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# The HAWC Observatory

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**Abstract:** The High Altitude Water Cherenkov (HAWC) Observatory is a very high-energy gamma-ray detector currently under construction at Sierra Negra in Mexico. HAWC will utilize the wide-angle, high duty cycle water Cherenkov technique developed by Milagro, but use new technology, a larger detection area, and higher altitude to improve sensitivity by an order of magnitude. HAWC will survey the TeV gamma-ray sky, measure spectra of galactic sources up to and beyond 100 TeV, and map galactic diffuse gamma-ray emission. With its wide field of view and continuous operation, HAWC will also be a powerful instrument with which to study transient phenomena. In this talk we will describe the science reach and performance of HAWC as well as how these overlap with space and ground-based detectors.

**Keywords:** HAWC TeV gamma ray

## 1 Overview

The HAWC Observatory is a very high-energy gamma-ray air-shower detector under construction at high altitude in Mexico. With its high duty cycle, wide field of view, and sensitivity to gamma-ray fluxes up to 100 TeV, HAWC will provide a view of the high energy universe complementary to that provided by IACTs. One of the primary goals of HAWC is to identify new TeV gamma-ray sources and extend measurements of known sources to higher energies.

Over a hundred TeV gamma-ray sources have now been discovered [1], including galactic supernova remnants and microquasars and extragalactic AGN. The galactic sources MGRO J1908+06 and MGRO J2019+37 detected by Milagro [2] show hard spectra of $\sim E^{-2}$, and the Cygnus region source MGRO J2019+37 remains undetected by IACTs. One interpretation is that this source has a finite spatial extent, negating the better angular resolution of IACTs, and extremely hard spectral index, pushing into energies where Milagro and HAWC have much better sensitivity. For such sources, HAWC will dominate the field. Measuring the spectra of these sources at energies to 100 TeV will provide a critical part to understanding the nature of these objects and may provide clues to understanding the sources of the galactic cosmic rays. Additionally, observations of a diffuse excess of TeV gamma rays in the Cygnus region [3] may indicate a local hadronic cosmic ray accelerator.

Another major goal of HAWC is identifying and characterizing time-variable sources at TeV energies. Observations of the Crab by AGILE [4] and Fermi [5] show significant flares at GeV energies. Observations at higher energies during these flares are less clear, with ARGO reporting a factor 3–4 increase in flux [6] while IACTs observe no significant increase [7, 8].

Efficient detection of short bursts requires instruments with a high duty cycle and wide field of view. GRBs are the extreme case, with the prompt phase gamma-ray emission the domain of purpose-built satellites. Recent observations of bright GRBs by Fermi-LAT show photons with energies above 30 GeV [9, 10]. At these energies, air shower detectors at very high altitude such as HAWC offer significantly larger effective area than possible on satellites and offer an opportunity for ground-based GRB detection.

## 2 The HAWC Detector

HAWC improves on the water-Cherenkov air-shower detection technique pioneered by Milagro. The site [11] is located near the mountain saddle between Sierra Negra and Pico de Orizaba at 19° N, 97° W, with an elevation of 4100 m above sea level. The site location allows simultaneous observation with IceCube and VERITAS. Particularly, the site elevation is a major improvement from Milagro (4100 m vs. 2650 m). This is more than three interaction lengths closer to shower maximum and significantly enhances the sensitivity of HAWC to photons below ~TeV energies, shown in figure 1.

HAWC will consist of a densely packed array of Water Cherenkov Detectors (WCDs) spanning an area of

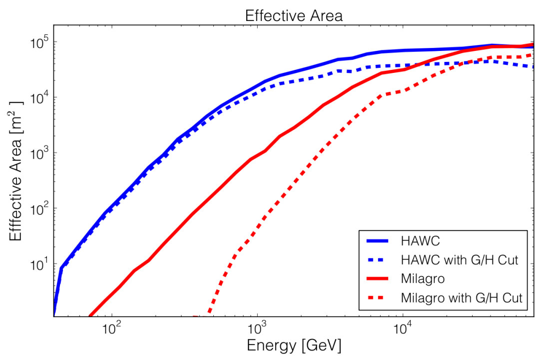


Figure 1: Effective area of HAWC and Milagro.

