The Large Aperture GRB Observatory

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***Abstract*. The Large Aperture GRB Observatory (LAGO) is aiming at the detection of the high energy (around 100 GeV) component of Gamma Ray Bursts, using the single particle technique in arrays of Water Cherenkov Detectors (WCD) in high mountain sites (Chacaltaya, Bolivia, 5300 m a.s.l., Pico Espejo, Venezuela, 4750 m a.s.l., Sierra Negra, Mexico, 4650 m a.s.l). WCD at high altitude offer a unique possibility of detecting low gamma fluxes in the 10 GeV - 1 TeV range. The status of the Observatory and data collected from 2007 to date will be presented.**

***Keywords*: Water Cherenkov Detector, Single Particle Technique, Gamma Ray Burst**

I. INTRODUCTION

Gamma Ray Burst are characterised by a sudden emission of electromagnetic radiation at hard X-ray and soft γ-ray (X/γ) energies during a short period of time, typically between 0.1 and 100 seconds. Since their discovery at the end of the 60s by the VELA satellites [1], GRB have been of high interest to astrophysics.

They occur at an average rate of a few events per day, and their duration shows a bimodal distribution with two different populations, short duration GRBs (sGRB), characterised by durations of less than two seconds, usually thought to be generated by the gravitational coalescence of two compact objects (neutron stars or black holes) and long duration GRBs (lGRB), usually associated with the core collapse (*collapsar*) of a massive star, which tends to have a softer spectrum than sGRB.

A first large data set of GRB was provided by the BATSE instrument on board the Compton Gamma Rays Observatory (1991-2000). BATSE GRBs incoming directions were isotropically distributed with no evidence of clustering. The fluences observed were furthermore incompatible with uniform distribution of sources, exhibiting a deficit at low fluences.

GRBs origin was determined following afterglows identification by Beppo-SAX (1996-2002). Due to better angular resolution than BATSE, afterglows could be detected at other wavelengths. Spectroscopic measurements allowed the direct measurement of GRBs redshifts, confirming they were cosmological in origin.

Currently, GRB are registered by HETE, INTEGRAL, Swift and GLAST (renamed Fermi Gamma-Ray Space Telescope). In the last 10 years, observation of the afterglows allowed a much better understanding of the GRB phenomena. Most observations have however been done below a few GeV of energy, and the high energy (above 10 GeV) component in the GRB spectrum is still poorly known. Fermi/GLAST sensitivity has already provided some hints on the high energy component of GRBs [2], and could allow to get individual GRB spectra up to 300 GeV should the flux of HE photon be 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.

II. GRB DETECTION AT GROUND LEVEL

A classical method to use is called “single particle technique” (SPT) [3]. 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 unsuccessfully applied by INCA [4] in Bolivia and ARGO [5] in Tibet among others. A general study of this technique can be found in [6]. 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 energy range for ground based detectors. Up to now, it has only been widely applied to arrays of scintillators or RPCs. We have already proposed using instead Water-Cherenkov Detectors [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.

To get an idea of the potential of ground based observation, and the range of parameters in which it can complement satellite observations, one can consider the Chacaltaya Observatory, in Bolivia, at 5300 m a.s.l., with a typical background rate of secondaries of 3 kHz/m^2 of WCD. A 5 σ excess over background during 1 second would be a $5 \times \sqrt{3000} \approx 270$ particle excess per m^2. At this altitude, a 100 GeV photon produces about 290 detectable particles in a WCD [8]. Therefore, a fluence of one particle per m^2 at 100 GeV could be seen from the ground with a 1 m^2 detector.

This SPT method has been tested on the largest WCD array in operation, the Pierre Auger Observatory [9]. The sensitivity of the Pierre Auger Observatory is however limited by its low altitude (1400 m a.s.l.) and should a burst be observed, the low bandwidth of each individual station would limit the scientific content of the results, as the only available data are integrated rates over one second. The LAGO project compensates a much smaller area of detection by going for high altitude sites, and uses a dedicated acquisition, optimised for the SPT with rates being monitored on a short time scale. 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 [7]. Figure 1 shows the equivalence between surface and altitude to get a similar sensitivity and compares the LAGO sites with previous experiments.

