The MURAVES telescope front-end electronics and data acquisition

Luigi Cimmino[1,*], Fabio Ambrosino[1,2], Lorenzo Bonechi[3], Roberto Ciaranfi[3], Raffaello D'Alessandro[3,4], Vincenzo Masone[1], Nicola Mori[3,4], Pasquale Noli[1], Giulio Saracino[1,2], Paolo Strolin[1,2]

[1] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Naples, Italy*

[2] *Università di Napoli Federico II, Dipartimento di Fisica, Naples, Italy*

[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze, Sesto Fiorentino, Florence, Italy*

[4] *Università di Firenze, Dipartimento di Fisica e Astronomia, Sesto Fiorentino, Florence, Italy*

Article history
Received July 5, 2016; accepted October 5, 2016.
Subject classification:
Muon radiography, Time of flight, SiPM read-out electronic, Raspberry Pi, Data acquisition control systems.

ABSTRACT

The MURAVES detector is a 4 m² muon tracker equipped with a low power consumption electronic and designed to work in volcanic areas. Due to the great amount of channels (~1500) the detector is equipped with a multilayer electronic for data acquisition. It consists of 12 slave boards and 1 master board per square meter of detector and a single Raspberry Pi board that rules the whole set of one-square-meter detectors. Because of this modularity, we can enlarge in principle the detector surface by adding more one-square-meter elements. In the present work, we resume the main features of the MURAVES detector designed for the muography of volcanoes and, more generally, for the imaging of the underground. We focus on the capability to fine tune every single channel of the detector and the precise measure of the time of flight of the muons. The latter uses a time expansion technique and it should allow us to make a background rejection never obtained until now.

1. Introduction

The MuRay detector prototype [Ambrosino et al. 2013, 2014] constitutes the basic part of the MURAVES Telescope. The MURAVES Telescope can work in volcanic areas. Thus, it has to be modular and easy to install. With respect to the MURAY detector, the basic plane arrangement has been modified to reduce weight and size. The latter assembles two modules, each consisting of 32 plastic scintillators, inside a solid shell that prevents mechanical stresses, weighing ~60 kg.

The MuRay detector is made of 6 planes of 64 triangular-shaped plastic scintillators, arranged in three XY stations. It acts as a tracker and the angular resolution is about 8 mrad, when the outer stations are 1 m spaced. Moreover, it is suitable for precise measurement of the muon time of flight.

The latter is one of the tools used to reduce background events. In particular, the measurement of the muon time of flight can determine the track. Further background rejection can be achieved by requiring coincident signals in three stations, instead of two.

Each scintillator is read by a Silicon photomultiplier (SiPM). A SiPM integrated read out chip EASIROC is used to manage the output signals of each group of 32 SiPMs coupled to the modules.

2. The slave board features

The Extended Analogue SiPM Integrated Read Out Chip (EASIROC) [Callier et al. 2012] has 32 analogue channels, each one provided with an 8-bit DAC (Figure 1) for fine-tuning the bias voltage of the connected SiPM. The SiPM signal is voltage amplified by means of a low noise pre-amplifier capacitively coupled with the photomultiplier. Low or high gain amplification are available for all 32 channels and the gain can be adjusted using a shared 4-bit register. Two dedicated tunable shapers and a track and hold provide the charge measurement. The track and hold circuit records the signal's peak and store the values inside a register, converted with a 12-bit ADC. The peaking time value depends on the slow control settings (Figure 2).

The amount of charge released by each SiPM is saved in the form of an amplified and shaped signal at the specified peaking time. Two programmable potentiometers set the hold time and the timeout. The hold potentiometer regulate the minimum time the SiPM

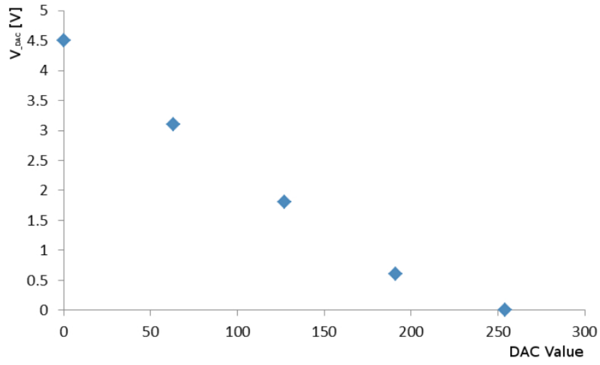

Figure 1. The fine tuning of the SiPM bias voltage is realized by setting an 8-bit DAC (DAC8). Higher DAC8 slow control setting corresponds to a lower voltage adjustment.

