

PAPER

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A modular and flexible data acquisition system for a cosmic rays detector network

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ABSTRACT. In this paper, we describe a modular data acquisition system developed as the foundation of a cosmic ray detector network. Each detector setup (henceforth referred as a station) is composed of an independent hardware device that can be controlled and read-out through the Internet. This device is designed to acquire and process the signal of up to eight different detector planes. Each of these detector planes uses plastic scintillator slabs that are optically coupled to silicon photomultipliers (SiPM). Within a single station, different geometries and plane orientations are possible using the same baseline design. The main readout is based on a programmable system-on-a-chip (PSoC), a flexible and re-configurable commodity hardware that is used to implement the trigger and timing logic. A Time to Digital Converter (TDC) is used to determine the precise timing of the event relative to a GPS timing signal and to estimate the signal amplitude through the Time-over-Threshold (ToT) method. An auxiliary set of sensors provide environmental information and station detector planes orientation that, together with other operation data, are periodically sent to a server using the MQTT protocol. Data is cached using an in-memory database for online monitoring and further persisted into a SQL database for offline analysis. The server framework is based in software application containers allowing easy replication of the server infrastructure.

KEYWORDS: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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1 Introduction

The detection of cosmic rays using simple apparatuses for quantitative data-taking have been explored over the years by several initiatives around the world for outreach and experimental High Energy Physics instrumentation teaching [1–3]. The possibility to connect geographically dispersed stations synchronized by a GPS timing signal [4] allows for a larger detection area suitable for the identification of high energy cosmic rays showers. In order for such system to be deployed in a high school or science museum environment (hence for outreach purposes), it must be safe (no flammable gases or high voltages) and ideally low cost, so the network can comprise as many stations as possible. The use of plastic scintillators, SiPMs and commodity electronic hardware allows the project to fulfill this objective. The readout, timing and trigger implementation supports a variety of geometries and even other cosmic rays detection methods (e.g. Cherenkov) that can be easily deployed in the system by a simple reconfiguration of the hardware. This enables a variety of experiments to be performed with a single design, thus reducing the complexity and cost of the system construction and operation.

2 The cosmic ray station

Each station is an autonomous hardware (and firmware) unity that detects cosmic ray events and transmits the raw data to the software stack through the Internet. These stations are composed of up to four *frontend* modules, in which the scintillators, SiPMs and the analog section of the electronics are located in separate boards and a *backend* module aggregating the trigger, timing, data acquisition, event building and network communication functions (figure 1).

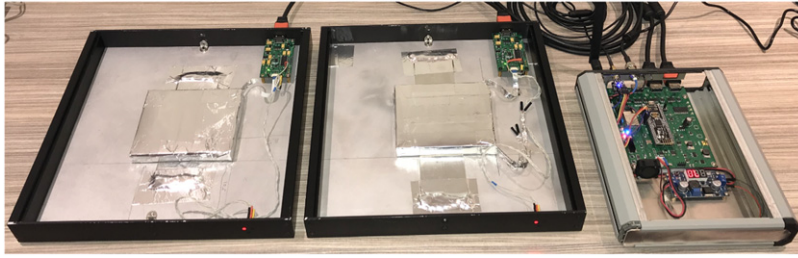


Figure 1. Photo showing 2 frontend modules (left) and a backend module (right).

2.1 Frontend detection board

The current system uses $3.9 \text{ mm} \times 3.9 \text{ mm}$ SiPMs sensors (Broadcom AFBR-S4N44C013 [5]) that can be installed as an array of up to four sensors mounted on dedicated PCBs. The SiPMs are attached to a plastic scintillator slab (BC408) using optical grease. The scintillators in use range from $150 \text{ mm} \times 150 \text{ mm} \times 10 \text{ mm}$ to $400 \text{ mm} \times 400 \text{ mm} \times 10 \text{ mm}$. The current design is able to use scintillators slabs as thick as 20 mm. An EEPROM device installed in each detection board (read-out by I2C protocol) allows for matching the inventory of built boards with the boards deployed in a given site. The system is sealed in a light-proof aluminum container and the connection to the readout electronics is made using a strip line flat cable. Two LEDs can be pulsed in order to provide a light signal for debug and calibration.

2.2 Frontend readout board

Each frontend holds a two-channel voltage amplifier followed by a discriminator circuit. Each channel can sum-up the signal from two SiPMs or be ganged together to sum the signal from four sensors when a thicker scintillator slab is used. A minimum detection system can comprise only one frontend module with two separate channels, and detect the passage of cosmic rays by requiring the coincidence of the two signals.

The frontend readout board also holds a microcontroller with digital-to-analog (DAC) converters which are used to set the threshold voltage of the two discriminators independently and to fine adjust the SiPM bias voltage. The discriminated signal is sent to a backend module, where all timing and acquisition are performed. This adjustment is made using a high voltage amplifier in a non-inverting setup, so the different SiPMs sensors can be biased by a low noise adjustable power supply.

