Calibration of the HAWC Observatory

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Abstract: The HAWC (High Altitude Water Cherenkov) observatory is a 2^{nd} generation, high-sensitivity gamma ray observatory building on experience from its predecessor, the Milagro observatory. In both observatories, water-cherenkov photons produced by air shower particles are detected and their arrival times at the photo multipliers are used to reconstruct the shower plane and direction. In HAWC, 300 7.3 meter diameter $\times$ 4.5 meter deep water tanks are each filled with water and placed in close proximity ($\sim$1 m separation). Each tank has 3 upward-looking, 8"-diameter PMTs positioned $\sim$0.5 meters from the bottom of the tank. The reconstruction of the initial gamma ray direction is highly dependent on the relative time differences between different tanks and PMT channels. In this paper, a calibration system is presented, modeled on the Milagro calibration system, using a pulsing laser with 300 ps long pulses. Pulses are directed into fiber optic cables, which are split and directed to $1/15^{th}$ of the tanks in the array at a time. For measuring PMT slewing times, neutral density filters will provide a range of laser intensities across 6 orders of magnitude. This system is planned to run autonomously in two different modes, for slow($\sim$5 Hz) laser pulsing at one light intensity, and for fast ($\sim$200 Hz) laser pulsing across several different intensities. We will report on recent studies made in Spring 2011 using the HAWC prototype water Cherenkov detector at Colorado State University to evaluate the performance of the calibration system.

Keywords: Gamma-rays, cosmic rays, water Cherenkov

1 Introduction

The HAWC Observatory, currently under construction in Mexico, represents the second generation of water Cherenkov Gamma-ray experiments, following the footprints of its predecessor, the Milagro Observatory, that was operated in New Mexico (USA) from 2001 and 2008 [1]. Its goal is to measure TeV gamma rays from galactic and extragalactic sources with a large field of view ($\sim$2 sr) and with a duty cycle $\sim$100% [2]. Thanks to these characteristics, HAWC is expected to play an important role in the discovery and study of new TeV sources and the monitoring of transient phenomena.

The water-cherenkov technology, succesfully tested and used by Milagro, underwent two different major upgrades. The observatory site will be at a higher elevation (4100 m above the sea level), in the saddle between Sierra Negra and Pico de Orizaba, at $19° \ N$, $97° \ W$ [3], and the collection area will span approximately $22,000$ m^2. This will place the detector closer to the shower maximum and produce a better sampling of the shower pattern, resulting in a sensitivity of ~ 60mCrab in the first year and an angular resolution from $0.35°$ at 1 TeV to $0.1°$ above 10 TeV [4].

The HAWC Observatory will consist of an array of 300 steel tanks, or Water Cherenkov Detectors (WCD, [5]), closely packed one to each other as shown in Fig.1, filled with countinuously filtered water and instrumented with 3 8" baffled and upward-facing Hamamatsu photo multiplier tubes each, for a total of 900 PMTs. The construction of the instrument will pass through 3 different stages. Following the currently working 7-tanks test array (VAMOS, [6]), in Spring 2012 the first 30 WCDs will be in place (HAWC30), than the 100 and the final 300-WCDs arrays respectively in Summer 2013 and Fall 2014.

2 The Calibration System

A TeV gamma-ray entering the earth atmosphere produces an electromagnetic shower that develops along the original particle direction. The relativistic secondary particles can reach a WCD of the observatory and produce Cherenkov light. The shower plane, and thus the direction of the incoming photon, is reconstructed from the measured arrival

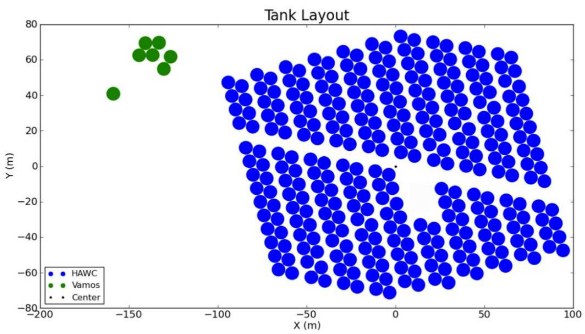

Figure 1: Schematics of the VAMOS test array (in green) and the HAWC300 array (in blue).

