

Instrumentation of the Data Acquisition System for the MonRat Telescope

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Abstract-- MonRat is a telescope designed to detect photons generated in the atmosphere by ultra-high energy cosmic ray particles. It is composed of a parabolic mirror focusing light onto a 64-pixel multianode photomultiplier tube. Ultraviolet-passing filters are positioned in front of the photocathode to select photons within the wavelength range of 300 to 400 nm. The data acquisition system consists of a front-end, a set of preamplifiers and FPGA-based boards able to record trigger times and waveforms from each channel. MonRat is being designed to detect air fluorescence radiation under different atmospheric and geomagnetic conditions. Also planned are Cherenkov radiation measurements as well as atmospheric monitoring in the lidar mode.

Index Term-- Cosmic rays, atmospheric fluorescence, data acquisition system.

1. INTRODUCTION

Cosmic rays studies through measurements of atmospheric nitrogen fluorescence light have long been shown to be successful and, nowadays, experiments like HiRes [1], the Pierre Auger Observatory [2] and Telescope Array[3] employ this technique to detect cosmic ray showers with energies exceeding 10^{17} eV. The detection is performed by measuring the amount of near-ultraviolet light generated by de-excitation of nitrogen molecules, after their excitations or ionizations due to air shower charged particles. For ultra-high energy showers, the huge number of charged particles near the shower axis is responsible for the light generation with enough intensity to be detected

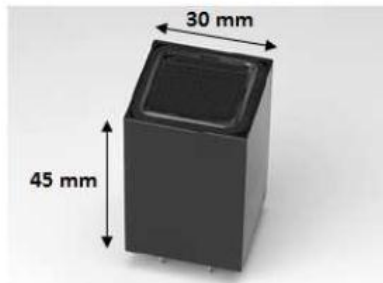
by photomultipliers placed kilometers away from the emission point.

The absolute fluorescence yield is known for some electron energies, air pressures and temperatures [4], [5], [6], [7], but further and more precise results are needed, since their extrapolation is the main sources of systematic errors in the reconstruction of showers using fluorescence telescopes [8], [9]. For a given atmospheric height h , the number of fluorescence photons N_γ is proportional to number of electrons N_e and the Fluorescence Yield (FY), which, in turn, depends on energy deposit by electrons in the air at, air pressure P , air temperature T and the emitted radiation wavelength λ :

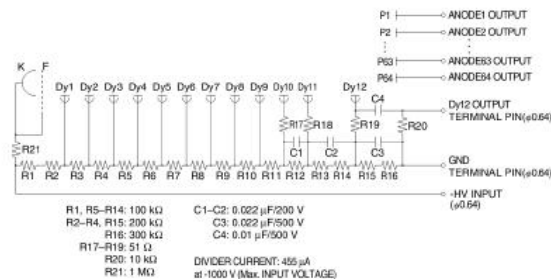
$$N_\gamma(h) = N_e(h) \cdot FY\left(\frac{dE}{dx}, \lambda, P(h), T(h)\right) \quad (1)$$

2. THE APPARATUS

MonRat¹ [10] is a compact telescope designed to detect fluorescence photons in the atmosphere. We use a 64-pixel MultiAnode PhotoMultiplier Tube (MAPMT) from Hamamatsu [11] (model H7546B) as the photosensitive component (see figure 1). The MAPMT is placed at the focus of a parabolic mirror mounted in a Newtonian setup. Therefore, the data acquisition system consists of the integration of several channels with preamplifiers, discriminators and digitizers. The digitizers are FPGA-based boards, able to record waveforms (ADCs) and time stamps (TDCs) from each channel and send this information through a USB interface to the computer running the data acquisition software.



(a) External view.



(b) Schematic of the voltage divider.

Figure 1: The MAPMT (model H7546B) from Hamamatsu [11].

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** Deceased.

¹ For the abbreviation of Atmospheric Radiation Monitor, in Portuguese.

