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SIMULATED PERFORMANCE OF THE AUGER OBSERVATORY WATER CHERENKOV ARRAYS

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ABSTRACT

The planned Auger Observatory will consist of two 3000 km^2 EAS arrays of 1600 water Cherenkov tanks each. Although the arrays will be equipped with fluorescence detectors the bulk of the data set will be ground array only ($\sim$ 90%). This paper describes the process used to generate simulated ground array data, and its subsequent reanalysis. The current predicted experimental performance is given.

INTRODUCTION

Simulations are being carried out to check and refine the design of the Auger Observatory of the highest energy cosmic rays (Auger Collaboration, 1997). This work has been described previously (C. Pryke, 1996a and 1996b) — this paper is an update with emphasis on those parts of the process which have recently been improved.

SHOWER SIMULATIONS

We are using the MOCCA air shower simulation code (A. Hillas, 1981 and 1995) together with the Sibyll hadronic interaction model (R. Fletcher et al., 1994). Recently 1000 showers were run with the "thinning threshold" set to 10^{-7} of the primary cosmic ray energy. Such showers take of order 1 day to generate on an up to date computer (180 MHz R5000 CPU). The primary particle parameters were sampled from the following distributions: energy $10^{19} < E_p < 10^{21}$ eV in 15 logarithmically spaced steps, zenith angle $\theta < 63^\circ$ with a distribution appropriate for a ground array, and an equal mix of proton and iron nuclei primaries. At the very low thinning level used the showers become usable individually for input into the array simulation procedures — artificial computationally induced fluctuations become smaller than those induced by fluctuations in the first interaction point etc. Figure 1 shows the longitudinal and lateral distributions of a single shower; notice that at more than 1 km from the axis the signal density remains a well defined quantity.

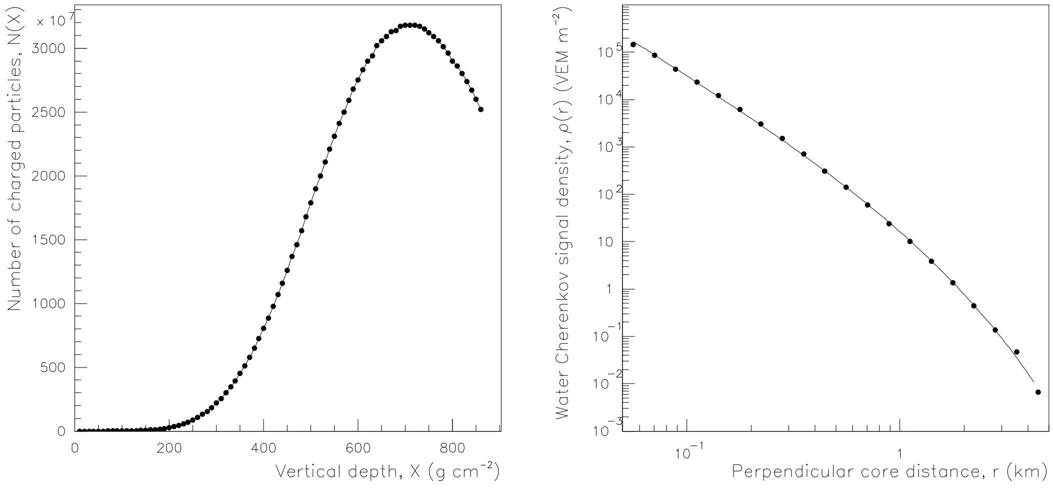

Fig. 1: The longitudinal and lateral distributions of a single MOCCA-Sibyll air shower at thinning level of 10^{-7}. The units of water Cherenkov signal are Vertical Equivalent Muons (VEM).

