



## Energy Spectrum Measured by Telescope Array Surface Detector

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**Abstract:** The Telescope Array experiment (TA) is the largest cosmic ray experiment in the northern hemisphere. It consists of a surface detector (SD) of 507 scintillation counters and three fluorescence detector (FD) stations overlooking the SD. We are analyzing the data collected by TA SD using a new technique which consists of generating a Monte Carlo (MC) simulation with all characteristics of the data, comparing the MC with the data to verify the validity of the MC, and calculation of the SD aperture from the MC information. In this paper, we describe our basic analysis, which is based solely upon the data, our method of generating CORSIKA showers without the problems caused by thinning, comparisons of our MC with the data, and the latest TA SD energy spectrum result.

**Keywords:** TA, SD, cosmic, ray, energy, spectrum

## 1 Introduction

The Telescope Array experiment, located in Millard County, UT, USA, is measuring the ultra high energy cosmic rays since the year 2007 and it is the largest cosmic ray detector in the northern hemisphere up to date. The TA has three fluorescence detectors looking at a surface detector of 507 counters, each consisting of 2 layers of  $3\text{m}^2 \times 1.2\text{cm}$  scintillators. The counters are positioned on a 1200m grid and span a  $680\text{m}^2$  area on the ground in total. Cosmic ray geometry, energy, and composition are measured best in hybrid detection mode, where each extensive air shower is simultaneously observed by the TA SD and FD. However, the FD duty cycle is limited by the daylight and weather. Therefore, for the purposes of calculating the energy spectrum, it is advantageous in terms of statistics to use a larger data set obtained by the TA SD operating in a stand-alone mode and resulting in an exposure that is uniform in time.

The TA SD energy spectrum calculation is done in 3 steps. First, AGASA [1] reconstruction procedures are adjusted to fit the TA SD data. This is sufficient for reconstructing the event geometry and the lateral distribution. Next, a detailed CORSIKA [2] MC is generated with full characteristics of the data and reconstructed using same exact procedures as the data. The MC is then compared to the data to verify its validity. An energy estimation routine is derived from the MC and is used to reconstruct energies in both data and the MC.

In the final step, the TA SD energy is normalized to match the TA FD scale using well reconstructed events seen by both types of TA detectors, thus reducing the model depen-

dence of the TA SD energy scale to that of the fluorescence detector.

## 2 TA SD Reconstruction and Monte-Carlo

### 2.1 Reconstruction

We use the AGASA formulas and procedures [1] adjusted to fit the TA SD data [3]. Figure 1 shows a typical high energy event footprint measured by the TA SD. Figure 2 shows the time fit using modified AGASA time delay function [4, 1] for describing the shower front curvature and lateral distribution fit using the AGASA lateral distribution function (LDF).

Next, we plot S800 (signal size 800m from the shower axis) versus secant of zenith angle for each true value of MC energy and construct a look-up table, shown in Figure 3. This provides energy as a function of *reconstructed* S800 and secant of zenith angle. We refer to this energy as the “initial” energy estimate.

Lastly, we calibrate the TA SD energy scale to the TA fluorescence detector [3]. This reduces the systematic uncertainty of the energy scale because the energy scale obtained from the air fluorescence measurements has been constrained experimentally better than the one provided by the hadronic model.

