Sensitivity and Design Optimization of HAWC

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***Abstract*. The High Altitude Water Cherenkov (HAWC) observatory is a proposed, large field of view (∼2 sr), high duty cycle (>95%) TeV gamma-ray detector to be constructed using a dense array of water tanks covering an area greater than 25,000m^2. HAWC will be located at an elevation of 4100m near the Sierra Negra volcano in Mexico. The instrument will use 900 photomultiplier tubes to observe the relativistic particles and secondary gamma rays in extensive air showers. This technique has been used successfully by the Milagro observatory to discover several new TeV sources. The PMTs and much of the data acquisition system of Milagro will be reused for HAWC resulting in a cost effective detector that can be built quickly (2-3 years). The design improvements of HAWC along with the higher elevation site will make HAWC 15 times more sensitive than Milagro. In this paper we present the details of the HAWC detector simulation and design optimization studies and present the details of the sensitivity calculation. We will also describe the improvements that can be achieved in the sensitivity above 50 TeV through the expansion of the HAWC area and, in the sensitivity to extra-galactic sources such as AGN and GRBs with a denser PMT core to lower the threshold energy of HAWC.**

***Keywords*: add keywords here**

I. Introduction

High energy gamma rays probe the most extreme astrophysical environments including those that produce the highest energy cosmic-ray particles. Most of the discoveries in the TeV energy range have been made by imaging atmospheric Cherenkov telescopes (IACTs) which have a few milli-steradian field of view and 10% duty cycle. However, the Milagro observatory has demonstrated that a detector with a wide field of view (2sr) and nearly 100% duty cycle can discover new sources of TeV gamma rays at energies between 10 and 100 TeV, and map the diffuse emission from the plane of our Galaxy[3]. The HAWC (High Altitude Water Cherenkov) observatory builds on the experience and technology of Milagro to make a second-generation high-sensitivity detector. This unique detector will be capable of continuously surveying the TeV sky for steady and transient sources from 100 GeV to 100 TeV.

HAWC will be built by a collaboration of scientists from the US and Mexico with joint support. The HAWC site is Sierra Negra, Mexico, which is a very high altitude (4100m) site near existing infrastructure and collaborating universities. The HAWC observatory will utilize water Cherenkov technology (as proven by Milagro) and many of the Milagro components. The first phase of HAWC can be operational quickly, surpassing Milagros sensitivity within 1-2 years of the onset of funding. Because of the increased altitude, the increased physical area, and optimized design, HAWC will have an improved angular resolution, larger effective area, lower energy threshold and better background rejection. These improvements will result in a sensitivity of 15× that of Milagro and can be accomplished without any new technology, but only a modest upgrade to the existing electronics. We have used the existing Milagro data and simulations to verify these calculations.

II. Detectror Design

The HAWC design builds upon our experience with the Milagro detector. Milagro is the first large, uniformly instrumented, air shower array using water Cherenkov technology. The Milagro pond was instrumented with 2 layers of PMTs, a shallow layer for triggering and shower angle reconstruction and a deep calorimetric layer used for hadron rejection. Surrounding the central pond is an array of plastic, outrigger tanks (1 m deep by 2.7 m diameter) used for core position and shower angle reconstruction. In contrast, the HAWC design utilizes a single deep layer of PMTs with wider separation than used in Milagro. This configuration gives HAWC a much larger active area than Milagro for the same photocathode area.

A critical improvement between the Milagro pond and the HAWC design is the optical isolation of the PMTs. In an open design such as Milagro's, triggering at low thresholds is complicated by the high rate of single muon events, which penetrate the detector and illuminate the entire reservoir with Cherenkov radiation. The Cherenkov photons from single muons are difficult to separate at the trigger level from low energy air showers. The two-layer design reduces the problem of single muons by positioning a layer of baffled PMTs near the surface that only observes the volume of water directly above and is relatively insensitive to muons. However, this shallow layer is a poor calorimeter, as it is close to the surface of the water and thus receives different light intensity depending on the EAS particles distance from the PMT. Therefore in the Milagro design, an additional deep layer is required for calorimetry. Calorimetry is essential for distinguishing the brighter penetrating particles in a hadronic showers from the electromagnetic particles in a gamma-ray initiated shower.