ARRAY SIMULATION

The MOCCA ground particle list file for each event is first summarized. A core position is then chosen at random on the array grid and the summary information re-sampled to produce a list of particles striking the relevant detector units. Note that an explicit list of particles is generated, each with appropriate energy, time and entry coordinates into the detector units; correlations between particle energy and arrival time are preserved. The Auger Cherenkov tanks are 10 m^2 in area and 1.2 m deep, completely filled with water, and lined with highly reflective material. Three 200 mm diameter photomultiplier tubes (PMTs) view the water volume from above. Each particle is tracked through each detector unit undergoing interactions and radiating Cherenkov light. Figure 2 illustrates this process. The particle interaction code is simple and fast but has been checked against GEANT and EGS4 and is believed to be adequate. The resulting Cherenkov photons are ray-traced until they are absorbed upon reflection, within the water, or they reach a PMT. Each time a photon strikes a PMT a list of photoelectron release times is updated. This allows a waveform trace to be constructed giving the anode current versus time; Figure 4 shows some sample waveforms. Each Auger ground detector will be equipped with waveform recorders, and the shower traces will be transmitted to the central station for analysis and storage. Figure 3 shows the hit pattern of an event on a ground array.

A simple algorithm is applied to the waveforms to determine if a given detector will self-trigger, and take part in an event. This exploits the time-dispersed characteristic of large air showers far from the axis to reduce the rate of background triggers. In the final experiment the trigger times will be cross correlated using GPS timing receivers (C. Pryke and J. Lloyd-Evans, 1995); this source of error is also included in the simulation.

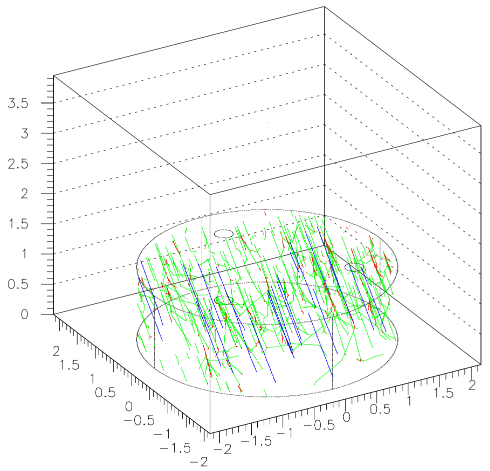

Fig. 2: Detector simulation display showing shower particle tracks in a water tank unit.

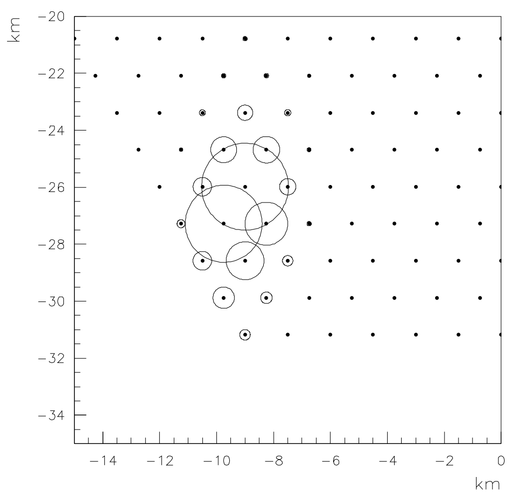

Fig. 3: Simulated hit pattern of an extreme event falling close to the boundary of an Auger array ($E_p = 4 \times 10^{20}$ eV, $\theta = 60°$). The radius of the circles is proportional to the log of the signal.

EVENT RECONSTRUCTION

Finally the simulated experimental data is reconstructed, and the results compared against the input parameters to make predictions of instrumental performance. In previous work the lateral distribution was fit using experimental parameterizations from the Haverah Park experiment (M. Lawrence, R. Reid and A. Watson, 1991). It has been shown that modern simulations reproduce these functions rather well (R. Coy et al., 1997). In this work we choose to use a new lateral distribution function (ldf); $\rho(r) = 10^{C_1} r^{-C_2} r^{-\sqrt{r}}$, where r is the perpendicular core distance in kilometers, $\rho(r)$ is the signal density, $C_1 = \log \rho(1km)$, and C_2 is a parameter expressing the ldf slope. This function fits every one of the 1000 simulated showers well, has only 2 free parameters, and is convenient to use. A sparse

