Telescope Array Surface Detector: Simulation and Analysis

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Abstract: The Telescope Array (TA) is the largest cosmic ray observatory in the Northern hemisphere. TA consists of a 730 km^2 surface detector (SD) array of 507 plastic scintillation counters (with 1200-meter spacing) augmented by three optical fluorescence telescope stations. The mission of TA is to study the energy spectrum, composition, and arrival direction anisotropy of ultra-high energy cosmic rays with primary energies above 1 EeV. In this poster, the techniques employed for the simulation and reconstruction of TA SD data are described. These techniques are validated via detailed comparisons between real and simulated data.

Keywords: TA, SD, simulation, reconstruction, 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 3m$^2 \times$ 1.2cm scintillators. The counters are positioned on a 1200m grid and span a 730m^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.

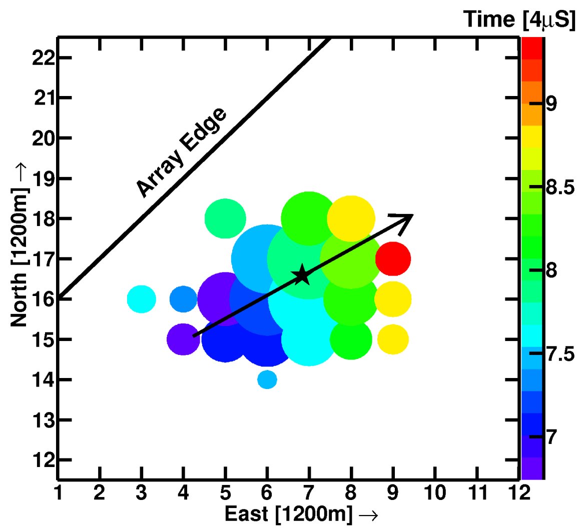

Fig. 1: A typical high energy event seen by the TA SD. Each circle represents a counter, positioned at the center of the circle, the area of the circle is logarithmically proportional to the counter pulse height, and the counter time is denoted by the color. The arrow represents the projection of the 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.

2 Reconstruction

We use the AGASA formulas and procedures [1, 2] adjusted to fit the TA SD data. Figure 1 shows a typical high energy event footprint measured by the TA SD. Figures 2,3 show the time fit using modified AGASA time delay function [3] for describing the shower front curvature and the 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 4. 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 [10]. 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.

3 Monte-Carlo Simulation

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, which is around $10^{18.8}$eV in case of the TA SD. Furthermore, every realistic reconstruction applies quality cuts to remove events with bad resolution. Non-uniform 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.

The TA SD Monte-Carlo uses CORSIKA QGSJET2 [4] events in $10^{17.0}$ – $10^{20.5}$eV range with 10^{-6} thinning to

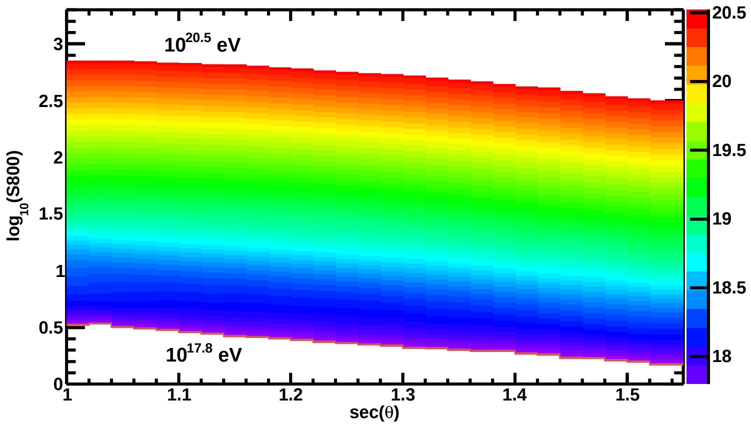

Fig. 4: Energy as a function of reconstructed S800 and $\sec(\theta)$ made from the CORSIKA MC. Z-axis described by color represents the true (MC generated) values of energy.