The design requirements of the HAWC instrument could be achieved with either a large deep instrumented pond or a series of close packed commercial water tanks. We have chosen to pursue the water tank design mostly because of flexibility in design and deployment schedule and the ability to reconfigure and re-optimized the array as demanded by the science. The modular tank configuration will also permit HAWC to become a fully operational scientific instrument prior to completion, since even with less than half of the experiment built, HAWC will be the world's most sensitive gamma-ray air-shower array. Finally, the tank array design provides optical isolation of the PMTs as a natural benefit. This would need to be achieved with the addition of curtains with a pond instrument.

The default design sees us deploying a single PMT in 900 4.3 m deep by 5.0 m diameter commercial plastic water tanks. The tanks will be deployed in a dense pattern that provides 65-75% coverage of the 28000m^2 instrument area. Each tank will contain an 8" baffled upward-facing PMT anchored to the bottom. Figure1 shows the proposed deployment pattern. Figure 2 shows a single tank cross-section diagram as visualized in GEANT4. While the sensitivity of this default design is described in this proceedings, the final design will be optimized. We are currently investigating 7.3m diameter constructed steel tanks similar to the one shown in figure 3 as a lower cost alternative. Detailed simulations have been performed for numerous designs from smaller 3.6m tanks to very large 11m tanks. We have found that for a wide variety of tank sizes, the same sensitivity can be achieved so long as the water area and photo-cathode area are roughtly maintained.

HAWC will re-use the 900 8" Hamamatsu PMTs recovered from Milagro. We will also reuse the PMT bases, encapsulations and custom front-end boards, which provide shaping necessary for time-over-threshold pulse amplitude measurements and generate trigger primitives. Reuse of this instrumentation will provide HAWC both a savings in time and money.

III. Detector Simulation

The simulation for HAWC is an extension of the Milagro simulation software package. CORSIKA v6.735[2] is used to simulate gamma-ray and hadron induced atmospheric showers. A custom detector simulation using GEANT4 v4.09 [1] is used to propagate the secondary shower particles that reach the detector elevation through the HAWC detector. Cherenkov light production is simulated and individual Cherenkov photons are tracked through the detector. Detailed optical modeling of the water, reflection and absorption at surfaces, and the PMT response are included. The simulation has been thoroughly tested through comparison with Milagro data. The Milagro electronics utilize the TOT method for pulse amplitude estimation. The response of this system is simulated by generating a pulse waveform for every detected photon. These simulated pulses are

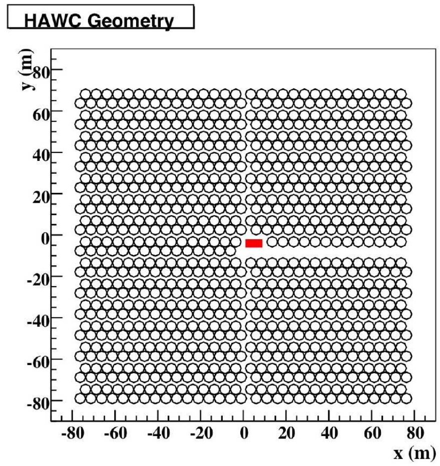

Fig. 1. Proposed layout of the HAWC detector. A dense array of 900 5m diameter water tanks will be deployed over an area of 25000m^2. The counting house will be situated in the middle of the array to minimize the length of the cables.

