Testing Electronics on the JNE 1-ton Prototype

Performance Evaluation of the PDS1500 System

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Outline

1. Background & Motivation
2. Test Platform & Methods
3. Performance Results
4. Scaling Up & Outlook
5. Summary

1 Background & Motivation

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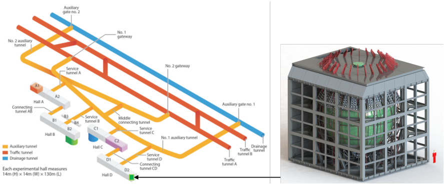
JNE at CJPL: Low-Background Neutrino Observatory

- Jinping Neutrino Experiment (JNE)
- Located at CJPL-I, 2400 m rock overburden
- 500 t slow liquid scintillator, ∼3000 PMTs
- Physics goals: solar ν, geoneutrinos, supernova ν, DSNB
- ∼1000 ns waveform window × thousands of channels



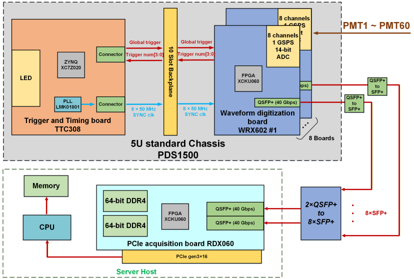
Why New Electronics?

What JNE Demands

- High sampling rate (1 GSPS, 14-bit)
- Large dynamic range for weak neutrino signals
- Strict time sync: inter-channel skew <200 ps
- High throughput: >50 Gbps per crate
- Commercial CAEN V1751 falls short in multiple aspects

Self-developed PDS1500

- 64-channel crate: WRX602 (1 GSPS / 14-bit) + TTC308 + RDX051
- Hardware clock sync, jitter <10 ps
- Measured throughput >50 Gbps



What to Test: Six Key Metrics

Metric	Question
1 Data Loss	Do we catch every event?
2 Baseline Noise	Is the trigger threshold stable?
3 Waveform Quality	Is signal fidelity sufficient?
4 Time Drift	Is the time calibration accurate?
5 Energy Threshold	Can we see low-energy signals?
6 Energy Resolution	Is the physics output solid?

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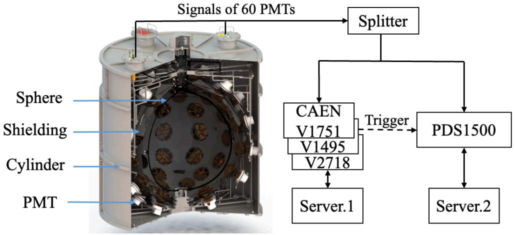
Test Platform: 1-ton Prototype + Synchronous Comparison

JNE-1ton Prototype

- CJPL-I, 2400 m overburden, ultralow cosmics
- 60 MCP-PMTs (53 operational)
- Slow liquid scintillator
- Reference: CAEN V1751 (8 cards, 64 ch)

Synchronous Comparison

- Same PMT → splitter → two paths
- CAEN + PDS1500 simultaneously
- CAEN V1495: common external trigger
- Same events, separate DAQ servers
- Fair, event-by-event comparison



Acquisition Strategy

Metric	DAQ Mode	Key Parameters
Loss / Baseline / Waveform	Synchronous ext. trigger	Same event, shared trigger
Time Drift	LED calibration	415 nm + diffuser, 5 power cycles
Energy Threshold	Standalone (nat. rad.)	$\mathrm{Tr}_{\mathrm{multi}}$: 45 $\rightarrow$ 10
Energy Resolution	AmBe source	n-H capture 2.2 MeV coincidence

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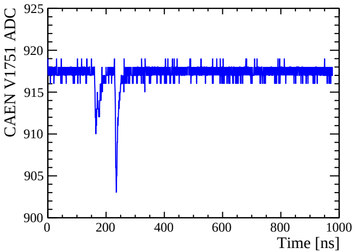
Metric 1: Data Loss

- Two synchronous datasets >1M events each
- **PDS1500: zero event loss**
- CAEN V1751: 2 events lost
- Cause: dead-time overlap during 8-board parallel readout
- Hardware-level sync → gapless continuous sampling