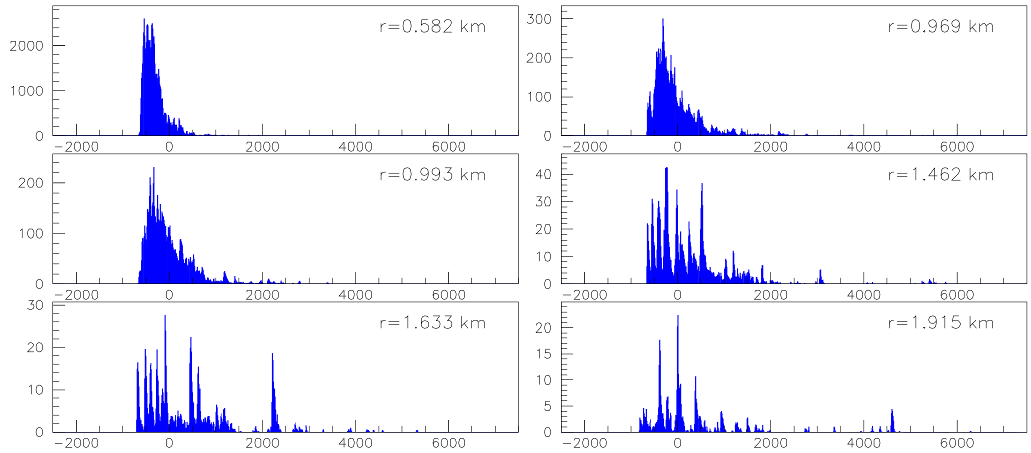

Fig. 4: Simulated amplitude versus time traces for several detectors taking part in a large air shower event. Time is in nanoseconds, with the detector self-trigger time at zero. Amplitude is in arbitrary units (a muon is $\approx$ 20). Note that each trace has a different vertical scale. ($E_p = 4 \times 10^{20}$ eV, $\theta = 60°$).

ground array determines the signal density with minimum dependence on the difference between the assumed and actual ldfs at a distance from core which is a fraction of the array spacing (A. Hillas, 1971); for the Auger arrays this distance is close to 1 km, and hence we use C_1 as energy parameter. The left frame of Figure 5 shows C_1 values for the simulated shower set plotted against $\sec\theta$ (recall that the events were generated at discreet steps of energy). Note that at the altitude of the Auger sites (870 g cm^{-2}), and the extreme energies considered, the signal size at 1 km has not reached maximum at ground level for vertical events. Correcting for the dependencies of C_1 on energy and zenith angle yields the right frame of Figure 5. This plot thus shows the predicted intrinsic energy measurement fluctuations to which a ground array is subject; the rms spread of the proton and iron distributions are 15% and 9% respectively, and the offset in the means is 22%. Note that in Figure 5 reconstruction error effects are *not* included.

The simulated experimental data is reconstructed using the ldf given above. Initially a typical C_2 value is used derived from the unreconstructed shower fits, but both C_1 and C_2 are allowed to go free in the final iteration. Similarly a curve fit is made to the time at which 10% of the total signal has arrived (t_{10}) with the curvature radius initially guided by the unreconstructed data, and then free in the last iteration. The energy and angular resolution results are good. Energy rms error is $\approx$ 20% for both proton and iron with the offset between species seen in Figure 5 propagating through to this stage. Figure 6 shows energy reconstruction results. Angular reconstruction error is 0.8° for proton and 0.6° for iron. All these figures represent average values over the realistic zenith angle distribution, and artificially flat energy spectrum simulated.

The most challenging aspect of ground array reconstruction is to have sensitivity to the nature of the primary particles. We find that 3 parameters have semi-independent sensitivity; the curvature of the shower front, the rise-time of the water Cherenkov signal, and the slope of the ldf (C_2). Making an aggregate of these parameters for each event results in distributions which have a separation of 0.6, where separation is defined to be $(\overline{p} - \overline{fe})/(\sigma_p + \sigma_{fe})$.

