A Water Cherenkov Detector prototype for the HAWC Gamma-Ray Observatory

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Abstract: A full-size Water Cherenkov Detector (WCD) prototype for the High Altitude Water Cherenkov (HAWC) gamma-ray Observatory was deployed and is being operated at Colorado State University. The HAWC Observatory will have 300 WCDs at the very high altitude site in Sierra Negra, Mexico. Each WCD will be instrumented with three 8” baffled upward-facing PMTs anchored to the bottom of a 5 m deep by 7.3 m diameter steel container with a self made multilayer hermetic plastic bag containing 200,000 liters of purified water. The full size WCD prototype is instrumented with seven HAWC PMTs, and scintillators under and above the volume of water. Besides the additional instrumentation, this prototype has the same laser calibration system that the detectors deployed at the site in Mexico will have. This WCD prototype serves as a testbed for the different subsystems before deployment at high altitude, and for optimizing the location of the three PMTs, the design of the light collectors, deployment procedures, etc. Simulations of the light inside the detectors, and the expected signals in the PMTs can also be benchmarked with this prototype. The prototype started operation on March 1, 2011.

Keywords: γ-rays, γ-ray instrumentation, water-Cherenkov detectors.

1 Introduction

The High Altitude Water Cherenkov (HAWC) Observatory [1] is a next generation air-shower array based upon technology that has been developed and proven with the Milagro detector. The HAWC Observatory combines the Milagro water Cherenkov technology with a very high altitude site. Re-deploying the existing Milagro photomultiplier tubes (PMTs) and electronics in a different configuration at an altitude of 4,100 m will lead to a sensitivity increase of a factor of ~ 15 over Milagro [2]. This dramatic improvement is due to three things: the increased altitude, the increased physical area, and the optical isolation of the PMTs. As a result of these improvements, HAWC will detect a 5σ signal from the Crab Nebula in a single 4 h transit [2]. HAWC will maintain this sensitivity over 2 sr.

The technical design of HAWC builds upon the experience with the Milagro detector. The water Cherenkov technique is the best technique for air-shower detection because of its superior detection efficiency, calorimetric capability, and low cost. In addition, the Cherenkov angle in water is $41°$, therefore a PMT array with a spacing of roughly one half the water depth is sensitive over essentially 100% of its area. This is in stark contrast to a traditional air-shower array that is only sensitive to particles over a few percent of the enclosed area. Finally, the water can be used as an effective shield to electromagnetic radiation. Therefore, a deep layer of PMTs ($\sim$ 4.5 m) is an effective muon detector. This is an inexpensive method to build an extremely large area muon/hadron detector. Milagro has proven the effectiveness of this method in rejecting the cosmic-ray background.

The final improvement over the Milagro design is the optical isolation of the PMTs by using individual water tanks instead of a single large reservoir (or pond). The angular resolution of HAWC will be improved with respect to Milagro by using optically isolated tanks [2]. PMTs cannot be stricken by light far from its point of origin which would be inherently late relative to the arrival time of the shower particles. In addition, the trigger level of HAWC can be lowered without overloading the data acquisition system with events triggered by the large number of nearly horizontal muons traversing the detector volume. This is a particularly important effect in HAWC because of its much larger area (and therefore higher muon rate).

Another practical advantage of an array of water tanks is the possibility of taking data during deployment.

2 WCD prototype

The main goal of the WCD prototype is to be able to test the subcomponents of the experiment before deployment at the high elevation site. An easy access full size prototype is also important to optimize the deployment techniques. The prototype installed at CSU has the same tank, bladder, PMTs, acquisition system, and laser calibration as the designed experiment. The three main differences with the HAWC WCDs are the simpler water filtration system, the larger number of PMTs, and the presence of scintillators above and below the water volume. The CSU prototype being filled with water is shown in Fig. 1.

Figure 1: WCD prototype at CSU being filled with water.

2.1 Tank

HAWC tanks are made of corrugated galvanized steel wall sheets. Each tank has five rings (making the $\sim$ 5 m in height) of eight steel sheets (completing the 7.3 m in diameter). The tank of the CSU prototype can be seen in Fig. 1.

The depth of the HAWC tanks was selected as a compromise between timing resolution and gamma-hadron separation. Milagro had 2 layers of PMTs: a shallow layer at ~ 1.5 m depth for shower plane reconstruction, and a deep layer at $\sim$ 6 m depth for gamma-hadron separation. In HAWC these 2 layers are combined into a single layer. For gamma-hadron separation, it is important to be able to distinguish between large and small energy depositions near the PMTs. Thus, PMTs need to be sufficiently deep such that the EM particles have interacted prior to reaching the depth of the PMTs, and the produced Cherenkov light has diffused. This requires a PMT depth much greater than the radiation length in water (~ 40 cm). The layer must also be much shallower than the attenuation length of Cherenkov light in water ($\sim$ 30 m for Milagro) to maximize the detected light. Monte Carlo studies indicated that a depth of $\sim$ 4 m or greater is sufficient for effective gamma-hadron separation, and that greater depth is not advantageous.

