Use of Water Cherenkov Detectors to detect Gamma Ray Bursts at the Large Aperture GRB Observatory

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Abstract

The LAGO project aims at the detection of high energy photons from Gamma Ray Bursts (GRB) using the single particle technique in ground based water Cherenkov detectors (WCD). To reach a reasonable sensitivity, high altitude mountain sites have been selected in Mexico (Sierra Negra, 4550 m a.s.l.), Bolivia (Chacaltaya, 5300 m a.s.l.) and Venezuela (Mérida, 4765 m,a.s.l.). We report on detector calibration and operation at high altitude, search for bursts in 4 months of preliminary data, as well as search for signal at ground level when satellites report a burst.

Key words: GRB, Cherenkov, LAGO
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1. Introduction

Since their discovery at the end of the 60s[1], Gamma Ray Bursts have been of high interest to astrophysics. A GRB is characterized by a sudden emission of gamma rays during a very short period of time (between 0.1 and 100 seconds). The luminosity reached during this flare, if isotropic, would be typically between 10^{51} and 10^{55} ergs. The astrophysical source of these bursts is still not fully understood but candidates could be coalescence of compact objects (for short bursts, less than 2 seconds) and gravitational supernovae (type Ib and II, for long bursts). Mechanisms based on internal shocks of relativistic winds in compact sources give good agreement between theory and observations.

A first large data set of GRB was provided by the BATSE instrument on board the Compton Gamma Rays Observatory (1991-2000). More GRB were then detected by BEPPO-SAX (1997-2002), allowing afterglow observations and distance determination. Currently, GRB are registered by HETE, INTEGRAL and Swift. In the last 10 years, the afterglows observed allowed a much better understanding of the GRB phenomena. Most observa-

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tions have however been done below a few GeV of energy, and the presence of a high energy (above 10 GeV) component in the GRB spectrum is still unknown. GLAST will be the next generation of GRB satellite experiment and should be launched in May 2008. Its sensitivity should allow to get individual GRB spectra up to 300 GeV, as long as the flux of photon is above a few per m^2. In the meantime, and at the highest energies where the flux is low, the only way to detect a high energy emission of GRB is to work at ground level.

A classical method to use is called "single particle technique" (SPT)[2]. When high energy photons from a GRB reach the atmosphere, they produce cosmic ray cascades. The energies are not enough to produce a shower with many particles detectable at ground level (even at high altitudes, only a few reach ground). However, many photons are expected to arrive during the burst, in a short period of time. Should one have a ground array of particle detectors, one would therefore see an increase of the background rate on all the detectors on this time scale. This technique has already been applied in INCA[3] in Bolivia and ARGO[4] in Tibet. A general study of this technique can be found in [5]. While affected by the atmospheric absorption (hence strongly dependant on the zenith angle of observation), it is still the only available method in the GeV-TeV range for ground based detectors. Up to now, it has only been applied to arrays of scintillators or RPCs. We have already proposed using instead Water-Cherenkov Detectors [6,7]. Their main advantage is their sensitivity to photons, which represent up to 90% of the secondary particles at ground level for high energy photon initiated showers.

This method has been tested on the largest WCD array in operation, the Pierre Auger Observatory[8]. The sensitivity of the Pierre Auger Observatory is however limited by its low altitude (1400 m a.s.l.) and the low bandwidth to each individual station. The LAGO project consists of operating WCD at high altitude sites, and with a dedicated acquisition, optimized for the SPT. The three sites currently being instrumented are Sierra Negra (Mexico, 4550 m a.s.l.), Chacaltaya (Bolivia, 5300 m a.s.l.) and Mérida (Venezuela, 4765 m a.s.l.). It has previously been reported that about 20 m^2 of WCD in operation at Mount Chacaltaya would have the same sensitivity as the full 16000 m^2 of active surface of Auger[6,7]. Figure 1 shows the equivalence between surface and altitude to get a similar sensitivity and compares the LAGO sites with previous experiments.

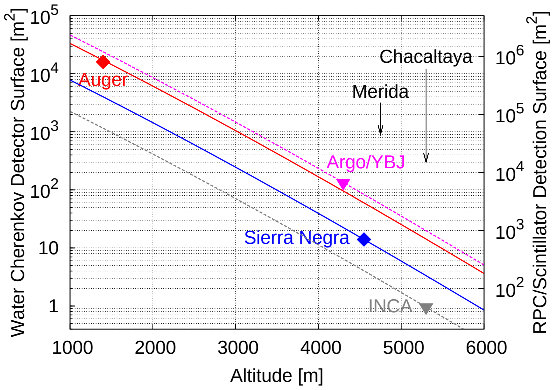

Fig. 1. Lines of equal sensitivity for experiments of different size and altitude, neglecting geolatitude cutoff and assuming similar scaler threshold. A few tens of m^2 of WCD at high altitude are as efficient as currently running experiments for the SPT.

