Development of a Modular Muography Detector with FPGA-Based Data Acquisition for Geological Imaging in Taiwan

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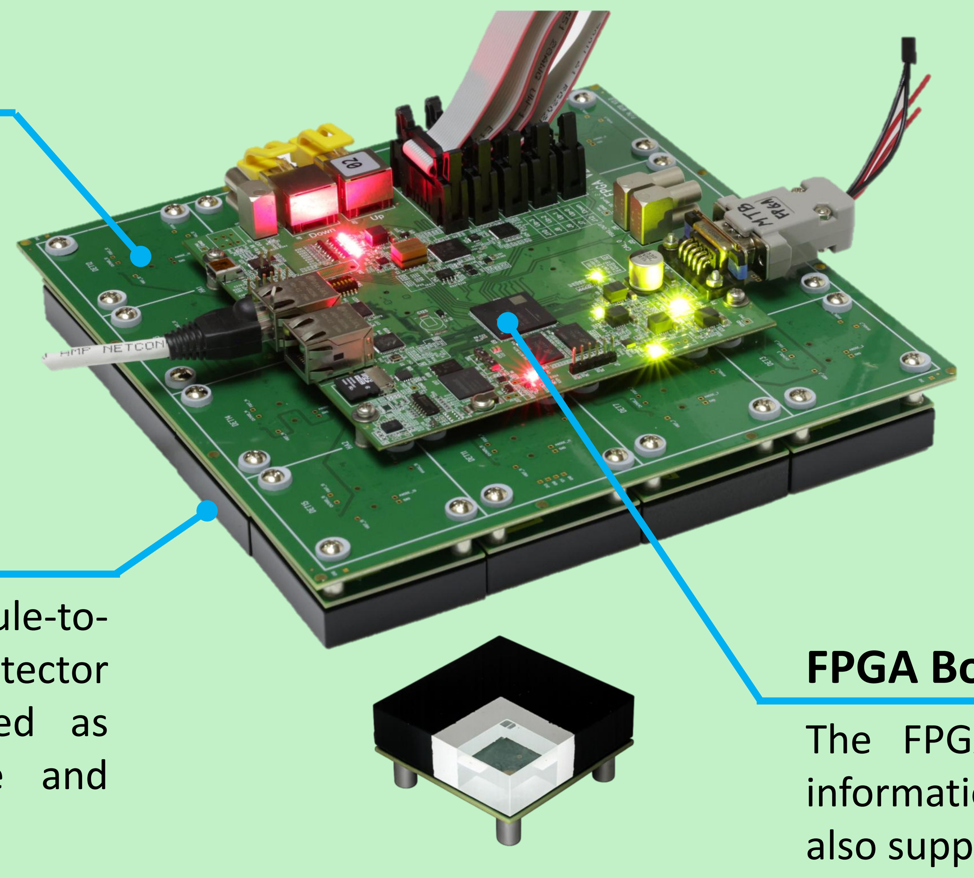
Introduction

National Central University and Academia Sinica have been developing a modular muography detector system for long-term geological exploration and mountain structure studies in Taiwan. The detector system is designed with a modular and scalable structure to improve long-term field operation, maintenance flexibility, and detector expansion capability. A synchronized FPGA-based streaming DAQ system enables multi-board event matching and directional muon tracking. The scalable readout structure supports large-scale field deployment.