2.2 Bladder

The HAWC tanks will be lined inside with light- and water-tight bladders. Each WCD will hold 200 m^3 of water without suffering any deformations or tilting. Bladders will be custom made for the HAWC tanks using 0.015” thick black PVC (XR3 PW) material or equivalent. They will have anchor points for supporting them to the steel structure, PMT mounting points on the bottom, and a hatch for access, PMT deployment, and water filling. The design of the bladders allows easy access to the interior for the installation of the photomultipliers. The lifetime of the tanks/bladders has to be longer than 10 years. The top of the tank will be covered with a low cost tarp to protect the bladder from sun, rain, and wind.

The CSU group has developed the capability to manufacture bladders for HAWC. This provides more control over the process, and a quality that is tuned to the needs of the experiment. Bladders are tested for light leaks using one of the Milagro PMTs. Three of the first bladders fabricated at CSU are shown in Fig. 2. The first bladder fabricated at CSU was successfully tested for water and light leaks, and was installed in the WCD prototype on March 1, 2011. The second CSU bladder was deployed at the site in Mexico in May, 2011 [3].

Figure 2: CSU bladders being tested for light leaks.

The depth of the water inside the CSU prototype is constantly monitored with a dedicated depth sensor. The level of water after installation was (432 ± 1) cm, and it has remained constant (within the uncertainty of the sensor) for over two months. The CSU bladder material has also been tested for water contamination. This is a critical issue because there is no recirculation planned for the HAWC tanks. The attenuation of light has been measured (at 325 nm) at the Univ. of California at Santa Cruz. The initial value for the CSU material was 18 m. The attenuation went down to 11 m during the first week, and remained constant for more than four months. (Both measurements are ongoing.)

2.3 PMTs and scintillators

HAWC will reuse the 900 8” Hamamatsu R5912 photomultiplier tubes, the bases, and the encapsulations from Milagro. A single RG-59 cable provides high voltage to each PMT and carries the high frequency signal back to the front-end electronics. In HAWC, the cable will be permanently attached to the PMT housing, thus avoiding problems with underwater connectors.

PMTs are secured to the bottom of the bladder with a weight such that the top of the photocathode is 4 m below the surface of the water. The PMT/weight unit is secured to a rope that extends to the top (through the hatch of the bladder; so that the PMT can be raised to the surface for maintenance or replacement.

The position of the PMTs was measured (dry) inside the bladder with an Altus 3 GPS system. The accuracy of this system (when used outside the tank) is ~ 0.3 mm. Inside the tank and lifting the base station up to only 2 m, the accuracy was of the order of 1 cm.

The CSU prototype has seven PMTs. There are three PMTs in the positions corresponding to the current HAWC design, a fourth in the center, and three “twin” PMTs. One twin PMT is in the center position but covered with the same material of the bladder, to study a dedicated muon trigger. Another twin PMT compares the use of baffles, and the third one compares a different distance from the center (6’ vs. 8’).

Another important difference between the prototype WCD at CSU and the planned detectors at the site is the presence of scintillators below and above the volume of water. There are four scintillators buried under the tank, one under each of the default PMT positions, and a fourth one in the center of the tank. There is only one scintillator at the top of the tank (between the top cover and the bladder), but its position can be varied. These scintillators will allow triggering on particular muon directions.

2.4 Calibration system

The laser calibration system for HAWC is designed to provide the relative timing and pulse-height calibrations for the PMTs in the HAWC detector. The calibration system is based on a Teem Photonics laser of 532 nm. The laser beam is split before a set of three filter wheels. Part of the light is fed into a 150 m return loop fiber that allows to measure the return time and to constantly monitor the physical status of the fibers. The light intensity through the filter wheels is measured with a radiometer to determine the relative decrease in laser intensity for different filter settings, and to calibrate the PMTs.

The calibration setup at CSU counts with four different diffusers, and four separate optical fibers going into the tank. The diffusers are made of different reflector and diffuser materials. The wheel with the four diffusers floats 3.5 m above the bottom of the tank, and can illuminate all seven PMTs. The CSU prototype will be used to determine the optimal diffuser design.

The calibration system can be controlled and operated remotely. A detailed description of the calibration system and the occupancy results for different filters and diffusers configurations (taken with the CSU prototype) are presented in these proceedings [4].

2.5 Water and filtration system

The filtration system used in Milagro will be the water purification system at the HAWC site. For the CSU prototype a simpler setup was built. This water system is able to provide 100 gpm at 87 psi maximum pressure. It consists of a parallel setup of 2×2 PVC vessels. The first stage has two granular media canisters with a 5 micron pre-filter and a charcoal filter each. The second stage has two bag canisters with 1 micron polyester bag filters.

The charcoal was pre-washed before being installed in the filters. A measured flow rate of 60 gpm was observed with a pressure of ~ 25 psi. This pressure did not change over the filling period of 15 hours.