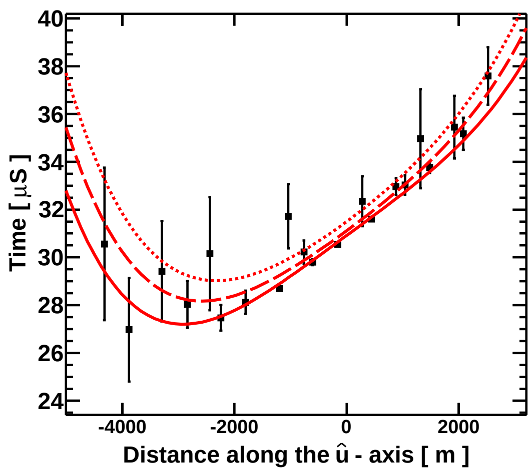

Fig. 2: TA SD time fit. Counter time is plotted versus the distance from the shower core along the $\hat{u}$ direction, which is the projection of the shower axis on the ground. Points with error bars are counter times, solid curve is the time expected by the fit for the counters lying on the $\hat{u}$ 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.

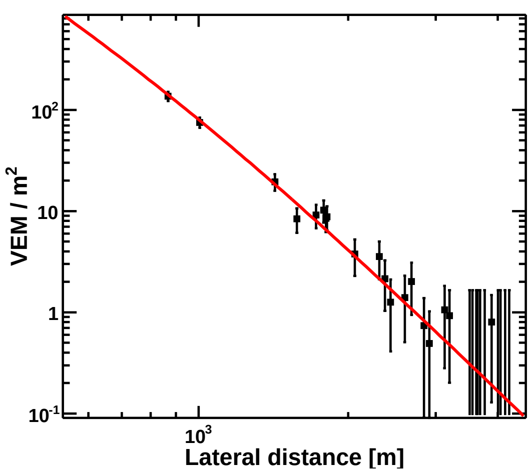

Fig. 3: Lateral distribution profile fit to the AGASA LDF. Vertical axis is the signal density and horizontal axis is the lateral distance from the shower core.

minimize the event generation time and dethinned [5, 6] 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 [7, 8].

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.

3.1 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 5,6,7. 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.

4 Cuts and Resolution

To remove events with poor resolution, the TA SD reconstruction applies quality cuts which were derived using the Monte-Carlo. These cuts include: at least 5 counters that are part of the event, $\chi^2/dof < 4$, zenith angle less than 45°, core position 1200 m within the edge of the array,

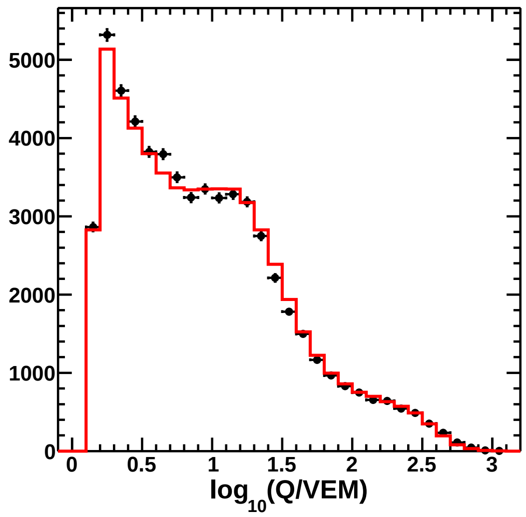

Fig. 5: Data and MC comparison of counter pulse height. The points with error bars represent the data histogram and the solid line represents the MC.

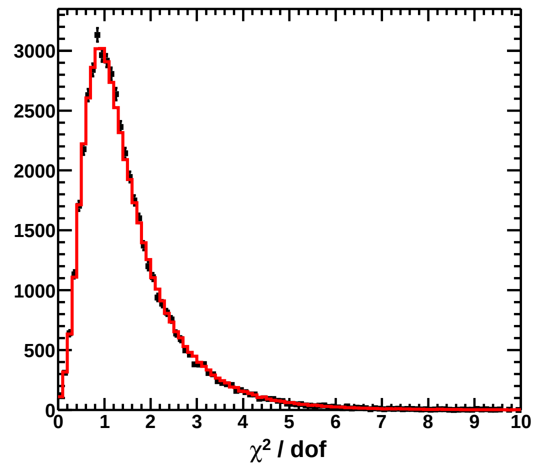

Fig. 6: TA SD data and MC comparison of the lateral distribution fit χ^2 per degree of freedom.

pointing direction uncertainty less than 5°, and fractional uncertainty of $S800$ less than 25%.