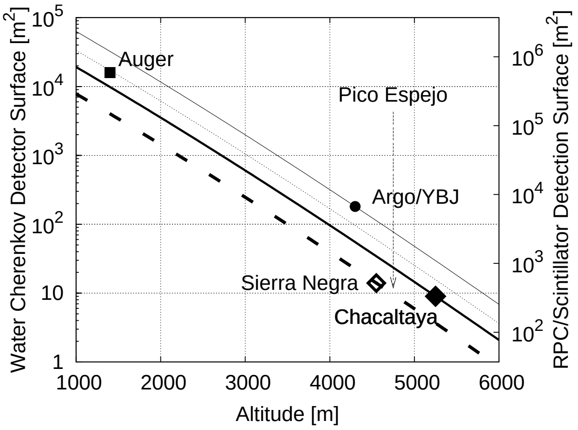

Fig. 1: Lines of equal sensitivity for experiments of different size and altitude, neglecting geolatitude cutoff and assuming similar scaler threshold. Sierra Negra is shown as a dashed line, and Chacaltaya as a solid one. A few tens of m^2 of WCD at high altitude are as efficient as currently running experiments for the SPT.

III. LAGO EXPERIMENTAL SETUP

Simulations were run to determine the optimal geometry of the WCDs. The aperture gain for detectors of more than 4 m^2 does not compensate the increase in cost and difficulty to operate them, especially in remote areas such as high altitude sites. The chosen design is a $\approx 4\,\mathrm{m}^2$ WCD, with a central PMT, filled with water up to a level of 1.2 m to 1.5 m in order to ensure a high probability of photon conversion in the water volume. The internal walls of the WCD are covered by Tyvek® or Banner-type material, 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. An upgrade of these boards to 100 or 200 MHz, for better SPE counting, and an improved communication link is under way [10].

The FPGA has been programmed to read out every 5 ms the content of 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 undershoot counter is used to detect High Frequency noise that could be picked-up by the PMTs cables during a lightning strike and would be erroneously interpreted as many consecutive particles.

The data are then collected via a serial line by an acquisition PC, and stored for data analysis. Replacing the acquisition PC by a single board PC or a low cost laptop with SSD drive is foreseen to minimise the impact of the harsh high altitude environment.

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.

Currently, the Sierra Negra site is taking data since 2007 with three 4 m^2 and two 1 m^2 WCD. PMT, DAQ PC failures and the rough hurricane season limited the total useful data accumulated since 2007 to the equivalent of 6 months of continuous data. Two 4 m^2 and one 1 m^2 WCD have started operation in Chacaltaya in 2008 and are in stable acquisition since beginning 2009. A 3.5 m^2 prototype and various smaller 1 m^2 detectors are in operation at the Universidad de los Andes, at 1600 m a.s.l., and in Caracas (Venezuela). Installation at high altitude is foreseen during 2009. More details on the LAGO sites and their operation can be found in [10]. A small 2 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 in Peru, and a first prototype is under construction in Lima. Colombia and the Himalaya are under study for new installations.