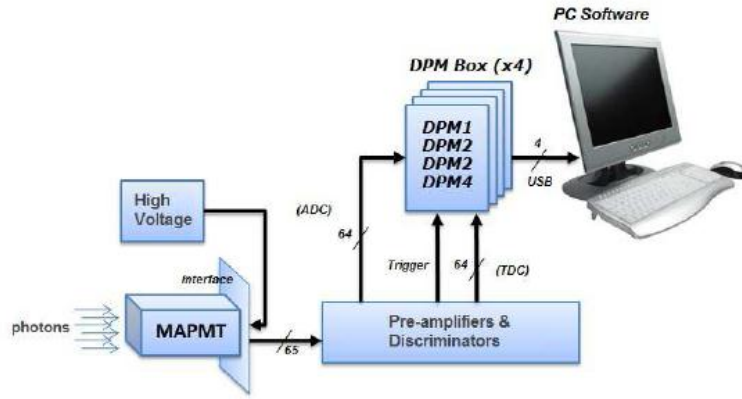


Figure 2: The MonRAt block diagram.

In figure 2, we show a diagram representing the main components of the MonRAt experiment [12] [13]. The signals from the MAPMT are initially collected by a front-end interface that reads 65 analog signals: 64 anodes plus the twelfth dynode which integrates them all. These signals are sent to a stage with a double function: amplification (about 10 times in amplitude for each anode signal) and pulse formatting (TTL for all the signals). The signals are then sent to 4 boxes housing 4 DPMs (Data Processing Modules) boards each, able to handle 4 channels each (totaling 64 analog inputs). The analog inputs are sampled by 12 bit ADCs and through the trigger inputs they give the start condition for all TDC channels (by the twelfth dynode) and the stop condition for each TDC channel (by the anodes). Part of the electronics has been purchased and part has been developed in our laboratories, in the next sections we will discuss these components in detail.

2.1. MAPMT front-end board and the divider boards

The front-end board to collect and condition the MAPMT signals was manufactured by Vertilon Corporation [14]. The board (model SIB164A) provides electrical and mechanical connectivity between the MAPMT and the signal processing electronics of the experiment. The MAPMT is connected through a 76 pin socket in the lower side of the front-end board, giving inputs for the high voltage and outputs for the 64 anodes, the twelfth dynode signal and a common ground.

In figure 3, one can see the two sides of the board with its main components and connections, according to the following legend: 1- high voltage input; 2- preamplifier output; 3- interface connector J1 (model SBC090P); 4- interface connector J2 (model SBC090P); 5- trigger indicator LED; 6- last (12th) dynode signal; 7- external input; 8- high voltage area; 9- socket to the H7546B MAPMT; 10- MAPMT

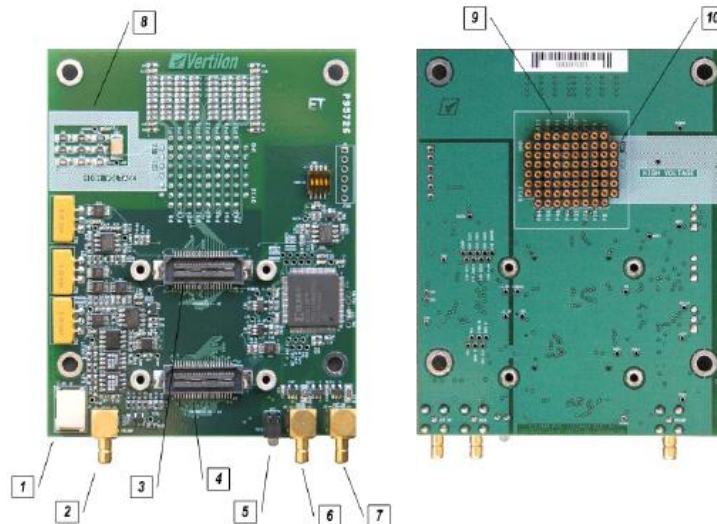
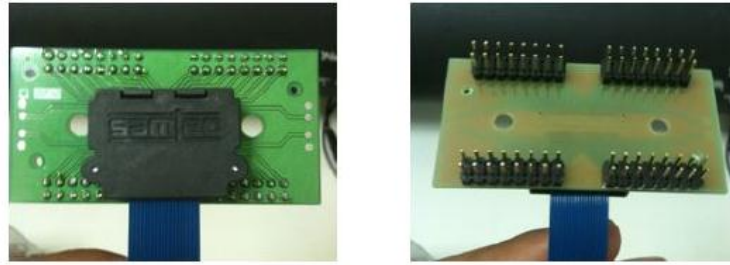


Figure 3: The front-end board SIB164A by Vertilon [14].



