the Large Aperture GRB Observatory

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Abstract. The Large Aperture GRB Observatory (LAGO) aims at the detection of high energy photons from Gamma Ray Bursts (GRB) using the single particle technique (SPT) 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 the project progresses and the first operation at high altitude, search for bursts in 6 months of preliminary data, as well as search for signal at ground level when satellites report a burst.

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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, defined as the time needed for the signal to reach 90% of the total signal, namely T_{90}, shows a bimodal distribution with two different populations:

- short duration GRBs (sGRB), characterised by durations of less than two seconds, are usually thought to be generated by the gravitational coalescence of two compact objects, typically two neutron stars (NS-NS) or a black hole-neutron star (BH-NS) binary;
- long duration GRBs (lGRB), are usually associated with the core collapse (*collapsar*) of a massive star, which tends to have a softer spectrum than sGRB.

In both cases, the final result will be a fast-rotating neutron star with an ultra-high magnetic field (known as *magnetar*, or a black hole surrounded by an accretion disk of stellar matter. One can also define two more classes of sources: low luminosity GRBs (producing lower energy releases than lGRBs) and X-ray flashes, which are similar to lGRBs but with their energy spectrum mainly peaked at X-ray energies. The time evolution of GRB provide clues of the geometry of the emitting regions and of the production mechanisms, showing a wide range of behaviours (see Figure 1), from highly variable curves with several individual peaks to smooth fast rise and quasi-exponential decays (*FRED*s).

A first large data set of GRB was provided by the BATSE instrument on board the Compton Gamma Rays Observatory (1991-2000). Before BATSE, it was believed that

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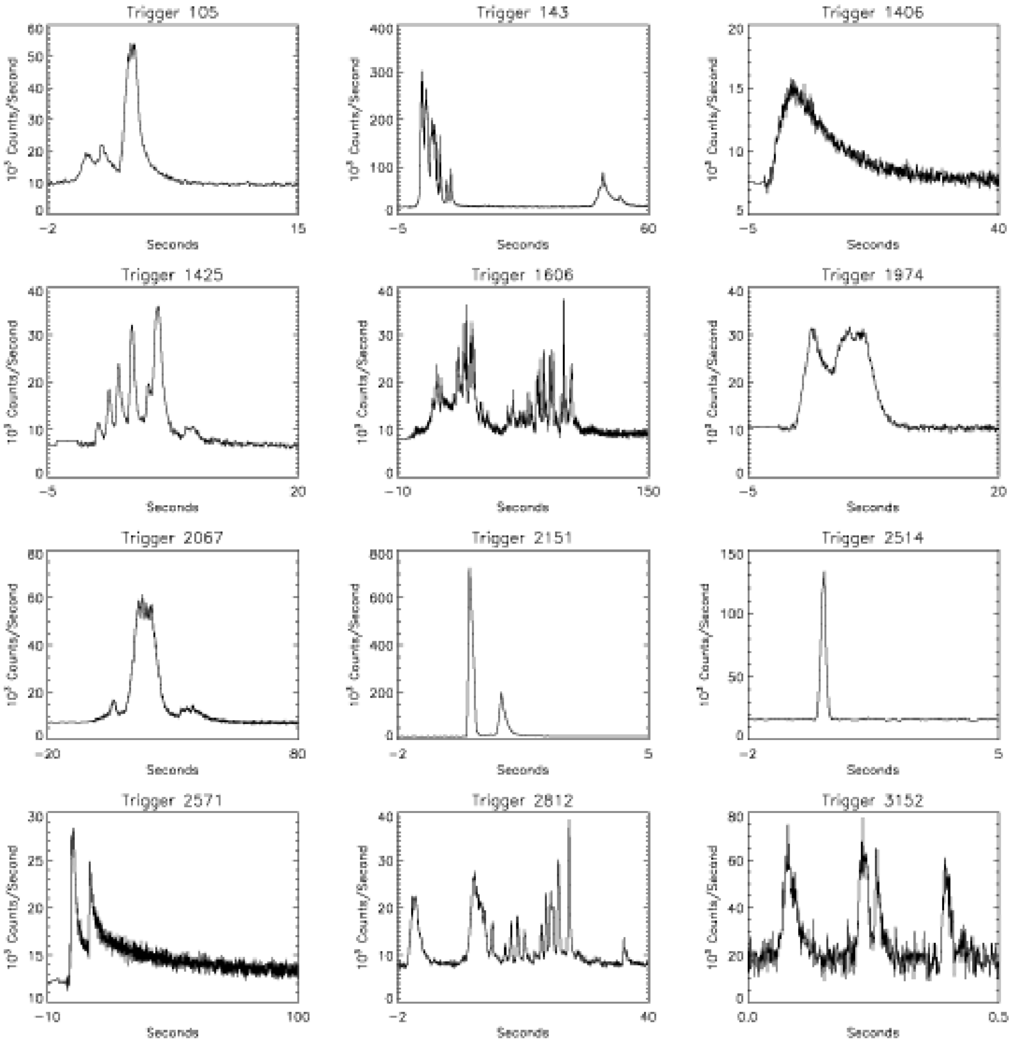

