Auger project technical note — Geometrical design studies for water Čerenkov detectors via simulation

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April 26, 1996

Abstract

A reasonably sophisticated Monte Carlo simulation of the interaction of airshower particles with a Water Čerenkov detector has been implemented. Here it is used to investigate two key parameters of such a detector — vertical depth, and lateral size. Firstly it is shown that 1.2 m depth is close to optimal when maximizing the photoelectron yield per penetrating muon for a 10 m^2 tank. Secondly the fraction of penetrating muons which have a long in-detector track length is calculated for several tank geometries at increasing zenith angle of incidence.

1 Introduction

The Auger Project Design Report [1] calls for two surface arrays of ≈ 1000 water Čerenkov detector units each, arranged in a hexagonal grid with spacing of 1.5 km. In the reference design each unit is a cylindrical tank of radius 1.8 m and depth of 1.2 m, lined with a highly reflective material, completely filled with water and viewed downwards from above by three large (200 mm diameter) photomultiplier tubes (arranged in a circle of radius 1.2 m). Although this arrangement is believed to be sensible systematic geometrical design studies have not previously been carried out.

During the Design Study Group hosted at Fermilab during the first half of 1996 a system of computer codes was developed by the author to simulate the response of a complete ground array of water Čerenkov detectors to incident EAS. This takes as input results from the Michael Hillas airshower simulation program MOCCA, and produces simulated experimental event data as output, attempting to account for all limitations of practical water tanks and electronics. The data can then be analyzed in an identical manner to that which would be used for real data, and hence the performance of given experimental configurations assessed. Details regarding the procedures and modeling used in these simulation programs can be found in [2] and will not be further discussed here. The detector simulation element of the system can also be used independently to make simple studies of the tank geometry; results of some work in this direction are presented in this paper.

2 Optimal tank depth

To maintain proportionality of Čerenkov light released (energy deposited) to signal output observed it is important that direct radiation onto the PMT photocathodes is minimized [2, section 5.4]. In the simplest scenario this dictates that the tubes be placed on the top surface of the tank viewing vertically down, and suggests the use of plane faced devices. Given the above, and holding the tank radius and photocathode area constant, the photoelectron yield for a vertical penetrating muon is a function of the assumed tank depth.

To investigate this effect in a quantitative manner batches of 1000×1 GeV vertical muons were injected into the simulated detector for tank depths from 0.2 m to 2.0 m, in 0.2 m increments (each muon at a random position on the top surface). The simulation program tracks each particle through the detector volume, radiating Čerenkov photons, and ray tracing each photon until it is absorbed on reflection, in the water, or at a PMT. The assumed detector and material parameters in these runs were as follows:

- Tank radius 1.8 m, with 3×200 mm diameter plane faced PMTs arranged in a circle of radius 1.2 m flush with the detector top surface.
- Tank completely full of water (refractive index $n = 1.33$).
- Lining material reflectivity 85% (10% spectral component).

- Effective PMT quantum efficiency 15% (convolving the response of a bialkali photocathode with the emission spectrum of Čerenkov light in the wavelength range 300 to 600 nm).

- Water absorption length 7 m (independent of wavelength).

These assumptions are believed to be justifiable [2, section5.3.3] but further work is required. Note that the assumed PMT radius has been reduced from the 115 mm value used in earlier work.

Figure 1 shows some results of this study. As the water depth increases from zero the photoelectron yield initially rises; this is a result of the increasing muon track length, and hence larger Čerenkov burst released. However, there are two effects which combine to counteract this rise; firstly the increasing depth results in decreasing photocathode area when expressed as a fraction of total tank wall area, and secondly the mean photon path length required to reach a photomultiplier (and hence the chance for absorption in the water) also grows. For a cylindrical tank of radius 1.8 m the pe yield is predicted to peak at a depth close to 1.2 m. The validity of this statement is dependent on the assumed lining material reflectivity and water absorption length values; larger values for these parameters would push the peak in the direction of greater depth.

The non-proportionality of the detector can be expressed in terms of the excess of the rms spread in the pe yield distribution over that which would be expected on statistical grounds alone. Figure 1 also shows this ratio; at tank depths of > 1 m the "hot-spots" around the PMTs do not improve further[1].

As the tank becomes deeper the time required for photons to reach the PMTs becomes larger, and the arrival time spread also increases. Figure 2 illustrates this effect. A Gaussian fit has been made to the prompt pulse, the sigma value of which is shown. These times are sufficiently small as to be quite irrelevant to the current discussion; the response of large PMTs to a delta function input pulse is many times longer than the predicted prompt pulse time spread value even at the largest tank depth.