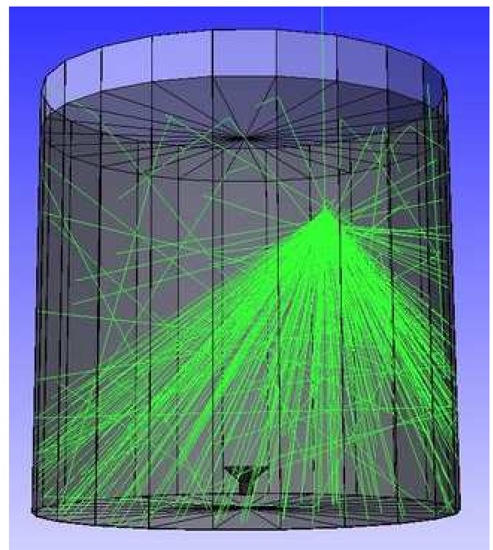

Fig. 2. Simulated 100MeV gamma-ray showering in a HAWC tank. The depth of the water must be sufficient that secondary shower particles never pass close to the PMTs producing large pulses that could be misidentified as muons.

Fig. 3. A 24ft (7.3m) prefabricated metal tank. This design is a potentially lower cost alternative to molded plastic tanks. The metal cylinder serves as a frame to support a light tight bladder that stores the water. Though this tank is attached to a concrete pad, HAWC tanks will be buried about 1ft deep.

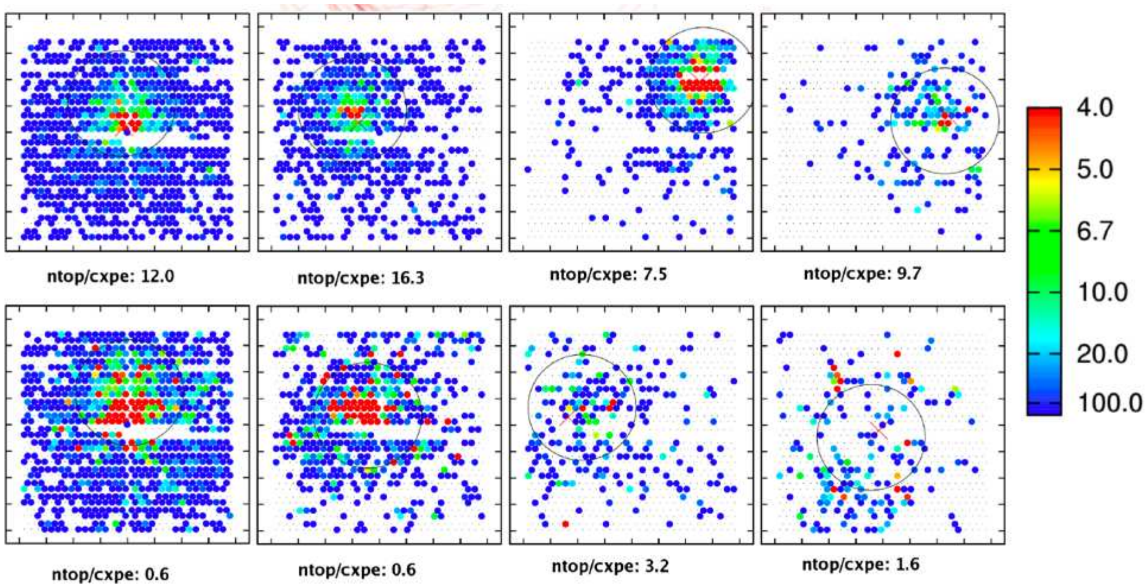

Fig. 4. Example of the HAWC gamma/hadron sepration technique. HAWC identifies hadron induced showers through their large energy depositions far from the shower core, typically due to muons. In this figure the top 4 panels show simulated gamma-ray induced showers and the bottom 4 panels show simulated hadron induced showers. The amplitude of each hit is indicated by color. Yellow or red hits outside the fit core region (circle) identify the presence high energy deposits far from the core. These events are rejected. At high energies, there are many large depositions outside the core region, so hadron events can be rejected with very high efficiency.

then digitized and converted to amplitude and timing measurements for use by the reconstruction software.