FIGURE 1. Signal as function of time as measured by the BATSE instrument on the Compton Gamma Rays Observatory satellite. A wide range of shape and total duration of the transient event is observed.

GRBs were originated within our Galaxy, and thus, anisotropic scenarios were expected, with GRBs prompt emissions correlated with the galactic plane. However, 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. Two explanations were proposed: GRBs have a cosmological origin (where the deficit comes from the expansion of the universe) or the source distribution has a local over-density (typically in the halo of our Galaxy).

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. These afterglows were found to decay as a power-law in time from soft γ-ray at the moment of the prompt emission to X-ray to optical to radio, as shown in Figure 2 for GRB 970508. Spectroscopic measurements allowed the direct measurement of GRBs redshifts, confirming they were cosmological in origin. However, this lead to another issue: the total energy released during the burst should be order of one solar rest mass, $\sim 10^{47}(\Delta\Omega/4\pi)$ J, therefore imposing a jet emission, since an important fraction of the energy is known to escape in the form of thermal neutrinos and gravitational waves.

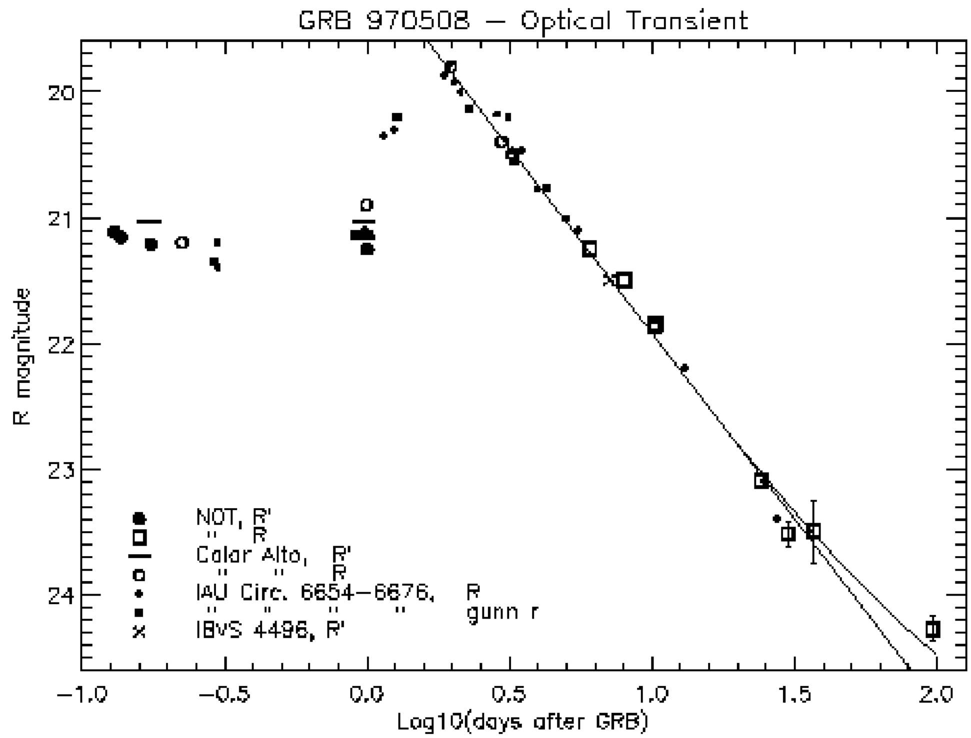

FIGURE 2. Afterglow light curve for GRB 970508, evidencing a softening on the energy spectrum from X-rays to radio in about 100 days.

