Signal Processing & TPC simulation for single-phase LArTPCs

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Workshop of Reconstruction and Machine Learning in Neutrino Experiments
@ DESY, Hamburg Germany
Signal Processing

An electrical engineering subfield that focuses on analyzing, modifying, and synthesizing signals. The principles of signal processing can be found in the classical numerical analysis techniques of the 17th century.

A typical digital processing system (hardware + software architectures)

A typical signal processing technique in waveform analysis: Fourier Transform

well-defined frequency components
Signal Processing

Widely used in image measurements and analyses such as medical imaging, astronomy imaging, ...
Signal Processing

Widely used in image measurements and analyses such as medical imaging, astronomy imaging, …

A crater on Mars
(NASA JPL 511-4353)

High-quality image with digital processing
Liquid Argon TPC (LArTPC)

- A state-of-the-art neutrino detector technology with excellent **3D tracking** & **calorimetry** for charged final state particles of neutrino interactions
- LArTPC experiments: MicroBooNE, SBND, ICARUS, ProtoDUNE/DUNE
- **Particle imaging detector**

An image post signal processing
LArTPC Signal Processing

collection plane view

ProtoDUNE Run 4696, Ev 103

induction U plane view

induction V plane view


Three 2D images (time vs wire) from three wire planes post signal processing

2 EM showers and a pion interaction with 4 outgoing particles

Foundation to high-level 3D event reconstruction

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Connections to traditional approaches

**Pandora (A. Smith’s talk):**

- Low-level image processing
- Hit finding
- Pattern recognition
- Particle fits: Tracks, Showers
- Calorimetric reconstruction
- Particle identification

**Signal Processing**

**Wire-Cell (C. Backhouse and C. Zhang’s talks):**

Under-determined linear equation


MicroBooNE Preliminary

JINST 13, P05032 (2018)
Connections to machine learning

- Facilitate the feature engineering (fundamental to machine learning): robustly decouple the common features (detector response) in the input
- Signal processing (deconvolution) $\leftrightarrow$ TPC simulation (convolution)
- The knowledge gained in the development of signal processing feeds back to the TPC simulation introducing a well-behaved machine-learning training samples

Deep learning (tomorrow’s talks):

Signal Processing

1. 2017 JINST 12 P03011
2. Phys. Rev. D 99, 092001
The MicroBooNE Experiment

- Accelerator $\nu$ experiment
- 8 GeV proton beam on beryllium target
- 800 MeV $\nu$ energy on average
- 470 m baseline
- Liquid Argon Time Projection Chamber (LArTPC) with 85 ton active mass

Has been taking data since 2015
Aiming for a definitive check on MiniBooNE Low Energy Excess, $\nu - Ar$ cross section measurement, LArTPC R&D
How Signal Processing Works

Linear time-invariant system (sensors, electronics, etc.)

Time domain

Detector Response

"*" convolution

\[ y(t) = h(t) \ast x(t) \]

Filter
(regularization, remove artificial effects, reduce noise)

\[ * f(t) \]

In many cases, Fourier Transform utilized (frequency analysis)

Frequency domain

Signal Processing always refer to a deconvolution

\[ X(s) = \frac{Y(s)}{H(s)} \]

\[ S(\omega) = \frac{M(\omega)}{R(\omega)} \]

(In physics analysis)
LArTPC Signal Processing

\[ S = \frac{M}{R} \]

- **S**: ionization electrons arriving at the anode plane (post attenuation & diffusion)
- **M**: ADC waveforms from all wires
- **R**: sense wire response (field response), electronics response

![Diagram of LArTPC](image)

- Photon sensors to detect scintillation light (t0 tagging)
- Wire pitch: 3 mm
- Wire plane gap: 3 mm
LArTPC Signal Processing

\[ S = \frac{M}{R} \]

- \( S \): ionization electrons arriving at the anode plane (post attenuation & diffusion)
- \( M \): ADC waveforms from all wires
- \( R \): sense wire response (field response), electronics response

Typical waveform for a wire

What we expect 😊

What we obtained 😞?
TPC Signal Formation

Drift direction

Beam direction

Point charge

Recombination

Attenuation

Diffusion

Space charge effect (curved $E$ field)

Profile of wire planes

Long-range induction

Field response (Plot in log scale, arbitrary unit) -- Time vs Wire

From Garfield 2D simulation
LArTPC Signal Processing

\[ S = \frac{M}{R} \]

