Calibration and Reconstruction Performance of the HAWC Observatory

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Abstract: The High Altitude Water Cherenkov (HAWC) experiment is being built at an altitude of 4100 m at Sierra Negra volcano near Puebla, Mexico, to serve as an observatory for gamma-rays with energies between 50 GeV and 100 TeV. Upon completion, the array will consist of 300 water Cherenkov detectors (WCDs) each equipped with four photo-multiplier tubes (PMTs) to detect Cherenkov light from air showers passing through the experiment. For optimal reconstruction of the direction of the shower primaries, in particular to map gamma-ray events, the relative timing of each PMT must be calibrated with nanosecond (ns) precision over the full dynamic range of the PMTs. This is achieved by sending short (300 picoseconds) laser light pulses through a network of optical fibers into every detector. As the laser calibration system provides intensities from < 0.1 photo electrons (PEs) to > 1000 PEs, the charge calibration of all PMTs is also obtained and further improves the angular resolution of gamma-ray event directions. In this contribution, we present the design and performance of the laser calibration system. The improvement of air shower reconstruction due to calibration is verified for an analysis of the shadow that the moon produces in the flux of cosmic rays, based on data collected with a partial array of 30 WCDs.

Keywords: HAWC, gamma ray, calibration, air shower

1 The HAWC Observatory

Gamma-ray astronomy has become a field of rapid progress, with imaging air Cherenkov telescopes and satellites detectors continuing to probe the sky at MeV to TeV energies. In a complimentary approach, the Milagro Observatory [1] has proven that the water Cherenkov technique allows a ground based TeV gamma-ray detector to operate with a high duty cycle and a wide field of view. The HAWC Observatory is being built as Milagro’s successor, based on the same principle but surpassing Milagro’s sensitivity by a factor of 15, see [2], [3], [4] for details. The higher altitude of 4,100 m above sea level at the HAWC site on the Sierra Negra volcano near Puebla, Mexico, improves the low energy response compared to Milagro, widening it to approximately 50 GeV to 100 TeV. HAWC’s modular design comprises a total of 300 WCDs each equipped with three 8-inch PMTs and one central 10-inch PMT. These detectors record the times and multiplicities of Cherenkov photons from high energy particles passing through the array and are used to reconstruct directions and energies of air shower primaries. HAWC has a duty cycle of > 90 % due to its fully enclosed WCD design and thus serves as a powerful instrument to monitor and survey the TeV sky. In September 2012, the first 30 WCDs of HAWC became operational, making it possible to start data taking while construction continues. The experiment will transition smoothly to full scientific operation with 100 WCDs in August 2013 and 300 WCDs in the summer of 2014.

The main data acquisition (DAQ) system is composed of time-to-digital converters (TDCs) with one channel for each PMT. When a photon induced pulse in a PMT crosses the low hardware threshold (~ 0.35 PE) or a high threshold (~ 8 PE), hit times get recorded as TDC counts (10.24 counts = 1 ns) relative to a trigger time. The time-over-threshold (ToT) of a pulse for the low or high threshold old can be converted into charge values, as described in section 3.3.

The calibrated charges of all PMT pulses that are part of an air shower event are used as weights to locate the core of the shower with a Gaussian fit of the charge distribution. This core fit serves as input to a second algorithm, the angle fit, that calculates the curved shower front based on the photon arrival times and thus yields a direction result for the event. The ability to reconstruct this direction of an air shower primary depends crucially on a precise time record for each PMT pulse. Statistical fluctuations introduce an irreducible spread of photon hit times on the order of a few ns around the passing shower front, thereby defining the goal to calibrate the pulse timing to at least this accuracy. The following sections discuss how these charge and timing calibrations are achieved in HAWC with a laser system.

2 The Laser Calibration System

The light source components of the HAWC calibration system were installed between December 2012 and March 2013 in the electronics facility in the center of the array. The calibration system relies on short laser pulses with a width of 300 ps, created with a Teem Photonics laser at a wavelength of 532 nanometers. An optical splitter cube located next to the laser creates a separate return light path, while the primary or light-to-tanks path, leads through a series of three filter wheels. Each of these wheels carries six neutral density filter disks of different absorption strength that can be cycled to attenuate the laser light. Aside from an open and an opaque setting, the range of filter wheel combinations covers optical depths from 0.2 to 8.0.

The primary light-to-tanks path after the filter wheels fans out into optical fibers via Dicon switches that can distribute the light into any of 150 separate channels, with up to 10 channels being illuminated simultaneously. At an
optical patch panel each channel is connected to a splitter that passes the same laser pulses into a pair of long, 170 m optical fibers going out to a connection box near a pair of WCDs. Light from the two outputs is then directed through short fibers into the two WCDs and exits through a Teflon diffuser, hanging from a float 3 m above the central PMT and illuminating all PMTs at the bottom of the tank.

