THE UPGRADE OF THE LAGO PROJECT AT SIERRA NEGRA, MEXICO

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Abstract: The LAGO project is an international effort of many groups in different countries to operate a network of water Cherenkov detectors (WCDs) in high-altitude sites in Latin America. Although data taking started in 2007, up to date no GRB has been observed, but we have set limits on 40 GRBs, the most stringent one being for GRB080904 in the 0.5 GeV - 100 GeV energy range. Currently we are undertaking an upgrade of the detection system at the Sierra Negra site (4550 m.a.s.l.) in Mexico. Four new WCDs of 40 m^2 have been installed, and are fully instrumented. The new detectors are cylindrical and segmented in four parts, with 7.3 m of diameter and 1.15 m height. The body and the bottom of the detectors are covered with a high diffusive and reflective banner bag. This bag is filled with purified water of high quality up to a height of 1.1 m Four 8" PMTs are distributed at 2.4 m from the center, with a regular separation, one for each segment. New electronics has been developed for the new LAGO detectors. The new system consists of an ADC daughter board running at 100 MSPS.We present the performance test of the new detectors with this new data acquisition system.

Keywords: CR-IN - Methods, techniques and instrumentation.

1 Introduction

Gamma Ray Bursts (GRBs) are at the intersection of many diferent areas of astrophysics: they are relativistic events connected with the final stages of stars; they reveal properties of their surrounding medium and of their host galaxies; they emit radiation from gamma-rays to radio wavelengths, as well as possibly non-electromagnetic signals, such as neutrinos, cosmic rays and gravitational waves. Due to their enormous luminosities, they can be detected even if they occur at vast distances, and are therefore also of great interest for cosmology. GRBs are extremely powerful flashes of γ-rays which occur approximately once per day and are isotropically distributed over the sky [1]. The variability of the bursts on time scales as short as a millisecond indicates that the sources are very compact, while the identification of host galaxies and the measurement of redshifts for more tan 100 bursts have shown that GRBs are of extra-galactic origin. GRBs are grouped into two broad classes by their characteristic duration and spectral hardness: long and short GRBs [3]. Moreover, cosmological GRBs are very likely powerful sources of high energy neutrinos and gravitational waves. According to the current interpretation of GRB phenomenology, the γ-ray emission is due to the dissipation of the kinetic energy of a relativistically expanding fireball [1]. The physical conditions allow protons to be accelerated to energies greater than 10^{20} eV according to the Fermi mechanism [2]. Such protons can not avoid interactions with fireball photons, starting a photo-meson production process that generates very high energy neutrinos and γ-rays. The occurrence of gravitational wave bursts (GWBs) associated with GRBs is a natural consequence of current models for the central engine. For instance, GRBs can be produced by certain classes of supernovae, known as collapsars or hypernovae, when a massive star collapses to form a spinning black hole; in the meantime the materials from the remaining core form an accreting torus with high angular momentum [3]. Another interesting scenario is a neutron star and black hole coalescing system ($\sim 7M_{\odot}$)) where the disruption of the neutron star, caused by the rapidly rotating black hole, will also form a torus emitting a large amount of energy ($\sim 0.1Mc^2$) both in gravitational and electromagnetic waves .