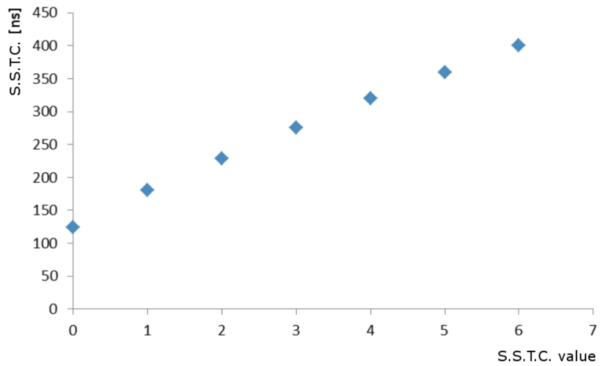

Figure 2. Slow Shaper time constant (S.S.T.C.) as a function of the slow control register setting.

signal is locked at a fixed amplitude value and the timeout setting specifies how long the system wait for a trigger coincidence, depending on the trigger logic.

All slave boards include a XILINX Spartan III FPGA for logic functions. The slave boards are low power consumption and can work in two modes, RUN and DIAG. The power consumption of the front-end electronics is below 25 W and it includes the SiPMs powering. Each board is equipped with a programmable voltage regulator (MAX1932) that can provide supply voltages in the range 28 V to 75 V. The slave working voltage is 6V and it uses linear and switching regulators to provide all the required voltages. The switching regulators work with a dedicated ground, in order to avoid the spreading of electrical noise through the board.

3. The trigger system

Every time at least one of the 32 SiPM has a signal with an amplitude exceeding a given threshold, a fast shaper followed by a discriminator produces a local trigger, the so-called FastOR logic signal. The threshold is set by a 10 bit register and the local trigger is 100ns long. Each station is routed to a multiplexer, which is usually programmed to have the logic OR of the two slaves of each single plane and the logic AND of the two planes belonging to the station. The logic output of each station is put in the coincidence with a fourth multiplexer to determine the AND trigger logic of the detector. The fulfillment of the trigger logic produces a global trigger that starts the data acquisition.

4. Time expansion technique

The time expansion technique is used to magnify the time of flight of the muon. This technique provides the accuracy necessary for digitizing the time, despite the fact that the limit on power consumption imposes a moderate clock frequency. The greater the time expansion, the better the accuracy with which we determine the time of flight.

The slave boards have therefore been equipped with a time-to-digital converter (TDC), based on a time expansion technique, that digitizes and records the time

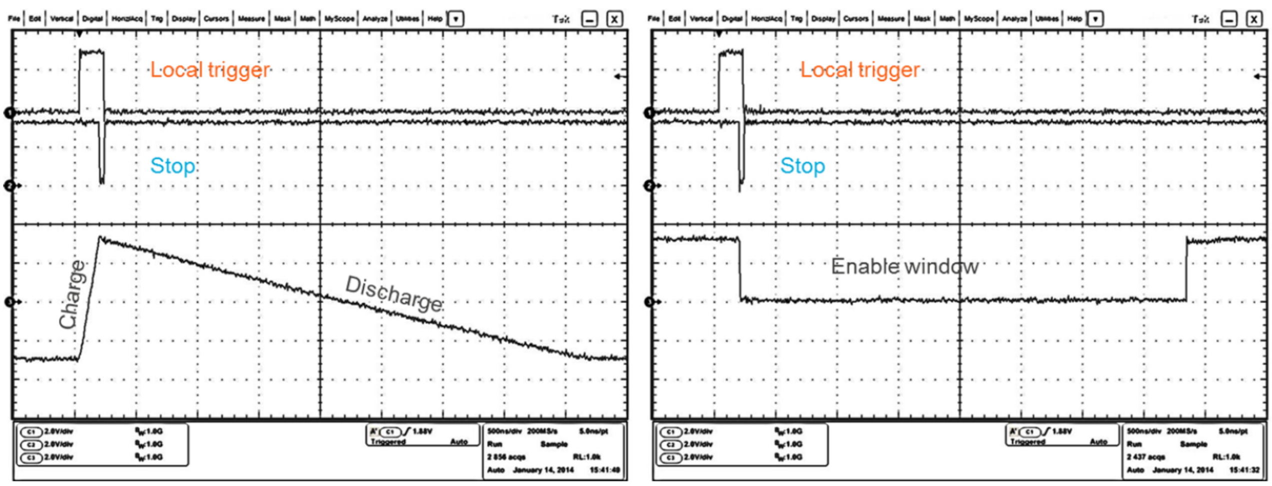

Figure 3. The relation between the charge and the discharge of a capacitor (left) and the corresponding enable window (right). With the Fast OR trigger signal a capacitor starts charging and it stops when the master board produces a global trigger. At the same time the enable signal is activated and it lasts until the same capacitor is discharged. Time is digitized by counting the clock pulses.