(a) Upper view of the divider board (with the cable CNN020 attached to it). (b) Lower view of the divider board (notice the 4 output pin headers).

Figure 4: A signal divider board.

high voltage input. The signals from the anodes are routed to 2 connectors (J1 and J2), located on the backside of the board, that allows us to conveniently mount the system with the photocathode facing the optical arrangement and take the cables from the other side.

We purchased the front-end board (model SIB164A), 2 flat cables (model CNN020) with 32 channels each and 2 extra connectors (model SBC090P) to build 2 *divider boards*. The divider boards are designed to attach the cables and divide their signals in groups of 4 each (see figure 4). The output signals from the divider boards are then sent to another 8 boards in order to be amplified and formatted, as described in the next section.

2.2. Preamplifiers and discriminators

The signals coming from the MAPMT must be pre-amplified, since they have low amplitude and short duration (~30 ns). Thus, circuits with low noise, broadband and performing the functions of integrator, amplifier and filter are required. The active element is the operational amplifier OPA657 (see upper part of figure 5 for the preamplifier circuit). The time constant of the second stage ($\tau = R_{shape}C_{shape}$) sets the rising and falling times for the signals which must be compatible to the sampling times of ~10 ns of the analog to digital converter. Moreover, R_{shape} and C_{shape} form a low-pass filter that influences the bandwidth of the preamplifier.

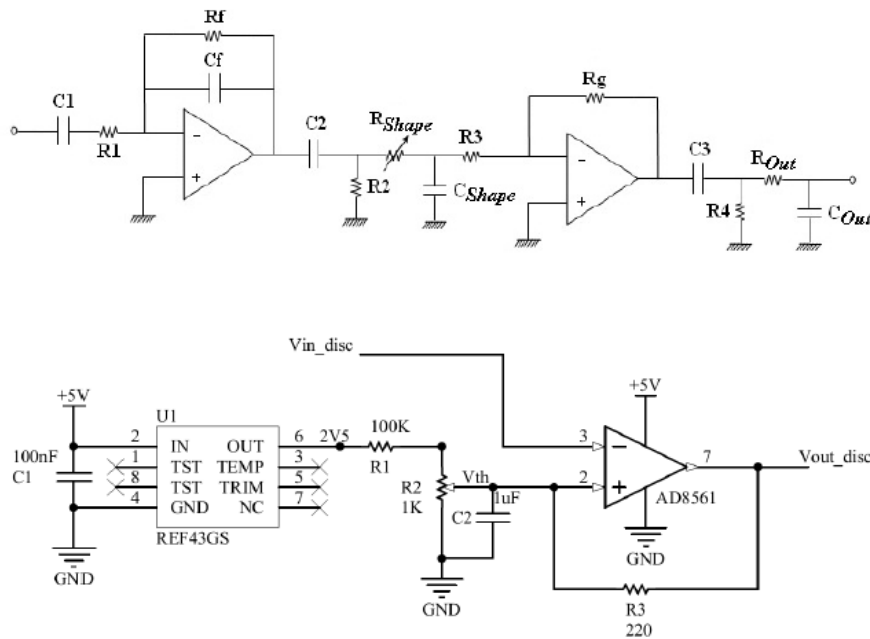


Figure 5: Upper panel: the preamplifier circuit; lower panel: the discriminator circuit.

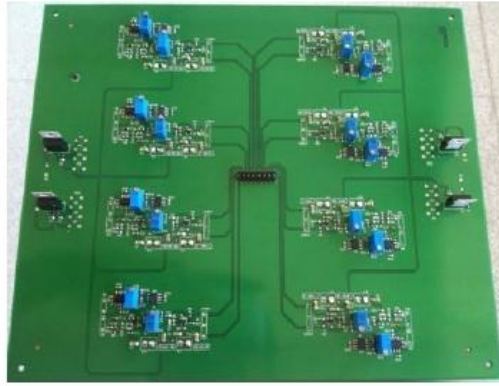


Figure 6: Photograph of 1 board with 8 channels of preamplifiers and discriminators.

