Simulation of Fano factor at HAWC-30 array

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Abstract. The High Altitude Water Cherenkov detector is a gamma-ray observatory which is able to scan the sky in energy from 100 GeV to 100 TeV and will be localized at Sierra La Negra volcano at 4100 m a.s.l. near to Puebla, México. In 2011 an engineering array called VAMOS was installed and in 2012, it will start the deployment of HAWC first step, the HAWC-30 array, with 30 water Cherenkov detectors. In this work it is presented the results of simulations where the goal is to get Fano factor in order to simulate the HAWC-30 array sensibility to gamma-ray bursts using the single particle technique.

1. Introduction

Gamma-ray bursts are short and intense pulses of gamma rays. The bursts last from a fraction of a second to hundreds of seconds. The overall observed fluences range from 10^{-4} erg/cm² to 10^{-7} erg/cm² (the lower limit depends, of course, on the characteristic of the detectors an not on the bursts themselves). This corresponds to an isotropic luminosity of $10^{51} - 10^{52}$ erg/sec, making GRBs the most luminous objects in the sky [1]. The Large Area Telescope (LAT) is the principal scientific instrument on the Fermi Gamma-ray Space Telescope Spacecraft and it is an imaging high-energy gamma-ray telescope covering a energy range from about 20 MeV to more than 300 GeV. The Fermi observations also show the most intense GeV emissions occur promptly and extend longer than the emission at low energies. A wide field of view, high duty factor observatory, such as HAWC, is required to observe these prompt emissions and determine their extension at high energy. In this work it is studied the possibility to detect high energy GRBs assuming their spectra is a power law form as Fermi has already detected, not with HAWC, but with HAWC-30 array, a first step in the whole detector construction.

2. The HAWC observatory

The HAWC observatory, a second generation water Cherenkov detector built on the success of the first generation, wide field-of-view, high duty cycle, TeV gamma-ray observatory, Milagro. HAWC is located in Sierra Negra volcano near to Puebla, México at 4100 m a.s.l. (N 18°59'48' and W 97°18'34"). The observatory will consist of 300 water Cherenkov detectors (WCDs) with 7.3 m on diameter and 4.5 m depth each with ~200,000 liters of ultra clean water, densely



Figure 1. HAWC observatory site. Artistic conception

packed to cover an area of 25,000 m^2 instrumented with three 20 cm and one 25 cm upwardlooking photomultiplier tubes mounted on the bottom of the WCD. The expanded detector area (~10 times the Milagro bottom layer), increased altitude, and optical isolation of the detector elements lead to a 15-fold increase in sensitivity to Milagro, which performed the deepest widefield survey of TeV sky to date. This is achieved by applying the experience with Milagro to the design of HAWC and reusing the Milagro's PMTs and front-end electronics.

2.1. HAWC construction

The HAWC observatory will be constructed in three stages where each is an array of tanks that includes the previous one. The first stage is the HAWC-30 array (to be finished by Summer, 2012), the next one to be constructed is HAWC-100 array (to be finished by Spring, 2013) and finally HAWC-300 (to be finished by Summer, 2014). In Figure 2 it is shown a layout with each array.

2.2. Engineering array

It is worth to mention that it has been constructed an engineering array (7-tanks array with the same dimensions to be used for HAWC) where all subsystems would be tested. This array is called VAMOS (Verification And Measuring Observatory Systems) and it has been taking data since October, 2011.



Figure 2. Layout of HAWC observatory. In red are the WCDs that form a 30 tank array, in magenta and red the ones for HAWC-100 and finally those in red, magenta and blue are HAWC-300

2.3. HAWC Scientific goals

Among the HAWC observatory scientific goals are: to map the galactic diffuse gamma-ray emission from 1 TeV to 100 TeV, to measure the spectrum of galactic sources to highest energies, to study transient emission from AGN, to study the local anisotropy in the cosmic radiation observed by Milagro and to measure its energy spectrum with better precision, monitor the sky for VHE emission for gamma-ray bursts and search for signals from fundamental particles. Although most of these goals will require the full HAWC array, some studies can be accomplished with a smaller (partially built) detector. In particular the single particle technique will provide the opportunity to detect high energy gamma-ray bursts already with HAWC-30.

3. Single particle technique

HAWC is going to observe gamma-rays by detecting, at ground level, the secondary particles that compose the extensive air showers. It is taking advantage of the Cherenkov light produced in water when a charged particle pass through, with high speed greater than the speed of light in this medium. The Cherenkov radiation consist of photons with wavelength in the range from 350 nm to 500 nm. 90% of the particles at ground level are photons [4]. High energy photons may produce electron-positron pairs, which then can be detected by Water Cherenkov Detectors.