[1]Note that the effect of Čerenkov light release in the glass of the PMTs themselves is not included at present.

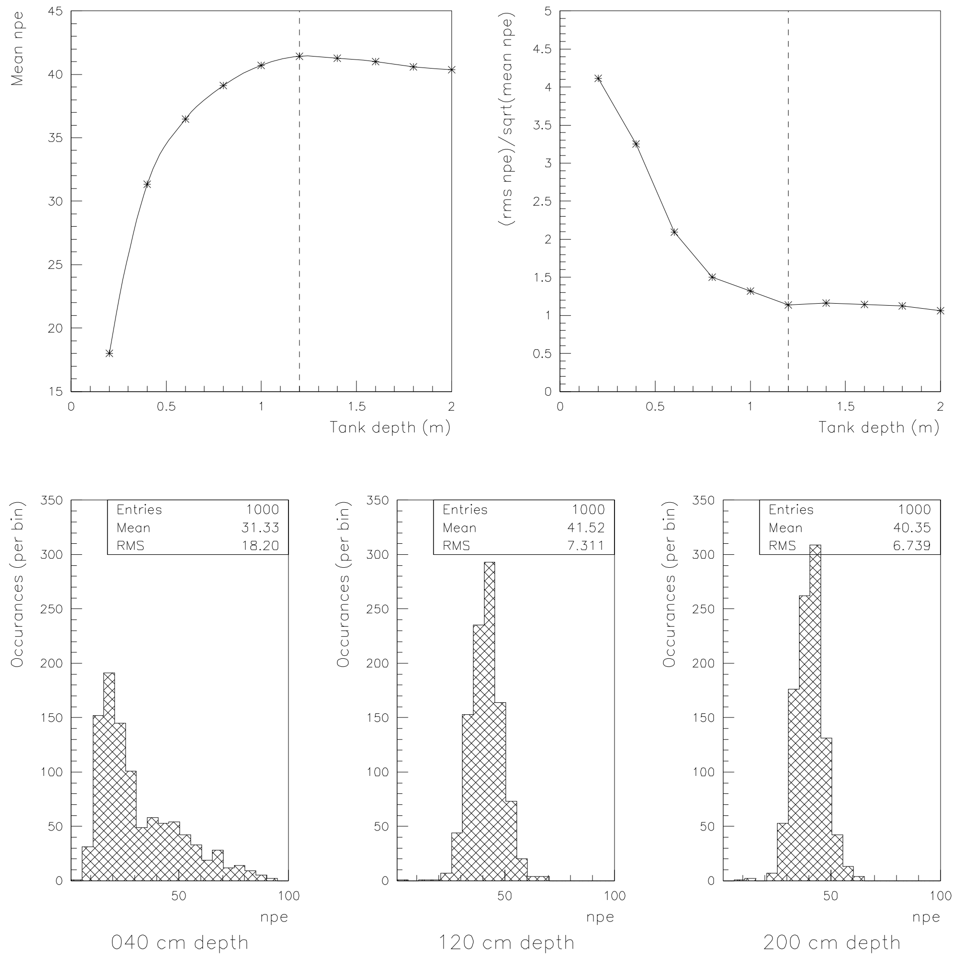

Figure 1: Water Čerenkov tank depth studies via simulation. At top left the mean pe yield as a function of tank depth for penetrating vertical muons is shown (see text for assumed parameters). At top right a measure of the non-proportionality of the detector is plotted; ideal response would be indicated by a value of 1. Along the bottom of the figure the photoelectron yield distributions are shown for three tank depths. The high side tail of the 40 cm case corresponds to those particles which enter the detector close to a PMT.