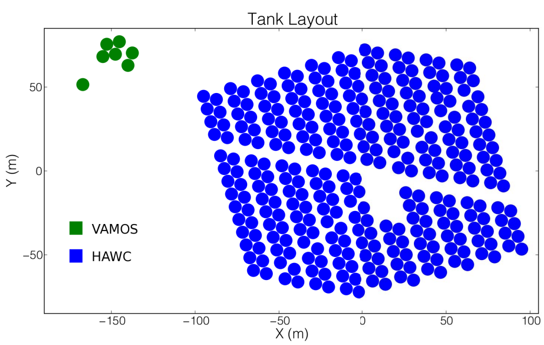


Figure 2: Layout of the HAWC array.

$\sim$22,000 m$^2$, shown in figure 2. Each WCD [12] is supported by a commercial corrugated steel tank measuring 7.3 m (diameter) by 4.5 m (deep) to withstand the load of the water column inside. A thin plastic bladder inside the tank contains $\sim$200,000 L of highly purified water and provides a light-tight environment. The inside surface of the bladder is black to minimize photon reflections. The bottom of each bladder is outfitted with three upward-looking Hamamatsu R5912 20 cm PMTs, reused from Milagro, to detect Cherenkov photons from relativistic air shower particles within the water volume. PMT signals are transmitted to the HAWC counting house, which will be built in the center of the array in the empty area in figure 2. The PMT signals will be processed by custom Milagro electronics, and resulting pulses are digitized by CAEN V1190 TDCs and Struck SiS3820 scalers. Air shower events will be identified using a PMT multiplicity trigger implemented by one of two potential trigger designs [13, 14]. The effective area of HAWC (figure 1) is substantially larger than that of Milagro primarily due to the higher elevation and larger area of densely-instrumented deep water.

The seven-WCD engineering test array VAMOS (figure 2) [15] is under construction and expected to be operational this summer. Preparations to the site have begun for the full HAWC detector, with the first 30 WCDs expected to be operational by Spring 2012. Given the current funding profile, HAWC is expected to be completed with 300 WCDs in 2014.

## 3 Simulated Performance of HAWC

Air showers and the response of HAWC are simulated by CORSIKA [16] and GEANT4 [17], respectively, using a modified version of the Milagro simulation. Each air shower event is reconstructed by locating the shower core on the detector plane by fitting a 2-D Gaussian to the observed PMT charge distribution. The shower axis is determined by fitting a plane to the PMT leading edge times. The axis reconstruction is dependent on sub-nanosecond timing precision. Edge times are corrected to remove the curvature of the shower front using a model determined from simulated data. Additionally, the variable offsets due to electronics, cable delays, and the effect of pulse charge on slewing rate must be corrected. To accomplish this, HAWC will use a laser calibration system [18] with an optical fiber to each WCD. The angular resolution for gamma rays in HAWC simulations ranges from $\sim$0.35° at 1 TeV to $\sim$0.1° above 10 TeV [19]. Improvements in core and angular reconstruction, including likelihood-based methods, promise to improve angular resolution.

