Using CORSIKA to quantify Telescope Array surface detector response

B.T. STOKES[1], R. CADY[1], D. IVANOV[1,2], J.N MATTHEWS[1], AND G.B. THOMSON[1]
FOR THE TELESCOPE ARRAY COLLABORATION
[1]*University of Utah, Department of Physics & Astronomy and High Energy Astrophysics Institute, Salt Lake City, Utah 84112, USA*
[2]*Rutgers—The State University of New Jersey, Department of Physics and Astronomy, Piscataway, New Jersey 08854, USA*
stokes@cosmic.utah.edu

Abstract: Historically, studies of surface detector response have been severely limited by the inability to simulate charge density fluctuations at the distance scale of individual detector units. We present a two-prong solution. First, we have developed a technique that allows us to run the unmodified CORSIKA in parallel mode. This has allowed us to simulate 100 non-thinned CORSIKA showers in the 10^{19} eV epoch. Second, we have developed a dethinning algorithm that enables us to reconstruct the information lost using the CORSIKA thinning option. This algorithm is validated by comparison with the non-thinned parallel showers mentioned above. By convolving a 10^4 event shower library of dethinned CORSIKA events with the Telescope Array surface detector response, we will characterize our surface detector observational capabilities and present extensive Data/Monte Carlo comparisons.

Keywords: UHECR, simulations, TA

1 Introduction

In the past 50 years, much progress has been made in the understanding of Extensive Air Showers (EAS) associated with Ultra-High Energy Cosmic Rays (UHECRs). However, the historical difference in energy determination between Surface Detection (SD) [1, 2, 3, 4] and Fluorescence Detection (FD) [5, 6, 7] has yet to be resolved. In its hybrid mode, the Pierre Auger experiment [8] reports a 30% discrepancy for simulation based energy determination between SD and FD for events observed in hybrid operation mode [9].

We posit that this discrepancy could be better understood if it were not for the fact that it has been computationally infeasible to simulate large numbers of EAS with primary energy $> 10^{18}$ eV without utilizing statistical thinning methods that fully simulate only a small representative fraction of the EAS. These thinned simulations certainly can be adequate for calculating longitudinal profiles [10] and average lateral distributions [11]. However, they neither capture the full breadth of fluctuations at the distance scale of individual surface detector counters nor do they provide all of the specific particle information necessary to properly estimate counter energy deposition and the consequent electronic response.

We approach this problem with a two-pronged strategy. We first developed the means to generate non-thinned EAS simulations. Simultaneously, we have developed an algorithm that takes a moderately thinned simulation and attempts to restore the lost information as was originally proposed by Billoir [12]. That is, the algorithm "dethins" the simulation. By creating thinned EAS simulations with identical input parameters to our non-thinned simulations, we are able to adjust the free parameters in our algorithm to achieve excellent spatial and temporal agreement between non-thinned and dethinned simulations across the full range of input parameters applicable to our detector.

While it is presently infeasible to generate a full spectrum with non-thinned EAS simulations, it is entirely feasible to do so with dethinned simulations. By generating a library of many dethinned EAS simulations, a simulation of a full spectral exposure for a physical detector system can be created in a relatively straightforward manner.

2 Non-thinned Simulations

For our EAS simulations, we employ CORSIKA v6.960 [13]. High energy hadronic interactions are modeled by QGSJET-II-03 [14], low energy hadronic interactions are modeled by FLUKA2008.3c [15, 16], and electromagnetic interactions are modeled by EGS4 [17]. Using the simulation code above, a non-thinned simulation of an EAS with a primary energy of 10^{19} eV requires ~ 5000 CPU hours on a current generation processor. However, we can dramatically reduce the elapsed time via parallelization.

Because CORSIKA is not self-interacting, a large EAS simulation can be thought of as a superposition of many somewhat smaller EAS simulations originating along the EAS path of propagation. In order to generate a large EAS simulation, we employ the following steps:

1. Initially, a single computer is utilized to separate the EAS simulation into many smaller, more manageable, simulations by running CORSIKA repeatedly through small steps in atmospheric depth.

2. At each step, the CORSIKA output is sorted with particles above a nominal threshold being passed back through CORSIKA and the rest of the output being appended to a master list.

3. Eventually, all the CORSIKA output is below the nominal threshold and the master list contains all the input parameter sets necessary for a series of simulations that can be superimposed to reconstitute the the original EAS.

4. The master list is then divided into sub-lists and divvied to a larger number of computers either manually or via clustering.

5. When all the sub-list simulations finished, the final total simulation can be reassembled.

A critical aspect of this procedure is that the actual CORSIKA source is in no way altered. All aspects of parallelization are achieved by translating each generation of CORSIKA output files into the next generation of CORSIKA input files via a series of scripts and compiled programs under the direction of a master script which explicitly tracks spatial and temporal information for each component simulation.