CONCLUSIONS

Simulations of the Auger detectors continue to be developed with increasing realism. Using air shower events run at thinning levels of 10^{-7} fluctuations effects are included in full detail for the first time — we believe that all significant effects which can degrade array performance are now included. The following paper describes simulations of the Auger fluorescence detectors in conjunction with the ground array simulation described here. We would like to thank the computing division of

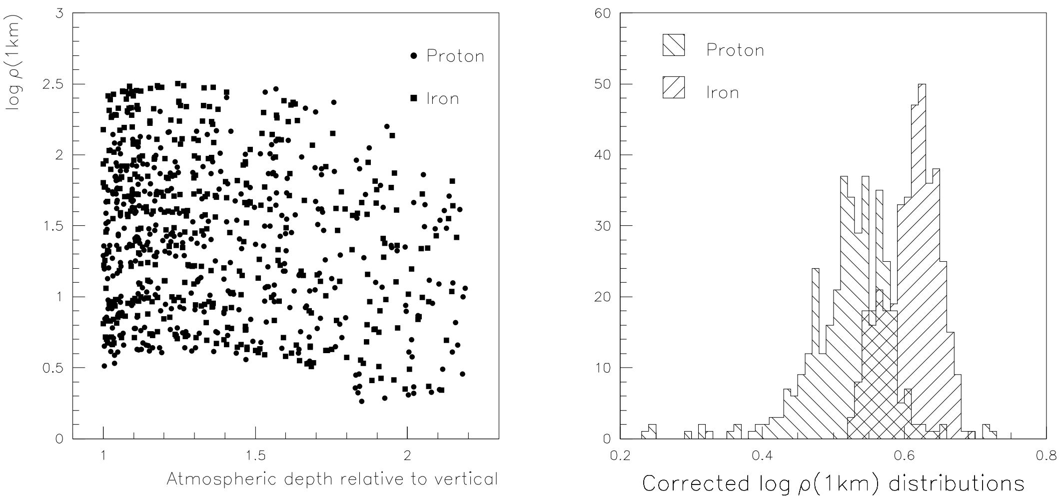

Fig. 5: Behaviour of the water Cherenkov signal density at 1 km. See text for details.

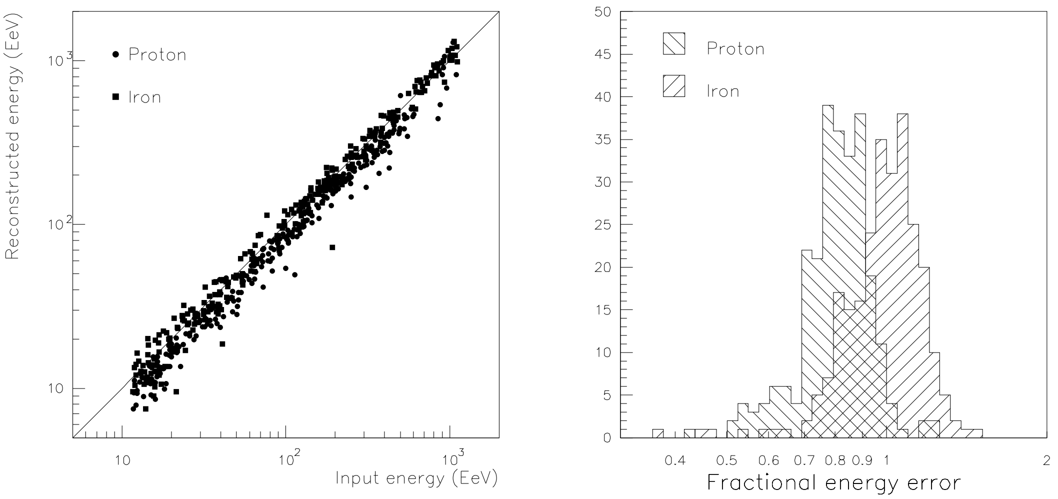

Fig. 6: Post reconstruction energy resolution results.

FNAL for the use a computer farm which made this work possible.

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