HAWC will use two kinds of data acquisition (DAQ) systems: the main DAQ system and the scaler DAQ system. The present work is dedicated to the scaler DAQ system. The technique applied below consists of monitoring all PMTs in fixed periods of 10 ms with a threshold of $\frac{1}{4}$ photo-electron, waiting for an increase in the background rate in coincidence with a GRB detected e.g. by Fermi. The single particle technique does not provide a reconstruction information on single showers but it provides better sensitivity than main DAQ system at low energies, where full event reconstruction may not be possible.



Figure 3. A HAWC water Cherenkov detector. A muon (in red) is passing through WCD and Cherenkov photons are created in a cone with a semi angle of $\sim 42^{\circ}$.



Figure 4. Detection of a shower as usually. For this operation mode HAWC will use main DAQ system.



Figure 5. Single particle technique. Detection of some of the secondary particles that belong to the shower. For this operation mode HAWC will use scaler DAQ system.

4. The fano factor

The Fano factor describes how much wider the real distribution is with respect to a Poisson distribution with the same mean value but without correlation. It is defined as:

$$F = \frac{\sigma^2}{\mu} \,, \tag{1}$$

In formula (1), σ is the spread of data and μ is the variance of a Poisson distribution with the same mean of the real distribution but without correlation. The Fano factor is a measure for the correlation in the random data. For scaler DAQ system, the random variable would be the number of hits in all PMTs in a given time window. For a Poisson process, the variance in the count equals the mean count, so F = 1. The most important sources of correlated noise are (hierarchically): a) air showers resulting in more than one PMT registering a signal, b) PMT after pulses and c) Michel's electrons due to muons that stop inside WCDs. The correlation result in a distribution that is wider than a Poisson distribution [3]. It is important to simulate Fano factor in order to know the HAWC capabilities to detect GRBs.

5. Simulation features

5.1. Fano factor simulation features

In order to get the simulated Fano factor of HAWC 30 it is mandatory to simulate the background expected at site level. For HAWC detector the main background is caused by secondary cosmic rays and extensive air showers (EASs), which are initiated by primary particle interactions at the top of the atmosphere. So, the first step was to simulate the EASs and for this purpose we used CORSIKA. All runs are done by using protons as primary particles, with energies in the range from 5 GeV to 50 TeV, zenith angles between 0° and 60°, the slope in the energy spectra of ~ 2.7 and the ground level at 4100 m a.s.l. In total, 2×10^{10} primary interactions were simulated. Every event contains all sub-particles created at ground with their respective momentum, position and arrival time. The second step was to simulate the detector, we used a GEANT4 based code. For this step it is worth to mention that each CORSIKA file has been oversampled 10 times in the GEANT4 code. Besides, every shower core was limited to a rectangular zone



Figure 6. Rate behavior in time for HAWC-30 array assuming 3 PMTs per WCD (MC simulation).

of 1500 m each side which includes the array. What this code gives us is the number of photoelectrons created by the secondary particles in each PMT. The WCDs localization is showed at Figure 2. At the last step the PMT afterpulses and electronics response are simulated, and finally the Fano factor is calculated.

5.2. Scaler effective area simulation features

For extensive air showers was used CORSIKA, this time with gammas as primaries with energies in the range from 5 GeV to 10 TeV, zenith angles between 0° and 65° , the slope of the energy spectra of -2 and ground level of 4100 m a.s.l. After that we used the GEANT4 based code to get detector response to ground level particles, and finally the official analysis software was used.

6. Results of Fano factor simulations

In the simulation presented in this work it has been considered 3 PMTs per tank (20 cm photomultiplier tubes) and the tanks localization is presented in red in Figure 2. This is because of the relatively new decision taken by the collaboration to increase the number of PMTs per tank from three to four. As it was mentioned in section 5, we only have 125 ms of background simulated so we chose a time window of 1 ms in order to calculate the rate and Fano factor for HAWC-30 array.

In Figure 6, the rate behavior in time is shown, y-axis is the number of hits in all PMTs each millisecond and x-axis is the time with 1 millisecond in each bin, and in Figure 7 it is shown the rate distribution, i.e. y-axis is the frequency of occurrence and x-axis is the number of hits in all PMTs each millisecond.



Figure 7. An example of the rate distribution for HAWC-30 array assuming 3 PMTs per WCD (MC simulation).

We found that simulated background rate per PMT is 30 kHz and the simulated Fano factor for HAWC-30 array is 2.9.