- **S**: ionization electrons arriving at the anode plane (post attenuation & diffusion)
- **M**: ADC waveforms from all wires
- **R**: sense wire response (field response), electronics response

\[ M = R \cdot S \]

\[
\begin{pmatrix}
M_1(\omega) \\
M_2(\omega) \\
\vdots \\
M_{n-1}(\omega) \\
M_n(\omega)
\end{pmatrix} =
\begin{pmatrix}
R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\
R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
R_{n-2}(\omega) & R_{n-3}(\omega) & \ldots & R_0(\omega) & R_1(\omega) \\
R_{n-1}(\omega) & R_{n-2}(\omega) & \ldots & R_1(\omega) & R_0(\omega)
\end{pmatrix} \cdot 
\begin{pmatrix}
S_1(\omega) \\
S_2(\omega) \\
\vdots \\
S_{n-1}(\omega) \\
S_n(\omega)
\end{pmatrix}
\]

- **M_i, S_i**: waveform, charge on the *i*th wire
- **R_j**: response on the *j*th adjacent wire (field response \(\otimes\) electronics response)

Wire dimension
2D vs 1D signal processing

Typical waveform for a wire

What we expect 😊

What we obtained 😞

2D Deconvolution (time + wire)

1D Deconvolution (time only)

Adjacent wire contribution (U plane as an example)
2D vs 1D signal processing

Prolonged track:
- Small angle relative to drift direction
- Signal processing deficient due to bipolar cancellation -- insignificant signal-to-noise ratio
- 2D signal processing retries charges from adjacent wires mitigating this issue
- **For significant prolonged tracks (>80° for MicroBooNE), still a problem with the appearance of gaps**
Event display of an EM shower

https://lar.bnl.gov/magnify/#/event/uboone-3493-041075
Merits of 2D signal processing

Induction plane = collection plane
Realize the identical “sense” of charge for all wire planes

~10% smear originating from electronics noise
Deviation due to the imperfection of detector
Consistent amount of charge.
Cosmic-muon $dQ/dx$

1D Signal Processing

2D Signal Processing

(a) Cosmic muon $dQ/dx$ distribution for the case of the 1D deconvolution.

(b) Cosmic muon $dQ/dx$ distribution for the case of the 2D deconvolution.
Wire-Cell 3D Imaging (see C. Zhang’s talk)

- 2D Signal Processing significantly enhanced the efficiency (continuous & uniform lines)
Evolution of Signal Processing

Drift time

Wire number

Raw Data

Noise removed
(JINST, 12, P08003)

1-D deconvolution

2-D deconvolution
(initial)

2-D deconvolution
(improved)

MicroBooNE data
41075, Run 3493
U plane view

Summarized in JINST 13 P07006 and JINST 13 P07007
Evolution of Signal Processing

Excess noise removal

- Coherent noise from LV regulator
- Harmonics noise from HV module
- Other pick-ups

ROI finding improvement

2-D deconvolution (initial)

2-D deconvolution (improved)

MicroBooNE data 41075, Run 3493 U plane view

Summarized in JINST 13 P07006 and JINST 13 P07007
ROI (Region of Interest) finding

\[ R^{-1} \cdot M \cdot Filter = S \cdot Filter + (R^{-1} \cdot Noise \cdot Filter) \]

- For collection plane, ROI finding is trivial which bases on the threshold determined by noise RMS.
- Unfortunately, for induction planes, the second term \((R^{-1} \cdot Noise \cdot Filter)\) is still significant due the low-frequency noise amplification. Various low-freq filters are jointly applied to suppress the noise and obtain an efficient signal ROI finding.
Further improvements (ongoing)

Match ROIs from all wire planes to suppress the “fake” charge hits.

In one wire plane (2D view) the artificial effects are less likely to appear in the other wire plane views.

Tear drops – dead channel boundary effect or noise

Prolonged tracks – low signal-to-noise ratio in one wire plane view

This can also be done in high-level 3D reconstruction, e.g. Wire-Cell

Wire-Cell 3D imaging
TPC simulation

Initial distribution of ionization electrons (with space charge effect, recombination)

Diffusion (Gauss, ~mm)
Absorption (electron lifetime ~ms)

Field response
(long-range induction ~cm)

Electronics response
(ASIC, RC filter, ADC, etc.)