Detector Architecture

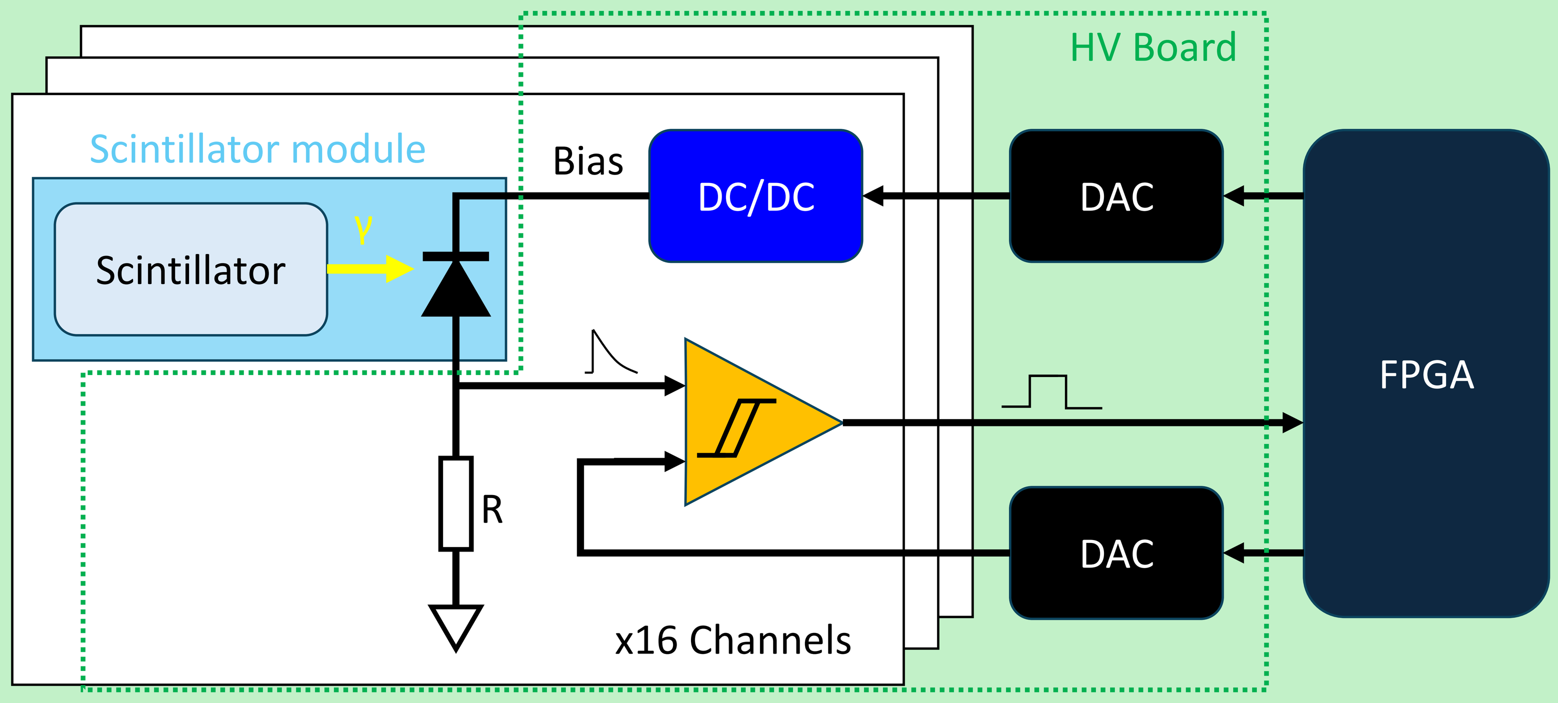
HV Board

Each scintillator module is connected to a 16-channel high-voltage board with independent DAC-controlled SiPM bias and threshold adjustment. The SiPM signals are digitized close to the detector modules to reduce analog signal degradation and simplify FPGA readout.



