Low Energy Triggering with HAWC

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Abstract: The High Altitude Water Cherenkov (HAWC) experiment is under construction at Sierra Negra, Mexico and will have unprecedented sensitivity to gamma ray sources between 50 GeV and 100 TeV across the entire sky. The low energy sensitivity is limited by the triggering condition for the instrument which nominally requires about 70 PMTs to observe light in 2 microseconds. I will discuss a potential design to the data acquisition which will allow readout of much smaller events enhancing the low energy response of the detector and increasing the experiment's capability to observe sources below 50 GeV.

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1 Introduction

The High Altitude Water Cherenkov experiment (HAWC) is a second-generation gamma ray air shower observatory which will exploit water-Cherenkov technology to identify high energy gamma rays and cosmic rays[1]. A ground array of 300 7.3 meter diameter, 4.5 meter deep steel water tanks – each hosting three 8 inch photo-multiplier tubes (PMTs) – will cover an area of approximately 22500 square meters. The 900 channels and front-end electronics are re-used from the Milagro experiment and being re-deployed at the HAWC site at Sierra Negra, Mexico. The experiment is sensitive to gamma rays and cosmic rays between 50 GeV and 100 TeV by measuring the energetic particle content reaching the ground when an energetic primary particle interacts in the atmosphere above the detector.

In the baseline design for the detector, events are triggered when the detector observes a pre-defined number of PMTs having a signal. This trigger threshold is approximately 70 PMTs to limit the data rate to the 40-60 MB/sec that the baseline electronics can manage. This relatively high trigger threshold constitutes the chief limitation to the low-energy response of the experiment because low-energy showers can result in events with fewer than 70 PMTs seeing a signal.

The HAWC Collaboration is pursuing a design for the electronics and software data acquisition system that have the potential to substantially increase the collection efficiency of these low-multiplicity events and improve the low-energy sensitivity of the instrument. This work details and effort to segment the hardware data acquisition system into small pieces allowing us to take every PMT hit and move the triggering logic into the software processing systems.

2 Scientific Motivation

HAWC will observe gamma ray sources inside and outside of the Galaxy. Though sources outside of the Galaxy are likely to have intrinsic source spectra extending out to tens or hundereds of TeV, the spectra for extra-Galactic objects cuts off in the GeV to low TeV range due to absorption on the extra-Galactic background light (EBL). This light is predominately a byproduct of the star formation history of the cosmos. A function of both the distance from the Earth and the energy of the gamma ray, the universe is essentially transparent below 100 GeV and the opacity rises quickly above this energy (see, for instance [2]).

Figure 1 shows the effective area of HAWC to gamma ray events in the baseline design of the instrument. The effective area is calculated from simulation using Equation 1 where A_{thrown} is the area over which simulated events are thrown, $N_{observed}$ is the number of events passing some specified cuts and N_{thrown} is the number of events thrown in the simulation.

$$A_{eff}(E,\theta) = A_{thrown}\frac{N_{observed}(E,\theta)}{N_{thrown}(E,\theta)} \qquad (1)$$

The effective area displayed in Figure 1 is obtained by selecting events with more than 70 PMTs hit and by insisting that events are well-reconstructed and within the optimal analysis bin of a source [3] of a hypothetical source. Above about 1 TeV, the effective area relatively flat and

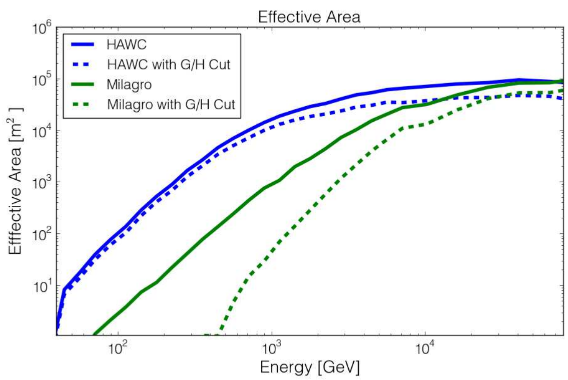

Figure 1: Effective area of HAWC along with the effective area of the predecessor experiment Milagro for comparison. Above about 1 TeV, the effective area approaches the geometrical footprint of the experiment and at lower energies the effective area is reduced due to the tendency of lower energy air showers to result in few energetic particles on the ground

