The Energy Spectrum of UHECRs using the TA Fluorescence Detectors in Monocular Mode

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Abstract: The fluorescence detectors of the Telescope Array (TA), operating in monocular mode, cover the widest energy range of any component of the TA detector, and give the largest statistical sample among the monocular fluorescence, stereo fluorescence and hybrid data sets. There are three fluorescence detectors in TA. The Middle Drum site uses hardware from the High Resolution Fly's Eye experiment, while the Black Rock Mesa and Long Ridge sites were built especially for TA and have identical instrumentation and data acquisition systems. All three sites have been in operation since the Autumn of 2007. The energy spectra from each of the sites will be presented.

Keywords: UHECR, Spectrum, Fluorescence, Monocular

1 Introduction

The Telescope Array Experiment (TA) is designed as a hybrid experiment to observe extensive air showers (EASs) created by ultra high energy cosmic rays (UHECRs) when they enter the atmosphere. It consists of both surface detectors (SDs) to measure the number of particles in the shower as it hits the ground and fluorescence detectors (FDs) to collect the fluorescence light created by the shower as it excites nitrogen in the atmosphere. The two techniques are complimentary as the fluorescence detectors can observe the shower development and make a calorimetric measurement of the primary UHECR energy but can only run on moonless nights. Surface detectors make an indirect measurement of the shower energy, but run continuously.

The SD measurement provides the largest statistical sample at the highest energies of any TA component. To give the best possible calibration for the energy of this data set, the subset of data (about 10%) also seen by one of the FDs is used. The FDs in this case provide not only an energy calibration for the SDs, they provide a measurement *in situ* of the SD efficiency as a function of energy and zenith angle. This is very important in determining the SD aperture at low energies where the efficiency is not close to 100%. Understanding the FDs energy scale and aperture are thus crucial to all the spectrum measurements made by TA.

In addition, because the monocular FD aperture grows with energy, the monocular FD spectrum covers a very large energy range, the largest of any TA component. While using two or more FD stations simultaneously (stereo) leads to a better determination of the air shower geometry (and thus of the primary energy), the calculation of the stereo aperture is complicated by the fact that two FD apertures overlap, compounding the uncertainty inherent in each. In fact, the monocular FD aperture is the most straightforward of all the aperture calculations in TA (because the SD aperture is complicated by its efficiency dropping off quickly at low energies).

2 TA Fluorescence Detectors

There are three FD stations in TA, overlooking the central array of SDs (see Figure 1). To the northeast is the Middle Drum (MD) station, consisting of 14 cameras in two rings. The cameras, mirrors and PMT clusters were taken and refurbished from the High Resolution Fly's Eye Experiment (HiRes)[1]. Having this HiRes instrumentation allows for very direct comparisons between the HiRes and TA energy scales. To the southeast and southwest are the Black Rock Mesa (BRM) and Long Ridge (LR) stations, respectively. These two stations each consist of 12 cameras, also in two rings. These cameras and their mirrors were built especially for TA. The mirrors in these stations have about 40% larger collecting area, leading to lower thresholds and larger apertures.

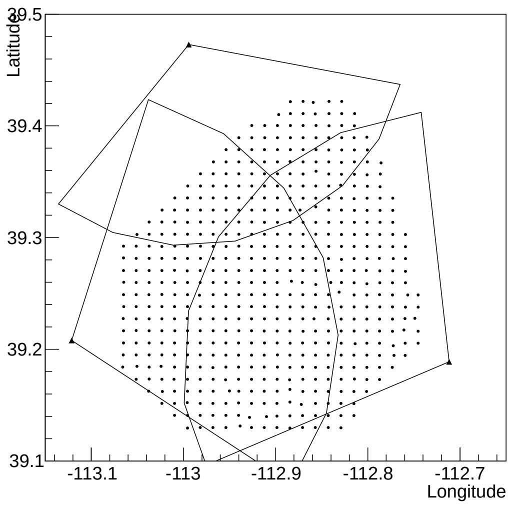

Figure 1: The arrangement of Telescope Array detectors. The circles represent the position of the 507 SDs, the triangles the location of the three FDs. The view of each FD at 10^{19} eV is indicated by the lines.