Each frontend board deploys an inertial measurement unit (IMU ICM-20948 [6]) sensor with a 3-axis accelerometer, gyroscope, and compass, so the orientation of the planes relative to the earth surface can always be determined. Alongside the IMU sensor, an environmental sensor (Bosch BME680 [7]) is used to measure temperature, humidity, and atmosphere pressure. The data can then be further used to correlate the cosmic rays flux measurements to the environmental and operating conditions.

2.3 Backend module

The backend module is a single board responsible for the trigger, timing and data acquisition. The power for all the station and network connectivity is also provided through the backend. Up to four

frontend modules can be connected to a single backend module through a commodity HDMI cable in which the four differential lanes are used to carry two digitized SiPM and two LED calibration signals. Figure 2 describes these connections and the peripherals around the PCBs.

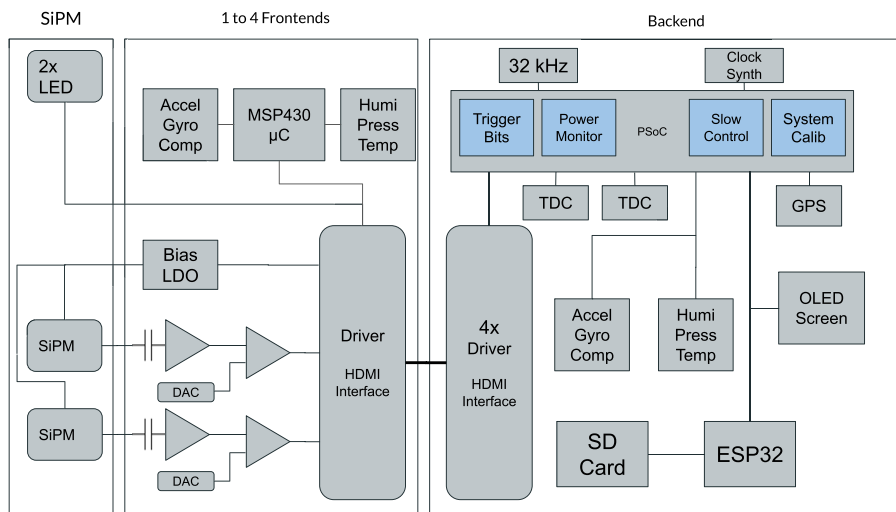


Figure 2. Block diagram of a detector showing the PCBs and their internal components.

A Cypress Semiconductor Programmable-System-on-a-Chip (Cypress PSoC5LP [8]) performs most of the data processing of the station. Using the PSoC programmable digital and analog circuitry, the signals from the frontend modules are routed to a trigger predefined look-up table, and the trigger signal is generated from its output. Up to 5 different combinatory operations between the inputs from the detector are possible, providing a reconfigurable trigger decision logic without the complexity of an external FPGA. Therefore, the user can choose to configure the trigger with any logical operation between any channels based on the spacial disposition of detection planes in the station, as an example, figure 3 shows a doubled detection area and telescope-like configuration of detection planes.

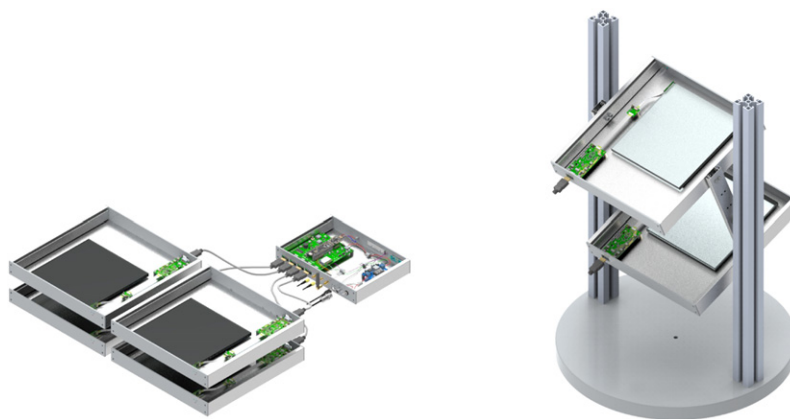


Figure 3. Some of the possible arrangements for the cosmic ray detector planes. The trigger configuration can be selected before the operation to reflect the geometrical placement of the planes.

Two external Time to Digital Converter (TI TDC7200) are used for precise (better than 50 ns [4]) timing determination between the trigger signal and the GPS timing synchronization signal. This allows for the off-line synchronization of events acquired by independent stations within the GPS timing resolution. The current GPS module (uBlox Neo-6 [9]) offers a final resolution of 30 ns, but the very high timing resolution of the TDC (in the range of 50 ps) enables the future use of GPS modules deploying advanced timing techniques, and hence providing a better timing resolution. For some applications, the SiPM discriminated signals can be internally routed in the PSoC to the TDC input channels for measuring the width of the pulse and through the use of a Time-over-Threshold (ToT) method, estimate the pulse amplitude and energy.

