Data Driven Correlated Noise Simulation for the ICEBERG LArTPC

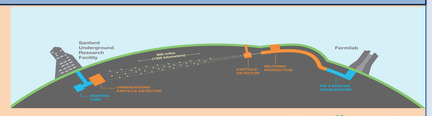
Avik Ghosh on behalf of the DUNE Collaboration
avikg@iastate.edu

FERMILAB-POSTER-26-0131-LBNF-V

The ICEBERG LArTPC

The **Deep Underground Neutrino Experiment (DUNE)** is a flagship long-baseline neutrino experiment designed to make precision measurements of neutrino oscillations and to search for physics beyond the Standard Model using massive **LArTPC (Liquid Argon Time Projection Chamber)** detectors.

The **ICEBERG LArTPC** at Fermilab
Photo: Reidar Hahn, Fermilab



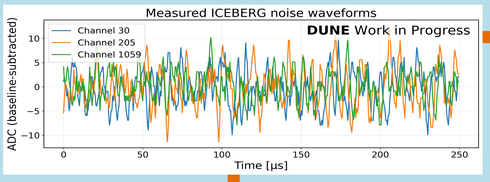
DUNE illustration

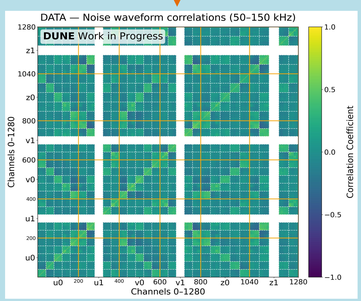
The ICEBERG detector:

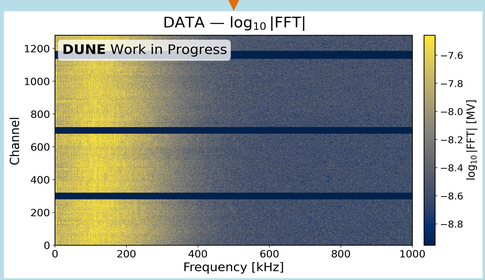
- **Integrated Cryostat and Electronics Built for Experimental Research Goals.**
- LArTPC test stand for **DUNE cold electronics** and **DAQ development.**
- Different **gain**, **shaping-time**, **trigger,** and **electric-field** configurations.
- **Upcoming studies** use **AI/ML** to identify:
  - Low-energy **Ar-39 deposits** for calibration.
  - **Michel electrons** for **supernova pointing**

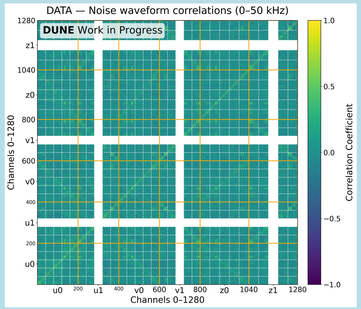
Noise in ICEBERG

- ICEBERG is a **low-noise LArTPC** --> **physics goals** involve **low-energy signals**.
- Must accurately **model this noise** for:
  1. Low-energy **reconstruction studies**.
  2. Training **AI-based signal-detection** algorithms.



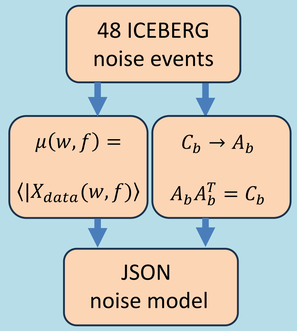






Measured ICEBERG noise shows structured frequency content and strong frequency-dependent correlations between channels.

Building the Model from Data



- **Data-driven noise model** is our input to the **correlated noise simulation**.
- 48 hand-scanned (to remove cosmic activity) **pure-noise ICEBERG events** with **≈1 ms waveform per wire**
- Calculate **ingredients to noise model**:
  - Measured per-channel **Fast Fourier Transform (FFT)** magnitude
  - **Wire-to-wire correlations** in **four frequency bands**

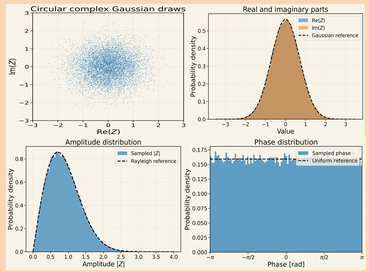
Simulation Procedure

Why circular complex gaussian?