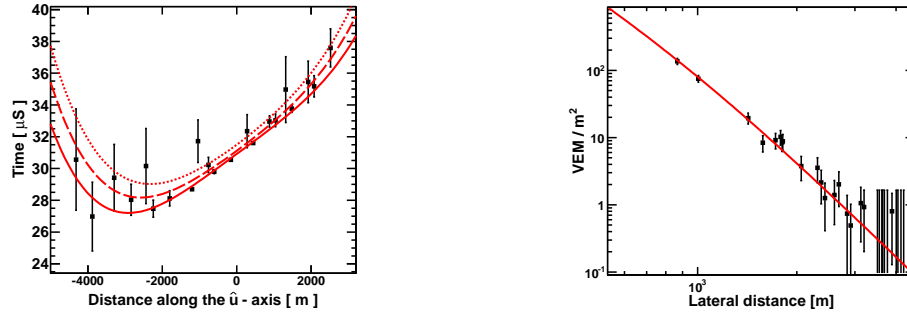


Figure 2: Time and lateral distribution fits for a typical TA SD event. Left: counter time versus distance from the shower core along the  $\hat{u}$  direction, which is the shower axis projected on the ground. Points with error bars are counter times, solid curve is the time expected by the fit for counters lying on the  $\hat{u}$  axis, dashed and dotted lines are the fit expectation times for the counters that are correspondingly 1.5 and 2.0 km off the  $\hat{u}$  axis. Right: Lateral distribution profile fit to the AGASA LDF. Vertical axis is the signal density and horizontal axis is the lateral distance from the shower core.

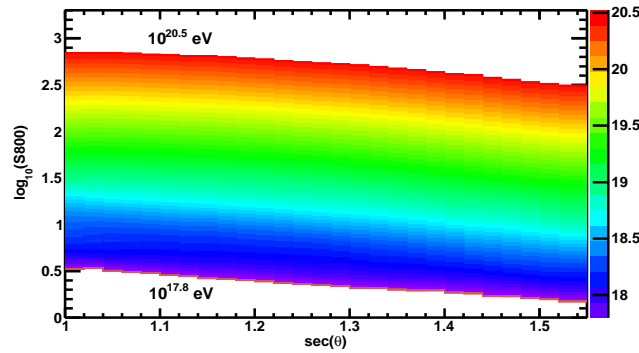


Figure 3: Energy as a function of reconstructed S800 and  $\sec(\theta)$  made from the CORSIKA MC. Z-axis described by color represents the true (MC generated) values of energy.

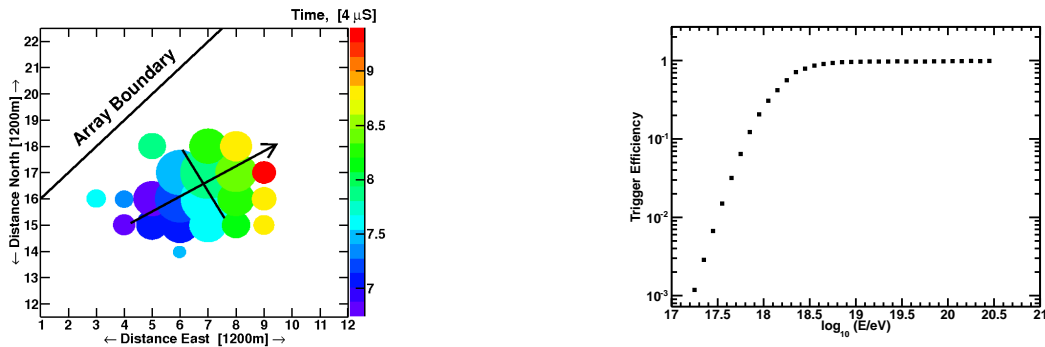


Figure 1: A typical high energy event seen by the TA SD. Each circle represents a counter, positioned at the center of the circle, the area of the circle is logarithmically proportional to the counter pulse height, and the counter time is denoted by the color. The arrow represents the projection of the shower axis onto the ground, which we label by  $\hat{u}$ , and it is bisected by the perpendicular line at the location of the shower core.