A sample of the water was sent for analysis, and a large number of small particles (between 1 and 7 microns) were found. (This is approximately equivalent to 60 times the amount of particles that there were in the Milagro pond.) The 1 micron bag filters (efficiency $\sim 60\%$) were replaced by absolute 1 micron filters (efficiency $\sim 90\%$). The water in the prototype was recirculated for one week using the higher efficiency filters. (The change in the PMT rates can be seen in Fig. 3.)

2.6 Readout system

The Milagro front-end electronics will be reused for HAWC with minor modifications. These modules isolate and process the high frequency signals from the PMTs. The pulses are shaped and analog edges are generated at two discriminator levels. Analog edges are subsequently digitized with TDCs. The time-over-threshold method is used to measure both pulse arrival time and amplitude with a single multi-hit TDC channel. Additionally, the front-end boards provide summed trigger signals and direct access to the analog pulses for debugging and calibration.

The Milagro front-end electronics generate a 190 ns duration square pulse for every PMT hit. Triggers are generated by discriminating an analog sum of these square wave pulses requiring a prescribed number of PMTs be hit within the trigger window. A simple 50-PMT multiplicity trigger can be easily implemented with a ~ 30 kHz/PMT noise rate. (The PMT singles rate has been verified by preliminary measurements with the prototype in Colorado.) Although the shower plane can be reliably reconstructed for events with as few as 20 hits, for thresholds below ~ 50 PMTs the combinatorial background grows rapidly. This background can be reduced by shrinking the trigger window, or by applying a geometrical event selection requiring that the hit PMTs are concentrated (indicating the presence of a shower core). The ability to trigger at low multiplicity will greatly increase the area of HAWC below 500 GeV which increases the sensitivity to distant sources and sources with intrinsic cutoffs such as AGNs and GRBs. A new system will be built to trigger on a reduced trigger window and hit geometry [5].

The throughput of the system used in Milagro was limited to about 2 kHz and 6 MB/s which is inadequate for HAWC. Instead, the CAEN V1190A VME TDCs will be used for HAWC because they can handle the increased data rate as well as simultaneous digitization and read-out, eliminating the principal source of dead time. One of these units is been used for the CSU prototype.

3 Results

Individual PMT (NIM) signals from the front-end board were digitized. The high voltage for all of the PMTs was set to 1720 V. An additional fast pulse (generated using the VME front-panel) was fed into the TDC along with the start and stop times from the laser calibration system. The fast pulse (or "heartbeat") consisted of a square wave with a width of 1.6 μs, and a period of 16 μs. During calibration runs, the laser was triggered at a rate of 50 Hz. Signals from the five muon paddles were additionally digitized by the TDC board.

Data were read in a "continuous storage mode," i.e., the module records a time for each signal received with respect to the last reset. The rate of the PMTs was low enough that, rather than using a trigger, every edge was recorded. The readout was initialized to provide a 100 ps resolution for each time stamp. Therefore, the module can accept hits for ≈ 52 μs before the "time" rolls over (19 bits available for recording the time). The double hit resolution was set to 5 ns, the lowest possible.

The rate of PMT pulses crossing threshold can be measured from the solar output on the front-end board. Rates have been monitored since installation and are shown in Fig. 3. This output does not have a high-threshold discriminator applied like the TDC input does. Therefore, the measured rates represent the PMTs seeing signals. (The rates of edges on the TDC output are 10%-20% higher than the solar output.)

A prototype of the scaler DAQ [6] was also successfully tested in the CSU WCD at the end of March, 2011.

4 Conclusions and Outlook

A full size water Cherenkov prototype detector was setup up at Colorado State University, and it is fully operational since March 1, 2001. A preliminary version of the calibration system was installed, and the PMTs can be illuminated with a wide range of light levels. The Milagro front

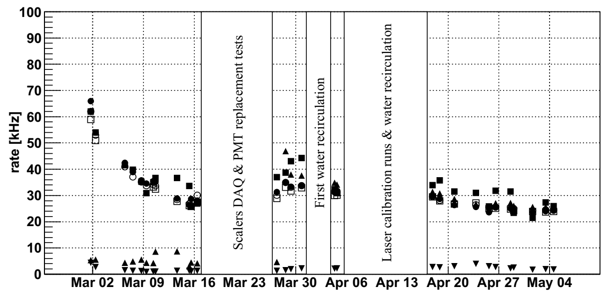

Figure 3: Rates measured in each PMT since deployment.

end boards were also installed, and an early version of the readout software is being used to digitized the edges of the pulses. First tests of the scalers readout were conducted. Data from air showers and the laser calibration have been successfully acquired with this prototype, and the first results are being processed.

It is also possible to search for true correlations due to air-shower events in the prototype data. The search for air-shower data is done by applying a sliding window of up to 150 ns, and measuring the coincidence rate for PMT multiplicities of 5 or more. Given the observed singles rates of ~ 25 kHz, the expected false coincidence rate is less than 10^{-4} Hz. Further analysis will reconcile these results with simulations.

The CSU prototype WCD will continue to serve as a development platform for HAWC. In the near future, new deployment techniques and procedures will be tested. It is in principle also possible to reconstruct muon directions inside the tank using triggers from coincidences of the scintillators (above and below the water volume),

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