- **Random noise** pulses occur at different times, producing different phases in each frequency bin.
- At fixed f, the Fourier coefficient behaves like a **2D random walk** in the complex plane.

$$X(f) = r(f)e^{i\phi(f)}$$

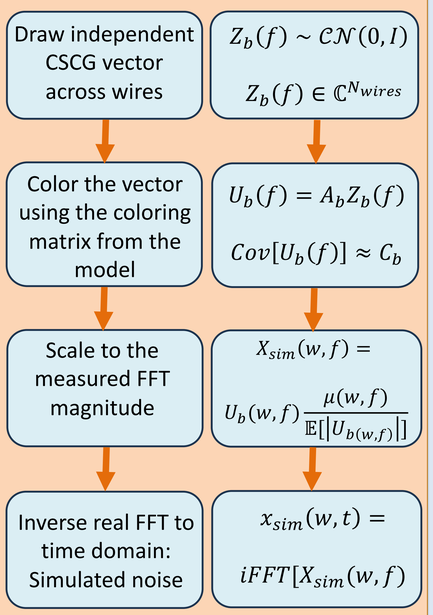
$r(f) \sim$ Rayleigh, $\phi(f) \sim$ Uniform



A **circular complex Gaussian draw** captures this behavior:

- Independent Gaussian real and imaginary parts.
- Rayleigh-distributed amplitude.
- Uniformly distributed phase.

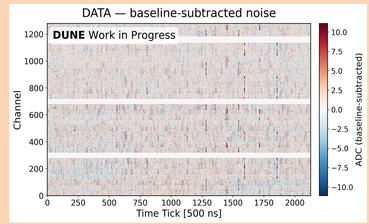
How the correlated noise is simulated?

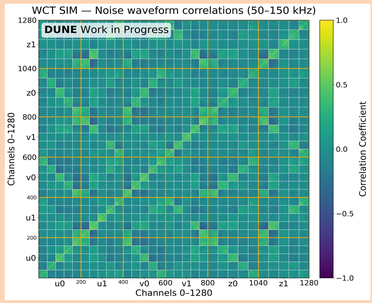


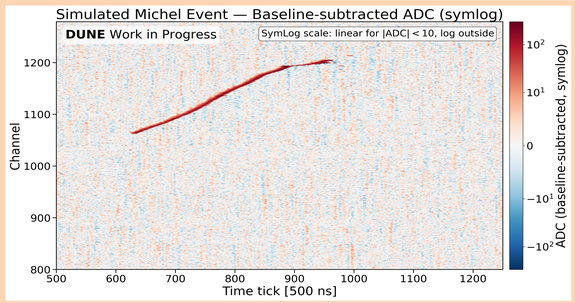
- In practice, the **JSON model** is used by a custom **Wire-Cell noise-injection component** within the **LArSoft + WCT** (Wire-Cell Toolkit) simulation workflow.
- The generated time-domain noise is added to the simulated detector waveforms before digitization.

Simulated Noise Validation

- **Simulated Michel-event** waveforms from the LArSoft + Wire-Cell workflow show that the reference **ICEBERG noise pattern** is reproduced in realistic signal-plus-noise samples.
- The example band-limited correlation matrix confirms that the measured **cross-correlation structures** are preserved.







Validation of simulated correlated noise. These show that the simulation reproduces the measured ICEBERG noise pattern and cross-correlation structure.

Conclusion and Future Work

This work presents the **most detailed LArTPC correlated-noise simulation** developed to date. The resulting noise model is implemented in the LArSoft + Wire-Cell workflow, enabling realistic signal-plus-noise simulation **for low-energy reconstruction** and **AI/ML** studies.

Future work will focus on extending the method to larger LArTPCs such as **ProtoDUNE** and the **DUNE Far Detector**, where model compression will be essential. Potential directions include exploiting **detector symmetries**, **locality of correlations**, and **sparse approximations** to reduce the size of the correlation matrices.

Acknowledgements

This document was prepared by the DUNE collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002. The author acknowledges the support of DOE award number DE-SC0015684.

This material is based upon work that is supported by the Visiting Scholars Award Program of the Universities Research Association. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Universities Research Association, Inc.