By reconstructing cosmic ray air showers at a high rate, HAWC will improve measurements of the cosmic ray anisotropy (e.g. [20, 21]). Sensitivity to gamma-ray sources, however, depends on rejecting the hadronic background that dominates by roughly three orders of magnitude. As was done in Milagro, this hadronic background is rejected by identifying air showers with a muonic component and pockets of high energy density away from the core. Electromagnetic particles deposit the vast majority of energy in the top meter of water; whereas muons penetrate deeper in the tank and closer to PMTs, resulting in a correspondingly larger PMT charge. Simulated HAWC events from cosmic ray and gamma-ray air showers are displayed in figure 3. Most of the charge in both gamma-ray (top) and hadron (bottom) events is concentrated near the shower core. Events from hadrons, however, produce hits with a large fraction of the event charge (red) well away from the shower core. HAWC uses as a gamma/hadron discriminator the total number of hits in the event divided by the charge of the largest hit outside of an exclusion radius of 40 m, optimized to maximize sensitivity to gamma-ray sources. Showers with high values of this discriminator do not contain large hits away from the core and are most gamma-ray-like; these events are used in gamma-ray source searches. HAWC will keep a significantly larger fraction of gamma-ray events than Milagro, shown in figure 1, especially below $\sim$TeV energies. Above a few TeV, HAWC will reject more than 99% of hadronic events while retaining half of gamma-ray events [19]. New methods of gamma/hadron discrimination, including pattern-matching [22] and machine-learning algorithms, are expected to significantly improve the rejection of hadronic cosmic ray events. Hadronic events are them-

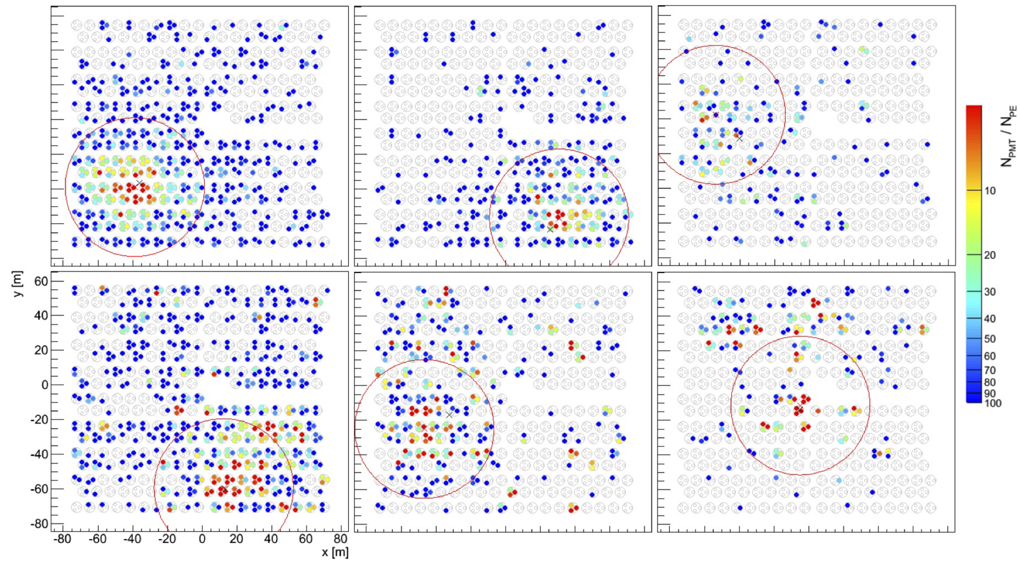


Figure 3: Simulated HAWC event display of gamma-ray (top) and cosmic-ray (bottom) air shower events. Each panel shows the positions of PMTs and hits for an event, where the hits are color coded according to the ratio of total number of hits in the event to the number of photoelectrons in the given hit. Red coloring indicates hits with a larger fraction of the total event charge. A circle with a 40 m radius is drawn, centered on the position of the shower core.

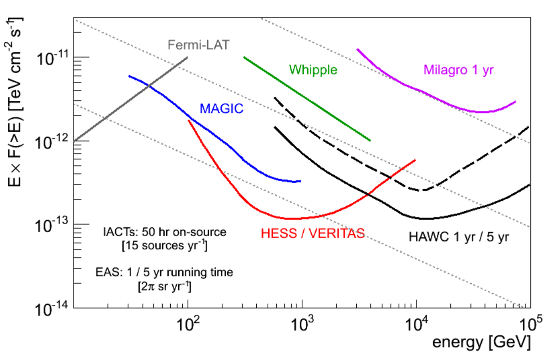


Figure 4: The sensitivity of HAWC to a Crab-like source compared to other gamma-ray observatories. 1 year HAWC exposure is shown with a dotted line, and 5 year exposure is shown with a solid line. A total exposure of 50 h is assumed for IACTs, allowing ~15 sources to be surveyed per year with such sensitivity. HAWC and other air shower detectors survey $\sim 2\pi$ sr of the sky at the given sensitivity.

