Calibration of water Čerenkov detectors for ultraenergetic cosmic rays

L. Villaseñor

Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Apdo. Postal 2-82, Morelia, Mich., 58040, México

Abstract. A water Čerenkov detector (WCD) prototype of reduced dimensions (cylinder 1.54 m diameter filled with purified water up to a height of 1.2 m) was used to obtain experimental results that validate the concept of remote calibration and monitoring of WCDs based on the use of muons that stop and decay inside the WCD and, in a complementary way, muons that cross the detector. Three clear peaks of PMT charge distributions have been identified which are useful for remote calibration and monitoring of WCDs: one for stopping muons, one for decay electrons and one for crossing muons. This method can be applied to unsegmented as well as segmented detectors.

INTRODUCTION

The Pierre Auger Observatory (PAO) will study cosmic rays reaching the earth with energies above $10^{19}$ eV [1]. The main purpose of the Auger Project is to study the origin and nature of these cosmic rays by measuring their energy spectra, their arrival direction and their composition. These cosmic rays carry macroscopic energies on microscopic particles and their acceleration mechanism remains as one of the biggest and oldest mysteries in astrophysics. Charged cosmic rays of these extreme energies are constrained to travel distances shorter than about 100 Mpc by the GZK effect [2,3]; as a consequence, their trajectories are deflected less or of the order of a few degrees in the typical intergalactic magnetic fields of a few nanogauss; therefore, their arrival direction provides important information about their source location in the sky. Besides the surface detector, each of the two sites of the PAO will have three fluorescence eyes to measure the longitudinal development of air shower cascades on clear and moonless nights. Both techniques of the hybrid Observatory have been tested extensively in previous detectors: the surface detector system at the Haverah Park [4] detector, and the fluorescence technique at the Fly’s Eye [5].

The Auger WCDs will consist of 10 $m^2$ cross section cylindrical tanks filled with purified water up to a height of 1.2 m; each tank will have with three 8" PMTs looking downwards at the top of the water surface. The detector stations will be
instrumented via solar panels. The three PMT's collect the Čerenkov light emitted
by particles in the shower front as they cross the tanks with speeds higher than the
speed of light in water. Front-end electronics will record the waveforms of each of
the three PMT pulses for trigger processing; eventually it will relay the data to a
communication system that will send it to a central station for further processing
[1].

For a surface array as big as the PAO’s, or any other planned in the future, it
is indispensable that the initial calibration and the continuous monitoring of each
WCD be done in a remote way. In the present paper we present experimental results
that validate a novel technique to perform these tasks, it is based on the secondary
cosmic ray radiation which has a typical flux of 250 muons/m²s at sea level [6]. The
low-energy component of these muons, with energies up to about 300 MeV, stop
and decay inside the detectors. The corresponding events are characterized by two
consecutive PMT pulses separated by a time interval distributed exponentially with
a decay constant of about 2 µs. The event trigger requires the coincidence of two
consecutive PMT pulses within a time window of 25.6 µs. The signal associated
to data collected this way is muon decays, where the first pulse corresponds to the
stopping muon, and the second to the decay electron. The background consists
of random coincidences of PMT pulses which include PMT noise and PMT after
pulses. This muon-decay technique can be complemented with the one based on
"lonely muons" crossing the detector, i.e., PMT pulses followed by no further PMT
activity in a time window of 25.6 µs.

It is useful to take the Čerenkov signal from muons crossing the detector near
vertically as a reference point. The mean values of the charge distributions of decay
electrons, as well as stopping and crossing muons are correlated with the mean value
of the charge distribution of muons crossing the detector vertically; the latter are
selected with a trigger given by the coincidence of signals from two scintillation
counters, one placed above and the other below the prototype WCD. A technique
based on inclusive muon signals is discussed in [7]. At present it is still debated
whether the Auger WCD’s should or should not be segmented into three isolated
sections each read out by a single PMT to improve the e/µ separation capability
of the surface system [8]. One advantage of the methods presented here is that
they apply equally well to segmented and unsegmented tanks, with the additional
handle in the case of unsegmented tanks of using coincidental pulses in the PMTs
to reduce PMT noise.