Finally, all the information collected by the PSoC5LP can be either stored in a local flash memory or sent to a WiFi SoC module (Espressif Systems ESP32 [10]) that, connected to a local Wi-Fi network, will relay the information to the Internet. The station uses the MQTT protocol [11] to receive configuration data and to send the acquired data to a server. In the server, data is cached in an *in-memory* database (Redis [12]) for on-line monitoring of all connected stations and persisted in a SQL (Oracle MySQL [13]) database for offline analysis.

2.4 Initialization, calibration and operation

During the initialization, the operating conditions of the station can be either read from the non-volatile memory in the PSoC5L or be set remotely by the network. This allows for fine tuning the detector bias and discriminator thresholds over time without physical intervention in the station. A calibration procedure was devised to establish the offsets in the time measurements and to verify the system integrity, and it is always performed before any data-taking. A series of test trigger patterns can also be injected by either pulsing the LEDs or by digitally forcing signals in the PSoC5LP internal logic in order to debug the station operation.

The normal operation is usually performed in an unattended fashion after choosing a specific trigger decision configuration. The data taking is sliced in time or in number of events in *cosmic blocks*, so the analysis can filter out whole cosmic blocks that were taken when the detector operating conditions are out of specifications. At the beginning of each cosmic block, all the environmental, voltages and currents of the system and the software state are read out by the backend module and sent to the database. A data quality procedure can later on check for non-conforming cosmic blocks, tagging them as not good for analysis. Using the timestamp information of the event, an offline analysis can search for timing coincidences among different nearby stations, indicating detection of a large cosmic rays showers.

3 Data management and analysis

Intended as an outreach focused project, the user interface allows many educational activities, ranging from just observing the detection rate from a fixed station to the combination of several stations or angular muon distribution. The infrastructure is built as a Docker stack [14], with each service running in its own container. Each station has a dedicated topic in our MQTT Broker [11] and a custom Python script offloads all messages transmitted in these topics to a Redis cache [12], a fast in-memory database. This script is also responsible for some data reconstruction and the Database (SQL) storage [13]. Two parallel services are available for the user interface: the first is a

Grafana panel [15], intended as a read-only web page showing all monitor information predefined by the team; the second one is a Jupyter Notebook [16] service, a web-based interactive notebook capable of running Python code with read access to the database through the network.

4 Results

Data taking with the detector started with a configuration of 2 frontend modules made of two $150\text{ mm} \times 150\text{ mm} \times 4\text{ mm}$ slabs of plastic scintillator (BC408) each. Figure 4 shows a preliminary result taken in the city of São Paulo, Brazil, at an altitude of approximately 760 m. The detector was located inside a building under a 40 cm thick concrete ceiling. Using an AND coincidence as a trigger between all 4 detection planes, the station registered an average of 90 events per minute.

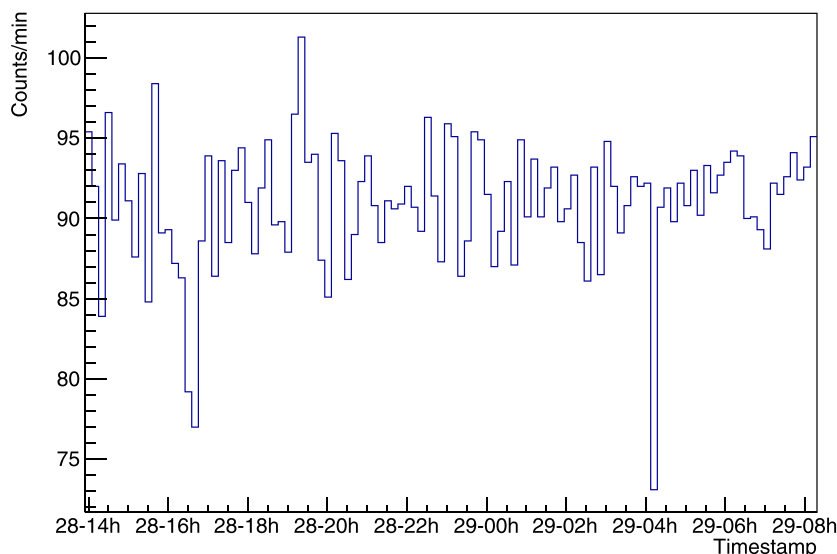


Figure 4. Plot showing the number of counts per minute of data taking over 2 days with an AND trigger logic between 4 stacked detection planes of $150\text{ mm} \times 150\text{ mm}$ using BC408 4 mm slabs.

Acknowledgments

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