selves interesting; HAWC will improve measurements of the hadronic cosmic ray anisotropy

### 3.1 DC Sky Survey

The sensitivity of HAWC to a Crab-like source is shown alongside that of other gamma-ray observatories in figure 4. Similar to Milagro, wide field of view and continuous operation make HAWC an ideal instrument to survey the TeV sky in a relatively unbiased fashion. Correlations of the Milagro skymap with the Fermi bright source list demonstrate that many GeV emitters are also TeV emitters, and therefore suggests that many TeV sources have yet to be discovered [23]. The hadronic interactions that may give rise to gamma-ray fluxes via the decay of neutral pions also produce charged pions, resulting in TeV neutrino fluxes. TeV gamma-ray surveys are therefore particularly interesting to the neutrino astronomy community, who often bias searches on these results to reduce trial factors [24, 25].

A diffuse TeV gamma-ray excess above the GALPROP expectation was detected in the Cygnus region by Milagro [3], and an effort to measure the diffuse spectrum in this region is ongoing [26]. This diffuse excess may indicate local hadronic cosmic ray acceleration. HAWC will improve these measurements and extend them to new regions in the galactic plane. In particular, the Fermi bubble structures [27] show hard GeV spectra $\sim E^{-2}$ and are partially within the HAWC field of view. HAWC will extend these measurements to TeV energies.

### 3.2 Transient Sources and AGN

HAWC will make daily observations of each source within its field of view. For the Crab, HAWC will accumulate ~2000 hours of observation time each year. Assuming the Crab spectrum above a few TeV continues as an unbroken power law with an index $\gamma$ =2.63, HAWC will see an excess of more than $6\sigma$ with each transit. Such statistics will permit HAWC to determine whether the flaring of the Crab at ~GeV energies extends to TeV energies.

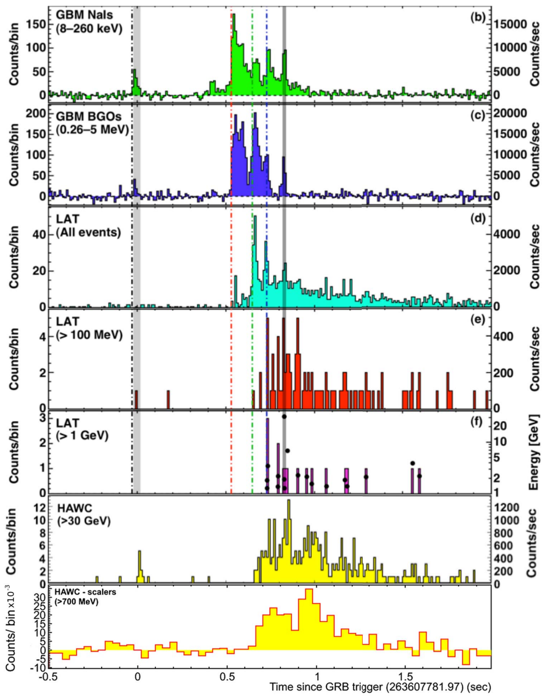


Figure 5: Observation of GRB 090510 by Fermi [9] (top 5 panels) at z=0.9, and simulated response of HAWC to a GRB with a similar flux 25° from zenith, assuming a cut off at 125 GeV, for the HAWC TDC DAQ (second panel from bottom) and HAWC scaler DAQ assuming a Fano factor of 4 (bottom panel).

HAWC will additionally produce light curves at TeV energies for AGN within a declination band of -20°–60° and alert the community when flaring is observed, triggering multiwavelength and multimessenger observations. Extragalactic TeV photons are attenuated at high energies by pair production against the extragalactic infrared background light (EBL). Measurements of AGN spectra above 10 TeV by HAWC are expected to constrain EBL models [28].