Figure 4: TA SD trigger efficiency determined from the MC. The trigger efficiency plateaus near  $E \sim 10^{18.8} \text{ eV}$

## 2.2 Monte-Carlo

The trigger efficiency of a typical surface array is expected to be close to 100% and nearly energy-independent only beyond a certain threshold energy, as shown in Figure 4. Furthermore, every realistic reconstruction applies quality cuts to remove events with bad resolution. Non-uniform

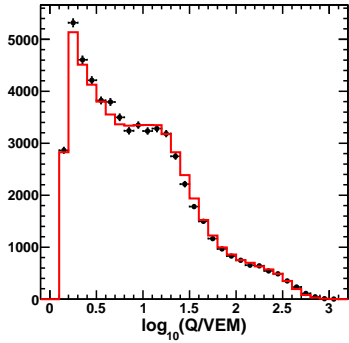


Figure 5: Data and MC comparison of counter pulse height. The points with error bars represent the data histogram and the solid line represents the MC.

trigger efficiency, cuts, and effects of the finite energy resolution are automatically taken into account when the aperture is calculated by a detailed MC that shares all characteristics of the data [5].

The TA SD Monte-Carlo uses CORSIKA QGSJET2 [2] events in  $10^{17.0} - 10^{20.5} eV$  range with  $10^{-6}$  thinning to minimize the event generation time and dethinned [6, 7] to restore the information on the ground needed by the surface detector. The events are distributed isotropically in the local sky and are sampled from the energy spectrum and proton composition measured by the HiRes experiment [8, 9], excluding the Greisen-Zatsepin-Kuz'min (GZK) suppression effect [10, 11] from the simulation.

The MC is subject to the same conditions as the data: real-time calibration constants are used and a full detector response simulation is done for each simulated event. The MC event sets are recorded in the same format as the data and are analyzed by the same analysis tools as the data.

### 2.3 Comparison of Data and MC

We verify the accuracy of our MC by performing direct comparisons of the distributions of the MC variables, when the MC is treated in the same way as the data, with the corresponding distributions obtained from the data. Typical comparisons of TA SD data and the MC are shown in Figures 5-8. In Figure 8, a small deficit at large S800 is seen in the data because S800 is roughly proportional to the event energy and our MC does not simulate the GZK suppression. Figures 5-8 demonstrate the agreement between the data and the MC. These are just a few examples of many comparisons we looked at to confirm the validity of our MC. A good agreement between the data and the MC means that we understand the response of the TA SD to cosmic rays and this allows us to control the systematic uncertainties.

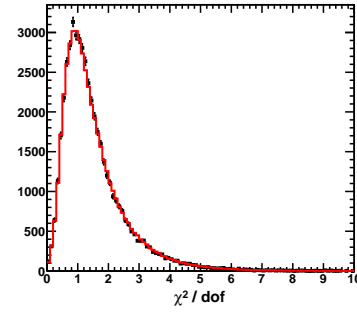


Figure 6: TA SD data and MC comparison of the lateral distribution fit  $\chi^2$  per degree of freedom.

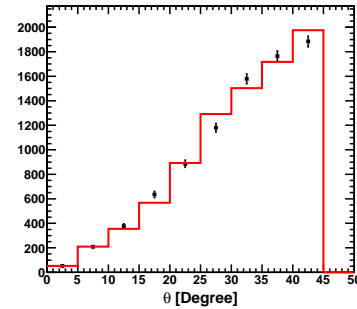


Figure 7: Data and MC comparison of the event zenith angle.

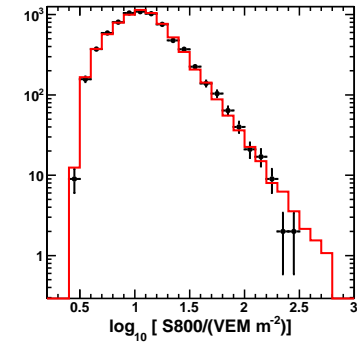


Figure 8: Data and MC comparison of the event S800.

## 3 Summary

We will present the latest cosmic ray energy spectrum calculated from the TA ground array data using a method that is new to the field. The most basic event reconstruction is developed using the data without referring to hadronic models. The cosmic ray energy, initially derived from the MC, is normalized to the fluorescence detector to reduce the systematic uncertainty of the energy scale. The surface detector aperture is accurately determined from the detailed

MC with an excellent understanding of the systematic uncertainties.

## 4 Acknowledgements

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