Using CORSIKA to quantify Telescope Array surface detector response

B.T. Stokes*, **R. Cady**†, **D. Ivanov***, **G.B. Thomson*** **and G.I. Rubtsov**‡
for the Telescope Array Collaboration

*Department of Physics and Astronomy, Rutgers—The State University of New Jersey
Piscataway, New Jersey 08854, USA
†Department of Physics and High Energy Astrophysics Institute, University of Utah
Salt Lake City, Utah 84112, USA
‡Institute for Nuclear Research, Russian Academy of Sciences
Moscow 117312, Russian Federation

***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 an interface script that allows us to simulate a cosmic ray shower, using CORSIKA, that runs in parallel on many computers simultaneously. In doing this no changes have been made to the CORSIKA program. In this "parallel mode" a very large number of computers can be used. This has allowed us to simulate 100 non-thinned CORSIKA showers in energy decade centered at 10^{19} eV. Second, we have developed an algorithm (called "dethinning") that enables us to reconstruct the information lost using the CORSIKA thinning option. The input to this algorithm is the list of weighted particles produced by CORSIKA, run with thinning, and the output is individual particles distributed in space and time as if no thinning had been used in the CORSIKA generation. We validate the algorithm by comparison with the non-thinned parallel showers mentioned above. We can then convolve a library of dethinned CORSIKA events with the Telescope Array (TA) surface detector response and simulate the surface detector's data. We will present estimates of the aperture and resolution of the TA surface detector array.**

***Keywords*: UHECR, simulations, TA**

I. 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% modeling discrepancy between SD and FD in its 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 EAS above a primary energy 10^{18} eV without utilizing a rather liberal dose of statistical thinning. While these thinned simulations are certainly adequate for calculating longitudinal profiles and average lateral distributions, 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 [10]. 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.

II. Non-thinned Simulations

For our EAS simulations, we employ CORSIKA v6.735 [11]. High energy hadronic interactions are modeled by QGSJET-II-03 [12], low energy hadronic interactions are modeled by UrQMD v1.3 [13], and electromagnetic interactions are modeled by EGS4 [14]. Using the simulation code above, a non-thinned simulation of an EAS with a primary energy of 10^{19} eV requires $\sim$ 5000 CPU hours on a current generation processor. However, we can dramatically by 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 though 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 [15][16].

So far, we have created a library of ~ 100 non-thinned EAS simulations with primary energies in the range of $10^{18.5}$ to $10^{19.5}$ eV. In Table I, we give a current list of the completed non-thinned EAS simulations.

While the non-thinned simulation of UHECRs has proved to be very useful, computational requirements are still such (e.g. $250,000+$ CPU hours for the simulations in Table I) that a full-sky non-thinned spectral set remains tantalizingly beyond our grasp. Nonetheless, our non-thinned library performs an invaluable function in that is provides the basis for tuning verifying the dethinning algorithm described in the next section.

III. DETHINNING

In a thinned EAS simulation, each particle in the output file is assigned a weight, w_i. Because this weight is due to a highly iterative process in the case of any substantial amount of thinning, the net result is of primary importance. This interpretation is that for a particle of weight w_i, CORSIKA, 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 where many the weighted particle emerged from a series of vertices where some number of mostly *dissimilar* particles were removed in a probabilistic fashion by the thinning algorithm.)

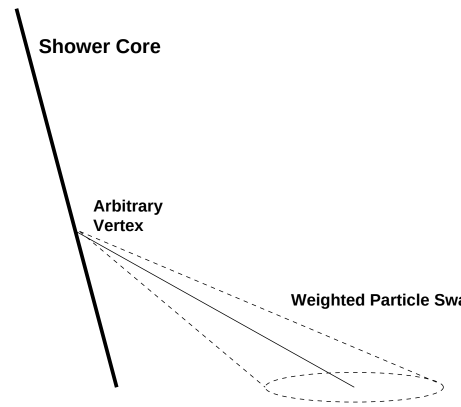

Fig. 1. Geometry for a “Gaussian cone” with an vertex placed at arbitrary position on the shower axis

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 constrain the missing particles to lateral distance similar to the weighted particle.
2) Particle type: For inclined showers, this parameter is dependent on shower age, thus it constrains the missing particles to an azimuthal position with respect to the shower 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 Fig. 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 time correction to sampled trajectory.
4) Duplicate the weighted particle only with the sampled trajectory.