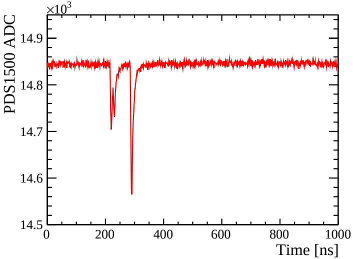
Dataset	CAEN	PDS1500
DAQ.1	409 598	409 600
DAQ.2	614 400	614 400

2 extra events in PDS1500 = caught during CAEN dead-time window

Metric 2: Waveform Alignment —The Problem



CAEN V1751 (ENOB ≈ 8.6)



PDS1500 (ENOB ≈ 10.6)

- Same PMT signal split to two systems —but raw waveforms look different
- **Vertical**: different ADC bit resolutions → raw ADC counts not comparable
- **Horizontal**: different trigger times + signal transit delays → time misalignment
- Need both amplitude normalization and time alignment before comparison

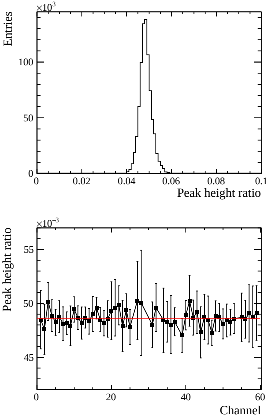
Metric 2: Waveform Alignment —Method

Amplitude Normalization

- Peak-height ratio: PDS1500 / CAEN for each event
- Fit distribution → normalization factor
- PDS1500 = 0.04858 × CAEN ADC

Time Alignment

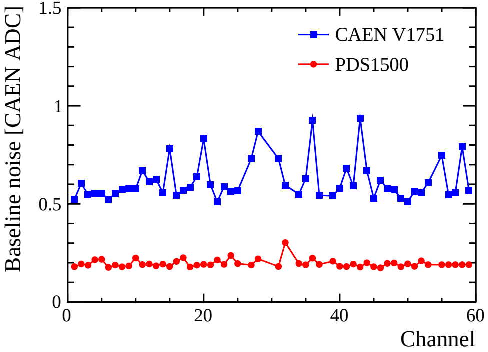
- Baseline subtraction first
- Find main peak, align at 20% rising-edge height



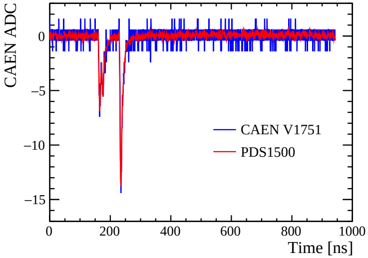
Top: one-channel ratio distribution.
Bottom: 53-channel summary.

Metric 2: Baseline Stability —Result

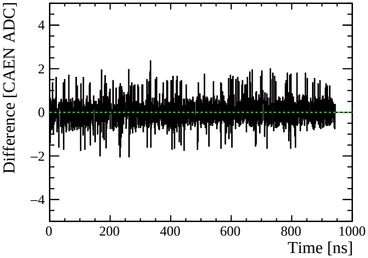
- Baseline noise ≡ std(ADC) over 50 ns pre-trigger window
- PDS1500 (53 ch): ≈ 1/3 of V1751
- Avoids false triggers near threshold edge
- Enables lower trigger thresholds



Metric 3: Waveform Subtraction & χ^2 Calculation



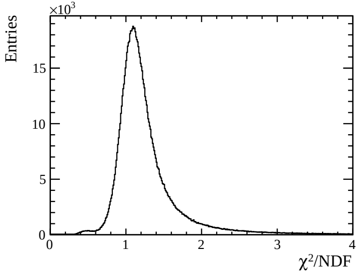
Aligned: PDS1500 (blue) vs CAEN (red)