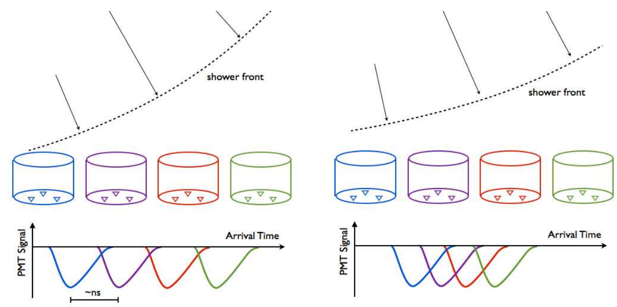

Figure 2: Diagram of two possible showers hitting 4 WCDs in the array. The relative arrival time is used to estimate the direction of the incoming gamma ray.

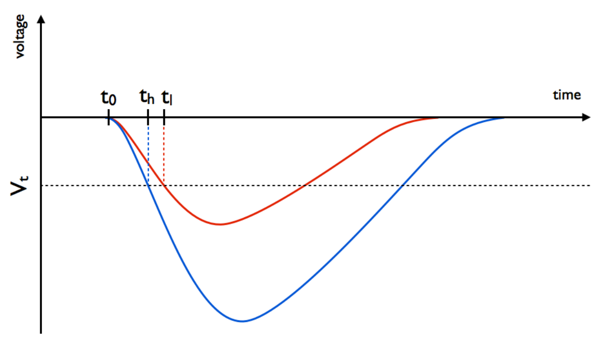

Figure 3: Example of a lower (red) and a higher (blue) TDC voltage pulses beginning at the same time. The slewing time is the gap between t_0 and t_l for the lower signal, and between t_0 and t_h for the higher one. Higher pulses cross the threshold (V_t) before lower ones.

times of the shower particles. In order to reach the performance goal of the observatory ($0.35° - 0.1°$ angular resolution), it is essential to perform a reliable timing calibration of each PMT in the array. Not only the position of each PMT must be known with an accuracy of a few cm, but also the relative hit time (i.e. the time, relative to a given trigger, when the Cherenkov light reaches the PMT) with an accuracy $\leq$1 ns (Figure 2).

To accomplish this, it is necessary to correct the measured hit time from each PMT by the slewing time, namely the gap between the real arrival time of the light to the PMT and the time the signal crosses the electronic threshold. The slewing time depends on the pulse height itself, being shorter for higher intensities (Figure 3).

The PMTs signal will be digitized by CAEN V1190 TDCs and the time over threshold will provide information about the pulse height itself. The time resolution is 100 ps, and the leading and the trailing edges will be recorded, in order to compute the total time the PMT signal is over the threshold (ToT). From the relation between the ToT and the slewing time it will be possible to draw the slewing curves as a function of the light intensity, measured in number of photo electrons, or PEs. The number of PEs are derived employing the occupancy method previously used by Milagro and other experiments [7].

The occupancy is given by $\eta = m/n$, where m is the number of times each PMT measures at least one PE and n is the number of laser pulses. Since the number of produced PEs obeys poissonian statistics, the occupancy can also be expressed as $\eta = 1 - e^{-\lambda}$, where λ is the mean number of observed PEs. The uncertainty on λ, however, diverges when η approaches 1. The low light level measurements ($\lambda \leq 2.5$) will be used to estimate the PE scale in the entire range, by taking advantage of the proportionality between λ and the light transmittance (T) of the filter.

This calibration system will be run in parallel with and independently of the normal data taking operations so that it will not introduce downtime. The system will provide nearly continuously updated parameters for the event reconstruction, as well as monitoring of the performances of each PMT over time. Two different sets of measurement will be taken, an intermediate-intensity continuous mode running at 5 Hz and continuously switching among the 15 regions into which the array will be divided (20 WCDs), and dedicated runs at a higher frequency (200 Hz) scanning through different light levels to provide a full calibration. The light sent into the tanks will be produced by a green laser (Teem Photonics Powerchip, [8]) and a series of 3 neutral density filter wheels will be used to cover a range from 0.1 to $>$1000 PEs.

