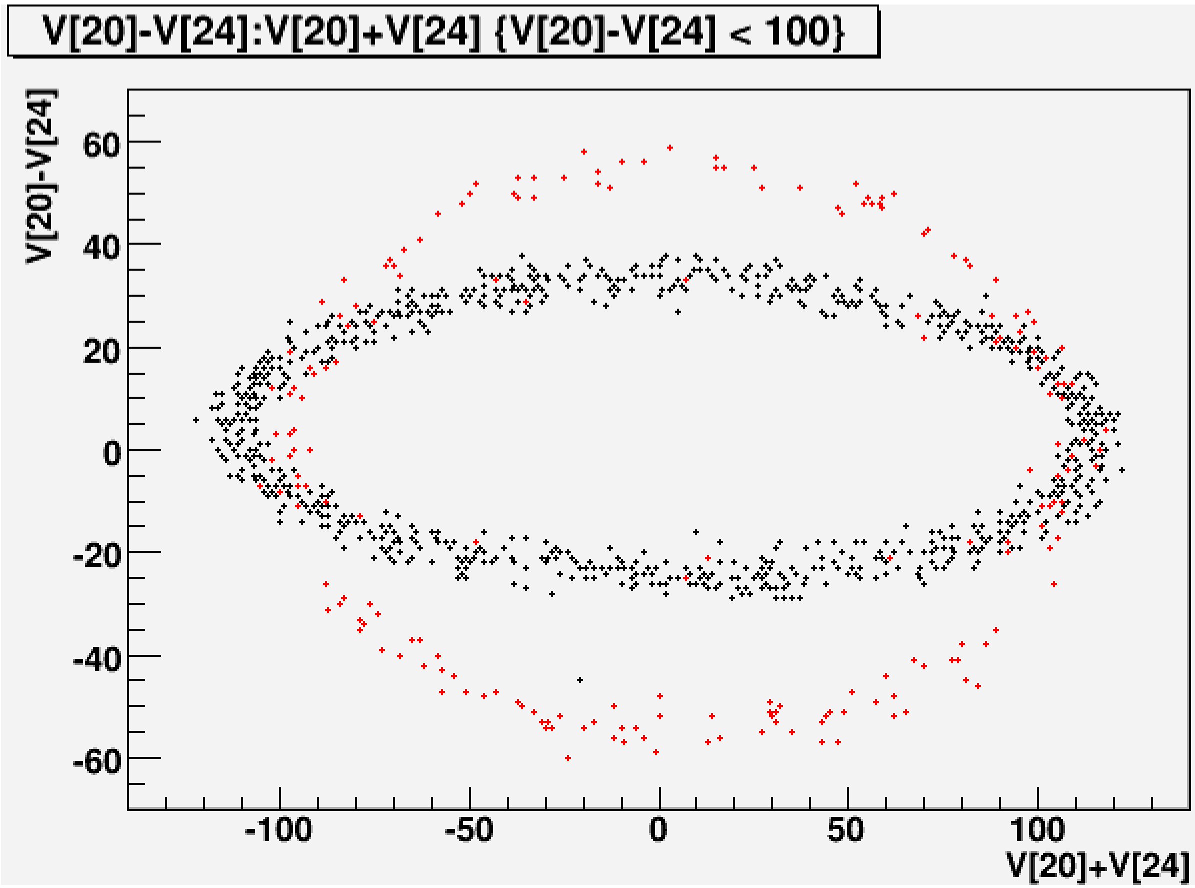
➔ We have written an ellipse fitter to perform this method.

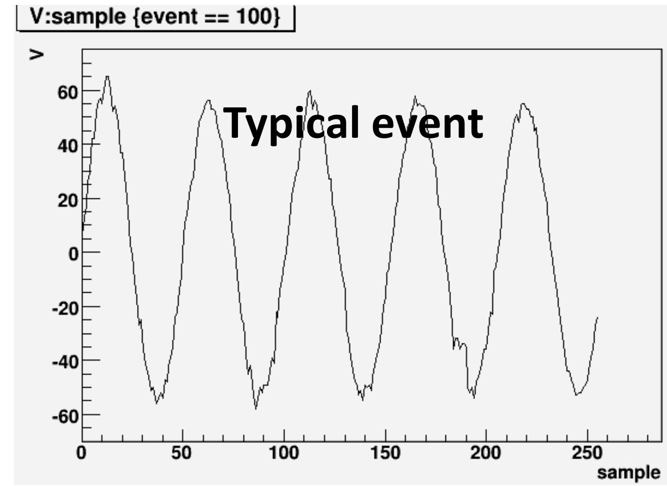
➔ Even without fitting, it provides nice qualitative check on results.