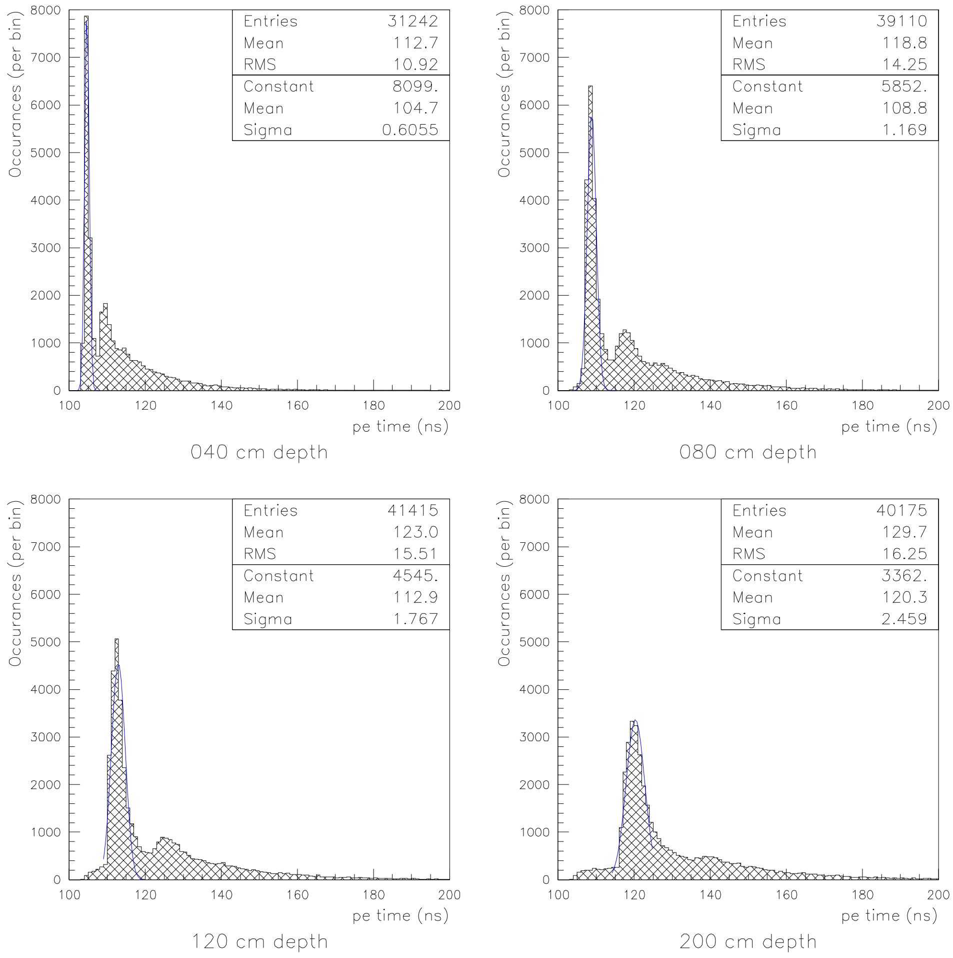

Figure 2: Water Čerenkov tank depth studies via simulation. Photoelectron arrival time distributions are shown averaged over 1000 vertically penetrating muons for four tank depth (see text for assumed parameters). The muons were injected into the simulation program at time $t = 100$ ns. In each case a prompt pulse is seen, followed by a smaller peak due to "second bounce" light, and a long tail. A Gaussian fit is made to the initial peak, and the fit parameters shown.

3 Segmentation

It is proposed to obtain a measure of the muonic to electromagnetic ratio of extensive air shower fronts by exploitation of the fast, large bursts of light released by penetrating muons. This implies that a large fraction of those muons which intersect the tank should have track length greater than some value (~ 1 m), and argues in favor of a single large tank to reduce "corner-clipping" to a minimum. Conversely practical considerations might suggest the use of (several) smaller tanks, referred to as segments, to ease installation logistics and provide partial redundancy.

To assess the above quantitatively simulation runs were made on the basis of segment top surface area of 10 m^2, 5 m^2, and 2.5 m^2 (radius 1.8 m, 1.25 m and 0.9 m); all cylindrical with depth of 1.2 m, and assumed material parameters the same as in the previous section. A large number of penetrating muons were injected over an area with radius $z \tan\theta$ larger than the detector top surface, where z is the detector depth, and θ is the zenith angle of incidence. The in-detector track length t of each particle was recorded allowing the ratio of $t > 1.2$ m / $t > 0$ m to be calculated. Figure 3 plots this ratio as a function of zenith angle; note that at 45° the fraction is ≈ 0.6 for a 10 m^2 tank and ≈ 0.4 for the 2.5 m^2 case — perhaps this difference is surprisingly small?

Presumably this calculation could be performed analytically for a simple shape such as a cylinder — however, since the Monte Carlo is available I use it. Note that the discussion here is based on the assumption that no attempt is made to analyze the outputs from the several detector segments in conjunction with one another. If the sub-units were to be placed close to one another then some of the muons which the clip the corner of one segment will pass into another. The summed signal therefore maintains equivalent information to that from a single unit. On the other hand, if the segments were to be separated (by a distance several times their depth) then the problem of low level triggering would be considerably eased. A simple coincidence requirement would then largely eliminate the KHz rate of ground level background muons (this technique was used by the SUGAR array, and more recently by CASA).