2.1 Light path

The light produced by the laser will be sent to the first splitter and travel along two different paths (Figure 4). The blue path will be a loop to the tank and back that will be used to monitor the light travel time and give a start/stop signal to the elecronics, the red path will send light to the WCDs. The real light attenuation will be measured by two Laser-Probe RM-3700 radiometers ([9]) with two RjP-465 silicon probes ([10]) positioned before and after the filter wheels.

LOOP BACK PATH (BLUE) – One output of a 1:17 splitter in the blue path will be sent to the first radiometer probe. A second output will send light to a Thorlabs photo sensor ([11]), whose output signal is discriminated to produce the start signal. The remaining outputs of the splitter will send light to 75 200 meter long quadplex optical fibers, each positioned 20 cm underground to reach a subset of 4 WCDs. The loop light will be sent back through another fiber of the quadplex cable to a second Thorlabs sensor to produce the stop signal.

OUTGOING LIGHT PATH (RED) – The other output of the first splitter will pass through a 1×3 beam expander, the filter wheels, and encounter a 1:19 (or a 1:37) splitter. Ten of these outputs will be sent to 10 1:16 switches, while the remaining will be sent to the second radiometer probe to measure the light after the filter wheels. The 15 used outputs of the 10 switches will send light to the WCDs through the quadplex fibers. In this picture each quadplex cable will host the loop back path and two fibers sending light to WCDs. At the end of these fibers, 150 1:2 splitters will send the light into two WCDs, where a light diffuser (1 mm teflon), will shine the light onto the PMTs in the water (see Figure 4).

3 Test of the calibration system and outlook

Performance testing of the laser calibration system is currently underway. Beside efficiency and software stability studies of various components such as the laser, the radiometers, and the optical switches, performed in the laboratory, and diffuser and fiber installation tests with the VAMOS array at the HAWC site in Mexico, complete calibration data sets have been collected with a WCD prototype at Colorado State University [5]. A fully operational calibration system has been deployed at the CSU site, that can be operated remotely, in order to take calibration data and verify the range of light intensities that are measured by the six PMTs in the WCD. Preliminary results are shown in Fig. 5 and Fig. 6. Figure 5 shows the occupancy measured with the six installed PMTs, Figure 6 shows example slewing curves for the central PMT (#1) at intermediate light intensities that produce a voltage signal crossing both high (5 PE) and low (0.25 PE) TDC thresholds. In general, the shapes of the distribution agrees with the expectations from experiences with the Milagro electronics, that also made use of the ToT method. The PE scale has been estimated by fitting the occupancy curve in the low light level regime and extrapolating it to higher intensities. Preliminary studies indicate that the estimated maximum light intensity exceeds the 100,000 PEs, confirming that the current design of the calibration system is capable of delivering more photons than required. More data are currently being collected and more detailed studies will be performed. Results from these will be used in the optimization of the HAWC calibration system, before it will be installed and run at HAWC-30, the first stage of data taking of the HAWC observatory [2].

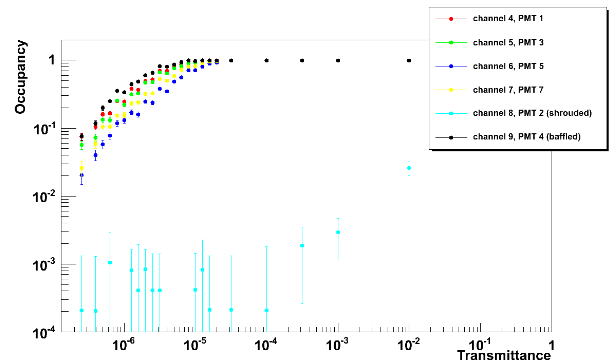

Figure 5: Occupancy curves for 6 different PMTs inside the test tank at CSU as a function of the transmittance. The baffled PMT (#4) sees the most light, even though it is located 8 ft from the tank center (PMT #1 is at the center but it is not baffled).