2.1 BRM & LR Data Acquisition and Analysis

The BRM and LR data acquisition system consists of a flash ADC (FADC) system operating at 10 MHz, giving a measurement of the state of each PMT every 100 ns. A signal in this waveform can be characterized by the significance of its departure from previously observed mean and its variance. Every 12.8 μs, a 25.6 μs period of the waveform (256 samples) is scanned; signals of significance greater than six sigma are made available for the next level of the trigger. A mirror is triggered, and a 51.2 μs period of the waveform of every PMT is recorded, when 5 adjacent tubes with significance greater than six sigma are observed within a given 25.6 μs period. (The 51.2 μs window includes the 25.6 μs trigger window and an extra 12.8 μs on either side.) In later analysis, only tubes with a significance greater than 3.5σ are stored and considered.

The monocular analysis of BRM and LR data proceeds by finding a set of PMTs aligned in both space and in the times of their signals. The best-fit plane containing the detector and the pointing directions of these tubes is determined, the shower-detector plane (SDP) (see Figure 2). Within the SDP, the angle of the EAS must be determined by fitting the tube times[2]. This fit determines both the angle and the impact parameter of the shower (see Figure 3).

With the geometry fixed we proceed to determine the best parameters for specifying the longitudinal development of the shower. We use the "Inverse Monte-Carlo Method", where we simulate a shower with a given set of parameters and compare the output of the simulation to the observed shower. The inputs to the simulation are the Gaisser-Hillas[3] parameters $X_{\max}$ and $N_{\max}$, with the other parameters fixed: $X_0 = -60$ g/cm^2, $\Lambda = 70$ g/cm^2. The comparison is made to the number of photoelectrons observed by each PMT. This comparison divides the individual PMT acceptances for each segment out of the data, avoiding any stochasticity in the simulation (which would make it impossible to minimize the Gaisser-Hillas parameters).

With the Gaisser-Hillas parameters determined, we determine the calorimetric energy by integrating the energy deposited in the atmosphere over the shower. For this calculation we use the $\alpha_{\rm eff}$ scheme of reference[4] as adjusted for the generation parameters of the collection of showers used above. The calorimetric energy is then corrected for shower particles that don't deposit all their energy in the atmosphere (neutrinos and muons).

2.2 MD Data Acquisition and Analysis

The data acquisition system at MD is identical to that used at the HiRes-I site, where each PMT digitizes the total signal from the PMT and the time the signal went over threshold (sample-and-hold). The mirror trigger depended on coincidences between tubes in 4×4 sub-clusters of PMTs. Three tubes in each of two sub-clusters are required for the trigger. In addition, two of the three tubes in a sub-cluster must be adjacent and the sub-clusters themselves must be adjacent. The analysis of this data is similar to that done by HiRes-I. See references [1] and [5] for details. This analysis has been updated to use the same physics models as in the BRM/LR analysis described above: it now uses the FLASH fluorescence yield spectrum[6] and the Nerling energy deposit model[4].

3 Aperture Calculations

The aperture of a FD grows with energy and must be estimated through a computer calculation. To ensure the reliability of this calculation, in our case a Monte Carlo simulation, we require the simulation to produce output in the same format in which the data is stored. This simulated data set can then be analyzed in the same way as data from the detector, and distributions from each source can be compared. If there are any significant shortcomings of the simulation, they become apparent in the comparisons of observable distributions of data.

In the calculation of the aperture of fluorescence detector, comparisons of the track brightness to assess the trigger, and the distributions of distances to the showers and their angles within the SDP to check the aperture are the most important. Comparisons of these distributions for the LR site are shown in Figures 4–6. A comparison of the zenith angle distribution for the MD site is shown in Figure 7.