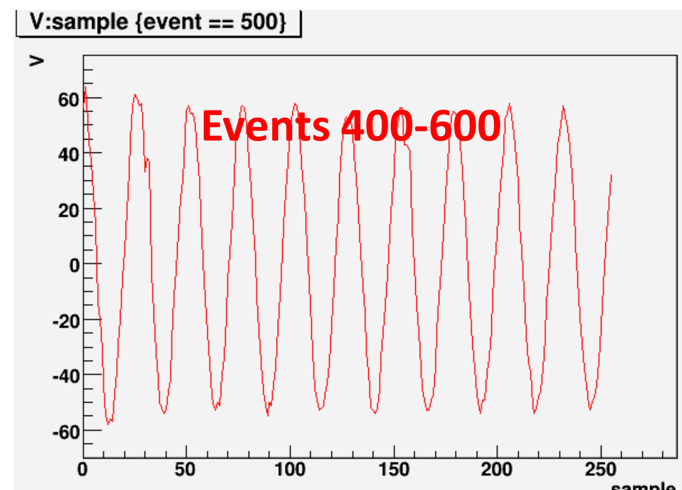
- <u>**Procedure tested on fast scope data…**</u>

Correlation-based Timing w/ PSEC3

- First attempts at timing calibration w/ PSEC3, 5 GSa/s:



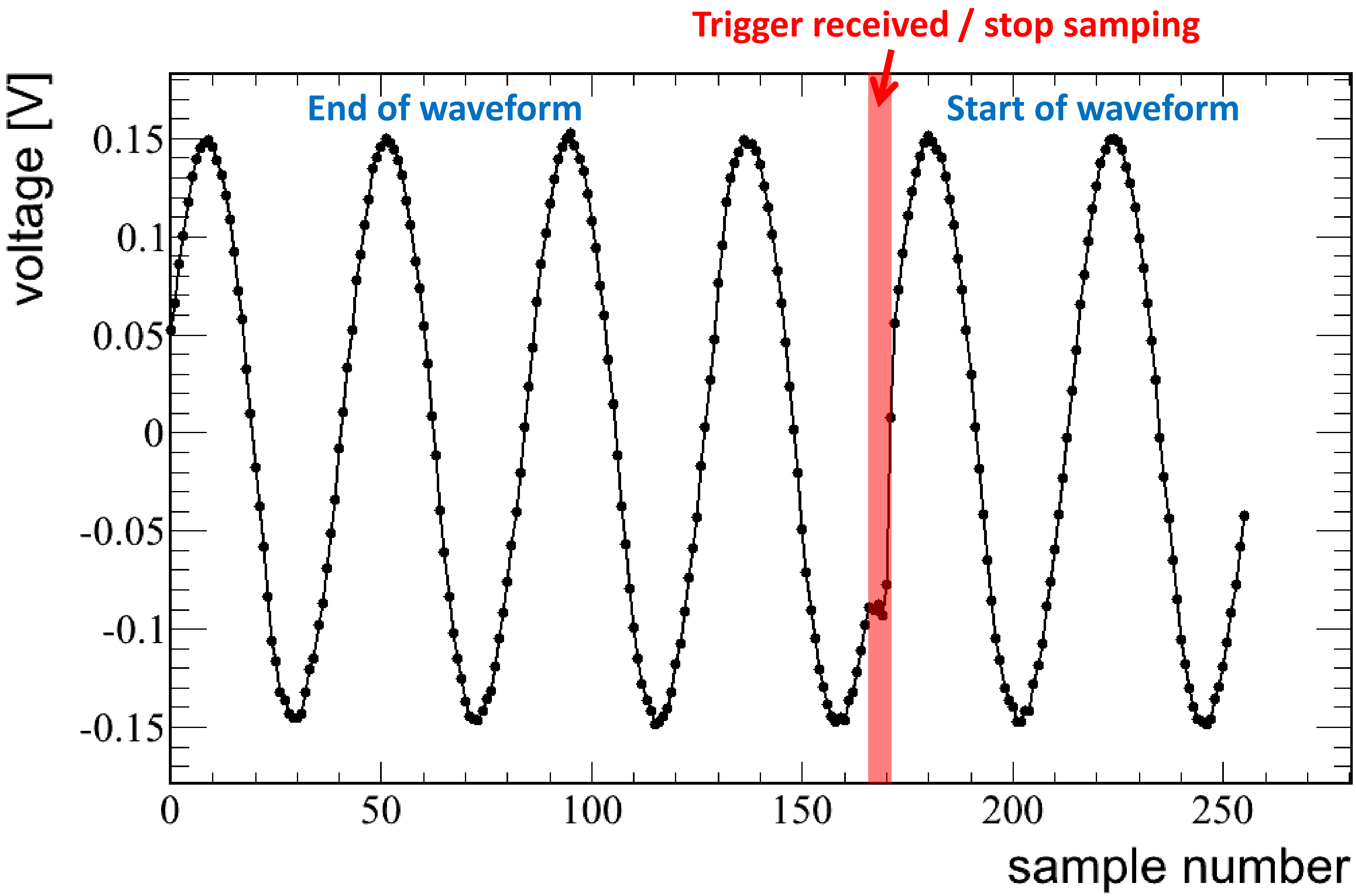




- Sampling rate slipped in events **~400-600**:

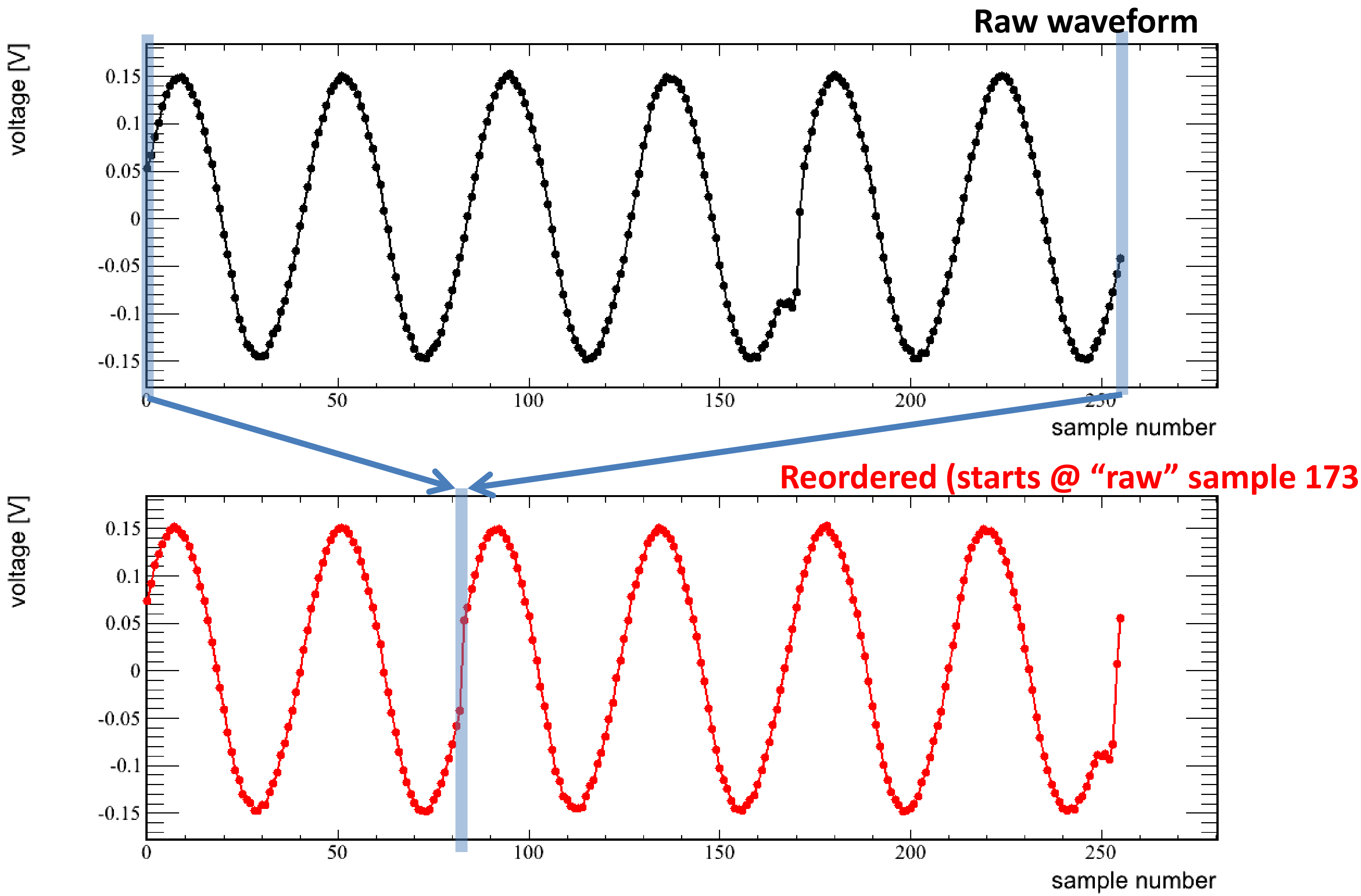
➔ **This technique was able to pick this out immediately.**