IV. DATA ANALYSIS AND RESULTS

We searched for signal within 100 seconds of a GRB detected by satellites in data taken from early 2007 to April 2009. We used the Gamma-Ray Burst Online Index (GRBOX [11]) to extract bursts data and selected those happening for each site with an apparent zenith angle lower than 60 degrees. We requested a site to have at least 2 detectors in operation at that moment, removing noisy detectors. This left us with 21 bursts for Chacaltaya and 20 for Sierra Negra, with one burst occurring in the field of view of both sites. We then averaged the data in bins of 100 ms and looked for excesses ($4\,\sigma$ with σ being the square root of the average rate over 200 seconds before the burst) in coincidence in at least 2 detectors. This left us with 2 bursts candidates for Chacaltaya and 2 candidates for Sierra Negra. These were individually checked and found consistent with statistical fluctuations. We then take the highest signal in a 100 ms bin to set a limit to the fluence between 0.5 GeV and 100 GeV assuming a spectral slope of -2.2, based on simulations[8]. The fluence limits obtained are summarised in figure 2. The lowest limit obtained is 1.6×10^{-6} erg.cm^{-2} for GRB 080904.

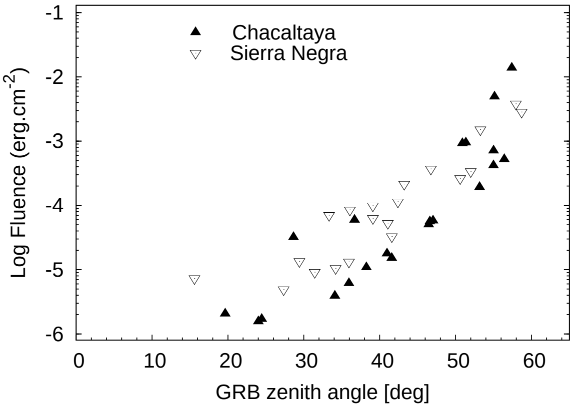

Fig. 2: Fluence limits in the 0.5 GeV - 100 GeV range for the 41 bursts in the field of view of LAGO in the 2007 - April 2009 period, assuming a a spectral slope of -2.2. Filled up-triangles are bursts occurring in Chacaltaya field of view. Empty down-triangles are bursts in Sierra Negra field of view.

Bursts can furthermore be searched independently of satellite data. However, should such a burst be found it would be very difficult to attribute it to a cosmic event and reject any possible instrument noise, unless a correlation is found between sites. The current large angular separation between the two sites of LAGO makes such a coincidence unlikely. New sites in between (Venezuela, Peru, Colombia) will greatly increase this possibility.

Nevertheless, an algorithm to search for potential bursts while rejecting known noises has been developed and applied to the current data. Data are averaged in 100 ms bins and a running average is obtained by a sigma-delta method, modifying the estimated average by 0.001 Hz every time bin in the direction of the rate of this bin. The second scaler of each channel is used as the first one can be noisy on some detectors. The fluctuations of each detector are assumed to be the square root of the estimated average. The distribution of the fluctuation obtained by this method can be seen on figure 3. It is a Gaussian with width 1.18, due to correlated noise and the method used to get the moving average.

A candidate burst is defined as an event where two detectors in coincidence see a 5 sigma fluctuation (equivalent to 5.9 of our estimated fluctuation) at least twice in a 5 minute window. 16 candidate bursts are found in Chacaltaya, probably produced by electronic noise as signals are also found on a disconnected channel (it is unlikely that these are true signals produced for example by crosstalk as a GRB should manifest as many small signals and not by large PMT signals which are the ones likely to produce electronic crosstalk). These candidate bursts are likely HF noise produced by storms.

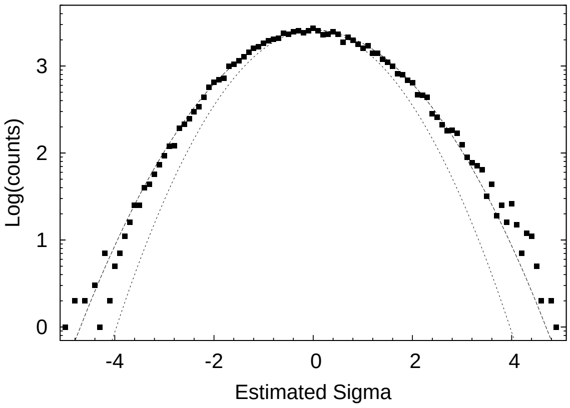

Fig. 3: Distribution of the estimated fluctuations by the sigma-delta method, with the underlying Gaussian of $1.18\,\sigma$ width. A one σ Gaussian is also drawn for comparison.