The end result of the MC calculation is the value for the aperture of the experiment as a function of the energy. These apertures, for all three sites, will be shown at the conference in Beijing in August.

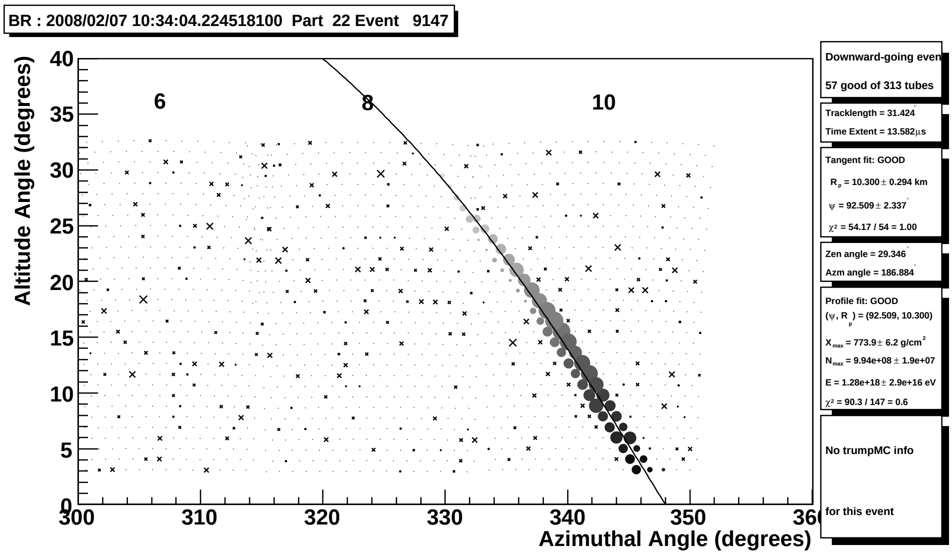

Figure 2: Mirror Plot

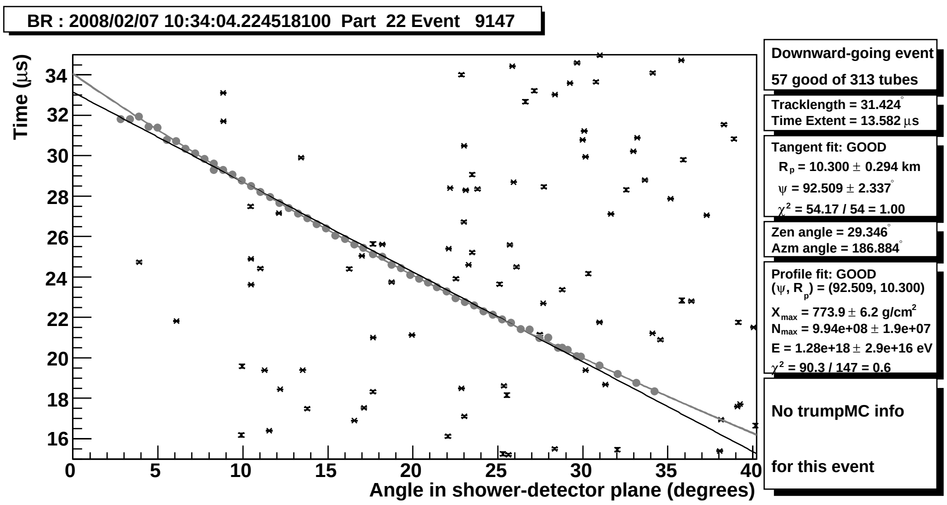

Figure 3: Time vs Angle plot

4 UHECR Flux Measurements

The spectrum of UHECRs is obtained by dividing the number of events in a given energy bin by the aperture for that bin, the width of the bin and the total running time of the experiment for the data being used. The monocular spectra from all three will be shown at the conference in Beijing in August.