2 Ground level GRB detection

A classical method to use for GRB detection is called the single-particle technique [8] where the detectors are used to count individual particles. When high energy photons from a GRB reach the atmosphere, they produce a cosmic ray cascade with secondaries at ground level that can be detected. One looks for an increase of the particle rate on all the detectors of a ground array on this time scale. This technique has already been applied in EAS-TOP [9] in Italy, INCA [10] in Bolivia and ARGO [11] in Tibet. A general study of this technique can be found in [12]. However, this technique had not been applied in the past to arrays of Water Cherenkov Detectors. The main advantage of using water Cherenkov detectors over the usual scintillator/RPC detectors is the WCD sensitivity to photons, which represent up to 90% of the particles at ground level for high energy photon initiated showers. This significantly increases the efficiency of detection, as reported in [13]. This method has been implemented since March 2005 in the Pierre Auger Observatory [14]. The Pierre Auger Observatory is the largest cosmic ray observatory in operation. It is located in Malargue, in Argentina and it is composed, among other detectors, of 1600 WCDs. Despite its low altitude (1440 m.a.s.l.), its large collecting surface ($16000m^2$) and high sensitivity to secondary photons makes it a possible competitor to higher-altitude experiments. The LAGO network compensates a much smaller area of detection by going for high altitude sites, and uses a dedicated acquisition, optimized for the single-particle technique, with rates being monitored on a short time scale. Recently, the HAWC observatory, under construction at 4100 m.a.s.l. near Sierra Negra in Mexico, may detect, or at least to establish some flux limits of several GRB detected by FERMI-LAT. Since HAWC and LAGO-

Mexico are on the same mountain, eventual crosschecks of ground detection of GRBs are feasible.

3 Sierra Negra experimental set up

The Sierra Negra site of the LAGO experiment has 4 detectors of 40 m^2. Three of them located at the vertex of an equilateral triangle of 30 m. Those detectors are cylindrical tanks, made with a corrugated steel plate bolted with stainless steel screws, 7.3 m of diameter and 1.15 m height. The tops and inside of each detector are covered by an EPDM black liner to contain and protect the radiator media. The EPDM material is elastic, easy to weld and mechanically very strong, helping to have a light tight and insulated inner environment, figure 4. The body and the bottom of the detector are covered with a bag of high diffusive and reflective material: white polyethylene banner. The white bag is filled with high quality purified water up to a level of 1.1 m and in the upper surface; there is a tyvek sheet floating in order to reflect the Cherenkov light produced as uniformly as possible. The special feature of this kind of water Cherenkov detector is its inner segmentation. To improve the light collection, we have installed reflective walls with the same material that the inner liner, figure 5. The cylinder was divided at four regular sectors, one hemispherical 8 inches diameter PMT located in the centroid of each one, looking downwards, The PMT photocathode is submerged to avoid losses by any air-water interface. The entire container is covered and protected externally by a black, light-tight bag and a canvas roof. The Cherenkov light is collected by the electron phototube 9354KB of Electron Tubes Ltd..

3.1 DAQ system

The custom-made electronics is in general a DAQ system of low power consumption, this includes: A 4-channel ADC daughter-board with two dual 10-bit ADC chips (AD9216 from Analog Devices). The AD9216 is a dual, 3 V, 10-bit, 105 MSPS analog-to-digital converter. It features dual high performance sample and hold amplifiers and an integrated voltage reference. The AD9216 uses a multistage differential pipelined architecture with output error-correction logic to provide 10-bit accuracy and guarantee no missing codes over the full operating temperature range at 105 MSPS;The digitalizer board is connected to a second board with an FPGA, for real-time data processing (Nexys2 from Digilent Inc); This board is a powerful digital system design platform built around a Xilinx Spartan 3E FPGA, with 16 Mb of fast SDRAM and 16 Mb of Flash ROM. The Nexys2 is ideally suited to embedded processors like Xilinx's 32-bit RISC Microblaze. Communication and control are based on a small minicomputer 8Raspberry PI model B 512MB with an ARM1176JZF-S 700 MHz processor). The algorithms developed uses advanced digital signal processing techniques and particularly digital pulse processing, where the purpose of the pulse processing is to perform on-line signal processing on the digitized signals directly to minimize the data transfer size, these algorithms are implemented on the FPGA and can be reprogrammed at any time. Each event is tagged with precise GPS time tags using an embedded GPS receiver with 1 PPS (one pulse per second) synchronized with UTC within an uncertainty of 50 ns (Motorola Oncore UT+ GPS receiver). A pressure and temperature sensor (HP03D) is also connected to the FPGA board, it provides 16 bit word data for pressure and temperature