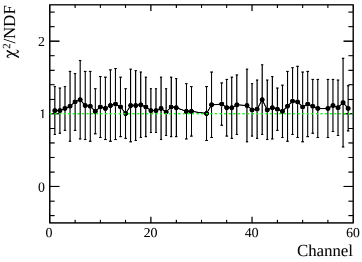
Residual: PDS1500 − CAEN

- Baseline subtraction + 20% rising-edge alignment, then PDS1500 − CAEN point-by-point
- $\chi^2 = \sum_i [w_1(t) - w_2(t)]^2 / (\sigma_1^2 + \sigma_2^2)$ over 250 ns time bins
- σ_i estimated from baseline noise of each system

Metric 3: χ^2 Results —All Channels



χ^2/NDF distribution (1M events)



χ^2/NDF per channel (53 ch)

- χ^2/NDF peak $\sim$1.0 —differences consistent with statistical fluctuations
- All 53 channels show good agreement; no channel is an outlier
- Confirms PDS1500 waveform fidelity is equivalent to CAEN V1751
- Combined with $+2$ bit ENOB advantage: PDS1500 records higher fidelity

Metric 4: Time Drift —Method

Experimental Design

- 415 nm LED + diffuser ball at detector center
- Equal photon TOF → all PMTs see synchronous light
- 5 power cycles → probe long-term stability

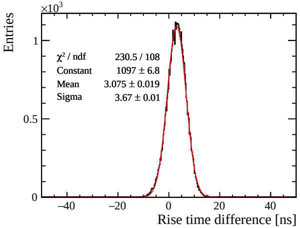
Pairwise Subtraction Method

- Rise time extracted at 20% of peak height
- T_{mi}: measured arrival time for flash m, PMT i
- t_m: common trigger jitter; T_i: per-channel time offset
- Pairwise difference cancels common terms → isolate T_i

$$T_{mi} = t_m + \mathrm{TOF}_{mi} + T_i + \tau_{mi}$$

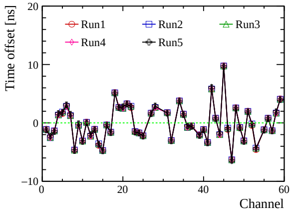
$$\Delta T_{ij} \equiv T_{mi} - T_{mj} \to T_i - T_j$$

$$\bar{T}_i = \frac{1}{N} \sum_j \Delta \hat{T}_{ij}$$

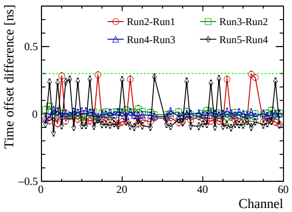


$\Delta T_{ij} = T_i - T_j$ (cancels t_m, TOF)

Metric 4: Time Drift —Result



Time calibration offsets for 5 runs



Pairwise differences between runs

Key Finding

16 ch shift in sync by ∼0.3 ns.
LMK04832 PLL zero-delay, phase step = 166 ps.

System	Time Drift	Impact
CAEN V1751	∼2 ns	Affects reco.
PDS1500	∼0.3 ns	Negligible

vs time bin 1 ns / PMT TTS 1.8 ns

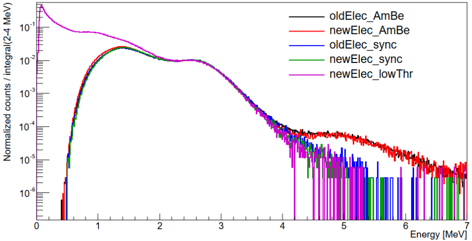
Metric 5: Energy Threshold

The CAEN Bottleneck

- $Tr_{multi} = 45 \rightarrow \sim 280$ Hz; lowering further crashes DAQ
- Effective energy threshold ~ 1.3 MeV

PDS1500 Breakthrough

- $Tr_{multi} = 45$: both systems agree well
- $Tr_{multi} = 10$ runs stably
- Energy spectrum extends to < 0.1 MeV



The reconstructed energy spectra obtained by analyzing different datasets with PreAnalysis codek

Metric 5: Why Low Threshold Matters

Solar Neutrino Energies

- *pp* ν: endpoint 0.42 MeV
- ^{7}Be ν: 0.862 MeV (mono-energetic)
- CNO ν: mostly $<$1.7 MeV
- *pep* ν: 1.44 MeV
- All require threshold $\ll$ 1 MeV

Key Implication

CAEN efficiency drops sharply below $\sim$1 MeV.

