Measurement of the Response of Water Cherenkov Detectors to Secondary Cosmic-Ray Particles in the HAWC Engineering Array Using a Fast Custom-Made DAQ System

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Abstract. **The High Altitude Water Cherenkov (HAWC) Observatory is under construction in Sierra Negra, Mexico, at 4100 m.a.s.l. It will be dedicated to the study of high-energy gamma and cosmic rays. A prototype array for HAWC is under construction in the same site but at 4550 m.a.s.l.; it consists of 3 cylindrical Water Cherenkov detector prototypes, with a diameter of 3m and filled with water up to 3.6m above the PMT. We have built a custom-made data acquisition (DAQ) system to sample the PMT signals from these detectors at 200 MS/s to evaluate their performance. We present measurements of the amplitude and charge spectra for one of these detectors. We also discuss a general method to calibrate these detectors around the energies of vertical muons and Michel electrons. We briefly discuss the benefits of sampling at 200 MS/s compared to slower sampling options and provide details of the cost/channel of this system.**

***Keywords*: Water Cherenkov detectors; fast custom-made electronics; HAWC Observatory**

I. Introduction

The HAWC (High Altitude Water Cherenkov) observatory is under construction by a collaboration of scientists from the US and Mexico at the Sierra Negra site, in Mexico, at an altitude of 4100m. It will make use of a compact array of water Cherenkov detectors (WCDs) to survey the sky in search of steady and transient gamma-ray sources in the 0.1-100 TeV energy range. The HAWC Observatory will reuse PMTs and electronics from the Milagro gamma-Ray Observatory [1]. The baseline design for the HAWC Observatory is described elsewhere in these proceedings.

A prototype array for the HAWC Observatory consisting of 3 Water Cherenkov detector prototypes, with a diameter of 3m and filled with purified water up to a height of 3.6m above the PMT, was built in the same site but at 4550 m.a.s.l. We have built a custom-made DAQ system to sample the PMT signals from these detectors at 200 MS/s to evaluate their performance.

The baseline design of the readout electronics for HAWC is based on VME modules. The electronics we present in this paper represents a low-power (about 5W) option of a portable, fast and easy-to-operate readout system that can be used along with a more powerful VME-based system during the construction phase of HAWC to test individual detectors.

II. Description of the DAQ Hardware

The fast DAQ system we built, see the schematic diagram shown in Fig. 1, consists of an FPGA mother board (Digilent D2FT), a 200 MS/s ADC daughter board, a RS-232 port (Digilent PModRS232), a GPS receiver (Motorola Oncore UT+) and a high-precision pressure sensor (Futurlec HP03D module). This system operates on a single 5V battery.

The hardware connects to a laptop PC using an RS232 link which can be a USB-serial cable adapter or a Bluetooth wireless serial port adapter (WCSC Bluetooth RS232), either of these two options is used at a communication baud rate of 230.4 or 115.2 Kbaud. The FPGA mother board consists of an FPGA (Xilinx XC2S300E) with 300K gates, a 2MB configuration Flash ROM (18V02), a 50MHz oscillator, a JTAG programming port, 172 user I/Os routed to six standard 40-pin expansion connectors and a 5V power supply.

The ADC daughter board uses an operational amplifier to set the input impedance equal to 50Ω and to invert and shape the PMT signal. This daughter board has two 10-bit ADC chips (Analog Devices AD9214). The maximum voltage we can digitize with this system is 2.048V, i.e., 1024 ADC counts with 1 ADC count being equal to 2mV. Each of the two ADCs runs at 100MHz, one clocked with the rising edge and the other with the falling edge of a 100MHz clock, to provide an effective sampling rate of 200 MS/s. The 100MHz signal used to clock the two ADCs is obtained by doubling the 50MHz

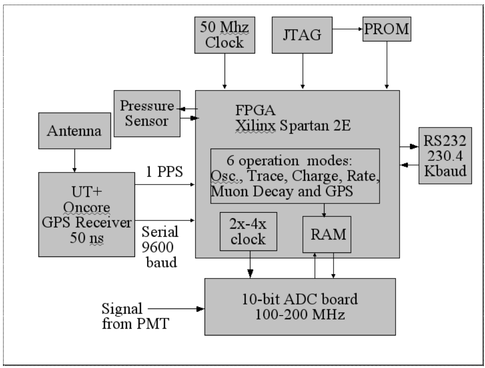

Fig. 1. Schematic diagram of the DAQ hardware.

clock signal from the mother board using one of the 4 FPGA's phase-locked loop circuits.

The GPS receiver we use provides one pulse per second (1PPS) into the FPGA. It also has a position-hold mode to maximize the 1PPS accuracy to 50ns and a Time RAIM (Time Receiver Autonomous Integrity Monitoring) option to allow detection and isolation of satellites that could introduce timing errors. In addition to using the 1PPS signal to discipline internal FPGA clocks that give rise to precise time labels, the PFGA captures the GPS information every second by using the Motorola binary format at 9600 baud and stores the relevant information on internal registers. The GPS receiver takes its 5V operation voltage from the FPGA board.