The depth and spacing of the PMTs was optimized for gamma-ray sensitivity from 1-100 TeV. The detector must act as an effective calorimeter in order for the background rejection methods to work effectively, so the PMTs need to be sufficiently deep that electro-magnetic particles are unable to pass close to the photo-cathode and produce large pulses that are not proportional to the deposited energy. We have found that this requires at least 3.5m of water (9 radiation lengths). However, if the PMTs are too deep, the sensitivity (PEs/GeV) is significantly reduced. At the selected depth of 4m (water above the photo-cathode), HAWC detects 40 PEs/GeV for EM particles and ¿30 PEs for through-going muons. The optimal radius of the tanks is determined by the Cherenkov angle in water. The illumination of EM particles is found to be roughly uniform over an area with a radius of 0.75 x depth. This dictates that for a tank of depth 4m, a radius of ¡3m is optimal. There is no scientific advantage to making the tanks smaller, but additional sensitivity to low energy showers can be achieved by increasing the photo-cathode density by placing more PMTs in each tank.

IV. Background Rejection

Hadronic showers are identified through the pattern of energy deposition in the detector. While gamma-ray induced showers have compact cores with smoothly falling lateral density, hadronic showers typically deposit large amounts of energy in distinct clumps far from the shower core. This is due not only to the presence of hadrons and muons in hadronic showers, but also clumps of EM energy far from the core caused by high P_T hadronic interactions in the development of the atmospheric shower. As a simple gamma/hadron discriminator, we have extended the compactness parameter, C, developed for Milagro. Here C is defined as the total number of PMTs hit divided by the largest pulse amplitude (in PEs) that is more than 40 m from the reconstructed core position. Gamma ray induced showers have only small hits far from the core and therefore have large values of C. Hadron induced showers with muons and hadrons and multiple clumps of EM energy have low values for C. Figure 4 shows Compactness distribution for gamma ray and hadron triggers for three different energies. The background rejection capability of HAWC improves with increasing energy. Figure 5(c) shows the efficiency for protons passing the gamma/hadron cut for HAWC when the gamma-ray efficiency is fixed at 50%. At similar energies, HAWC can reject hadronic backgrounds 10x better than Milagro.

V. Sensitivity

The sensitivity of the detector is dependent on the zenith angle of the source being studied. Therefore, we compute the sensitivity by estimating of the number of signal and background events collected during a single transit of the source from horizon to horizon. As a reference source, the Crab is selected. The baseline sensitivity is defined for a source that transits 15^{O} from zenith. In each day of observing HAWC will record a 4σ excess with a median energy of about 2.5 TeV assuming a trigger threshold of 150 hits, which will produce a trigger rate of about 1000 ev/s. In this single baseline transit, HAWC will detect about 18 gamma-ray events

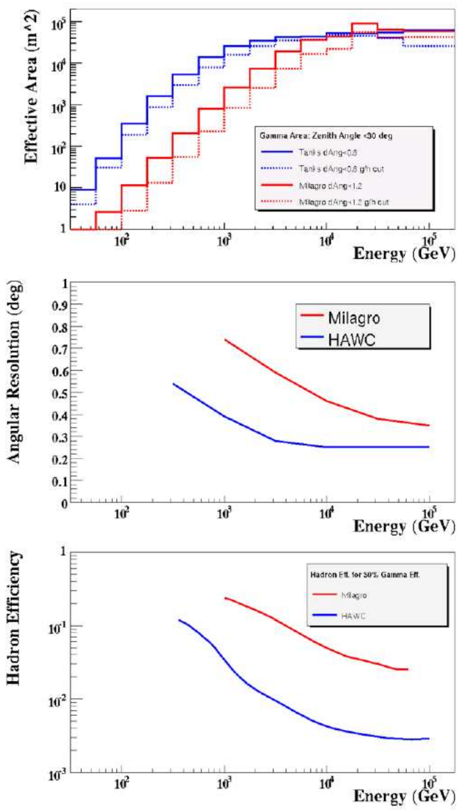

Fig. 5. Comparison of Milagro (red) and HAWC (blue) sensitivity. HAWC will see large improvements in effective area, angular resolution and gamma/hadron separation compared to Milagro.

on a background of about 24 events. Integrating over an entire year, HAWC will detect a crab-like source at about 75σ and survey the sky with a 5σ detection threshold at 65mCrab with these simple cuts.