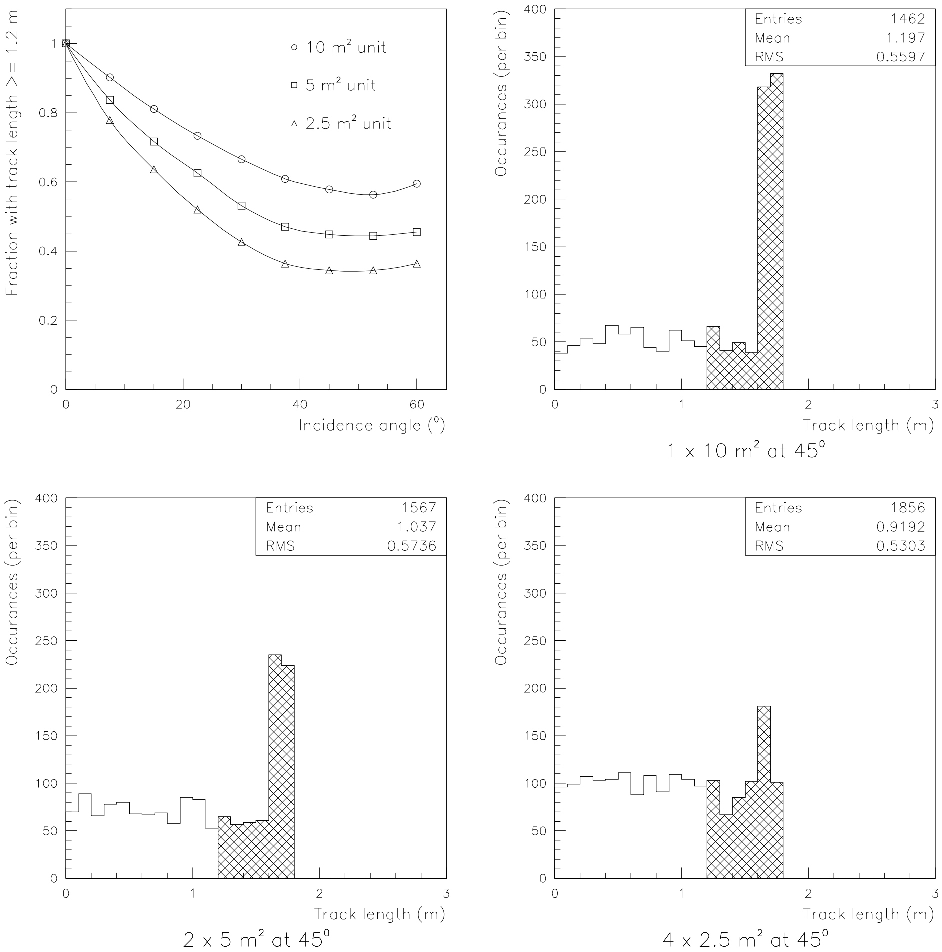

Figure 3: Water Čerenkov tank segmentation studies via simulation. At top left the number of muons having track length > 1.2 m is plotted as a fraction of the total number of muons intersecting the detector volume; curves are shown for three alternative tank geometries. The other quadrants show three of the track length distributions from which the upper left plot was extracted, track length > 1.2 m being shown hatched. (The muon density was 100 m^{-2} in the plane of the detector top surface for each of these runs.)

4 Conclusions

It is important to note that optimization of pe yield for given Čerenkov light release is not necessarily the most important consideration if the proposal to extract muonic content information from the time/amplitude profile is to be pursued. The difference in yield between long track muons and non-penetrating electromagnetic particles will continue to grow with increasing tank depth even when the absolute number of pes is falling. This effect will be considered further in a future note.

Conversely if direct muonic content analysis were not to be pursued the cost trade-off between obtaining greater pe yield through increased tank depth, as opposed to adding additional (or larger) PMTs would need to be considered. Engineering input is in any case required.

5 Further work

Collaboration members may care to suggest further illuminating studies. Alternatively, a future note will describe the operational specifics of the simulation proceedures and a "public" release of the software will be made available so that others may explore optimization studies.

References

[1] The Auger Collaboration, *Design Report* (August 1995).

[2] C.L. Pryke, PhD thesis, *Instrumentation development and experimental design for a next generation detector of the highest energy cosmic rays* (The University of Leeds 1996).