### 3.3 GRBs

Fermi LAT recorded photons with energies above ∼30 GeV from GRB 090510 [9] and GRB 090902B [10]. This is well above the low energy threshold of HAWC; with an effective area of ∼10 $m^2$ at 30 GeV (figure 1), HAWC will observe a factor ∼10 more events at this energy than Fermi. If spectra continue well above 30 GeV, HAWC will do even better. High energy photons produced in the GRB jet are attenuated by pair production at energies determined by the bulk Lorentz factor of the jet. By measuring GRB spectra at high energies, HAWC will constrain the Lorentz boost factor of the jets, search for violation of Lorentz invariance, constrain EBL models, and constrain models on the mechanisms of the VHE gamma-ray production. HAWC will operate with a continuous duty cycle and monitor 15% of the sky with zenith angle less than 45°. About 40 GRBs detected by Fermi GBM each year will be within this field of view, with ∼1.5 GRB yearly in coincidence with the LAT. Simulated HAWC observations to an event similar to GRB 090510 are shown in figure 5, assuming a cut off energy of 125 GeV and zenith angle less than 25°. HAWC would observe ∼200 events in the first second from such a burst. Even with a cut off at 50 GeV, HAWC would observe 5$\sigma$ from such a burst. The HAWC scaler DAQ will be sensitive to events too small to trigger the TDC DAQ; such events increase counting rates and provide an additional channel to detect GRBs, shown in figure 5. HAWC will perform an independent online data analysis to look for GRBs and issue GCN notices when one is observed.

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## References

[1] TeVCat, http://tevcat.uchicago.edu/.
[2] A. Abdo **et al.**, Astrophys. J. Lett. **664**, L91 (2007).
[3] A. A. Abdo **et al.**, Astrophys. J. **688**, 1078 (2008).
[4] M. Tavani *et al.*, Science **331**, 736 (2011).
[5] A. A. Abdo *et al.*, Science **331**, 739 (2011).
[6] G. Aielli *et al.*, The Astronomer's Telegram #2921.
[7] M. Mariotti *et al.*, The Astronomer's Telegram #2967.
[8] R. Ong *et al.*, The Astronomer's Telegram #2968.
[9] M. Ackermann *et al.*, Astrophys. J. **716**, 1178 (2010).
[10] A. A. Abdo *et al.*, Astrophys. J. Lett. **706**, L138 (2009).
[11] I. Torres *et al.* (HAWC Coll.), these proc.
[12] M. Longo *et al.* (HAWC Coll.), these proc.
[13] M. DuVernois *et al.* (HAWC Coll.), these proc.
[14] J. Pretz *et al.* (HAWC Coll.), these proc.
[15] A. Sandoval *et al.* (HAWC Coll.), these proc.
[16] D. Heck **et al.**, Forschungszentrum Karlsruhe, Tech. Rep. FZKA 6019 (1998).
[17] S. Agostinelli **et al.**, Nucl. Instr. Meth. A **506**, 250 (2003)
[18] P. Huentemeyer *et al.* (HAWC Coll.), these proc.
[19] B. Baughman *et al.* (HAWC Coll.), these proc.
[20] A. A. Abdo *et al.*, Astrophys. J. **698**, 2121 (2009).
[21] R. Abbasi *et al.*, Astrophys. J. **718**, L194 (2010).
[22] V. Grabski *et al.* (HAWC Coll.), these proc.
[23] A. A. Abdo *et al.*, Astrophys. J. Lett. **700**, L127 (2009).
[24] R. Abbasi *et al.*, Phys. Rev. D **79**, 062001 (2009).
[25] R. Abbasi *et al.*, Astrophys. J. **732**, 18 (2011).
[26] J. Galbraith-Frew *et al.* (HAWC Coll.), these proc.
[27] M. Su, T. R. Slatyer, and D. P. Finkbeiner, Astrophys. J. **724**, 1044 (2010).
[28] A. Imran *et al.* (HAWC Coll.), these proc.
[29] I. Taboada *et al.* (HAWC Coll.), these proc.