Enhancing HAWC's Response to sub-TeV Transient Sources

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Abstract: The High Altitude Water Cherenkov (HAWC) Observatory, currently being built 4,100 meters above sea level on Sierra Negra, Mexico, is a ground-based detector well-suited for observing transient phenomena in the TeV energy range. This is due to its large field of view (2 sr), high up time (>90%), and high efficiency for triggering on showers above 1 TeV. However, sub-TeV transient events are of interest due to the overlap in energy with satellite experiments such as the Fermi gamma-ray space telescope. The standard HAWC reconstruction chain will achieve an effective area of 100 m^2 at 100 GeV while rejecting lower multiplicity events in the detector. Triggering on small showers from primaries with energies below 100 GeV is difficult due to the large number of uncorrelated signals in the detector during the large time window required to accept showers from all arrival directions. To address this problem and augment the sensitivity of HAWC below 100 GeV, we propose a method in which particle arrival directions are fit for triplets of triggered photomultipler tubes (PMTs) in a short sliding trigger window (100 ns). The resulting arrival directions are then summed in a coarsely-binned significance map of the sky with a time window of one to several seconds. This fast algorithm will run online and will be able to localize the positions of transient sources to within 8°. Applying this technique to data from the currently-operational 10% of the final array allows us to obtain actual noise rates and use them in conjunction with simulations to calculate the sensitivity to transients.

Keywords: HAWC, Gamma-Ray Burst, Transient Phenomena

1 Introduction

The Gamma-Ray Coordinates Network (GCN) [1] has made possible rapid observations between multiple experiments to be triggered on transient phenomena. Satellite experiments such as Fermi and Swift have so far contributed thousands of alerts in the MeV and GeV bands. The size of the orbital experiments limits the observations of the highest energy gamma rays, but the alerts allow imaging air cherenkov telescopes to follow up with observations and probe for TeV emission. Simultaneous observations of a transient source like a gamma-ray burst (GRB) [2] by multiple experiments with a combined sensitivity spanning keV to TeV would be of particular interest . Such an observation would give insight not only into the emission mechanism of the GRB but also other interesting physics, *e.g.*, limits on Lorentz invariance violation [3, 4] and bulk Lorentz factors of jets [5].

The High Altitude Water Cherenkov (HAWC) observatory is an extensive air shower array currently being constructed at 4,100 meters above sea level on the Volcano Sierra Negra in Mexico. HAWC will have a wide field of view (∼2 sr) and a high duty cycle (>90%). It will cover an area of $\sim 22,000\,\mathrm{m}^2$, giving the detector excellent sensitivity to gamma rays between 100 GeV and 100 TeV [6]. These traits make HAWC ideal for unbiased surveys of the northern sky and searches for transient sources such as GRBs, which so far have not been observed in the TeV band.

2 The HAWC Detector

The final HAWC array will consist of 300 optically isolated water cherenkov detectors (WCDs). The WCDs are cylindrical tanks 7.3 m in diameter and 4.5 m tall that hold approximately 200,000 liters of purified, clear water. They are instrumented with four upward facing PMTs (three Hamamatsu R5912 PMTs and one central Hamamatsu R7081 high quantum efficiency PMT). The array is scheduled to be completed in the summer of 2014 but has started taking data with WCDs as they are added in September 2012.

The PMTs are read out using custom front-end board electronics that are reused from the Milagro experiment. The boards amplify, shape, and discriminate the pulse across a low and a high threshold. Instead of digitizing the waveform, the time over these thresholds (ToT) is used as a proxy for pulse height and width. These digital ToT signals are time-stamped by a CAEN VX1190 Time to Digital Converter (TDC), and read out using a VME single-board computer. All the data are then sent to an online computer farm for processing. This allows the full data stream of all 1200 PMTs (∼500 MB/s) to be seen by the online system which triggers in real time.

3 Low-Energy Challenges

Low energy showers produce challenges for extensive air shower detectors due to the limited amount of information that reaches the ground. As the energy of the primary gamma ray decreases, the number of PMTs that detect secondary particles in a sliding time window (*nHit*) decreases. Even though HAWC is built at a high altitude in order to get close to the shower maximum, in sub-TeV showers, typically only a small fraction of the maximum number of secondary particles reaches the array. The low number of hits causes the separation of gamma-ray and hadronic primaries to fail.

An additional challenge comes from the noise rate of the PMTs, ~ 20 kHz. For events with a low $nHit$, the noise hits become a significant fraction of the hits in the time window. This will significantly hinder the performance of standard N-point plane fits and skew them from their original direction. Despite these challenges, the relative abundance of sub-TeV showers makes them particularly interesting for transient searches.