The resolution of the TA SD is evaluated using the Monte-Carlo. As can be seen from the Figures 8 and 9, the resolution of the TA SD above 10^{19}eV is 1.4° in angle and better than 20% in energy.

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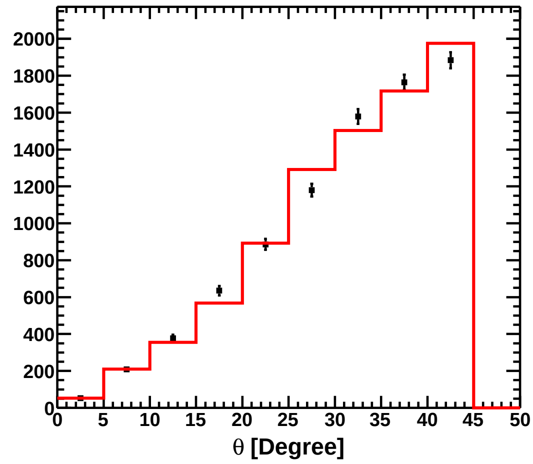

Fig. 7: Data and MC comparison of the event zenith angle.

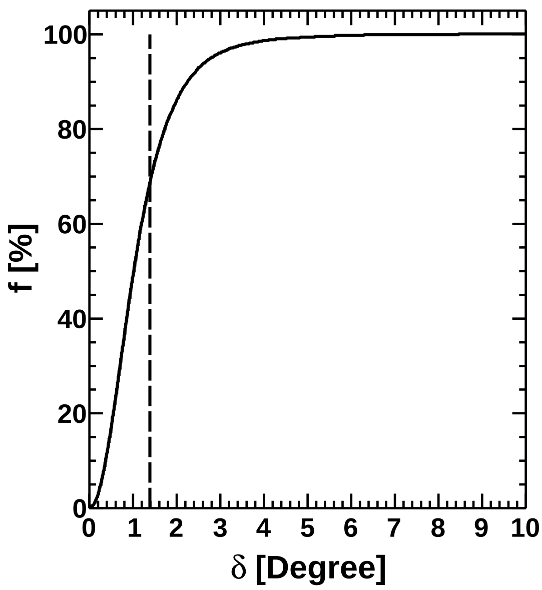

Fig. 8: Angular resolution of the TA SD evaluated by Monte-Carlo. Fraction of events (f) reconstructing within a certain opening angle (δ) of the true event direction is plotted versus the opening angle. 68% of events reconstruct within 1.4° of the true event direction.

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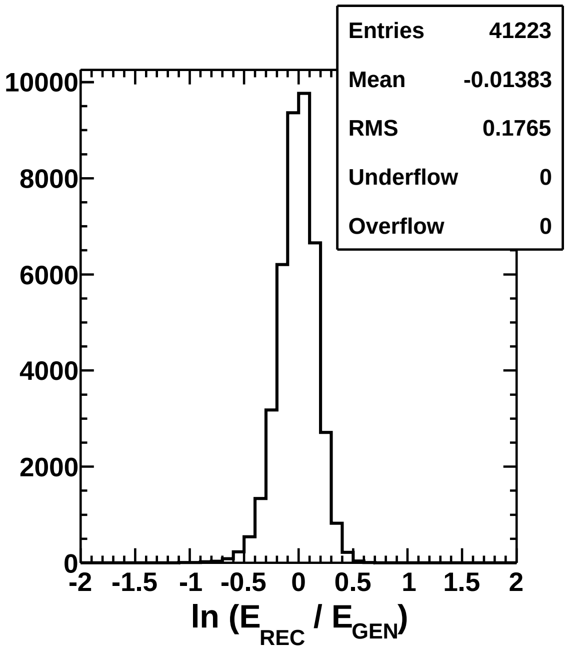

Fig. 9: Energy resolution of the TA SD evaluated by the Monte-Carlo. The histogram shows the distribution of the natural logarithm of the reconstructed (E_{REC}) energy divided by the true energy (E_{GEN}).

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