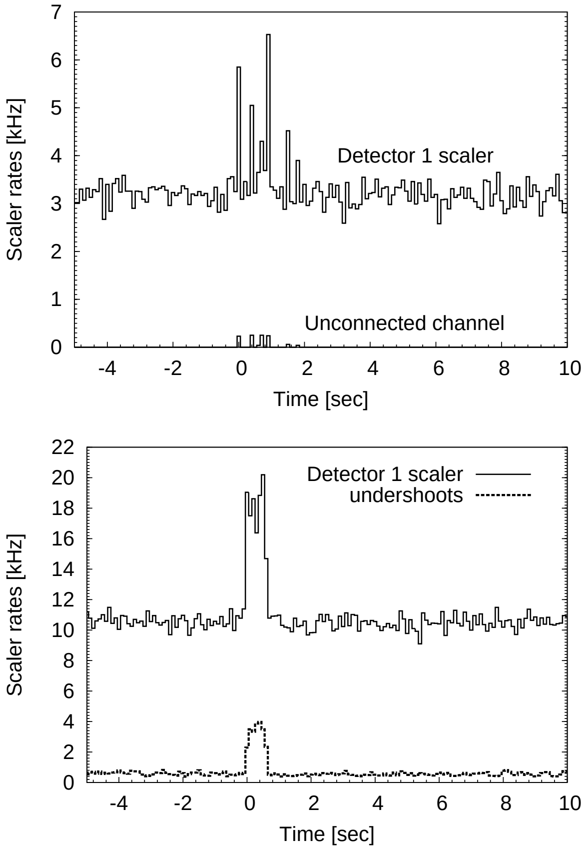

Fig. 4: Example of noisy counting rates for Chacaltaya (top) and Sierra Negra (bottom). One channel is shown, together with an unconnected channel (top) or the undershoot counter (bottom). In both cases, signals in the other counter indicate the burst is due to noise.

The same analysis on the Sierra Negra data set provides a large set of 230 candidate bursts. While the Chacaltaya detectors are installed inside a building under a thin roof, the Sierra Negra ones are less protected and suffer more directly from the harsh weather conditions of the site. Furthermore, Sierra Negra is quite isolated (together with the close-by Pico de Orizaba) in a vast plain while Chacaltaya is in a mountain range. Finally, the hurricane season in Mexico is worse than the Bolivian summer rains. All bursts are however rejected as HF noise candidates, either using a disconnected channel or using the undershoot counter scaler. Examples of these noisy events are given in figure 4.

V. CONCLUSIONS

The LAGO has been taking data since 2006 and is entering now in stable data taking with two sites in operation. The Sierra Negra site counts currently with $14\,\mathrm{m}^2$ of calibrated and operating WCD, while $9\,\mathrm{m}^2$ of WCD are taking data in Chacaltaya. Prototypes are in operation in Mérida and Bariloche, while new ones are under construction in Peru. Further sites are being investigated in Colombia, Guatemala and the Himalaya.

The data acquired since 2007 are of better quality than the one previously reported [12] and a clean search for self-triggered bursts has been done. No event out of HF noise has been found. 41 GRBs were reported by satellites in the field of view of LAGO, and a specific search for excess within 100 seconds of the burst was performed, with no excess found.

Limits were set for the fluences of these 41 bursts in the 0.5 GeV - 100 GeV range. The lowest limit obtained is $1.6 \times 10^{-6}\,\mathrm{erg.cm}^{-2}$, comparable to what the Pierre Auger Observatory can achieve [13].

In order to improve these limits, higher altitude sites are being looked for. Higher gain PMTs, higher frequency sampling, and more stable acquisition chain should also improve the data to be taken.

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