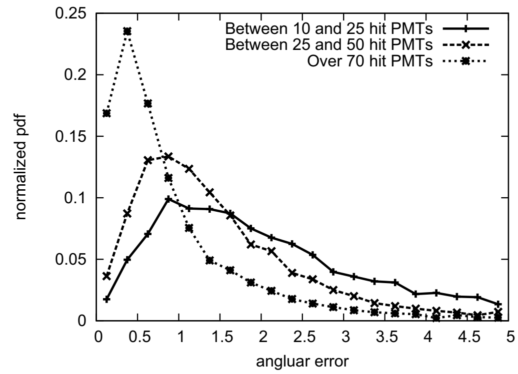

Figure 2: Angular error distribution for events with different numbers of non-noise PMTs participating in the event. Though the angular resolution is degraded for smaller events, smaller events are quite reconstructable and can be associated with astrophysical objects

approaches the geometrical area of the instrument because events above 1 TeV result in enough particles on the ground to nearly always trigger the instrument if the primary was directed at the geometrical area of the detector. Events which fall off the detector are, by the current generation of algorithms, typically mis-reconstructed and fall out of the analysis bin.

Below 1 TeV, the effective area of HAWC falls steeply. This fall is primarily due to the tendancy of lower energy gamma rays to produce fewer secondary particles on the ground. The number of particles on the ground is a strong function of the depth of the primary particle interaction and at lower energies we are typically seeing primary particles which happened to interact particularly low in the atmosphere.

Two of the main scientific targets for HAWC, Gamma-ray bursts and Active Galactic Nuclei, are attenuated above 100 GeV by the EBL and increasing our sensitivity at and below 100 GeV is particularly useful to extra-Galactic science with HAWC. Lowering the trigger threshold is one relatively simple way to achieve this. Figure 2 shows the angular resolution of the experiment for the baseline detector configuration and for smaller events. Quoting the angular resolution as the radius to contain 68% of the events, the reolution is anticipated to be 0.95 degrees for events with more than 70 PMTs, 1.69 for events with between 25 and 50 PMTs and 2.3 for events between 10 and 25 PMTs. The angular resolution of the small events is naturally worse than for large events, but it is still quite possible to make astronomical observations with the resolution of the small events.

3 Potential DAQ / Online Design

The baseline data acquision and data processing system for HAWC is shown schematically in Figure 3 along with a potential modification to allow for higher data rates. The design for the data acquisition system for HAWC centers around custom front-end boards (FEB) re-used from the Milagro experiment [4]. These FEBs are connected to each PMT by a single cable, carrying both the PMT signal and the high DC voltage to power the PMT. The high-frequency PMT signal is picked off by the FEB. The PMT signal is shaped, split and two discriminator thresholds are applied to the shaped pulse, one at a low threshold of approximately 1/3 of a photo-electron (PE) and one at approximately 5 PEs. The logic of the FEB combines these pulses so that we get single square ECL signal out for a PMT when the PMT signal is below the high threshold and two ECL pulses when the PMT is above the high threshold. The duration of these pulses is related to the original number of photons that the PMT detected and varies between about 100 ns several hundred ns depending on how much light the PMTs detected. [5]

This ECL output from the FEBs are fed into CAEN V1190 VME time-to-digital converters (TDCs) which digitize the time of voltage transitions on channels of the FEB. The TDCs are read out into computer memory by a CAEN V2718 optical bridge which serves as the VME controller. Each TDC can digitize up to 128 PMT channels. The required 8 TDCs occupy one VME backplane and are PMT signals are preserved in a few μs window whenever a trigger occurs and read out from VME by a single computer process [6]. Blocks of events are then transferred to one of several reconstruction clients for calibration and determination of reconstruction parameters.

This design faces a limitation due to the maximum data transfer rate across the VME of between 40 and 60 MB/sec.