Figure 1: A view of the custom electronics used at LAGO. It consists of a daughter board with four input analog channels, a mother board based on an FPGA (Spartan 3E XC3S500K), a pressure-temperature sensor (HP3D), a GPS receiver (Oncore UT+). The main control is based on the single-board computer (Raspberry PI).

related voltage [6]; and, finally, the RS-232 port is used for slow communications, and control with the Raspberry. Using the Raspberry resources the DAQ system communication is made with the exterior by means of wireless networks, see figure 1

The PMTs convert the signals deposited on the detectors by charged particles into negative pulses with typical widths of 5-10 ns. These pulses are conditioned and shaped inside the ADC board into positive pulses with widths of 20-40 ns. The use of dual ADCs simplifies the firmware program written in hardware description language (VHDL) of the whole DAQ system. The bitstream firmware of the DAQ system resides permanently on the Flash ROM chip located on the mother board and it gets downloaded into the FPGA upon power on. On the PC side we use Perl and Python under Linux to process, store and display the data acquired. Finally, we use ROOT programs to histogram and analyze the data.

The main operation of the DAQ system includes the following modes:

- Calibration mode, it consists on the data acquisition of 32 consecutive samples in 10 ns intervals (100MSPS) of the digital pulses produced by an ultraviolet LED with wavelength of 405 nm with a 15 ns wide pulse in a frequency of 10kHz located 60 cm from one of the PMTs. The phototube polarization voltage and the LED polarization voltage are fine tuned. It provides us with a minimal response that represents a fundamental part for the calibration of a PMT, figure 2. The script used for the capture of the digitalized signal is ./getOlyOneFileTrace.sh or send to the parameter '#{t..h}' by the serial port at 115200 baud.

- Line Base mode, for calculating this one, in an average value for each digitalized input signal. It is taking a arithmetic reference level for the operation of traces and rates capture. The baseline is calculated every 600 μs. An indirect way for knowing the line base middle value is making a trace capture with

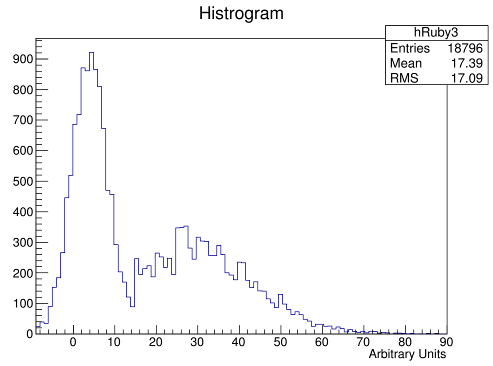

Figure 2: Response to a single photo-electron, using our new DAQ.

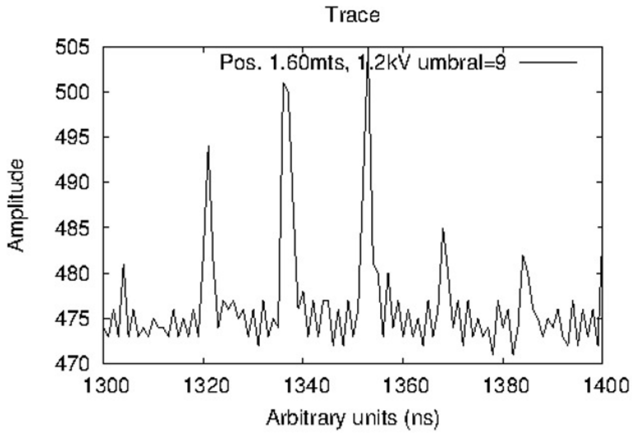

Figure 3: Trace mode operation.

Figure 4: LAGO Sierra Negra WCDs. The old array of small tanks are clearly seen between the new big stainless steel tanks. Those are covered by an black EPDM liner.

a threshold value of 1 mV or 2 mV (1 or 2 ADC counts).