Scintillator + SiPM Module

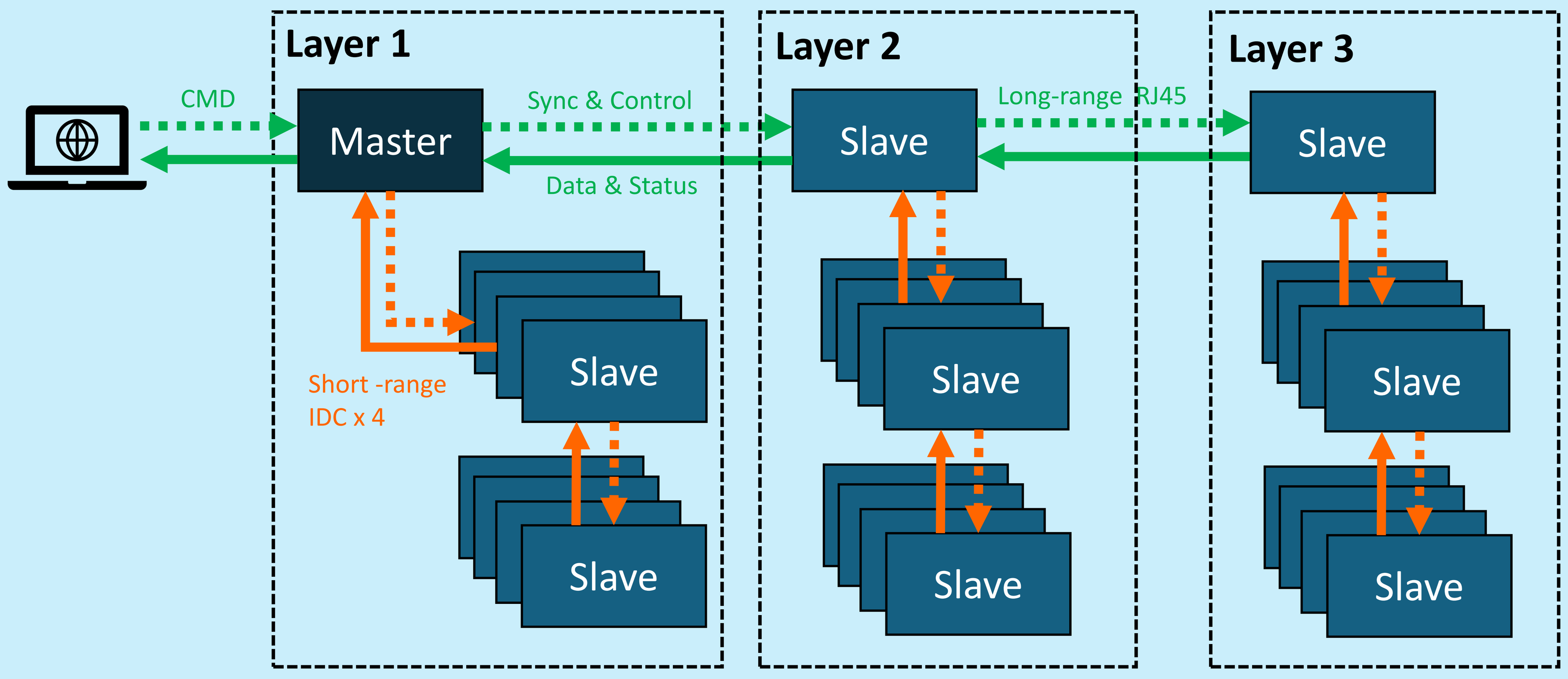
A pad-type optical coupling design improves module-to-module response consistency and simplifies detector assembly. The scintillator and SiPM are packaged as independent modules for simplified maintenance and detector expansion.



FPGA Board

The FPGA board records the Time-of-Arrival (TOA) and Time-over-Threshold (TOT) information of each signal for event matching and track reconstruction. Each FPGA board also supports upstream and downstream cascading for scalable detector deployment.