A collimated jet emission reduces the necessary energy release by about two orders of magnitude, allowing catastrophic collapses of stellar masses objects to be the energy source of GRBs. For lGRBs, a possible explanation can be provided by the core collapse of very massive stars (*hypernovae*), supported by the association of some lGRBs with supernova explosions (e.g. the GRB980425/SN1998bw association). Short GRBs were associated with compact binary mergers. In both cases, the gravitational energy is released in a relatively small volume ($< 100 km^3$) and on milliseconds timescales, allowing conversion of an important fraction of that energy into neutrinos and gravitational waves, while only a small fraction $x_f \simeq 10^{-2}$ is released as a *fireball* of γ-rays, $e^{\pm}$ and hadrons expanding at relativistic velocities.

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 presence of a high energy (above 10 GeV) component in the GRB spectrum is still unknown. Fermi/GLAST 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.

GRB DETECTION 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 by 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.

To get an idea of the potential of ground based observation, and the range of parameters in which it can complement satellite observations, let's consider the site of Chacaltaya, in Bolivia, at 5300 m a.s.l., with a typical background rate of secondaries of 3 kHz/m^2 of WCD. An 8 σ 1 second burst would be a $8 \times \sqrt{3000} \approx 440$ particle excess. At this altitude, a 100 GeV photon produces about 500 detectable particles in a WCD. Therefore, a fluence of 1 particle per m^2 at 100 GeV could be seen from the ground with a 1 m^2 detector, while it would be out of range of any satellite.

This SPT 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 should a burst be observed, the low bandwidth to 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 will compensate a much smaller area of detection by going for high altitude sites, and will use 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[6, 7]. Figure 3 shows the equivalence between surface and altitude to get a similar sensitivity and compares the LAGO sites with previous experiments.

LAGO EXPERIMENTAL SETUP

Simulations were run to determine the chosen 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 m^2 WCD, with a central PMT, filled with water up to a level of 1.2 m to 1.4 m in order to ensure a high probability of photon conversion in the water volume. The