- Trace mode, fixing a threshold trigger of the input pulse, when this pulse crosses the threshold, the trace or profile is capture from the pulse. It consists of 16 consecutive samples but seven samples are previous and 9 are subsequent to the trigger. The trace has information of the secondary particles generated by the collision of the primary elements in the atmosphere, the script used for capturing them is ./getOlyOneFileTrace.sh or send the parameter '#{t,r,s,h}' by the serial port at 115200 baud.
- Rate mode, once established four levels of tresholds for each input signal the overpass is counted of each pulse to each threshold; this counting is made during a period of 1 ms or 5 ms, obtaining four rates for each signal, counting 16 rates every period. Figure 7 and 8 illustrate these precesses. In addition, each 250 ms or 1 second the environment parameters of the sensor HP03D are inserted (pressure - temperature), and time label digital with the GPS; the script used for capturing the rate and the paramenters is ./getOnlyOneRate.sh or send the parameter '#r' by the serial port at 115200 baud.
- Sensor mode, it makes the capture of the environmental parameter of temperature and atmospheric pressure, in this mode the parameters are sent every 250 ms. This mode can be activated by sending sending the combination '#e' for temperature and '#p' for pressure by the serial port at 115200 baud.
- GPS mode, it is used to capture the GPS values. You can capture it just sending the combination '#g' through the serial port at 15200 baud; all of this operating modes of the DAQ are widely described in technical notes of the LAGO Colaboration.

The position of the photo-detectors has been optimized by means of the measurement of the response of the detector (rate of signals above a fixed threshold) as a function of the distance to the center. We have measured the response of the detector for distances of 0.6 m, 1.8 m and 2.7 m from the edge of the tank. The experimental result are shown in figures 7 and 8.

In order to characterize the responses of the PMTs, and then to set different levels of threshold for the scaler system, we have evaluated the amplitude distribution for one photo-electron as a function of the high voltage. As shown in figure 6, the curves correspond to high voltages of 1.25 kV, 1.3 kV, and 1.35 kV. The best single photo-electron response is obtained at 1.3 kV and this value was set as the operation one.

The values of the charge spectra obtained by the custom electronics are shown in figure 2.

4 Sensitivity

From figure 6, the calibration curve of the PMT shows the response of 1 photo-electron at a high voltage of 1.3kV, with this response, we set the best sensitivity to the rate of the system in some geometrical spot. Outlining an imaginary line from the central apex to the edge of the tank formed by similar triangles (each one of the four segments has a detection area of $10m^2$ figure 5) and on this axis, where four spots are selected for measuring the sensitivity: 0.6 m, 1.6 m, 1.8 m, and 2.7 m from the edge.The sensitivity evidence consist in determinate from the previous spots where the PMT has bigger sensitivity for counting the particles, when a bigger sensitivity location is determined the same geometric spot in the three similar sectors. On the other hand, the new kind of fotomultiplier is used in this upgrade of the instrumentation.

As result, we can determine the sensitivity in this way:

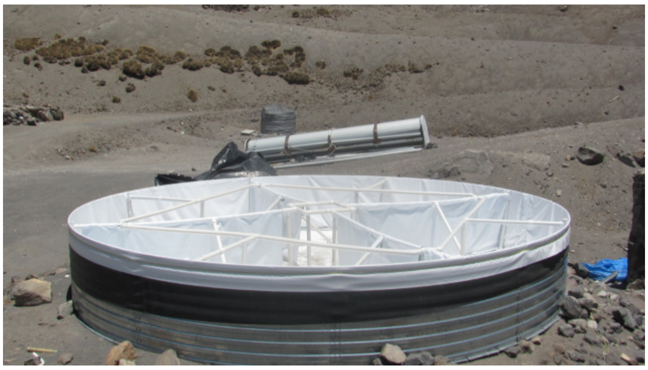

Figure 5: Internal structure of the new WCD. The structure of the PVC pipes allows us to set the banner walls to divide it into four sectors and fix the PMT and cables in a safety way. Also help us to keep the upper liner and a canvas roof.