This simple analysis serves a an illustration of a HAWC sensitivity computation, however, in practice we anticipate triggering at a threshold of 30-50 PMTs with a raw rate of 10-20 kHz. This low threshold will give HAWC greater reach to lower energies, but at the cost of greater background. For Milagro we have developed a likelihood analysis that weights each event by the ratio of the probability that it is a gamma ray to the probability that it is a hadron. In Milagro, we have found that this results in a 60% improvement in sensitivity. We have applied the same technique to the simulated HAWC data where a similar sensitivity increase is predicted. For HAWC, we anticipate 6σ detection for a crab-like source from a single transit and 120σ for a year of observing. For a 1 year survey of the overhead sky, HAWC will have a 5σ point source detection threshold of 40 mCrab. As stated above, the sensitivity depends on zenith angle, but is not substantially reduced for transit zenith angles ¡30 deg. As seen in Figure 6, the HAWC detector deployed at latitude 19°N will survey 44% of the entire sky (4π sr) with a sensitivity ¡50mCrab and 64% of the sky with sensitivity ¡80mCrab in one year of operation.

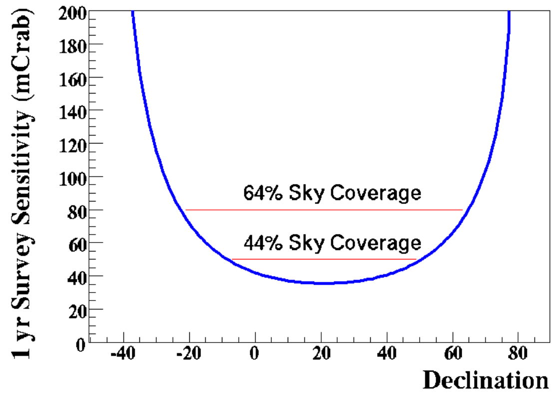

Fig. 6. Sensitivity of HAWC in mCrab vs declination. HAWC will be able to survey 44% of the sky with a sensitivity of better than 50mCrab in a year and 68 of the sky to the 80 mCrab level. These estimates assume a point-like source with the spectrum of the Crab.

VI. Upgrade Paths

We anticipate that at the highest energies (E¿50TeV), the hadronic background will be highly suppressed by the very efficient hadron rejection capabilities of HAWC. At these energies background rates are likely to be as low as a few events per year or less, so the sensitivity will be determined more by collection area than by the background. At these energies, events that fall within 100-200m of the edge will readily trigger the detector, but in order to properly reconstruct these events having a high energy, the rough location of the shower core must be known. A sparse array of ”outriggers”, similar to the milagro outrigger array, surrounding the dense tank array could, for a modest added cost, increase the effective area at the highest energies by a factor of $\sim 3\times$. This additional array is not in the HAWC proposal.

HAWC will have an effective area of $\sim$100m^2 at 100 GeV, 100$\times$ larger than Milagro. No other wide field instrument has comparable area in this energy range. Of particular interest is the potential for the discovery of high energy radiation from gamma-ray bursts (GRBs). If HAWC can detect prompt radiation from GRBs, it could not only be used to study the high energy radiation from these fleeting astrophysical objects, but it could be used to trigger other experiments. Studies have found that we can increase the sensitivity of HAWC at the lowest energies by increasing the number of PMTs in each tank. Doubling the photo-cathode density could increase the area at 100 GeV by a factor of 2 of more depending on the nature of the low energy backgrounds, which are under study.

References

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