In order to verify the parallelization was working properly, we made spatial and temporal comparisons between EAS simulations with primary energies around 10^{17} eV generated both with and without parallelization. We then repeated the same comparison by generating simulations in parallel that were compared with 10^{18} eV EAS simulations in the Livni Shower Library [11, 18].

While the non-thinned simulation of UHECRs has proved to be very useful, computational requirements are still such that a full-sky non-thinned spectral set remains tantalizingly beyond our grasp. Nonetheless, our non-thinned library performs an invaluable function in that in provides the basis for tuning and verifying the dethinning algorithm described in the next section.

3 Dethinning

In a thinned EAS simulation, each particle in the output file is assigned a weight, w_i. Because this weight is typically the endpoint of a highly iterative process, it is useful to view thinning in terms of the net result to the simulation output. By this interpretation, a particle of weight, w_i, the simulation, on average, removed $w_i - 1$ particles of a similar nature. (It is important to emphasize that this interpretation is a concatenation of what actually happens in the simulation. Many of the weighted particles emerged from a series of vertices where some number of mostly *dissimilar* particles were removed in a probabilistic fashion by the thinning algorithm.)

The pivotal question is then: Which particle properties constitute "similar" from the viewpoint of a surface array detection unit? By considering which properties must be conserved in the restoration of missing particles, we can develop a set of constraints to guide missing particle generation:

1. Position and incident angle: The combination of these two parameters effectively constrains the missing particles to a lateral distance similar to that of the weighted particle.

2. Particle type: Secondary particle composition is highly dependent upon shower age. For non-vertical simulations, this dependence effectively constrains the missing particles to a rotational angle with respect to the EAS axis that is similar to the weighted particle.

3. Arrival time: This parameter is constrained by the time of EAS onset at a given position and consequently constrains the possible range of values for the parameters of the missing particles.

When considered simultaneously, the first two critical properties require that the missing particles have similar trajectories and positions as the weighted particles. As such, we propose the following method to reinsert the missing particles (see Figure 1):

1. Suppose an arbitrary vertex point on the trajectory of the weighted particle.

2. Sample a two-dimensional "Gaussian cone" defined by the arbitrary vertex, the trajectory of the weighted particle, and a predetermined angular spread.

3. Calculate the difference in time-of-flight between the original and sampled trajectories and apply a time correction to sampled trajectory.

4. Replicate the weighted particle except with the sampled trajectory rather than the original weighted particle trajectory.

5. Repeat steps 2-4 $w_i - 1$ times.

The third critical property of the missing particles, arrival time, provides the final constraint on the EAS sampled trajectories . In order for dethinning to be consistent with the rest of the EAS simulation, the arbitrary vertex must have

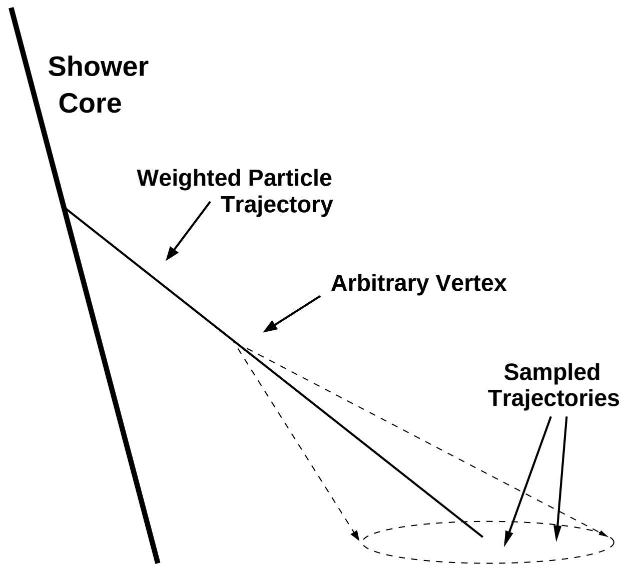

Figure 1: Geometry for a "Gaussian cone" with a vertex placed at arbitrary position on the trajectory of the weighted particle