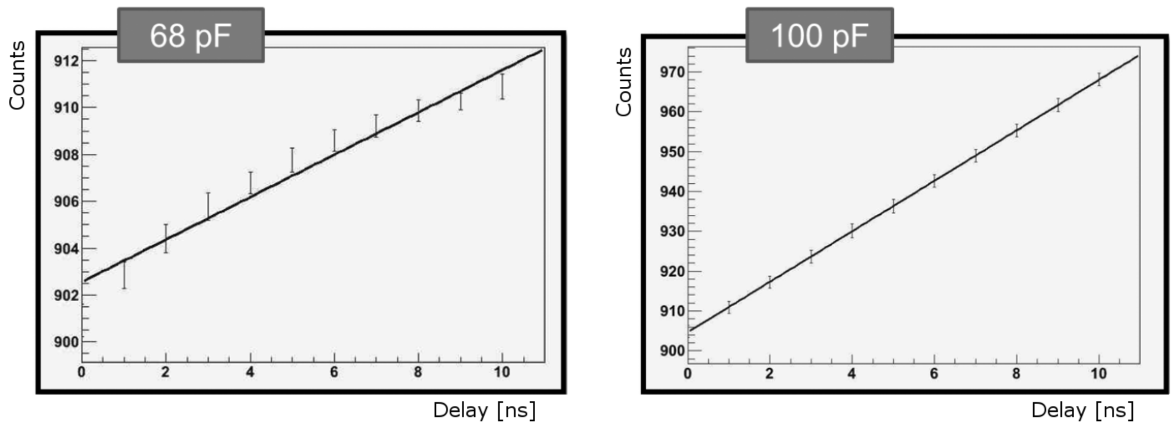

Figure 4. Plot of the experimental data relative to the sizing of the time expansion circuit. The value of the capacitance has been chosen in order to have a TDC linear response.

interval between the production of a local trigger and the reception of a stop signal.

The stop signal is sent by the master board and represents a signal common to all slave boards. The digital time value is inferred from the discharge of a capacitor with respect to a reference clock. Counting the number of clock pulses occurred during the discharge, the time is expanded using a discharge circuit, with greater time constant with respect to the one that previously charged the capacitor. This time expansion technique increases both the accuracy of the digitization and the system latency. A discharge circuit is used to count the number of clock pulses occurred during the discharge. For the last version of the circuit, the expansion factor is $E = 20$. Figure 3 shows the entire process relative to a single slave board.

When sizing the discharge circuit, it would be desirable to use low capacitance values, because the steepness of the discharge sharply cuts through the threshold. This event determines the closing of the enable window and its jitter reduces in this case. A small jitter of the enable signal, corresponds to a small error in the counts. However, as it can be seen in Figure 4, small values of the capacitance lead to a non-linear response. The time expansion circuit uses a 100 pF capacitor which offers good linearity. The measured RMS was 1.8 counts, suitable for a sub-ns time resolution.

5. The Master board

A Master board manages all the slave boards in a MuRay Telescope. The Master board is equipped with a credit-card-sized computer, the Raspberry Pi (RPi). The most interesting features of the RPi is the on-board general purpose input/output (GPIO) unit, based on which we implemented a low level protocol with the master board. We obtained a link speed of 20 Mbps, the maximum data transfer rate supported by the RPi.

The protocol works so that the data acquisition starts when the RPi sets slave boards in RUN mode; when a trigger occurs, the RPi stops the acquisition and switches the slave boards in DIAG mode. The RPi interprets physical events by means of hardware interrupts. Once a physical event is recognized, the RPi downloads and records the hit by sending 32 clock pulses per time to the Master board. In response to each clock train, the RPi receives a 32 bit packet from the master board, up empty the FIFO memory of the latter. A handshaking procedure, written in C language, runs at the end of every communication and uses the RPi GPIO native libraries. Another important feature used during data acquisition, is the possibility to set the number of events to be collected. Since the RPi is not a real time processing device, the software stores the data acquired from the master board inside the RAM; when the acquisition stops, the program runs a separated thread that writes the data on a USB hard disk drive. Then the acquisition restarts, cutting down the dead time (several ms) due to the hard disk drive access.