PDS1500 threshold $<$0.1 MeV

$\Rightarrow$ key enabling capability for JNE solar ν physics.

Metric 6: Energy Resolution —Setup

Apparatus

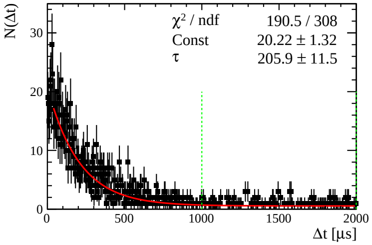
- AmBe source + 50 mm Pb shield (8 mm hole for neutrons)
- n-H capture: prompt 4.4 MeV γ + delayed 2.2 MeV γ

Coincidence Selection

- Fold = 2 (prompt + delayed pair)
- Prompt energy cut: $E \in [3.8, 5.0]$ MeV (selects 4.4 MeV γ)
- Capture time $\tau \approx 200\,\mu$s

Energy Calibration

- Use delayed 2.2 MeV n-H capture γ peak
- Crystal Ball fit of 2.2 MeV peak; PDS 3.1 h / CAEN 19.3 h



The time difference distributions of the prompt-delayed signals obtained using the Ostw packing program

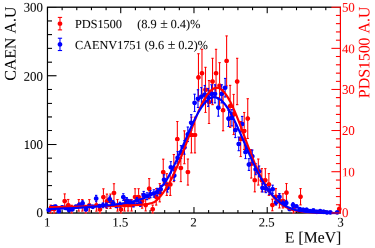
Metric 6: Energy Resolution —Result

Crystal Ball Fit (2.2 MeV γ)

- PDS1500: $(8.9 \pm 0.4)\%$
- CAEN V1751: $(9.6 \pm 0.2)\%$
- Within 3σ $\rightarrow$ statistically compatible

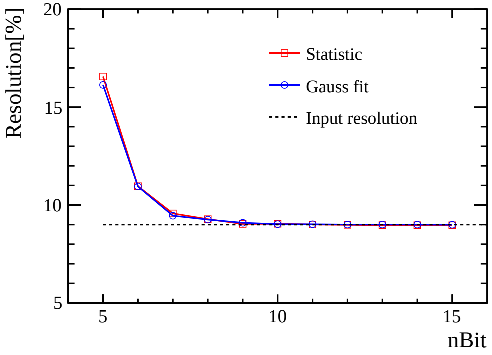
Why no ENOB advantage?

- Photon statistics is the dominant bottleneck
- LS: $\sim$200 ph/MeV, PMT: $\sim$10% coverage
- $\rightarrow$ $\sim$20 p.e./MeV at photocathode



The neutron capture energy spectra measured by the PDS1500 and CAEN V1751 systems, fitted using the Crystal Ball function

Metric 6: Resolution Ceiling —MC



- MC: ENOB > 9 bit $\rightarrow$ energy resolution saturates at $\sim$9%
- **Electronics is no longer the bottleneck**
- To improve resolution $\rightarrow$ higher light yield or larger PMT coverage

Six-Metric Summary

Metric	PDS1500	CAEN V1751	Verdict
1 Data Loss	Zero	2 lost	Superior
2 Baseline Noise	$\approx$1/3	Baseline	Superior
3 Waveform	χ^2/NDF$\sim$1, ENOB 10.6	ENOB 8.6	Better
4 Time Drift	$\sim$0.3 ns	$\sim$2 ns	$\times$10 better
5 Energy Threshold	<0.1 MeV	$\sim$1.3 MeV	Breakthrough
6 Energy Res.	(8.9$\pm$0.4)%	(9.6$\pm$0.2)%	Compatible*

*Photon-statistics limited —not an electronics issue

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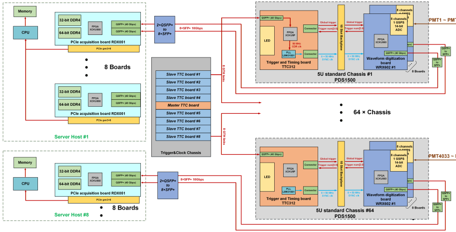
From 60 Channels to 4000 Channels