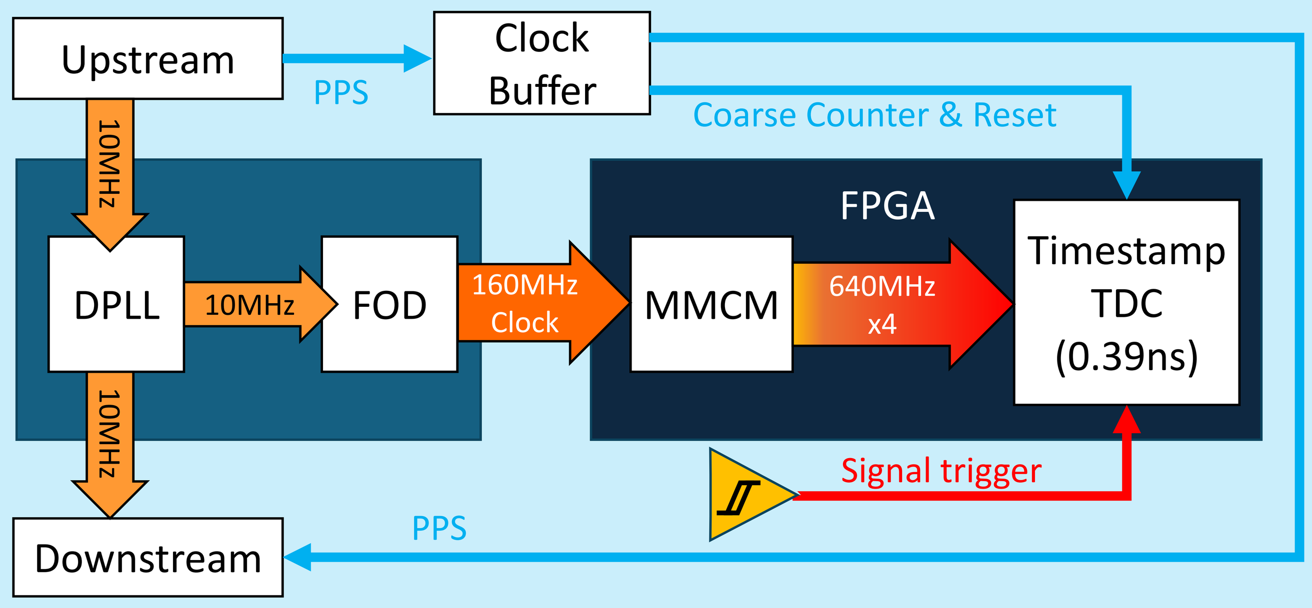
Communication Architecture



Each FPGA board supports short-range connecting and long-distance inter-layer transmission for scalable detector deployment. Slave FPGA boards function as both local readout units and relay nodes, forwarding downstream event data to the master FPGA for centralized aggregation. The master FPGA organizes the incoming data stream into prioritized UDP packet types for detector operation and monitoring.

1. Synchronization packets: *Report board synchronization status.*
2. Event packets: *Contain detector event information including TOA and TOT data.*
3. Housekeeping packets: *Record detector operating conditions such as bias voltage, temperature, and timing stability.*

Timing and Synchronization



Clock Synchronization

A common 10 MHz reference clock generated by the master FPGA is distributed throughout the detector system, while slave FPGA boards synchronize their local clocks through DPLL locking.

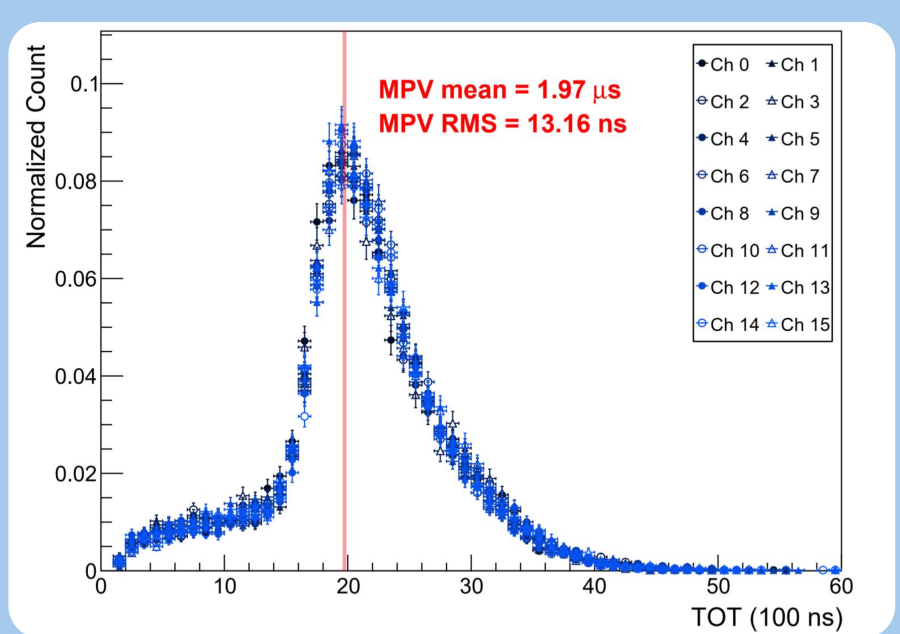
Timestamp-based TDC

Independent timestamps are assigned to each channel for offline event matching and track reconstruction. Multi-phase clock interpolation implemented with MMCM achieves a 0.39 ns TOA resolution.