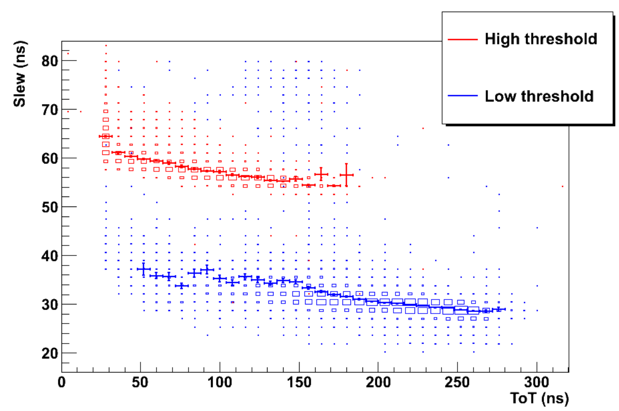

Figure 6: Example of two slewing curves computed for PMT #1 for both the low threshold (0.25 PEs, blue points below) and the high threshold (5 PEs, red points above), obtained for intermediate light levels ($10^{-6} < T < 10^{-3}$). The x axis is the ToT time (ns), the y axis is the time gap between the laser trigger and the PMT signal crossing the threshold (an arbitrary offset of 1220 ns has been subtracted). The high threshold times are delayed by the electronics by 25 ns.

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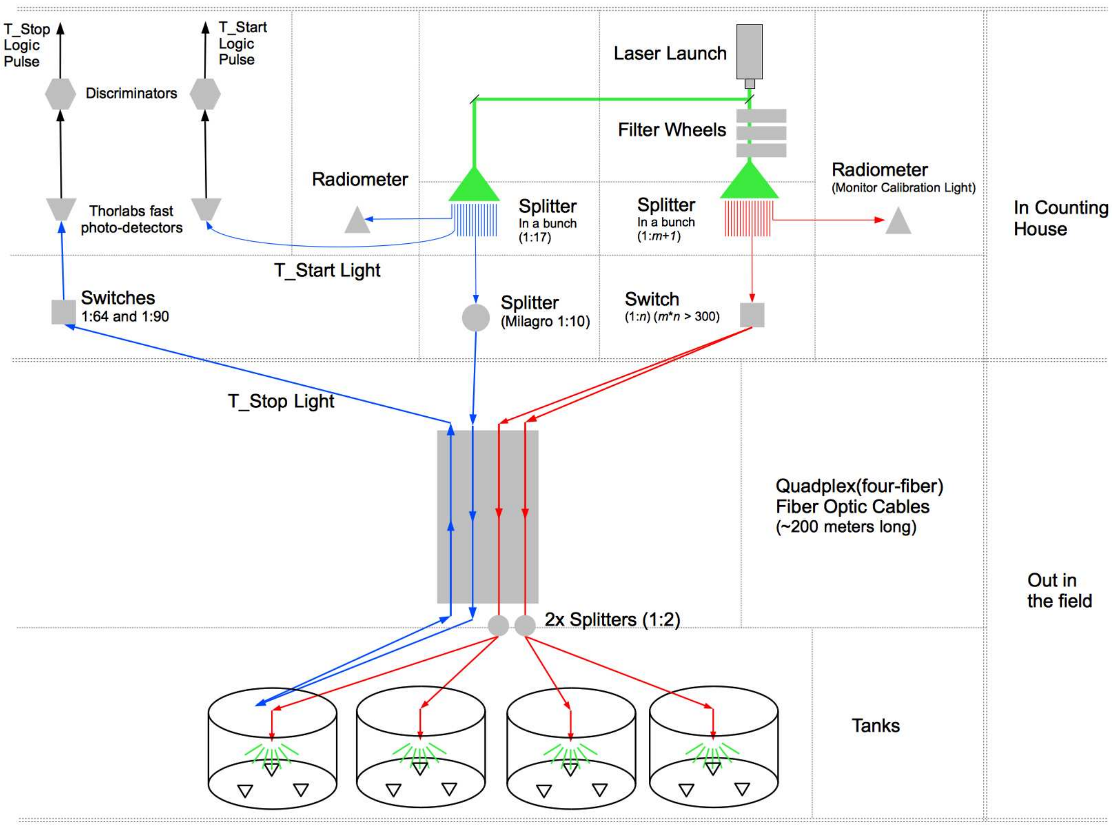