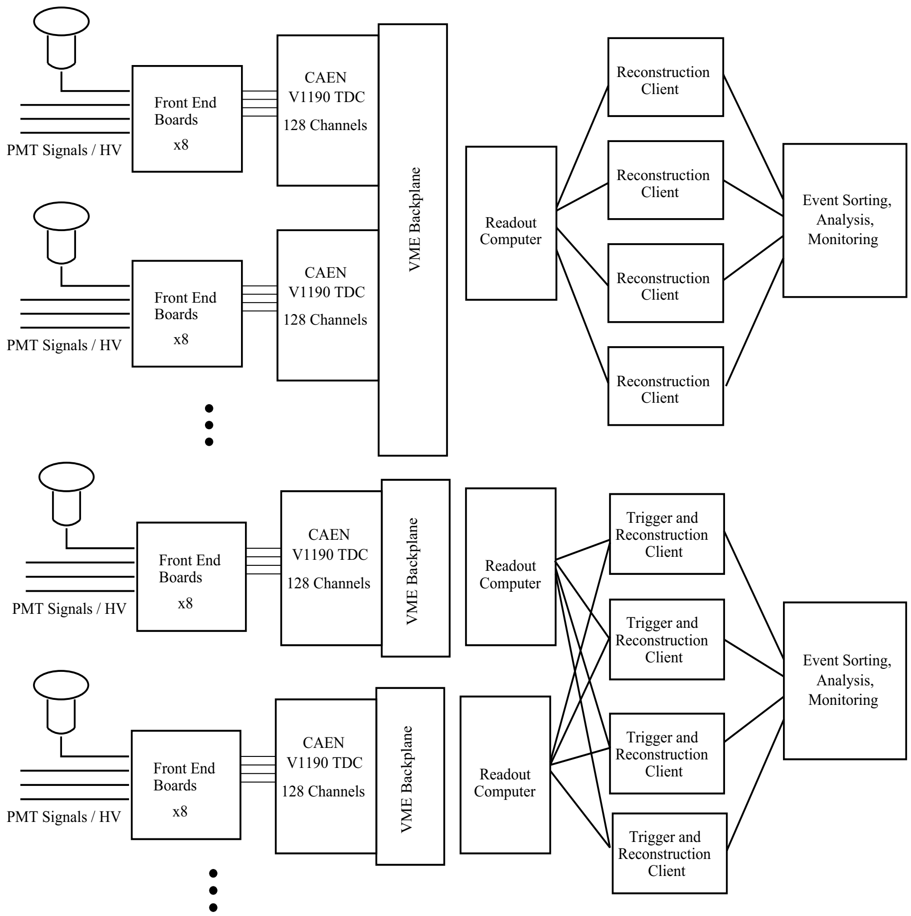

Figure 3: Two potential designs for the HAWC data acquisition system described in the text. The top figure is the baseline design and has all data read out across one VME backplane whereas the potential improvement in the lower figure does not have the same bottleneck.

Given this limitation, a tentative trigger threshold for the experiment has been set at approximately 70 PMTs to reduce the data transferred across VME.

Early work at the VAMOS prototype array for the experiment [7] and a test tank in Colorado [8] indicates that a typical rate of PMT signals crossing the low FEB threshold is approximately 30 kHz. This sets an approximate data rate for the 900 channels of the experiment at 270 MB/sec if every PMT hit were to be preserved.

An alternative design for the DAQ involves using multiple independent VME backplanes, each given a single TDC and a single optical bridge / controller. The trigger would be periodic, initiating a readout window equal to the trigger period: every PMT signal would be digitized and transferred into computer memory. Each TDC/bridge pair would be read out by an independent computer process. Each independent backplane suffers the same 40-60 MB/s data transfer limitation but since each backplane has only a fraction of the array, the full 270 MB/sec data rate can be read out. This allows every PMT signal observed by the array to be brought into computer memory and transfers the task of identifying and assembling events from a hardware problem to a software problem.

Figure 3 shows the treatement of this increased data rate. The readout processes each have the responsiblity to read out and buffer data from its TDC. Since each TDC receives the same trigger pulse, blocks of triggered events line up between the different readout processes. All triggers from all TDCs for some time duration would be forwarded to a single reconstruction client which, having all the data from the array for this time duration, would apply the trigger condition and reconstruct the events. Another reconstruction client would receive the data from the next second and so on. Assuming there are N reconstruction clients, they each have N times real time to apply the trigger condition and reconstruct the data. These reconstruction clients then forward their (reduced) event data stream to a single event sorting process which assembles the time-ordered event stream provides the data for downstream analysis. The network that the readout computers and reconstruction clients use to transfer data limits this design and modern computer hardware can handle the anticipated 270 MB/sec instantaneous rate. In the lab, sustained transfers of 400 MB/sec have been seen using typical computer hardware.