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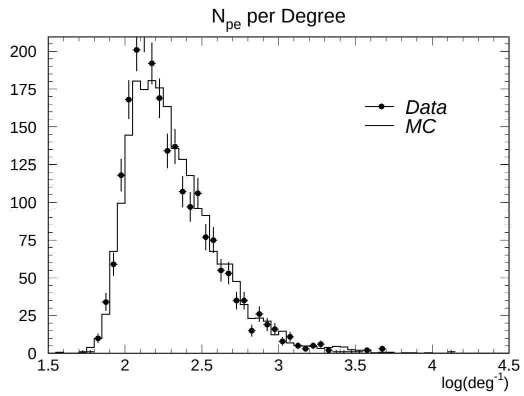

Figure 4: Data/MC comparison of the brightness of events.

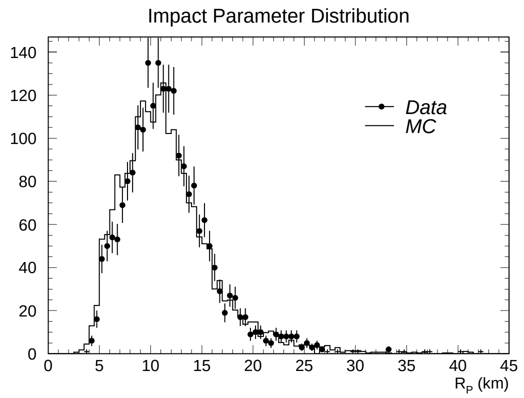

Figure 5: Data/MC comparison of the impact parameter of showers.

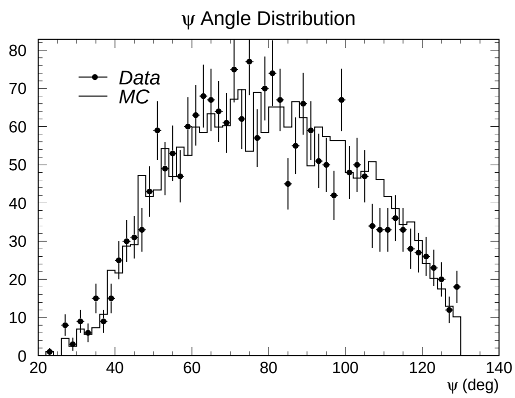

Figure 6: Data/MC comparison of the angle of showers within the SDP.

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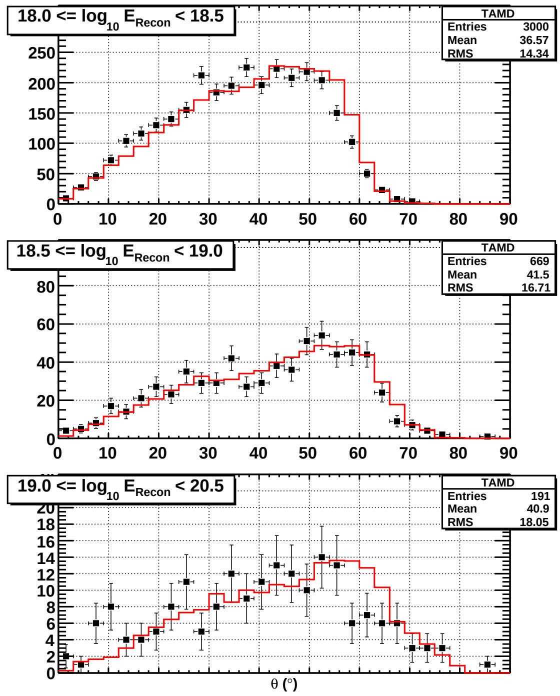

Figure 7: Data/MC comparison of the zentih angle of showers observed by Middle Drum in three enegy band: 10^{18}–$10^{18.5}$ eV, $10^{18.5}$–10^{19} eV, and above 10^{19} eV.

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