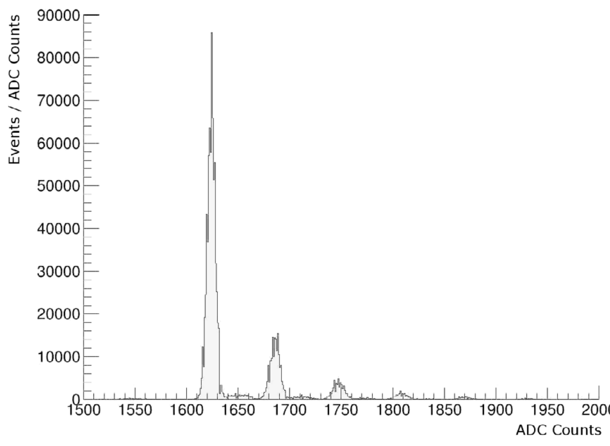

Figure 5. Measured pulse height dark spectrum of a Hamamatsu MPPC S12825-050P. The peaks of the first, second and third photoelectron distribution are well visible.

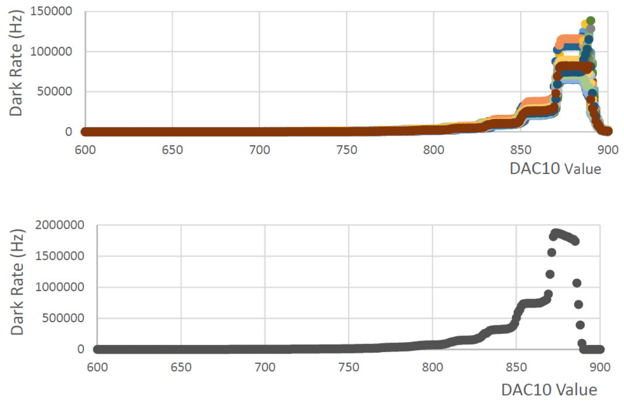

Figure 6. Plot of the dark rates of the 32 SiPMs vs DAC10 slow control setting (top) and the corresponding OR32 of all dark rates (bottom). Higher DAC10 values corresponds to lower thresholds.

6. Telescope characterization

The SiPM used is the Hamamatsu MPPC S12825-050P, whose pulse height spectrum is shown in Figure 5. This kind of SiPM has a low dark rate and the variation of the operating voltage as function of the temperature is about 50 mV. The operating voltage varies from 66.34 V to 66.60 V. In general, a change of the temperature produces a variation of the breakdown voltage of the SiPM, where the gain and the photon detection efficiency (PDE) vary of some percent per Celsius degree following these changes. Moreover, the dark rate increases with increasing temperature [Renker 2006]. In Figure 6 is reported a recorded dark rate vs threshold scan, relative to a slave of the telescope. We choose a test working point with the OR32 dark rates between 50 KHz and 100 KHz, so considering the fourth photoelectron signals.

Up to now, we have a trigger efficiency for the coincidence of six planes greater than 80%, with some planes reaching the 99% efficiency. The trigger efficiency was measured with the planes in the horizontal position. The measured muon flux in a steradian is about 40 Hz.

7. Conclusions

Muon radiography applications in the field of volcanology requires tracking with high spatial resolution and rejection of backward muons mimicking muons coming from the volcano. A precise time of flight measurement is necessary for the backward muon rejection.

In order to satisfy these requirements, the MuRay prototype was improved and the MURAVES detector is provided with high spatial/angular resolution, high resolution timing, time of flight measurement and can be used in extreme environment (few tens of watts of power consumption and modularity).

While the MURAVES detector is under construction, we tested and characterized the front-end electronics to obtain the best performances. We studied the 8-bit DAC response for the fine tuning of the SiPMs bias voltage and characterized the tunable settings to improve signal acquisition. The signal formation and its conversion can be adjusted by setting *ad hoc* values for the pre-amplification, the slow shaper and the peaking time.

The SiPM response to the threshold variation and trigger efficiency are actually under investigation, to set the working point of the detector. The high detection efficiency and the good quality of the collected data are suitable for the data analysis. The resolution of the muon time of flight was measured to be better than 400 ps.

Finally, a complete acquisition software in Python programming language was written and runs on a Raspberry Pi computer. The software has auto control functions and can detect malfunctions, a mandatory requirement for long stand-alone data acquisitions.

References

Ambrosino, F., et al. (2013). The MU-RAY detector for muon radiography of volcanoes, Nucl. Instrum. Meth. A, 732, 423-426.

Ambrosino, F., et al. (2014). The MU-RAY project: detector technology and first data from Mt. Vesuvius, J. Instrum., 9, C02029.

Callier, S., C. de La Taille, G. Martin-Chassard and L. Raux (2012). EASIROC, an Easy & Versatile ReadOut Device for SiPM, Physics Procedia, 37, 1569-1576, (TIPP 2011).

Renker, D. (2006). Geiger-mode avalanche photodiodes, history, properties and problems, Nucl. Instrum. Meth. A, 567, 48-56.

*Corresponding author: Luigi Cimmino,
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Naples, Italy; email: cimmino@na.infn.it.