**EXPERIMENTAL SETUP**

The WCD we use consists of a reduced-size prototype made of a polyethylene
cylinder 1.54 m diameter, white on the inside and black on the outside wall, filled
with commercially purified water up to a height of 1.2 m. The inner surface of the
tank was covered with a highly reflective tyvek sheet (reflectivity of about 90% in
the ultraviolet region of the EM spectrum) cut to the cylindrical shape and kept
in place by circular PVC hoses tightly stretched against the inner walls of the tank [9].

Two slightly different experimental setups were used for this work: one for collecting muons decaying inside the detector and the other for collecting muons traversing the detector vertically. The main difference between them is the way the trigger is done. In the first case the trigger is produced by the occurrence of two consecutive pulses at the tank PMT within a time window of 25.6 $\mu$s. The trigger for the second case is simply given by the time coincidence of the PMT pulses from two scintillation hodoscopes placed vertically, one above and the other below the tank. A single Hamamatsu 8" R1408 PMT looking downwards was located at the center of the tank with the PMT slightly immersed in the water. The PMT signal was transmitted via RG58 coaxial cable to a digital oscilloscope, Tektronix TDS220, and to a commercial NIM [10] discriminator module. The dimensions of the scintillation counters were 20x40 cm$^2$ and the discrimination threshold of their PMT's was -30 mV. A 1" slab of steel was placed between the bottom of the tank and the lower hodoscope in order to harden the energy spectrum of the triggering muons. The high voltage of the PMT was 1.38 kV, providing a single-pulse rate of 800 Hz for the 1.86 m$^2$ WCD, i.e., 430 Hz/m$^2$. A custom-made CAMAC [11] TDC module was used to measure the time interval between consecutive pulses coming out of the discriminator. The CAMAC controller used was the LeCroy 8901; it was connected to a National Instruments GPIB port on a pentium PC running at 133 MHz. The DAQ program was written in LabView, which is a graphic programming package from National Instruments.

The time interval between consecutive pulses and the waveform of the PMT signal for a time interval of about 22 $\mu$s prior to and including the second pulse were written to hard disk for about 25 000 events. The second pulse occurring inside a time window of 25.6 $\mu$s after the first pulse is used to trigger the DAQ by means of a 10 bit counter fed by a 40 MHz clock in the muon module. The waveform was digitized using the digital scope with a sampling period of 10 ns. The integrated charge and the amplitude of the PMT pulses were obtained offline from the recorded waveform for every event. The analysis was carried out by using PAW [12].

RESULTS AND DISCUSSION

After using a number of cuts, we found out that the cut that most efficiently filters out the structure in the time distribution of pairs of consecutive pulses coming out of the PMT, leaving a clear exponential distribution with a decay constant compatible with the muon lifetime, and with the lowest value for the $\chi^2$ over number of degrees of freedom for the fit, is the one that requires that the integrated charge of the second pulse be greater than the integrated charge of the first pulse.

By comparing the peak position for the charge distribution of the decay electron with the peak position for the charge distribution of muons crossing the WCD
vertically which turned out to be 250 pC, we conclude that the average Čerenkov light radiated by the decay electron is 0.18 times the Čerenkov signal coming from muons crossing the WCD vertically. The rate of raw data events was measured by reducing the processing time of each event so as to render a DAQ system with no dead time; it turned out to be 50 Hz. Therefore the rate of events that pass the final selection cuts is about 4 Hz. By extrapolating this number to a full-size WCD of 10 m² we expect a rate of muon decay events useful for calibration and monitoring of about 20 Hz. The average Čerenkov signal produced by a stopping muon is 0.70 times that produced by a decay electron or equivalently 0.12 times that produced by an average vertical muon. Additional information can be found somewhere else [13,14].

CONCLUSIONS

We have demonstrated experimentally that the "muon-decay trigger", characterized by the cuts: \( C_2 > C_1 \) and time between two consecutive pulses < 8 µs, selects stopping-muon events useful for remote calibration and monitoring of WCDs. The muon-decay trigger as described in this paper has already been incorporated to the trigger hierarchy of the front-end electronics for the Auger WCD's [15].

REFERENCES

2. Greisen, K., Phys. Rev Letters 16, 748 (1965)