The pressure-sensor module interfaces with the FPGA by using a standard I^2C interface. The temperature and pressure sensors contained in this module make use of 11 calibration constants to convert the uncompensated temperature and pressure measurements into temperature and atmospheric pressure with accuracies of 0.8°C and 0.5hPa, respectively. This module takes its 3.3V operation voltage from the FPGA mother board.

We are working on the incorporation of time-to-digital converters (TDC) into our electronics to make it more compatible with the requirements of HAWC.

III. Description of the DAQ Software

The bitstream firmware of the DAQ system resides permanently on the Flash PROM chip located on the mother board and it gets downloaded into the FPGA upon power on. The firmware was written using hardware description language (VHDL). On the PC side we use Perl and Python under Linux to process, store and display the data acquired. We use ROOT to histogram and analyze the data.

The transfer rate of data between the FPGA and the PC can be selected as 230.4 or 115.4 Kbaud through the serial port. We are migrating our PC-FPGA communications link to USB 2.0 to profit from the much higher, up to 480 Mb/s, transfer rates. The present version of the firmware includes the following modes of operation: Oscilloscope mode, Waveform mode, Charge mode, Rate mode, Muon-Decay mode and GPS mode. We describe these modes in some detail in the next subsections.

A. Oscilloscope Mode

This mode is used to display on-line the digitized waveforms on the PC monitor. A custom-made graphical user interface is used to set the trigger threshold of the ADCs and the vertical scale on the display. Waveforms satisfying the threshold condition are displayed at a rate of about 2Hz. The horizontal trigger position is fixed at 80ns and the length of the waveforms is fixed at 310ns.

B. Waveform Mode

In this mode of operation the DAQ system sends digitized waveforms whenever they satisfy the trigger condition, i.e., the digitized amplitude exceeds a simple threshold. The width of the waveforms is fixed at 310ns each. The FPGA also sends the maximum amplitude and the sum of the first 30 points along with each digitized waveform.

Since each ADC value is 2 byte long, the total length of each digitized waveform is 64 bytes. When we operate the serial communication link between the PC and the FPGA at 230.4 Kbaud, the maximum data transfer rate we get is about 160 full waveforms per second (using 11 clock periods to transfer each byte). Unlike the Oscilloscope mode, in this mode the PC stores the digitized waveforms on a file for off-line analysis and display.

C. Charge Mode

This mode is similar to the except that the FPGA sends only the maximum and the sum of the first 30 points digitized out of the input signal for each of the two ADCs, i.e., 4 bytes for each event. Therefore, the maximum trigger rate that our system can handle is 32 faster than in the Waveform mode, i.e., about 5000 events/s.

D. Rate Mode

This mode is tailored to the search of gamma-ray bursts using the single-particle technique [2]. The FPGA measures the number of pulses with amplitudes above four thresholds in 5ms time intervals and sends these numbers to the PC along with GPS time tags. In this mode the system also measures, and sends to the PC, the values of atmospheric pressure and temperature every minute. Fig. 2 shows the rates measured in one of the first HAWC WCD prototypes at 4 thresholds set at 18, 28, 68 and 108 mV above the baseline.

E. Muon-Decay Mode

The trigger signal in this mode occurs whenever there are two consecutive pulses above threshold in a 20μs time window. The FPGA sends the time-over-threshold of the two pulses and the time between the two pulses, both of them measured with a granularity of 10ns.

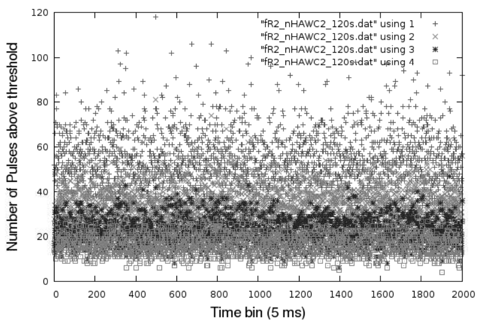

Fig. 2. Rates measured with the first HAWC WCD prototype as taken with our DAQ system. The four thresholds were set at 18, 28, 68 and 108 mV above the baseline. The Y axis shows the number of pulses above each threshold for the 5ms intervals shown on the X axis.

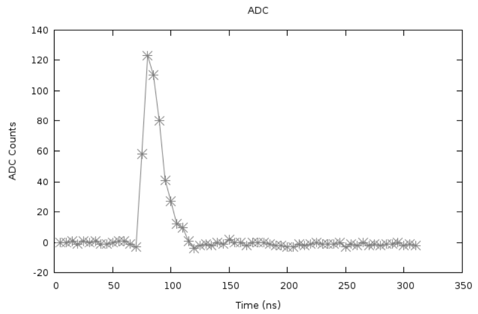

Fig. 3. Typical waveform from the first HAWC WCD prototype as sampled with our system at 200 MS/s. The pulse shape is widened by the shaper of the ADC module. Each ADC count is equal to 2mV.