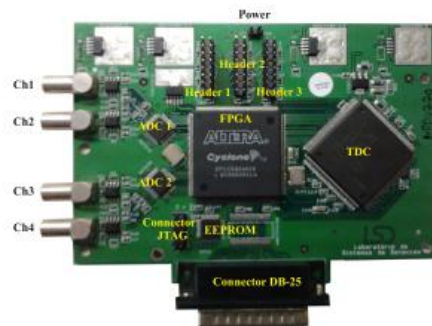
The discriminator produces digital TTL pulses when the input signal has a higher amplitude than a threshold. For this project we used a fast analog comparator (propagation time of 7 ns), model AD8561 from Analog Devices (see lower part of figure 5 for the discriminator circuit). The input voltage (V_{in_disc}) is compared to a constant threshold voltage (V_{th}), adjusted by the potentiometer R2. If V_{in_disc} is greater than V_{th} , the comparator is left enabled (~ 3.5 V), otherwise it remains at 0 V. A digital output signal compatible with the TTL standard is then produced. A high precision stable voltage reference (2.5 V) is provided for the potentiometers. This is generated by the integrated circuit REF43GS. The comparator is configured with hysteresis by adding feedback to the non-inverting input through the resistor R3. The addition of

hysteresis to the comparator offers advantages in noisy environments, where is not desirable for the output signal to switch between states when the input signal is near threshold.

The MonRat detector uses a set of 64 preamplifiers and discriminators, housed in 8 boards of 8 channels each, as shown in figure 6. Subsequently, the signals are sent to the DPMs.

2.3. Data processing module

The Data Processing Module (DPM), shown in figure 7, is the main circuit of the acquisition of MonRat. It is based on a logic Field Programmable Gate Array (FPGA)



(a) One single board for 4 input channels.



(b) A DPM box, consisting of a set of 4 DPMs (1 master and 3 slaves).

Figure 7: The Data Processing Modules.

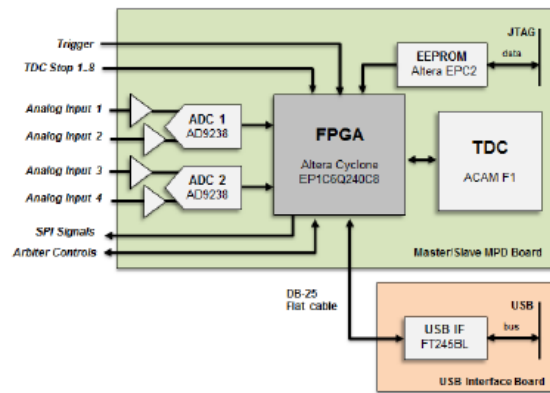


Figure 8: Block diagram of the DPM and the USB communication board.

device and is responsible for the digital signal processing and communication with the computer via a USB port. Each module has 2 ADCs (2 channels each, totaling 4 analog input channels), 8 channels of time-to-digital conversions, the FPGA device, 24 channels of digital input/output pins and a bus interface for communication with a DB-25 connector. A USB board interface module enables communication with the computer via the communication bus of one DPM, positioned in the top of the box and called *master*. This master board also controls the communication of the other 3 DPMs in the box, through the DB-25 connector, and sends their data to the USB board. The USB interface uses a commercial chip transceiver (FT232BL). The analog inputs at each DPM board are 50 Ω LEMO connectors supporting high frequency signals.

Each module contains two analog-to-digital converters with a resolution of 2 channels of 12 bits and a sampling rate of 60 MSs^{-1} . Amplitude measurements of analog signals are

made within the dynamic range of 2 Vpp , with theoretical resolution of $2/2^{12} \text{ V} \sim 0.5 \text{ mV}$. The first stage of each channel scanning is an amplifier circuit that has a single-ended input signal and differential output. In the converter, the analog signal is sampled and digitized continuously, operating in free running mode. The resulting digital word from conversion remains available in synchronism with a clock signal of 60 MHz, generated by the FPGA. The data of the first channel are synchronized with the rising edge of the clock, while data from the second channel are synchronized with the falling edge. This feature permits the synchronous transfer of the converted data to the FPGA which controls the flow of data acquisition and stores it in internal FIFO (First-In First-Out) memories. Following the diagram shown in figure 8, the data available in the internal memory can be transferred by the USB bus communication through the control performed by the logic FPGA circuits.