Inherent Noise (ASIC) + Excess Noise

dE/dx $\rightarrow$ dQ/dx

TPC Simulation
-- input charge deposition
output ADC raw waveforms

Signal Processing
TPC simulation

- Initial distribution of ionization electrons (with space charge effect, recombination)
- Diffusion (Gauss, ~mm)
- Absorption (electron lifetime ~ms)
- Field response (long-range induction ~cm)
- Electronics response (ASIC, RC filter, ADC, etc.)
- Inherent Noise (ASIC) + Excess Noise

TPC Simulation
-- input charge deposition
output ADC raw waveforms

\[ \text{dE/dx} \rightarrow \text{dQ/dx} \]
TPC simulation

Initial distribution of ionization electrons (with space charge effect, recombination)

Diffusion (Gauss, ~mm)
Absorption (electron lifetime ~ms)

2D (time + wire) Field response (long-range induction ~cm)

Signal Processing
2D deconvolution

TPC Simulation
2D convolution

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\begin{bmatrix}
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\vdots \\
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\end{bmatrix} =
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R_{n-1}(\omega) & R_{n-2}(\omega) & \ldots & R_1(\omega) & R_0(\omega)
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\end{bmatrix}
\]
TPC Simulation

- Facts of 2D TPC simulation
  - Point charge → 2D Gaussian cloud → 0.5 us × 0.3 mm pixelization post diffusion ~100 pixels
  - Long-range & fine-grained 2D field response → 21 × 10 = 210 sub-pitch field responses

- Speed & Memory optimization

- A practical & reliable TPC simulation consistent with data (field response validation)

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Isochronous track

Moderate angle track (40 – 50°)
Summary

• The signal processing (2D deconvolution + ROI finding) provides a solid foundation to fully utilize the capabilities of LArTPC
  
  ✓ Improves the correlation of signals between multiple 1D projective wire readout and helps to resolve the degeneracies (where the charge is along the wire) and remove the noise (e.g. tear drops)
  
  ✓ Is essential for 3D event reconstruction using tomographic concept (e.g. Wire-Cell, see C. Zhang & X. Qian’s talk) and is expected to further enhance 3D reconstruction for techniques (Pandora, Deep-learning, etc.) that match the image in different 2D projection views.

• A TPC simulation with fine-grained 2D field response has been implemented to match the 2D signal processing and respects the long-range induction in real data

• Developed and applied in MicroBooNE

• Stay tuned for ProtoDUNE/DUNE, other LArTPCs

• Further improvements are underway
Main References


Backup slides
Overview of full TPC simulation

\[ \text{Wave} = (\text{Depo} \odot \text{Drift} \odot \text{Duct} + \text{Noise} \odot \text{Digit}) \]

- Diffusion (longitudinal, transverse) \( \propto \sqrt{D_{\text{drift}}} \)
- Attenuation (exponential lifetime)
- Key (2D) convolution in two dimensions
- Time domain + Wire domain
- Sampling & linear scaling from voltage to ADC
- Data-driven frequency spectra
  - In complex plane (frequency domain)
  - Noise follows a random walk

https://indico.fnal.gov/event/12345/session/12/material/slides/0?contribId=30
TPC Simulation Speed

• Facts of 2D TPC simulation
  • Point charge → 2D Gaussian cloud → 0.5 us × 0.3 mm pixelization post diffusion ~100 pixels
  • Long-range & fine-grained 2D field response → 21 × 10 = 210 sub-pitch field responses

• 2D convolution in wire domain in a minimal range of time vs wire (a factor of 10)
  • Compared to 1D convolution in time domain + loop in wire dimension

• Symmetry in field response (a factor of 2)
  • Use complex FFT to incorporate half convolution in the real part and the symmetrical/mirror half in the imaginary part

• "Magic" length of array (e.g. number of ticks) in FFT (a factor of >2)
  • Power-of-two length → faster
  • Prime factorization → more factors, faster
  • E.g. $n=10240$ is 30% faster than $n=9600$, $n=9600$ is twice faster than $n=9595$
  • A table is created to contain all the local minimal “magic” numbers and used in the FFT (need additional padding)
    • Local minimal: Input $N_0$, magic number $N_1 \geq N_0$ but time($N_1$) is minimal
    • In total 78 “magic” numbers from 1 to $2^{14} = 16384$
2D Signal Processing

A Toeplitz matrix
(a matrix in which each descending diagonal from left to right is constant.)