This mode can be used to calibrate WCDs at low energies using the characteristic Michel spectrum of decay electrons [3] which has a sharp endpoint at about 53 MeV. Michel electrons have a range lower than 20cm so most of them will be fully contained in the detector volume. In addition, counting the rate of muons decaying in the water volume of our WCDs can be used to measure the intensity at low energies of muons associated to cosmic-ray showers. The firmware of our DAQ system would require a slight modification to allow the use of the present Muon-Decay mode in conjunction with extensive air-shower (EAS) triggers.

F. GPS mode

This mode is used to display all the relevant GPS information (time, position, number of visible satellites, etc.) and it also allows the PC to change some of the GPS receiver options (position-hold parameters, set TRAIM mode, etc.). The FPGA controls the GPS receiver and redirects all the data from the GPS receiver into the PC at 9600 baud.

IV. MEASUREMENTS OF PMT SIGNALS FROM HAWC

In this section we present data taken with the first HAWC detector prototype with the DAQ system at a sampling rate of 200 MS/s and a serial communication rate of 115.2 Kbaud. We used an inclusive amplitude-over-threshold. This detector prototype had an 8" PMT

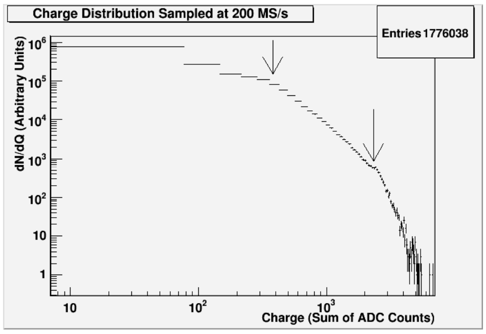

Fig. 4. Charge distribution of inclusive amplitude-over-threshold signals measured with the first HAWC WCD prototype with our DAQ system at a sampling rate of 200 MS/s.

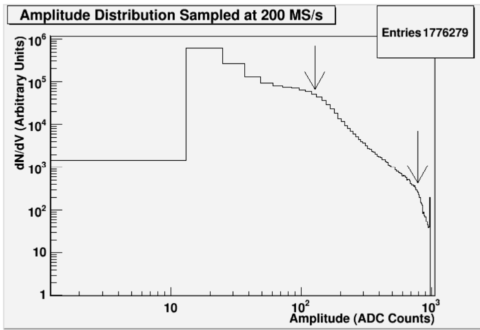

Fig. 5. Amplitude distribution of inclusive amplitude-over-threshold signals measured with the first HAWC WCD prototype with our DAQ system at a sampling rate of 200 MS/s. Each ADC count is equal to 2mV.

(Hamamatsu R5912) anchored 0.2m from the bottom facing upwards; the data shown correspond to a PMT high voltage of 1600V. Fig. 3 shows a typical waveform for this detector with a FWHM of 15ns. The amplitude is given in ADC counts (1 ADC count equals 2mV) with the baseline signal level subtracted. Note that our ADC module has a signal shaper that widens the pulse; otherwise, the unshaped pulse would be too narrow to be sampled in our dual 100MHz system.

Figs. 4, 5 and 6 show the charge distribution, amplitude distribution and amplitude vs charge, respectively, of the same data. The charge is given as the sum of the 60 baseline-subtracted digitized values of the waveforms (corresponding to a time window of 300ns per pulse). The arrow on Fig. 6 indicates the position of the knee-like structural features on the charge and amplitude distributions shown by the right-side arrow in Fig. 4 and Fig. 5.

In previous work with smaller WCDs [4] we have used scintillation hodoscopes to trigger on vertical muons with the result that their signals are about 5% lower than the knee-like change on slope indicated by the left-side arrows shown in Figs. 4 and 5. Therefore we can expect the signal of vertical muons to have charge and amplitude values near the left-side arrows in Fig. 4 and Fig. 5, respectively.

The strong correlation between the signal of vertical equivalent muons (VEM) with the location of the charac-

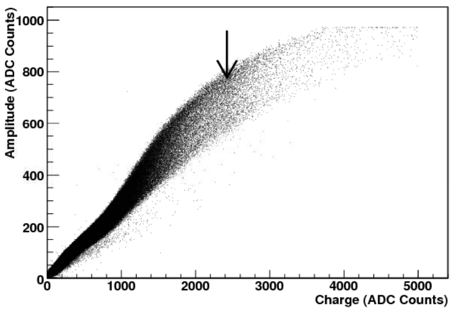

Fig. 6. Amplitude vs charge of inclusive amplitude-over-threshold signals measured with the first HAWC WCD prototype at a sampling rate of 200 MS/s. The arrow shows the position corresponding to the right-side arrows shown in Fig. 4 and Fig. 5.