TABLE I
CURRENT (MAY 2009) INVENTORY OF NON-THINNED EAS SIMULATION LIBRARY WITH RESPECT TO PRIMARY ENERGY, ZENITH ANGLE, AND COMPOSITION

eV	$10^{18.5}$	$10^{18.6}$	$10^{18.7}$	$10^{18.8}$	$10^{18.9}$	$10^{19.0}$	$10^{19.1}$	$10^{19.2}$	$10^{19.3}$	$10^{19.4}$	$10^{19.5}$
0°	$1p$					$2p, 1Fe$	$1p$	$1p$	$1p$	$1p$	$1p$
5°						$1p, 1Fe$					$1p$
10°						$1p, 1Fe$					$1p$
15°						$1p, 1Fe$					$1p$
20°						$1p, 1Fe$					$1p$
25°						$1p, 1Fe$					$1p$
30°	$7p$	$6p$	$5p$	$5p$	$5p$	$5p, 1Fe$	$5p$	$5p$	$5p$	$5p$	$1p$
35°						$1p, 1Fe$					$6p$
40°						$1p, 1Fe$					$1p$
45°	$1p$					$2p, 1Fe$					$2p$
50°						$1p, 1Fe$					$1p$
55°						$1p, 1Fe$					$1p$
60°	$1p$					$2p, 1Fe$					$2p$

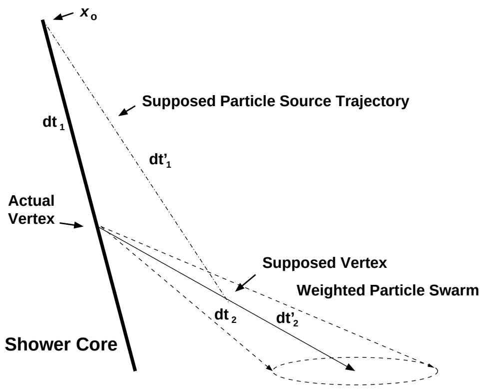

Fig. 2. If $\mathrm{d}t_1 + \mathrm{d}t_2 > \mathrm{d}t'_1 + \mathrm{d}t'_2$, the sampled trajectory will arrive before EAS onset.

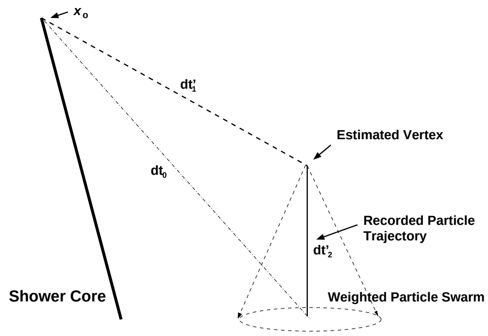

Fig. 3. If $\mathrm{d}t_0 + t_f < \mathrm{d}t'_1 + \mathrm{d}t'_2$, where t_f is the delay between the onset of the EAS and arrival of the weighted particle, the sampled trajectory will always arrive after EAS onset.

5) Repeat $w_i - 1$ times.

The third critical property for the missing particles, arrival time, provides the last constraint on the EAS: sampled trajectories cannot precede the onset of the EAS, that is, the shower front. In Fig. 2, we consider the case where the weighted particle was scattered at a point far from the EAS core. It is geometrically possible to have scenarios where the time-of-flight for the sampled trajectory is less than that of a direct path to the primary interaction point at the top of the EAS. This would result in sampled trajectories arriving before EAS onset. This is solved by calculating a maximum distance between the imaginary vertex and the ground as is shown in Figure 3.

For the case of CORSIKA, a particle can be defined by its momentum, $\mathbf{p_i}$, position with respect to the shower axis at the observation level, $\mathbf{x_i}$, and arrival time, t_o, with respect to the time of first interaction. Using the law of cosines, the maximum distance, D_{max}, between the arbitrary vertex and $\mathbf{x_i}$ can be shown to be:

$$D_{max} = \frac{c^2 t_i^2 - \mathbf{x_i^2}}{2(ct_i + \mathbf{x_i} \cdot \mathbf{\hat{p}_i})}, \quad (1)$$

where c is the speed of light.

At this point there are a number of free parameters that can adjusted. The most obvious parameters are the position of the imaginary vertex, and the value of σ for the Gaussian cone. By comparing dethinned and non-thinned simulations with identical input parameters, we adjust the free parameters until we achieve agreement between the non-thinned and dethinned simulation techniques. We will present a set of parameters that provide across the full range of EAS characteristics that we observe.

IV. SPECTRAL GENERATION

We currently have a library of $\sim 25,000$ dethinned EAS simulations with primary energies ranging from $10^{17.3}$ eV to 10^{20} eV and from 0° to 60° in zenith angle. For this set we utilized the optimal thinning as described by Kobal [17].

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 [18]. Both the concatenation and conversion correspond to the characteristics of Telescope Array Surface Detector (TASD) [19][20] 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.

V. Acknowledgments

The Telescope Array experiment is supported by the Ministry of Education, Culture, Sports, Science and Technology-Japan through Kakenhi grants on priority area (431) “Highest Energy Cosmic Rays”, basic research awards 18204020(A), 18403004(B) and 20340057(B); by the U.S. National Science Foundation awards PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the Korean Science and Engineering Foundation (KOSEF, Grant No. R01-2007-000-21088-0); by the Russian Academy of Sciences, RFBR grants 07-02-00820a and 09-07-00388a (INR), the FNRS contract 1.5.335.08, IISN and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The simulations presented herein have only been possible due to the availability of computational resources at the Center for High Performance Computing at the University of Utah which is gratefully acknowledged. A portion of the computational resources for this project has been provided by the U.S. National Institutes of Health (Grant # NCRR 1 S10 RR17214-01) on the Arches Metacluster, administered by the University of Utah Center for High Performance Computing. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions.

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