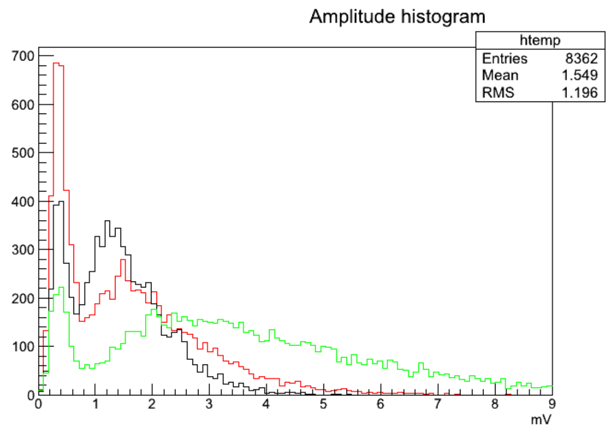

Figure 6: Plot of the response to a single photo-electron by the PMT at 1.25 kV (black), 1.3 kV (red), and 1.35 kV (green). The operation voltage was fixed at 1.3 kV.

from figure 7 the counting of the particles corresponds to data reading with a threshold of four counts ADC (4mV) in 0.6 m (see the figure 6, the threshold four and five correspond to two and three photo-electrons) for an operation voltage of 1.3 kV. The counting window of the rate is every 5 ms (for this case). The result of the counting shows that under this conditions the rate is 200*164.5 = 32.9 kHz in an detection area of $10m^2$, in similar conditions in a distance of 1.8 m 8, the average count is 200*141.5 = 28.2 kHz.

Making the comparison between the rate of LAGO previous [16], where is determined that the rate of particles is similar conditions in an detection area of $4m^2$ is 6 kHz, and comparing with the counting of 0.6 m (32.9 KHz) this increase about five times in an area of detection $10m^2$. Nevertheless, as counting was made in a sector of four, then the total counting in the tanq is increasing at least four times, for instance 20 times more sensible than previously register in LAGO.

5 Conclusions

The LAGO Mexico upgrade is under construction and from the preliminary results shown, we can conclude that the new detectors can reach 20 times the sensitivity of the small ones. In this way the price of the detector area decreases.

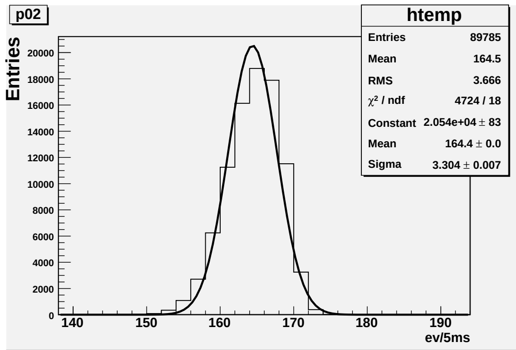

Figure 7: This plot corresponds to the rate recorded each 5 ms at 0.6 m from the edge of the tank with and HV of 1.3 kV.

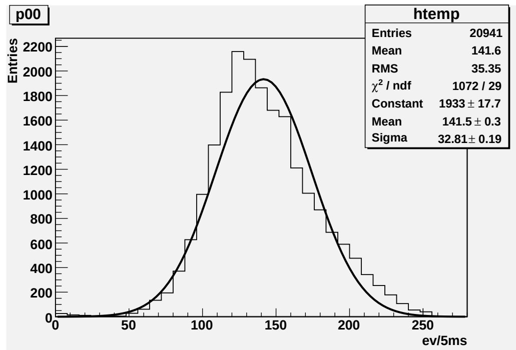

Figure 8: This plot corresponds to the rate recorded every 5 ms at 1.8 m from the edge of the tank with and HV of 1.3 kV.

This new system may be implemented in other high-altitude observatories of the LAGO collaboration.

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