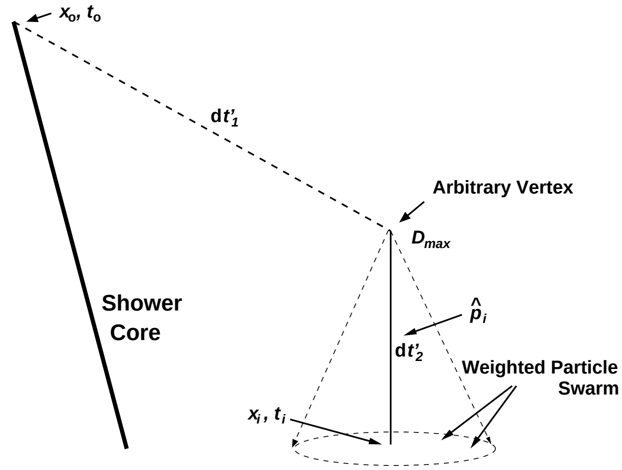

Figure 2: In order to ensure temporal consistency in the EAS simulation, we require $t_i - t_0 \leq \mathrm{d}t'_1 + \mathrm{d}t'_2$, where t_i is the recorded arrival time for weighted particle and t_0 is the time of first interaction.

space-time coordinates that are consistent with the time, t_0, and position, $\mathbf{x_0}$, of the point of first interaction and the time, t_i, position, $\mathbf{x_i}$, and trajectory, $\mathbf{p_i}$, of the weighted particle arriving at the ground level. This is accomplished by calculating a maximum distance between the arbitrary vertex and the ground level as is shown in Figure 2. By using the law of cosines, the maximum distance, D_{max}, between the arbitrary vertex and $\mathbf{x_i}$ can be shown to be:

$$D_{max} = \frac{c^2(t_i - t_0)^2 - |\mathbf{x_i} - \mathbf{x_0}|^2}{2(c(t_i - t_0) - (\mathbf{x_i} - \mathbf{x_0}) \cdot \hat{\mathbf{p}}_\mathbf{i})}, \quad (1)$$

where c is the speed of light.

At this point, a number of free parameters remain that can be adjusted. These parameters include the position of the arbitrary vertex and the width, σ, of the Gaussian cone. By comparing thinned, dethinned and non-thinned (parallelized) simulations with identical input parameters, we adjust the free parameters until we achieve agreement between the different simulation techniques. This results in the following corrections:

1. Height of Gaussian cone: Set to the smaller of D_{max} and

$$D'_{max} = |\mathbf{x_i} - \mathbf{x_0}| - X^{-1}(\mathbf{x_i}, \mathbf{x_0}, \alpha h), \quad (2)$$

   where $\mathbf{x_0}$ is the point of first interaction, h is the generation of the hadron from which the particle originated, $\alpha = 30$ g/cm^2, and $X^{-1}(\mathbf{x_i}, \mathbf{x_0}, \alpha h)$ is the distance equivalent of αh slant depth on the trajectory from $\mathbf{x_0}$ to $\mathbf{x_i}$. This correction ensures that weighted particles originating from points on the EAS core deep in the atmosphere do not lead to swarms with particles of implausibly high lateral distances from the EAS core, thus preserving the distribution of lateral distances in the non-thinned simulation.

2. Angle subtended by Gaussian cone: Set to βd where d is the lateral distance from the shower core for the weighted particle and $\beta = 3°$/km for electromagnetic particles and $1°$/km for muons and hadrons. These β values reflect differences in trajectories for electromagnetic cascades versus heavier particles. The values of β are the minimum necessary to dethin simulations with a 10^{-6} thinning coefficient. A lower thinning coefficient enables the use of smaller β values.

3. Particle acceptance: For particles in the swarm with longer trajectories than the original weighted particle, acceptance has probability: $P = e^{-\Delta\chi/\epsilon}$, where $\Delta\chi$ is the difference in slant depth between the trajectories and $\epsilon = 50$ g/cm^2. In essence, ϵ is a pseudo-radiation length which helps compensate for rapidly falling particle density as a function of lateral distance from the EAS core.

4. Minimum lateral distance: The rapidly changing lateral density near the EAS core also necessitates two minimum lateral distance cuts. The first, r_{min}, is the minimum lateral distance for which weighted particles are processed through the sampling procedure. The second, r'_{min}, is the minimum lateral distance for which the particles resulting from the dethinning process are retained. In general, $r_{min} \geq 100$ m, and $r'_{min} - r_{min} \geq 200$ m.

4 Spectral Generation

We currently have a library of $16,800$ dethinned EAS simulations with primary energies ranging from $10^{16.8}$ eV to $10^{20.5}$ eV and from 0° to 60° in zenith angle. For this set we utilized the optimal thinning as described by Kobal [19].

Each EAS simulation footprint is concatenated into spatial and temporal tiles and converted from individual particles to energy deposition via a look-up table derived from GEANT4 [20]. Both the concatenation and conversion correspond to the characteristics of Telescope Array Surface Detector (TASD) [21, 22] units.

We then superimpose the EAS simulations on the TASD to create highly detailed spatial and temporal simulations of the TASD response. We will present estimates of the aperture, efficiency, and resolution of the TA surface detector array.

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