Example “raw” event



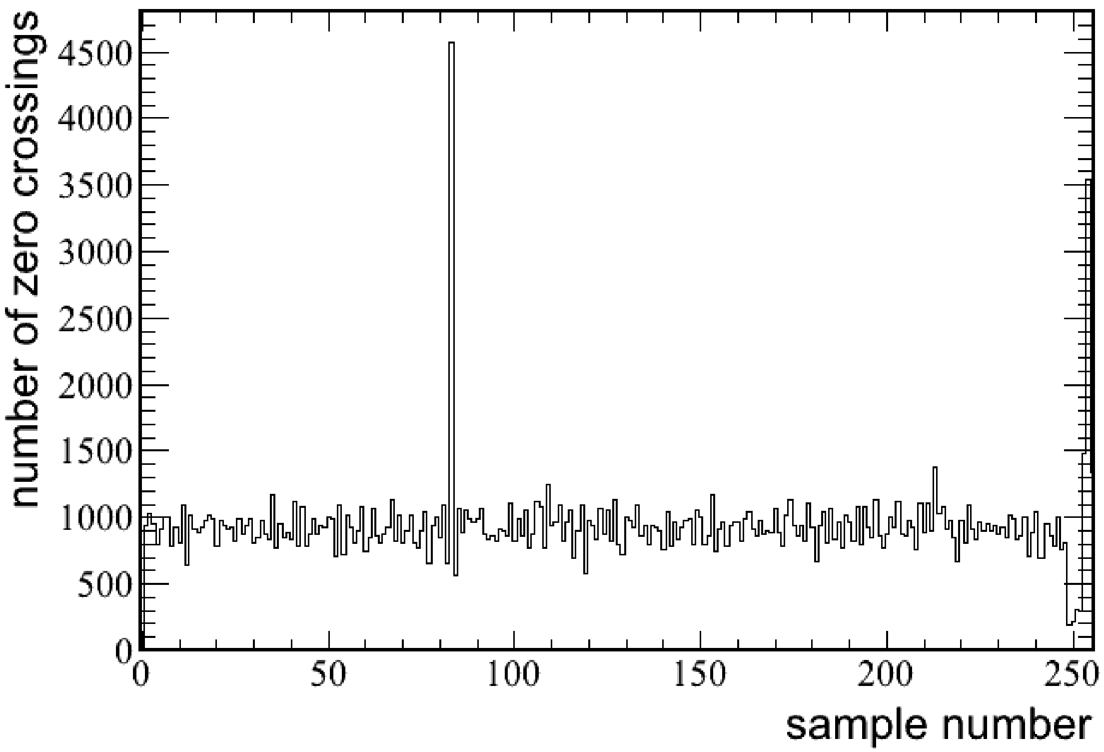
Sample numbers must be reordered to properly align the waveform in time.

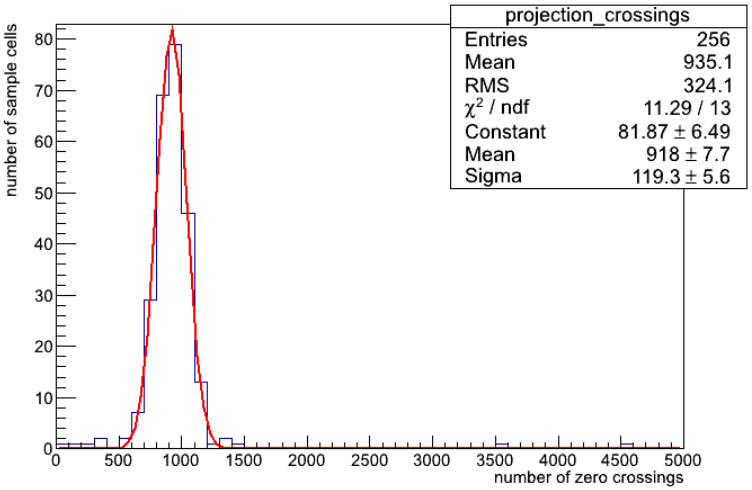
Step 1 – Reordering waveform



Known "gap" at wraparound point between sample 255 and 0

Step 3b - Zero Crossing Occupancy





(Above) Projection of left plot onto y-axis.
~13% spread in Δt values

<u>Corresponding Δt files available for CH3 and CH5.</u>

Still running some cross-checks / residuals with these Δt values.