7. Results of scaler effective area simulations

The effective area $A_{eff}(E, \theta)$ of HAWC-30 array describes its efficiency of converting an incoming gamma-ray flux at the top of the atmosphere in detected hits. The effective area is calculated by simulating the response of the detector to extensive air showers generated by incoming gammarays [3]. The calculation uses formula (2), where A_{trhown} is the area over which the simulated EAS are thrown, $N_{obs}(E, \theta)$ is the number of showers that result in at least one PMT being hit, N_{thrown} is the number of simulated EASs and η_{PMT} is the average number of PMTs hits for this energy E and Zenith θ ,

$$A_{eff}^{Scaler} = A_{thrown} \eta_{PMT} \frac{N_{obs}(E,\theta)}{N_{thrown}(E,\theta)} \,. \tag{2}$$

The obtained scaler effective area is shown in Fig 8. Note that the meaning of the scaler effective area differs from the traditional concept of effective area used e.g. for air shower arrays. Because of the number of PMTs hits is the signal (and not the individual showers) the scaler effective area is not restricted to the detector area, so it never saturates to a value. It is interesting to compare this effective area with the effective area of Fermi LAT. For instance, for a primary photon energy of 30 GeV and a zenith angle between 0° and 25.8° the Fermi LAT effective area differs from the traditional concept of effective area used e.g. for air shower arrays is ~ $1m^2$ and the scaler effective area of HAWC-30 array is ~ $4900m^2$. The scaler effective area decreases as the zenith angle increases.



Figure 8. Scaler effective area of HAWC-30 array for 4 zenith angle bands and different primary photon energies.



Figure 9. Scaler DAQ system sensitivity to GRBs for HAWC-30 array taking into account 3 PMTs/tank. Necessary flux at 10 GeV multiplied by square root of the GRB duration to produce a 5 σ signal. The range of zenith angle is from 25.8° to 36.8°.

8. Sensitivity to GRBs

In this section we describe the HAWC-30 array sensitivity to GRBs, as obtained using the single particle technique (scaler DAQ system) described above. The background for HAWC-30 array



Figure 10. Scaler DAQ system sensitivity to GRBs for HAWC-30 array taking into account 3 PMTs/tank). Necessary flux at 10 GeV multiplied by square root of t he GRB duration to produce a 5 σ signal. The range of zenith angle is from 0° to 25.8°.

is 30 WCDs \times 3 PMTs \times 30 kHz = 2.7 MHz.

The signal to background ratio or significance of an observation with HAWC is defined as

$$Sigf = \sqrt{\frac{\Delta T}{F\eta_{PMT}R_{PMT}}} \int_{E_{min}}^{E_{max}} dE \frac{dN}{dE} A_{eff}^{scaler} , \qquad (3)$$

in formula (3), ΔT is the observation time window, F is the Fano factor, η_{PMT} the number of PMTs in the detector, R_{PMT} is the average PMT rate, θ is the observed GRB zenith angle, $A_{eff}^{scaler}(\theta)$ is the scaler effective area and $\frac{dN}{dE}$ is the observed GRB flux.

For these calculations we assumed that GRB energy spectrum, in the high energy zone, is a power law form with a high energy cutoff. The calculations are done in two zenith angle bands: from 0° to 25.8° (Figure 10) and from 25.8° to 36.87° (Figure 9) and the following values for the high energy cutoff in the GRB espectrum: 10 GeV, 30 GeV, 55 GeV, 100 GeV, 1 TeV and 100 TeV and a spectral index in the range from -3 to -1. Effects of extra galactic background light (EBL) have been ignored. The computed sensitivity is shown in Figures 9 and 10, in terms of differential flux at 10 GeV multiplied by square root of the GRB duration. The sensitivity corresponds to a 5 σ detection of the GRB. The flux of the GRB 090510 measured by Fermi LAT is shown for reference [5].

In Figures 9 and 10 one can see as the zenith angle for GRBs decreases the necessary flux to detect a GRB at 5 σ decreases and, as the energy cutoff increases the necessary flux to detect GRBs at 5 σ decreases and as the spectral index increases the necessary flux to detect GRBs decreases. The GRB090510 could be seen if its energy spectrum would extend to 55 GeV.

9. Conclusions

The HAWC observatory is a new generation wide field of view gamma-ray telescope currently under construction in Mexico. The wide field of view and high duty cycle of HAWC offer exciting prospects for the first detection of a gamma-ray burst by a ground-based experiment. In this paper the capabilities of the partially build array (HAWC-30) to detect high energy GRBs using single particle technique are analyzed. As a comparison GRB090510 flux could be seen with HAWC-30 array if its energy spectrum would extend to 55 GeV. Thus, although much smaller than complete HAWC, HAWC-30 provides a realistic opportunity to observe powerful GRBs. Measurements could constrain high energy cutoffs in GRB spectra, thus providing information on intrinsic spectral cutoff of the GRB or EBL absorption.

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