2. Experimental Setup

Simulations were run to determine the optimal geometry of the WCDs. The small aperture gain for detectors of more than 4 m^2 does not compensate the increase in cost and difficulty to operate them. The optimal design is therefore a 4 m^2 WCD, with a central PMT, filled with water up to a level of 1.2 m to ensure a high probability of photon conversion in the water volume. The internal walls of the WCD are covered by Tyvek® to ensure a good reflectivity and diffusivity. The PMT is connected to an acquisition board from the prototype phase of the Pierre Auger Observatory[9]. These boards provide 6 analog entries which are sampled by 40 MHz FADC allowing therefore up to 6 WCD to be controlled by a single DAQ board. The digital signals are processed by an APEX FPGA.

The FPGA has been programmed to read out every 5 ms the content of the four scalers per channel. The thresholds are set depending on the PMTs characteristics (gain and noise). At Sierra Negra, they are set to about 15, 150 and 600 MeV deposited in the WCD, while a special scaler counts undershoots. At Chacaltaya and Mérida, where higher gain phototubes are available, they are set to 1/2, 5 and 20 photoelectrons (about 2, 25 and 100 MeV deposited), with the same undershoot counter.

The data is then collected via a serial line by an acquisition PC, and stored for data analysis.

It is worth noting that these data have a sampling rate of 5 ms, much smaller than what is usually used for the SPT. While this only marginally lowers the detection threshold, it would provide crucial time structure information should a burst be registered.

2.1. *Operation and data taking*

Currently only the Sierra Negra site is taking data at the highest altitude. Datat taking with three $4\,\mathrm{m}^2$ and two $1\,\mathrm{m}^2$ WCD in operation started in 2007. More details on the site can be found in [10]. PMT, DAQ PC failures and the harsh hurricane season limited the total useful data accumulated from January to September 2007 to 3 months.

A small $1\,\mathrm{m}^2$ prototype detector is in operation at the Universidad Mayor de San Andres campus, at 3600 m a.s.l. (Bolivia), while a $3.5\,\mathrm{m}^2$ prototype is in operation at the Universidad de los Andes, at 1600 m a.s.l. (Venezuela). Installation at high altitude is foreseen for 2008.

A small $1\,\mathrm{m}^2$ prototype is instrumented at the Centro Atómico Bariloche (Argentina, 780 m a.s.l.) and used for software development. Two extra sites are under consideration, one in the Argentine altiplano, and one in Peru.

2.2. *Calibration*

Calibrating and monitoring a WCD at high altitude is not an easy task. While at lower altitudes background muons provide a perfect beam for calibration[11], at high altitude they are overwhelmed by electrons and photons, making the characteristic muon peak difficult to identify. An extra difficulty comes from the fact that the muon peak used in [11] depends on the geometry of the detector. In smaller tanks as the ones the LAGO project uses with respect of the Auger, the characteristic peak is less visible, washed by corner clipping muons which do not cross the detector entirely. Two different calibration modes have therefore been selected, depending on the PMTs characteristics. When high gain PMTs are available, it is easier to calibrate using the single photo-electron signal. However, at Sierra Negra, we need to use the muon peak. While it is almost indistinguishable on a pulse amplitude histogram, a characteristic change in slope can be seen on a charge histogram, shown on figure 2. One can therefore use this break point to intercalibrate detectors. The rate obtained for values above the break point, about $600\,\mathrm{Hz.m}^{-2}$, is compatible with a muonic origin. It is important to note that as we are going to work in amplitude (scalers), we need to correct for different charge to amplitude ratio from different detectors (mainly due to different water qualities). We therefore determine the average charge to peak ratio for each detector at the level of the break, and use this ratio to fix the value in amplitude equivalent to one muon for each WCD.