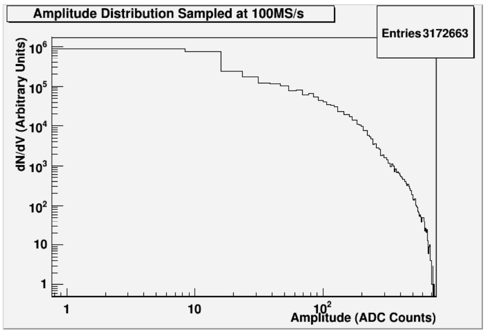

Fig. 7. Amplitude distribution of inclusive amplitude-over-threshold signals measured with the first HAWC WCD prototype with our DAQ system at a sampling rate of 100 MS/s. Each ADC count is equal to 2mV.

teristic knee-like structure shown by the left-side arrows in Fig. 4 and Fig. 5 plays a very important practical role in the calibration procedure of our detectors and in the HAWC operation cycle, i.e., we can calibrate constantly our detectors without the need of special calibration runs. One would expect that the smearing effect on the charge and amplitude caused by a lower sampling rate might smear out the sharp knee-like structures of the charge and amplitude distributions. Fig. 7 shows the amplitude spectrum obtained with our DAQ system at a samplig rate of 100 MS/s; the changes in slope are, as expected, not as sharply localized as when we sample at 200 MS/s, see Fig. 5 to make a direct comparison of the effect of sampling at the lower rate.

We know, from previous work with smaller WCDs [5], [6], that the ratio charge/amplitude can replace the rise-time of the pulses, which our electronics does not measure directly , although we plan to incorporate this feature as a firmware update in the near future.

Fig. 8 shows the presence of distinct fast and slower groups of events in our data. The slow signals (the group of events curving to the right in Fig. 8) occur for amplitudes in the 100-250 range in units of ADC counts (200-500mV) whereas faster signals (the group of points curving to the left in Fig. 8) occur for amplitudes between 500mV and 1200mv. A careful examination of Fig. 5 shows that the previous effect also manifests

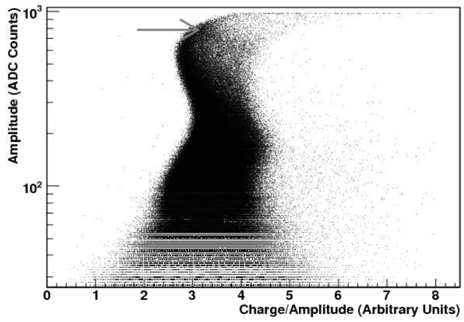

Fig. 8. Amplitude vs charge/amplitude of inclusive amplitude-over-threshold signals measured with the first HAWC WCD prototype at a sampling rate of 200 MS/s. The arrow shows the position corresponding to the right-side arrows shown in Fig. 4 and Fig. 5.

itself in the slightly different slopes of the amplitude distribution in the same region. Further measurements and comparisons with MC simulations will allow us to fully understand this effect on the PMT signals of inclined muons.

V. Conclusion

We have described the hardware and software of a fast custom-made DAQ system based on an FPGA mother board, an ADC daughter board with a 10-bit dynamic range, a GPS receiver and a pressure and temperature sensor. We have presented and analyzed data taken with the first WCD prototype of the HAWC Observatory. These data were taken at sampling rates of 200 and 100 MS/s using an inclusive amplitude-over-threshold trigger. We have also described a general method to calibrate our WCDs at two energies, one around the signal level of vertical muons and the other around the smaller signals of Michel electrons. If we implement our system on PCBs of 3 channels, the cost per channel would be around 35 USD. We are updating our system to use a USB 2.0 port on the PC and to incorporate time-to-digital converters (TDC) into our electronics to make it more compatible with the requirements of HAWC. We will also incorporate the ability to compute the rise-time of the signals directly in the FPGA.

VI. ACKNOWLEDGEMENTS

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References

[1] AIP Conf.Proc.*510*:642-645, 2004.
[2] H. Salazar et al, AIP Conf.Proc.*857*:259-267, 2006.
[3] P. Allison et al., 29th International Cosmic Ray Conference Pune *8*, 299-302, 2005.
[4] M.Alarcon et al., Nucl.Instrum.Meth. *A420*:39-47, 1999.
[5] Y. Jeronimo, H. Salazar, C. Vargas and L. Villasenor, AIP Conf. Proceedings Volumen *670*:479-486, 2003.
[6] H. Salazar and L. Villasenor, Nucl.Instrum.Meth.*A553*:295-298, 2005.