The return light path, splitting off before the filter wheels, triggers a Thorlabs photo diode to generate a start time record for each laser pulse and fans out into 150 separate optical fibers that go out to the connection boxes near each tank pair. Inside each box, the return light path connects to a 30 m fiber, replicating the length of the fiber connection between box and tank, and loops back through another 170 m fiber into the laser room. Here, each channel can be selected individually via a Dicon switch to measure the laser pulse return time with a Hamamatsu photomultiplier tube. The knowledge of these individual time constants of the detector array provides the possibility to monitor even local variations, for example due to temperature dependent expansion or contraction of fibers. A schematic of the laser system layout can be found in [3].

3 Calibration Method

3.1 Data Taking

For a calibration run, the system cycles through a wide range of optical filter wheel combinations that vary the laser intensity over more than 4 orders of magnitude up to several thousand photo electrons (PE). 2000 laser pulses at each intensity setting generate sufficient statistics for charge and slewing calibrations. The laser can be operated with frequencies up to 500 Hz, but initial studies at the HAWC test WCD in Fort Collins, Colorado, US, showed that operation at more than 200 Hz can lead to undesirable intensity variation. Using a frequency of 200 Hz and generating 2000 laser hits per filter wheel setting, a calibration cycle with 63 different intensities takes approximately 15 minutes. This has to be repeated for 15 switch settings, each illuminating up to 10 tank pairs simultaneously. The duration of a calibration run for the whole array will thus be less than 4 hours. Furthermore, these runs do not increase the experiment’s dead time significantly, since data taking is done with the normal TDC DAQ which receives electronic trigger flags for the start time of each laser pulse. Only a window of 10 microseconds (µs) around the PMT response to each laser hit is tagged and excluded for air shower reconstruction. Calibration runs are scheduled on a weekly basis and longterm studies of the calibration stability will show if longer intervals in between are acceptable in future.

3.2 Timing Calibration

The photo diode measurement of the laser pulse start time provides the trigger signal for the DAQ. A separate Berkeley Nucleonics counter stores the time between this start signal and the second signal produced by the light from the return loop. After averaging, half this time difference is a reliable measurement for the time between the calibration trigger and the instance the laser photons reach the diffuser inside the tank. Subtracting this delay and the time for traversing ~ 3 m of water from the response time between trigger and TDC pulse measurement yields the time offset due to electronics for each individual PMT. The correction of these time constants for each pulse time that is part of an air shower event reduces timing mismatches and improves the angle fit of air shower fronts.

While not all fiber connections are installed, an alternative method to obtain time offset corrections without laser signals is used. By reconstructing a large number of air showers, a systematic shift of pulse times relative to the fitted shower front can be calculated for each individual PMT channel. The details and results from this approach are discussed in the separate contribution [6].

The exact relationship between the impact of a photon on the PMT cathode and the subsequent TDC record of an electronic threshold crossing depends also on the pulse shape and its amplitude. A pulse with a higher charge, and therefore larger TDC, has a shorter rise time and thus a reduced intrinsic delay, called slewing, for the TDC time record when compared to a pulse of lower energy. Using the wide intensity range produced in a laser run, the relation between either low threshold or high threshold ToT measurements and the slewing offset can be mapped as a two-dimensional histogram. After subtracting the constant time offset, an empirical fit produces slewing curves for both thresholds for each PMT. In the performance analysis in section 3.3 individual slewing results were not yet available for all active HAWC PMTs. Instead, average low and high threshold slewing curves were used, derived from data collected at the HAWC test WCD. Details and examples of the slewing procedure and results are presented in [6].

3.3 Charge Calibration

In HAWC, following the techniques used in the predecessor Milagro, the charge, and thus the weight, of individual PMT pulses in an air shower event is measured as a ToT signal for two thresholds. Both values have to be calibrated with the laser system. Cycling through 63 different attenuation settings provides a wide laser intensity range that is monitored with a LaserProbe radiometer. It receives light through a splitting cube in the light-to-tanks path and is usually operated in a mode that averages over the 2000 laser pulses at a fixed filter wheel setting. The occupancy η = m/n for each laser intensity setting is obtained by counting the number of TDC responses m in the predetermined coincidence time window after the trigger signal, divided by the number of laser pulses n. The averaged occupancy at a fixed intensity λ in PE is equivalent to the Poisson probability of producing at least a 1 PE pulse, η = 1 − exp(−λ). By substituting λ = a · ri/τn, the measured occupancies are expressed as a function of the laser radiometer measurements ri, normalized by an arbitrary value τn. A fit of the occupancies to low intensities ≤∼ 2 PE is performed to obtain the a parameter, avoiding the regime where the uncertainty on λ diverges.