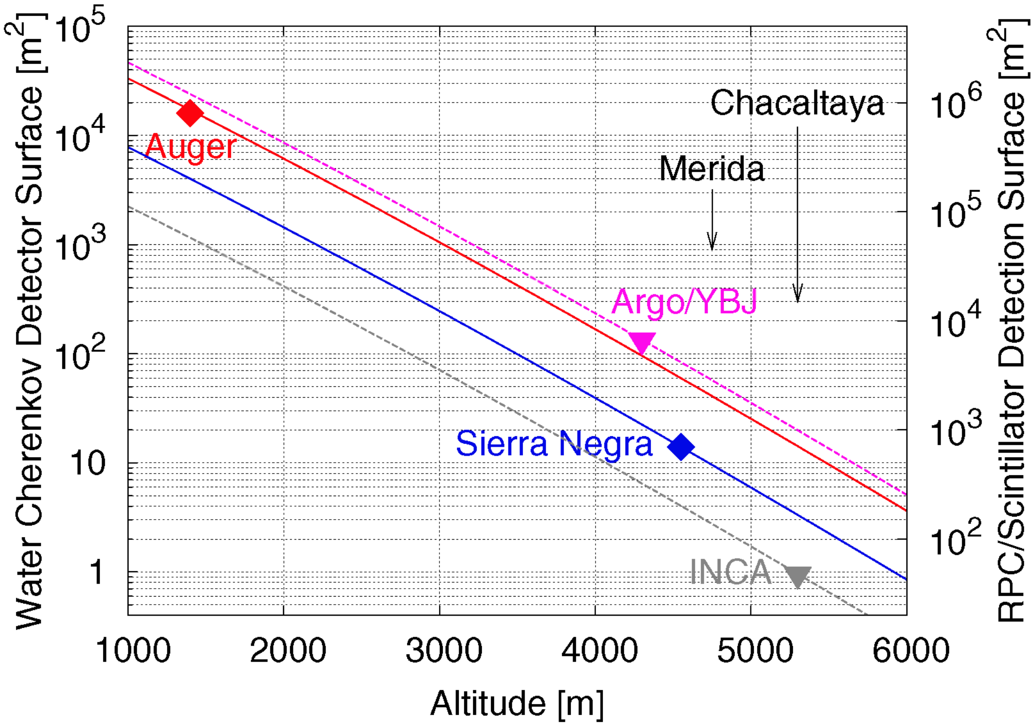

FIGURE 3. Lines of equal sensitivity for experiments of different size and altitude, neglecting geo-latitude cutoff and assuming similar scaler threshold. A few tens of m^2 of WCD at high altitude are as efficient as currently running experiments for the SPT.

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.

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 data is 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.

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.

Currently, the Sierra Negra site is taking data with three 4 m^2 and two 1 m^2 WCD, since 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 since 2007 to the equivalent of 6 months of continuous data. Two $4\,m^2$ detectors are starting operation in Chacaltaya since early 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 for 2009. 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 equipment for building of initial prototypes has already been received by local institutions.

DATA ANALYSIS AND RESULTS

Bursts were looked for in Sierra Negra data from 2007. We selected the most stable $4\,m^2$ 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 centred on the second being analysed. High frequency noise from thunderstorm was removed using the special undershoot scaler.

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. Based on the analysis of the statistics of these bursts, we looked for consecutive bins above threshold, or many pulses in a short period of time. When significant excess was observed, the signal of the other detectors was looked at. No burst was found.

On the other hand, during the operation of the Sierra Negra detectors in 2007, 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 4 gives the fluence limits obtained as a function of the burst zenith angle at the Sierra Negra site.

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, while $8\,m^2$ of WCD are starting data acquisition in Chacaltaya. Prototypes are in operation in Mérida and Bariloche, while new ones are under construction in Peru.

A search for bursts in an equivalent of six 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).

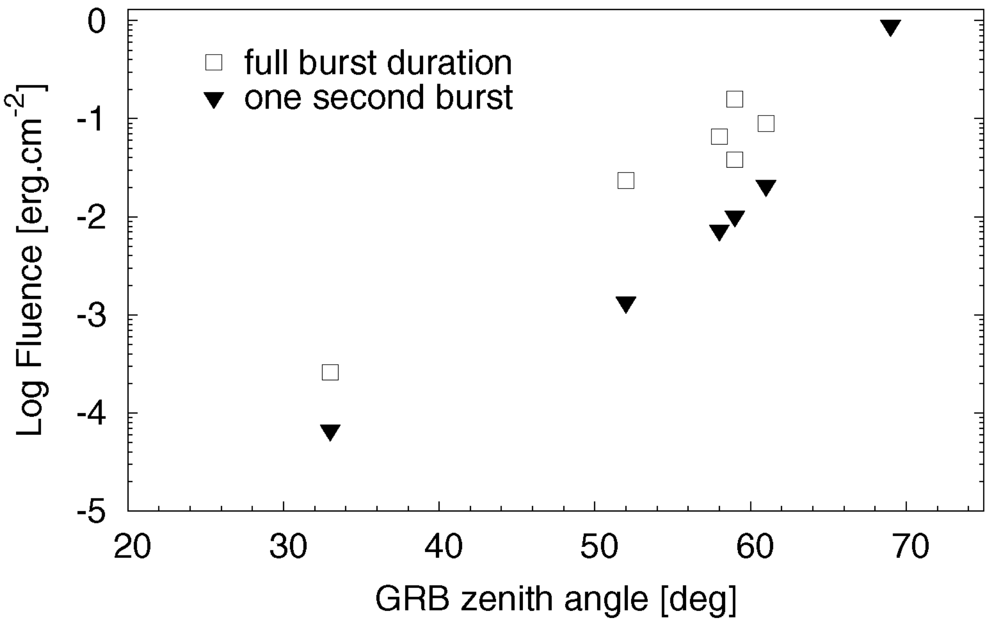

FIGURE 4. 5-σ fluence limits in the 1 GeV - 1 TeV energy range for the bursts in the field of view of Sierra Negra, for a single second burst or for a burst of same duration as detected by the satellite, assuming a spectral index of -2.

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

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