Figure 4: Light path diagram. After the laser the light is split in two and sent to the loop path (in blue) and to the WCD (in red), passing through a series of splitters and swithces and in 200 meters quadplex fibers. The light intensity is measured before and after the filter wheels.

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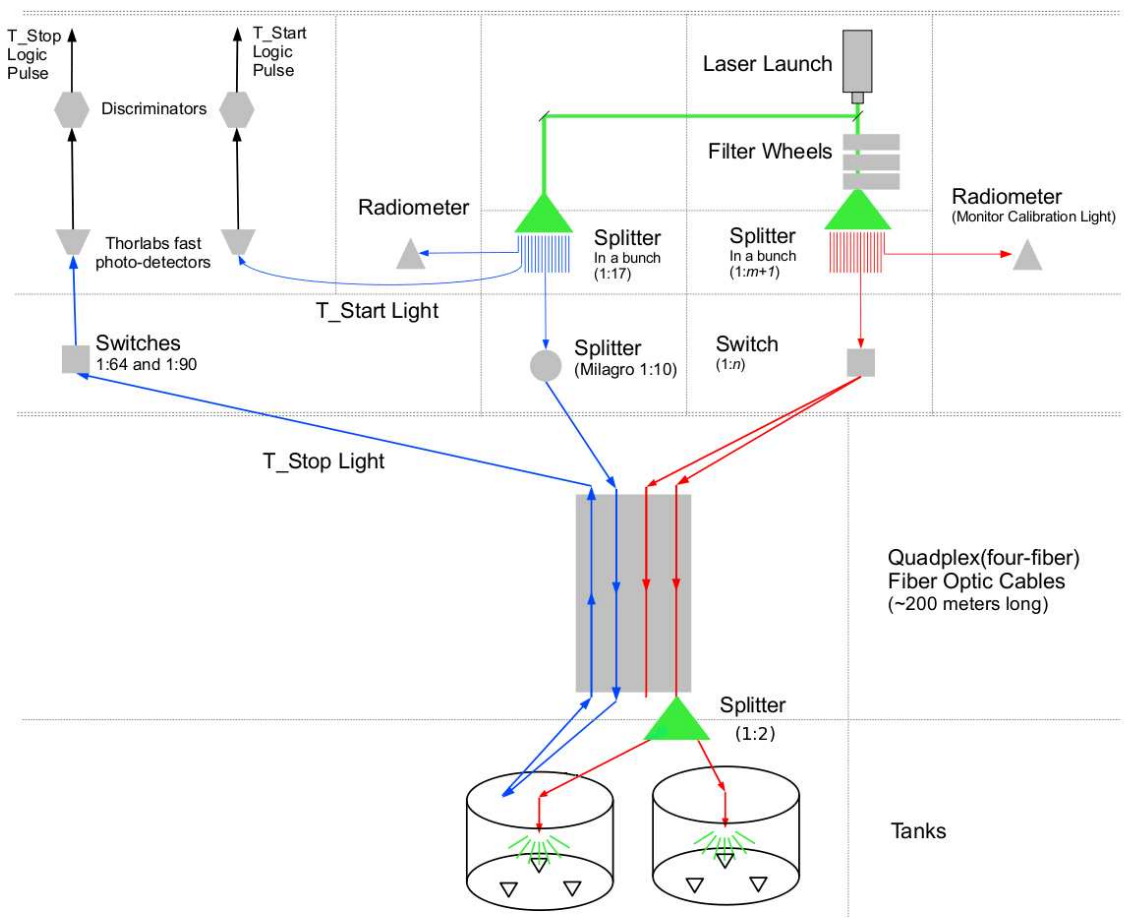

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