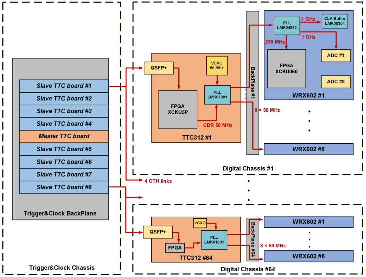
Scale-up Plan

- 64 PDS1500 crates ≈ 4000 channels
- Total bandwidth: 2.56 Tbps
- Central TTC Chassis (1 master + 8 slaves)
- Two-stage fiber network + 8-server DAQ cluster

Clock Distribution

- Multi-level tree topology
- CDR → LMK01801+VCXO → LMK04832 (per crate)
- Two-stage PLL for jitter suppression
- Goal: global phase lock for all ADCs





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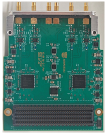
Summary

1. PDS1500 evaluated on JNE-1ton prototype at CJPL
2. **Four metrics significantly outperform** CAEN V1751:
   - Zero data loss / Baseline $\sim$1/3 / ENOB +2 bit / Time drift 0.3 ns
3. **Energy threshold $<$0.1 MeV** — enabler for JNE solar neutrino physics
4. Energy resolution $\sim$9% — photon-statistics ceiling, not electronics
5. Scalable to 4000 channels — architecture plan ready

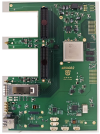
Thank You!

Questions & Discussion

PDS1500 Board Details

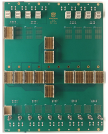


ADAM103 Mezzanine

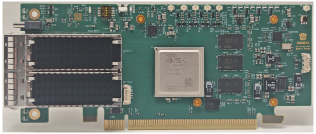


WRX602 Digitizer

TTC308 Trig/Clk

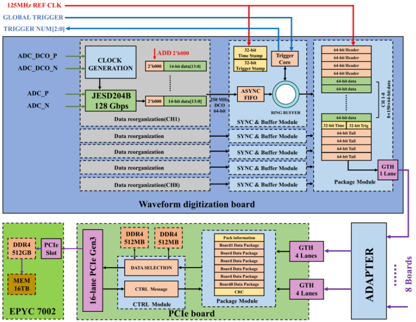


BP6U10S Backplane



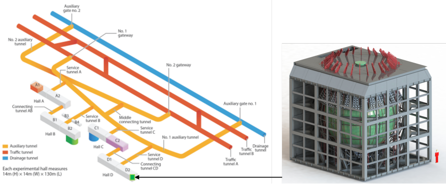
RDX051 PCIe Board (KU5P FPGA, 64 Gb DDR4)

Data Processing Workflow



ADC (1 GSPS, 14-bit) $\to$ 16-bit $\to$ deserialize 250 MHz$\times$64 bit $\to$ threshold eval. $\to$ global trigger $\to$ package (100 ns pre + 900 ns post) $\to$ fiber $\to$ DDR4 ping-pong $\to$ PCIe Gen3$\times$8 $\to$ ROOT

JNE Physics Goals



- Solar neutrinos + day-night asymmetry
- Geoneutrinos (U/Th decay chains)
- Supernova & supernova relic neutrinos
- Neutrinoless double-beta decay search

Time Calibration —Full Derivation

$$T_{mi} = t_m + \mathrm{TOF}_{mi} + T_i + \tau_{mi} \quad \text{(Eq.2)}$$

$$\Delta T_{ij} = T_{mi} - T_{mj} = T_i - T_j \pm \sigma_{\mathrm{stat}} \quad \text{(Eq.3)}$$

$$\bar{T}_i = \frac{1}{N}\sum_j \Delta \hat{T}_{ij} \quad \text{(Eq.4)}$$

$$\delta_i^{(r,s)} = \bar{T}_i^{(r)} - \bar{T}_i^{(s)} \quad \text{(Eq.5)}$$

$$\sigma_{\delta_i} \approx \sqrt{\frac{2\sigma_i^2}{N}} \quad \text{(Eq.6)}$$

Pairwise subtraction cancels trigger jitter t_m and photon TOF. Decentering $\bar{T}_i$ avoids over-dependence on any single channel.