This approach carries some increased risk over the single-backplane approach because it requires more sophisticated software and does not allow for hardware data rate limitation. This approach has the benefit, however, that we can devote substantial computer to the identification and reconstruction of small showers, enhancing our low energy reach. The number of reconstruction clients can be expanded to accommodate our CPU needs.

4 Smart Trigger Algorithms

The principal potential for improvement over the baseline DAQ design is simply allowing a larger number of events to be collected and reconstructed. It is not clear yet what the limiting data rate will be, but it will be better than the nominal data rate of 40-60 MB/sec and 5kHz trigger rate.

In addition to the improvement from allowing more events, we anticipate improved event collection by trigger algorithms that are better able to distinguish genuine air showers (which arrive in a correlated plane) from other sources of random noise.

Figure 4 shows an an example of what is possible. Since the main source of background is low-PE values from small fragments of air showers, radiation in PMT glass and other sources, we consider a trigger that, rather than forming a multiplicity condition over all PMTs that see light, forms a multiplicity condition that sees two or more PEs. The top panel shows where the threshold would have to be set to achieve a target event rate for both the nominal trigger (counting PMTs over their hardware threshold) and this new condition (counting PMTs over 1 PE). Selecting a condition for each algorithm that produces a 20 kHz rate, we can calculate the effective area to the instrument shown on the bottom panel of Figure 4. The 20 kHz target is a plausible target based on initial performance estimates.

The capacity for improvement is large. Simply increasing the rate from the baseline 5 kHz to 20 kHz gives an increased effective area at 100 GeV of over an order of magnitude and smart trigger algorithms have the capacity to improve this further.

5 Conclusions

The HAWC instrument is unique among high-energy gamma ray observatories because of its ability to montior the entire overhead sky for sources above 50 GeV. This is particularly valuable because extra-Galactic gamma ray sources (AGN and GRBs) are strongly transient. Because these extra-Galactic sources are attenuated by the EBL starting at about 100 GeV, it is important to maximize HAWC's low-energy reach. The sensitivity of the instrument is limited at the low energy by the need to trigger at a relatively high threshold. Potential improvements to the DAQ include bringing all of the raw PMT data into computer servers and applying trigger and reconstruction algorithms in software and have the potential to increase the effective area of the instrument to low-energy events by an order of magnitude or more.

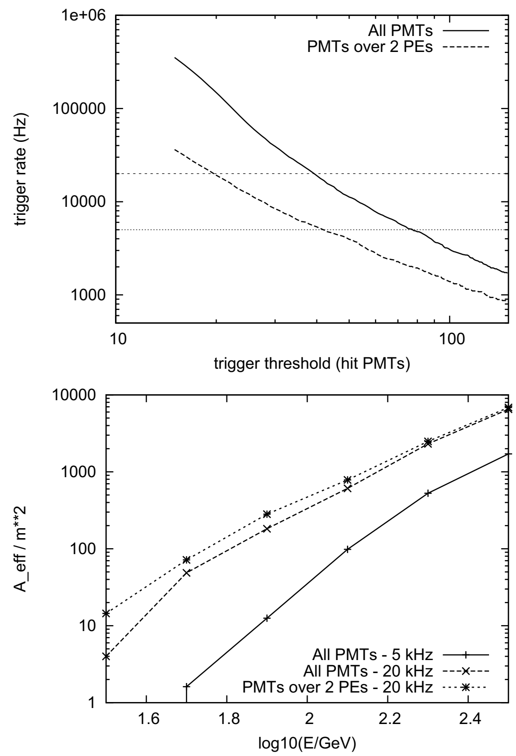

Figure 4: The top panel shows the trigger threshold required to obtain given threshold for different potential trigger algorithms. The bottom panel shows the effective area at trigger level for different potential trigger algorithms at 20 kHz rate along with the baseline. The potential for improvement at 100 GeV is evident.

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