Timestamp Alignment

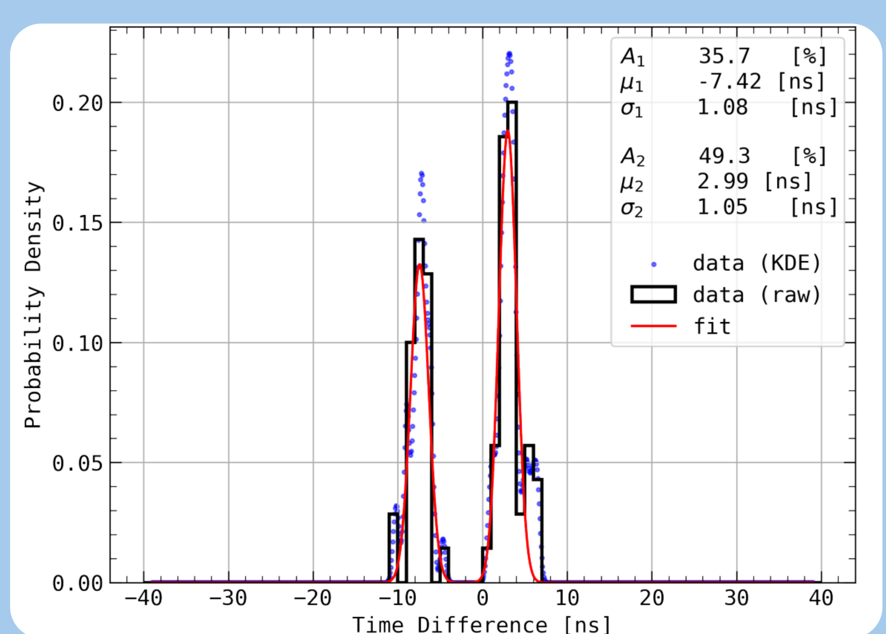
The master FPGA periodically distributes PPS synchronization signals to maintain global timing alignment during long-term operation.