The conversion factor a can then be used to translate any relative radiometer measurement into a mean PE intensity λ. A Poisson distribution for each such λ, smeared with the energy resolution of the PMTs, produces an expected distribution of numbers of PE (nPE) that can be matched with quantities of a histogram of the TDC ToT measurements at that intensity. For either the low or the high threshold response, all these nPE-ToT pairs are merged together in profile histograms and fitted with an empirical function. Using the calibration data from cycling through the full intensity spectrum of < 0.1 PE to > 1000 PE (exact values are channel dependent) thus yields individual low and high threshold charge calibration curves for each PMT.

The fitted ToT-PE conversions are applied analytically to every PMT pulse that is part of a triggered air shower event.
to provide the calibrated charge as an accurate weight for the reconstruction algorithms. Whenever a pulse crosses the high threshold, the corresponding ToT is the more reliable charge estimator and is used instead of the low threshold ToT. All PMTs were characterized before installation at the site and are grouped in batches with voltages chosen to produce approximately the same gain of $1.4 \cdot 10^7$. This procedure also results in charge calibration curves that are generally well aligned when comparing individual PMTs, see Fig. 1 for some examples. This similarity allows for use of an average charge calibration curve, derived from data collected at the HAWC WCD test site, that will be replaced with individual curves when the completion of the optical fiber network allows for a calibration of all PMTs at the HAWC site. The average charge calibration was used for the performance analysis shown in section 4.

4 Calibration Performance

The first data collected with 30 HAWC WCDs has limited sensitivity and statistics for gamma ray observations, but a verification of the calibration performance can be achieved by mapping air shower event directions, dominated by charged primary particles, around the position of the moon. The moon blocks these cosmic rays and produces a deficit. A detailed analysis of this observation is presented in [7]. Here, a qualitative comparison of the position and shape of the moon shadow deficit for data from 30 HAWC WCDs with different processing conditions highlights the improvement of event reconstruction through laser calibration. A subset of data collected with the partial HAWC array between September and December 2012 with a total live time of 24.8 days was processed with four different calibration settings:

(a) All charges set to 1 PE and no timing calibration;
(b) Charge calibration applied with average curve;
(c) Timing calibration applied with average slewing curve and individual shower residual offsets, all charges set to 1 PE;
(d) Charge calibration as in (b) and timing calibration as in (c) applied.

For these data sets, all air shower events were reconstructed. Besides requiring that the angle fit succeeded, the only cut applied to the results was removing events with less than 32 PMT channels participating, to exclude low energy showers that reduce the deficit significance. To correct for a known inaccuracy in the survey of PMT positions, an overall shift was applied to all direction results, chosen in such a way that the maximum of the angular shower distribution realigns with the local zenith. A check was performed to confirm that this correction slightly increases the deficit significance but does not strongly affect the shape of the moon shadow in any of the four cases. The results for the four cases are shown in Fig. 2 as maps of binned statistical significances with a radial smoothing of 3° applied. In the first map (a), no unambiguous moon shadow is visible and no deficit with a significance of at least $-5.0 \sigma$ can be found. After applying only the charge calibration (b), a deficit (peak significance $-5.0 \sigma$) is visible but is both of irregular shape and offset from the moon position by several degrees. Fig. 2(c) shows that using only the timing calibration and no charge calibration deepens the deficit only slightly ($-5.1 \sigma$) but produces a clearer image of the moon shadow closer to the actual location. This was expected due to the importance of individual pulse times for fitting the shower front. The final comparison with the map (d) in which both charge and timing calibrations are applied reveals a much more pronounced deficit ($-6.4 \sigma$) and a more symmetric and well centered moon shadow. Counting events over the full sky coverage, the last map contains $\sim 1.1 \cdot 10^9$ events and thus $\sim 3 \cdot 10^8$ more than those maps from cases (a), (b) and (c), due to the fact that more shower angle fits are successful when full calibrations are used.

5 Conclusions

The main components of the HAWC laser calibration system are installed and operational and calibration runs can be performed without significantly reducing the array’s dead time. The experience gained from a WCD test setup and systematic time residuals derived from shower fits made it possible to calibrate early HAWC data even before calibration results for all individual PMT channels are available. Both charge and timing calibrations significantly im-
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**Figure 2**: Significance maps of air shower event directions centered on the position of the moon, with $\alpha = \text{event right ascension (RA)} - \text{moon RA} + 180^\circ$ and $\delta = \text{event declination} - \text{moon declination}$. Map (a) is based on reconstructions with all pulse charges set to 1 PE and no timing calibration, map (b) has only charge calibrations included, map (c) has slewing and time residual calibrations applied but all charges are 1 PE, and map (d) was produced with full charge and timing calibrations included.

prove air shower reconstruction as is shown here based on the mapping of the moon shadow deficit for a subset of early HAWC data. The optical fiber network will continue to grow with the HAWC array and provides the means for regular calibrations of all PMTs to guarantee a strong and stable performance in gamma-ray observations.

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**References**

[7] D. Fiorino et al. (HAWC Collaboration), these proc.