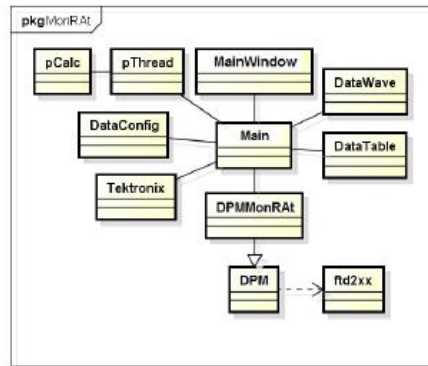


Figure 9: Simplified diagram of classes used in the data acquisition software.

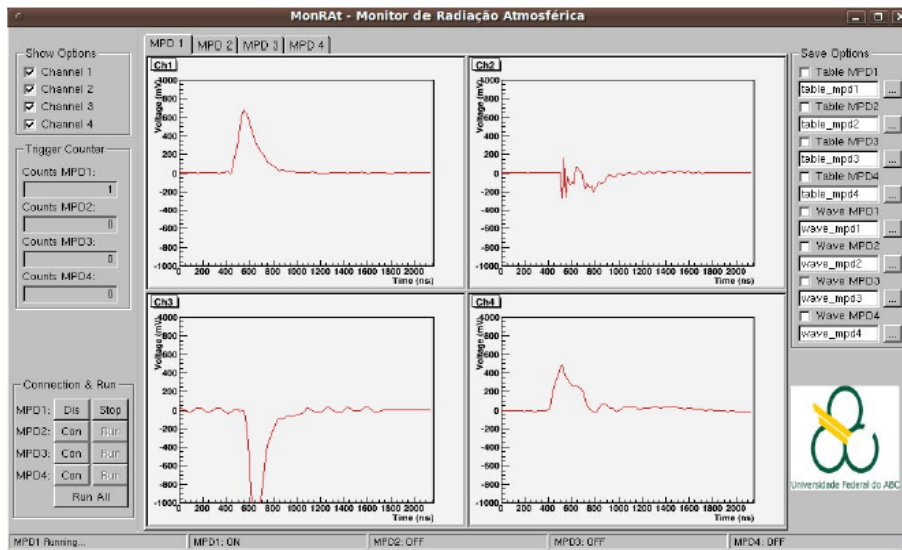


Figure 10: Graphical interface of the data acquisition software.

The DPM has a single time-integrated digital converter, TDC F1 circuit, manufactured by Acam. The F1 has 8 channels with resolution of ~ 120 ps per channel and 16 bit precision, which can measure time intervals between 5 ns and $7.8 \mu\text{s}$. The resolution is adjustable by internal configuration and is calibrated by a crystal oscillator through a PLL (Phase Locked Loop) circuit. There is only a single signal common to all stop channels. Once the signal is detected, the TDC begins the process of measurement of time and waits for the stop signals. The converted output value is placed on the digital bus, identifying the respective conversion channel. All these bus signals are connected to the FPGA, where the synthesized logic circuits are responsible for receiving the converted data and sending them to the computer via the USB port. Besides the main components mentioned above, on the board there is a device for configuration of the FPGA with JTAG (Joint Test Action Group), which stores the synthesized logic. Moreover,

there are other active and passive electronic components, which are essential for the functioning of all other devices.

For use in MonRat we grouped 4 boxes with 4 DPMs each, totaling 64 input channels. In addition to the analog inputs, the DPM has a digital input, which activates the process of data acquisition at the analog channels in their positive transition. The set of DPMs has a single power input shared by every board with a supply voltage of +6 V and maximum current of 2.8 A. There is also another input for feeding the cooling fan, with a voltage of +12 V and maximum current of 0.15 A.

3. SOFTWARE

The data acquisition software was developed using the platform ROOT [15] – developed at CERN and widely used by the high energy physics community for tasks such as data analysis, as well as the construction and development of graphic applications – and the library of functions for the USB transceiver.