\[
\begin{pmatrix}
M_1(\omega) \\
M_2(\omega) \\
\vdots \\
M_{n-1}(\omega) \\
M_n(\omega)
\end{pmatrix} = \begin{pmatrix}
R_0(\omega) & R_1(\omega) & \cdots & R_{n-2}(\omega) & R_{n-1}(\omega) \\
R_1(\omega) & R_0(\omega) & \cdots & R_{n-3}(\omega) & R_{n-2}(\omega) \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
R_{n-2}(\omega) & R_{n-3}(\omega) & \cdots & R_0(\omega) & R_1(\omega) \\
R_{n-1}(\omega) & R_{n-2}(\omega) & \cdots & R_1(\omega) & R_0(\omega)
\end{pmatrix} \cdot \begin{pmatrix}
S_1(\omega) \\
S_2(\omega) \\
\vdots \\
S_{n-1}(\omega) \\
S_n(\omega)
\end{pmatrix}
\]

Linear discrete convolution = multiplication by a Toeplitz matrix.

✓ Core deconvolution [wire domain]: inverse (division) of the response matrix R given a \( \omega \)

✓ FFT & IFFT [time domain \( \leftrightarrow \) frequency domain \( \leftrightarrow \) wire domain]

✓ Commonly, filters (one for time domain, one for wire domain) are needed to suppress the “catastrophic oscillation” of the direction inverse solution
2D Deconvolution

Convolution in frequency domain

Deconvolution to obtain each column vector first

Inverse Fourier transform on each row vector $\rightarrow$ final result

Two Filters

$F^w: \text{Fourier transform w.r.t. wire}$

$F^t: \text{Fourier transform w.r.t. time}$

$R_i(\omega) = F^t[r_i(t)]$, response on the $i$th adjacent wire

$M_i(\omega) = F^t[m_i(t)]$, ADC waveform on the $i$th wire
Loose + Tight ROIs

Missing part of this large $\theta_{xz}$ track
Break ROIs

![Graph showing ADC Counts/1 tick vs Time Ticks for MicroBooNE, with comparisons between Raw Waveform, With Break ROIs, and Without Break ROIs.](image)

- **MicroBooNE**
- **Time Ticks:** 5400 to 5900
- **ADC Counts/1 tick:** 0 to 40
- **Electrons/6 ticks (x 500):** -40 to 40

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Shrink ROIs

![Graph showing ADC Counts vs. Time Ticks with MicroBooNE data, comparing Raw Waveform, With Shrink ROIs, and Without Shrink ROIs]
Signal Processing Flow Chart

- **Low-f noise amplification**
- **Better shape without negative part**
- **Low-f noise, strong correlation (baseline-like) within ROI**

Explain later
Signal Processing Evaluation

MIP line charge simulated as indicated by red line

- Good performance, but deteriorates with increasing $\theta_{xz}$
- Induction plane considerably worse than collection plane

Total Charge within one wire ± half pitch

MicroBooNE

Noise dominated

ZERO charge extracted i.e. no ROI
Necessity of Cold Electronics

• Electronics noise dominates the charge resolution and has a big impact on the bias as well the inefficiency.

• MicroBooNE pioneered the usage of ultra-low noise cold electronics, which allows for the good performance of the signal processing
  • Simpler cryostat design + cabling, shorter signal cables
  • **Lower electronics noise: noise scales with temperature + length of cable**

Temperature: 80-90 K
Garfield calculation setup (MicroBooNE)

- **Fine-grained**: 10 drift paths (per 0.3 mm) per wire pitch
- **Long-range**: 0 (central wire) ± 10 wires
- 126 (21 wires × 6) field responses are calculated (considering symmetry)
Discussions – 3D calculation

• Finite Element Method (FEM)
  • Garfield: not support three dimensional structures
  • Detector edge effect
  • CPU/RAM requirements scale with “volume” of the problem
  • “Impossible”? to do 3D at LArTPC wire readout (mm) scale
  • Leon Rochester @ slac is braving this challenge with custom FEM

• Boundary Element Method (BEM) solves some problems
  • CPU/RAM requirements scale with “surface”
  • Fewer software implementations (compared to FEM)
  • Brett Viren @ BNL is exploring on this

• A dedicated test-stand facility would greatly aid in validating the residual 3D effect to a 2D field response calculation (LArFCS initiated by Chao Zhang @ BNL).