TOT Calibration

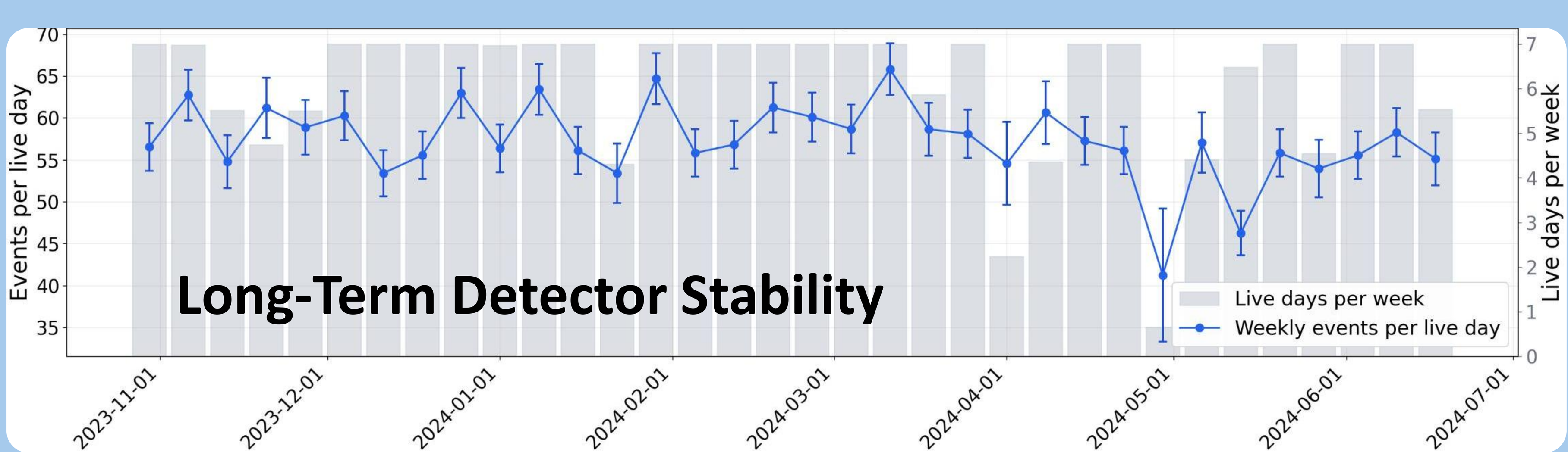


Per-channel SiPM bias and threshold calibration align the TOT distributions of all detector channels, improving response uniformity and reducing channel-dependent TOA variations caused by time walk.

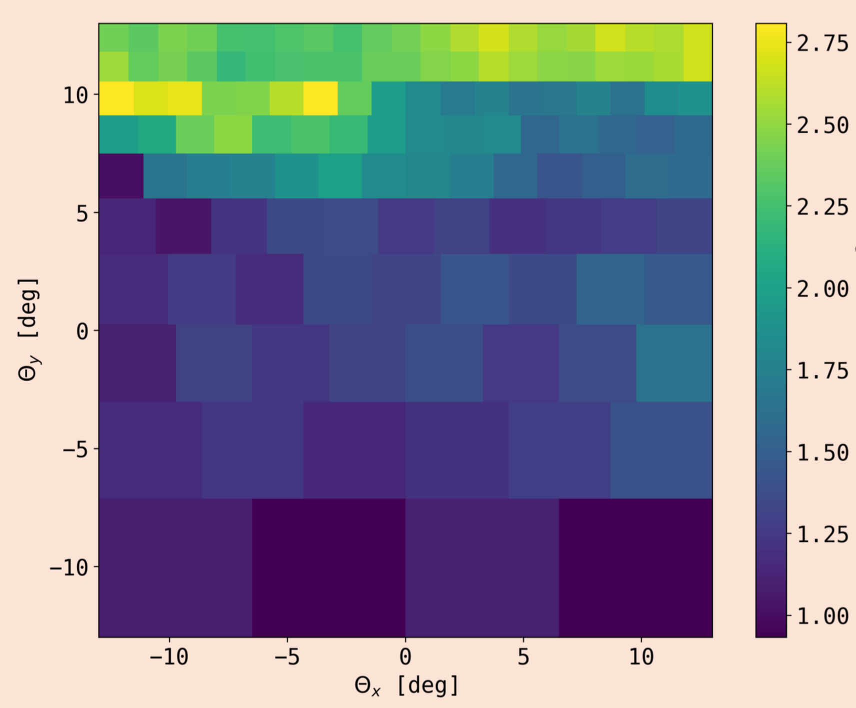
TOF Performance



The detector achieves an overall TOF resolution of approximately 1.3 ns. This timing performance enables directional discrimination and suppresses backward-going muon background, improving the signal-to-noise ratio at low elevation angles.



Muography Result



The Xizhou Mountain measurement shows recognizable density variation trends at elevation angles above 5°, which may be associated with local geological structure variations. At lower elevation angles, the increased mountain thickness and near-horizontal detection geometry significantly reduce the detector signal-to-noise ratio. This limits the reliability of the reconstructed density distribution.

Summary

A modular FPGA-based muography detector system has been developed for long-term geological exploration in Taiwan. The synchronized timestamp-based DAQ system achieves an overall TOF resolution of approximately 1.3 ns for directional discrimination. The detector demonstrated stable long-term operation during field deployment at Xizhou Mountain. Preliminary results show recognizable density variation trends through approximately one kilometer of mountain thickness.

Future work will focus on improving TOF performance and energy selection capability to enhance the detector signal-to-noise ratio and extend the probing capability for thicker mountainous structures. Improved timing performance may also enable more compact detector deployment in the future.

Reference

1) H. K. M. Tanaka et al., Earth, Planets and Space 62, 119–129 (2010).