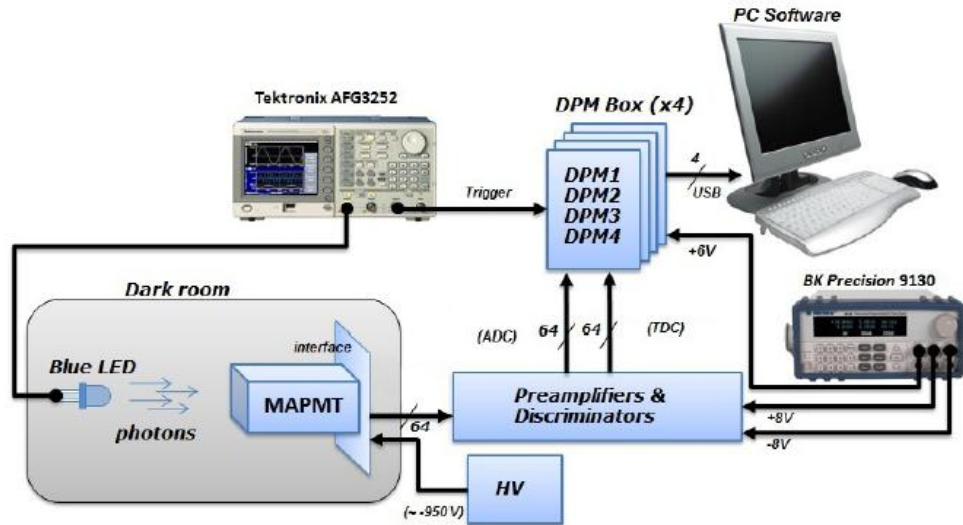


Figure 11: The single photoelectron setup.

The program is written in C++, under Linux operating system, and is object-oriented. The software has the main objectives of running data acquisitions, provide visualizations of the signals and output files for offline analyses. It was modeled and implemented with a structure of packages, which assembles a group of 12 classes that provides the functionality of each part of the application. The class diagram is shown in figure 9. Most relationships between classes are associations, with only one inheritance relationship between the DPM and DPMMonRA classes, and one single dependency relationship between DPM and ftd2xx classes.

The graphic interface of the software was built from several objects belonging to the ROOT framework. Figure 10 shows the acquisition program running, taking data from a DPM board. The program features 4 visualization areas for graphics (one for each input in this given DPM) and options for writing outputs into files. These options are user selectable via checkboxes located in the upper left side and the right side. The recording options, on the right side, include the types of files that will be generated (waveforms or tables), the nomenclature (or the initial path of the files) and the DPM box data source. The content of these areas, i.e. the analog or TDC channel, can be selected by combo boxes located on the left upper side. Event counters for each device are shown on screen and a status bar displays the conditions of the connections and messages to the user. The components of the user interface feature information and instructions that are displayed when the mouse overlaps the component.

To connect a device function it is required to press the *Con* respective button and then press the *Run* button. Afterwards, the class starts pThread responsible for the device, which, in turn, executes the acquisition routine and processes the data. These routines monitor the buffer data from the USB port: when this buffer has reached a minimum amount of data, they are read and processed for validation by reading headers. After the validation, the acquisition of the event is held, otherwise it is discarded.

4. THE SINGLE PHOTOELECTRON AND THE GAIN OF INDIVIDUAL PIXELS

In order to test the MonRA system, we performed the measurement of the gain of each channel of the MAPMT, using the single photoelectron procedure. In this procedure, we impinge the minimal amount of light (~ 1 photon) on each MAPMT pixel with a blue LED, both placed in a dark room (see figure 11), and read the resulting ADC signals, after preamplification and conversion in the DPMs. In this method, the probability of converting the photon into a single photoelectron inside the tube is maximized. Thus, obtaining the spectrum of signals of multiplied electrons in the anodes, one can measure the gain of each MAPMT channels.

A power supply provides three channels for the preamplifiers (± 8 V and ground), and two for the DPMs (± 6 V), while a high voltage source (C4900 from Hamamatsu) feeds the MAPMT with 950 V. A pulse generator provided signals to turn on the LED synchronized with TTL pulses to trigger the data acquisition in the DPMs.