4 Online Reconstruction

The online software trigger system gives the HAWC detector a great deal of flexibility to explore interesting trigger options. The only caveat is that since the algorithms have to keep up with the full data rate of the detector, they cannot be processor intensive. In addition, the trigger has to have sufficient compression or rejection capability to reduce the 500 MB/s rate to a more manageable level. The default running mode is a simple multiplicity trigger that looks for events with more than n hits in a short time window. If the trigger condition is passed, all the hit information is saved.

Due to the high rate, low multiplicity events will be reconstructed online, and only reconstructed track and energy parameters will be saved. The remaining low-hit events are not usable by the standard reconstruction but still contain useful information that can be extracted using a different method.

4.1 Low Multiplicity Reconstruction

Extracting useful information from low-energy, low-hit showers is difficult, but the challenges described in Section 3 can be mitigated or overcome. Our method (affectionally called the "vector telescope"), breaks down into two steps: a low multiplicity event fitter and a short time-window skymap search.

A triplet fitter finds all combinations of 3 WCDs in a 100 ns time window and analytically fits a plane to all triplets individually. The normal vector to this plane then points back to the source. This procedure has two advantages; it can be performed for a low number of hits very quickly; and it decouples the noise hits from those associated with the shower. Though the noise hits will pull a fraction of the triplet normal vectors away from the source the remaining triplet normal vectors point back to the source. Due to the rapid ($_nC_3$) growth of the number of triplets with event size, we only apply the algorithm to events with $n \leq 10$.

Once a fit to the triplets is calculated, it is pushed into a 1 s time buffer. Events in this buffer are placed in a HEALPix skymap, which is evaluated for significant excesses. The length of the buffer and the size of the HEALPix binning can be adjusted to search for different types of sources, *e.g.* GRBs of different duration.

5 Performance and Results

To determine the performance, the method was applied to simulated data for the full detector. Cuts were made to remove select events that would pass the normal trigger in HAWC. Since the method utilizes air showers that are normally discarded, the effective area increases with respect to the standard trigger (Fig. 1).

We also study the performance of the vector telescope reconstruction by calculating the detector's Point Spread Function (PSF) for the algorithm. The PSF is derived by determining the difference between the simulated direction and the reconstructed direction. While the resulting PSF of 8° (Fig. 2) is worse than the PSF of the standard reconstruction, it still provides a good angular resolution for low energy events that would otherwise not be reconstructed. The detection of a significant excess in the skymap can trigger alerts to other detectors, for example air Cherenkov detectors.

The method cannot distinguish between hadronic and gamma-ray primaries. This is not so much a limit of the method, but more likely a lack of information at the ground to distinguish the two types using the standard containment cuts. Future work that could tag muons could provide the needed information.

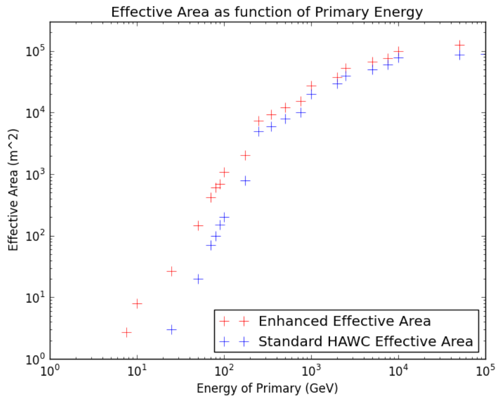

Fig. 1: Effective area as a function of primary energy for the standard event reconstruction (blue) and the vetor telescope algorithmR described here (red). There is a considerable increase of effective area at low energies.

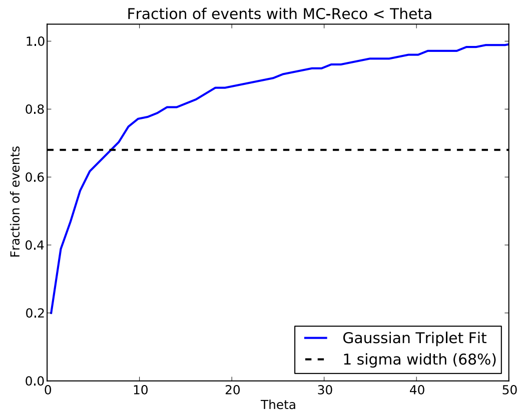

Fig. 2: Angular resolution of the vector telescope algorithm. The plot shows the fraction of events reconstructed with an angular distance of less than θ between the simulated and reconstructed direction, as a function of θ.

6 Conclusions

We are optimizing the skymap significance transient finder using data from the 30 tank deployment of HAWC. Results will be shown at the conference.

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