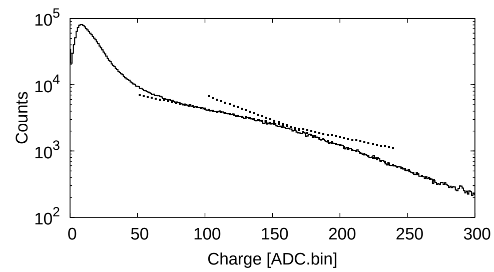

Fig. 2. Charge histogram for one minute of data of a $4\,\mathrm{m}^2$ detector at Sierra Negra. While there is no characteristic muon peak at this altitude, a change in the slope can be determined and used for calibration. The intersection of the two fitted dotted lines is used to determine a calibration reference point.

3. Data analysis

In order to use the scalers to detect bursts, it is important to get rid of high frequency noises which can be interpreted as a succession of particles. These noises are particularly frequent during thunderstorms. A dedicated scaler per detector is used to detect this HF noise by counting spikes below the baseline. These are uncommon and mainly due to signal undershoot after big pulses. They are counted in unit of 32 (this number has been chosen to ensure insensitivity to normal electronic and large pulse noise). For this preliminary analysis, when more than 96 spikes below the baseline are detected in 5 ms, the noise flag is raised. When the flag is raised a second time in a 500 ms window, the last one second of data and the next second are dropped as noisy. This method produces a dead time of about 4.4 %, and removes many artificial bursts.

3.1. *Search for bursts*

To search for bursts in the Sierra Negra data, we selected the most stable $4\,\mathrm{m}^2$ detector, and looked at the difference between the two lowest scalers (15 and 150 MeV) where the sensitivity to a burst is expected to be higher. The expected average rate is obtained by an average over 5 minutes of data centered on the second being analized.

Many excesses can be found in the 5 ms data. These come from noise, both analog and digital, as well as showers. We expect to lower the noise by improving both the hardware and the software in the near future. In the meantime, we can reject these single bin noises by asking for a few consecutive bins above a specific threshold. A check on the statistics of the data indicated that 3 consecutive bins at more than 6 times the square root of the current average has a 10% chance probability of occurring once for the current amount of collected data.

We used this criteria and got one excess. One can then check the other detectors and none registered a similar spike. We conclude that no burst has been detected in the data set.

Another way to look for bursts would be to search for various spikes in a somewhat short period of time. We've looked at spikes of 5 times the square root of the average in windows of 500 ms, 1 and 2 s. Chance of getting respectively more than 8, 9 or 11 spikes are less than 20% each. No candidate burst was found.

3.2. *Comparison with Satellite data*

During the operation of the Sierra Negra detectors, 9 GRBs detected by satellites occurred in the field of view of the WCD. For each of them, an excess was looked for in the data within 100 seconds of the burst, or integrating in a period corresponding to the duration of the burst. No relevant signal was found, allowing to derive fluence limits in the 1 GeV - 1 TeV range, assuming a spectral index of -2, based on specific simulations of the signal expected at the Sierra Negra site for a GRB. Figure 3 gives the fluence limits obtained as a function of the burst zenith angle at the Sierra Negra site.

4. Conclusions

The LAGO project has been taking data in its prototype phase. Operation at high altitude has proved to be difficult, but important improvements have been achieved. The Sierra Negra site counts currently with 14 m^2 of calibrated and operating WCD, and a prototype detector is being tested before deployment at Chacaltaya and Mérida.

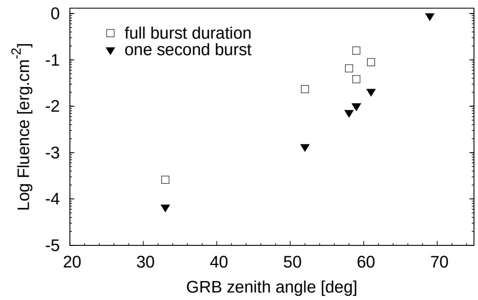

Fig. 3. 5-σ fluence limits in the 1 GeV - 1 TeV energy range for the bursts in the field of view of Sierra Negra, for a single second burst or for a burst of same duration as detected by the satellite, assuming a spectral index of -2.

A search for bursts in an equivalent of two full months of data taking gave no significant signal. No signal was found either in coincidence with satellites, and upper bounds on the fluence of 9 GRBs for the 1 GeV - 1 TeV range were set (most stringent limit was 6.7×10^{-5} erg cm^{-2} for GRB 070224).

The study presented here, together with the analysis of the Pierre Auger Observatory scalers[8], confirm that only a bright burst close to the vertical could probably be detected with the SPT. However, should such a burst occur, the 5 ms sampling time of LAGO would give novel timing and burst shape information for the high energy emission.

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