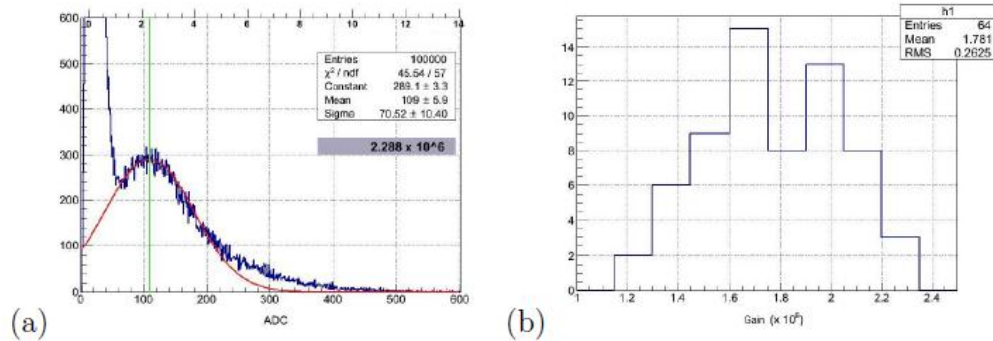
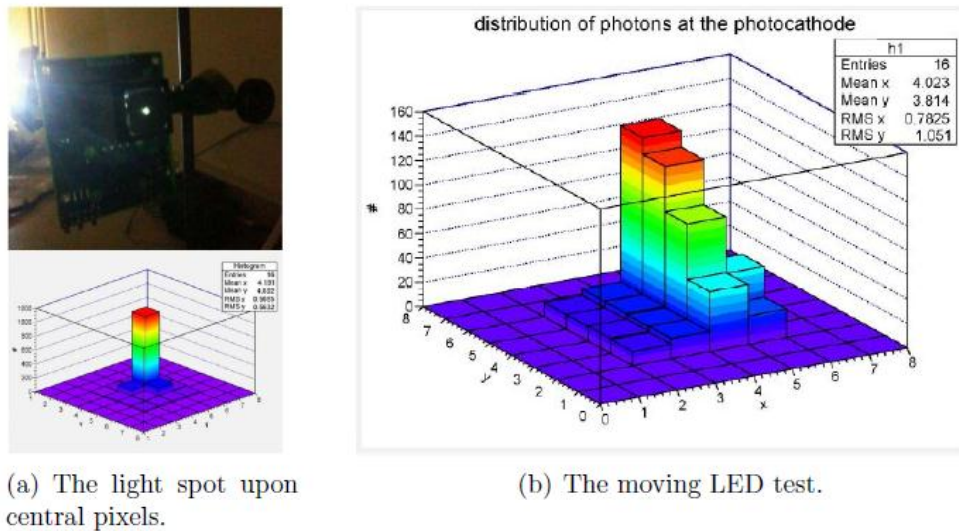


Figure 12: (a) single photon for channel 27; (b) histogram of gains.



(a) The light spot upon central pixels.

(b) The moving LED test.

Figure 13: Light tests with MonRat system.

In the left side of figure 12, we can see the single photon spectrum for a selected channel and, on the right side, the histogram of gains for all the channels. We estimate an average gain of 1.78×10^6 , in accordance with the manufacturer of the photomultiplier[11].

5. THE LIGHT SPOT AND TRANSIT TEST

Another test to the MonRat system was to use the same blue LED as light source in the dark room, aligned near the optical axis and positioned 2.5 m away from a small spherical mirror (15 cm of diameter). The spot size formed at the MAPMT photocathode can be seen at the upper part of figure 13(a) for an amount of light much bigger than used. Actually, this test has been performed near the single photon regime, such that this light would be impossible to be seen by naked eye. Then, the data acquisition system (MAPMT, front-end, preamplifiers and DPMs) for the 16 central pixels was turned on and the signals read through the MonRat software. In the lower part of figure 13(a), we plot the histogram of signals: there is one central pixel with counts well above the others (showing the most illuminated pixel) and a small aberration upon two neighbors. However, the MonRat system was able

to collect this small amount of light, which gives us confidence that the experiment can detect fluorescence photons under the desired conditions: moonless and clear night skies.

A second test was to progressively displace the LED by some centimeters to simulate a cosmic ray shower track developing in the MAPMT field of view. The result for this acquisition is given in figure 13(b).

6. CONCLUSIONS

We have presented the design of the MonRat detector electronics and software, measurements of individual channels gains, and its expected performance under simulated conditions. MonRat is designed for the detection of atmospheric fluorescence radiation generated by cosmic ray showers of energies greater than $10^{17.5}$ eV.

The detector construction has been finished and the assemblies of the mechanical and optical structures are under way. We soon will be able to measure real events, pioneering detecting the fluorescence radiation in Brazil.

7. ACKNOWLEDGEMENTS

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