The Energy Spectrum of UHECR's using the TA Fluorescence Detectors in Monocular Mode

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Abstract. **The Telescope Array (TA) Experiment is a hybrid UHE cosmic ray detector consisting of both surface detectors and fluorescence detectors. Using each of the fluorescence detectors by itself to reconstruct extensive air showers (monocular mode) provides the widest possible range of energies for a spectrum measurement. Using the subset of events seen by more than one detectors one can also determine the relative uncertainty of each detector. We will present the energy spectra from each of the three TA fluorescence detectors along with an estimate of their individual and combined apertures.**

Keywords: **UHECR spectrum, fluorescence, Telecope Array.**

I. INTRODUCTION

The Telescope Array Experiment (TA) was designed as a hybrid experiment to observe extensive air showers (EAS's) created by ultra high energy cosmic rays (UHECR's) when they enter the atmosphere. It consists of both surface detectors (SD's) to measure the number of particles in the shower as it hits the ground and fluorescence detectors (FD's) 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 will provide 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 ($\sim$10%) also seen by one of the FD's is used. The FD's in this case provide not only a energy calibration for the SD's, 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 FD's energy 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 can cover a very large energy range, the largest of any TA component. In addition, 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).

II. TA FLUORESCNECE DETECTORS

There are three FD stations in TA, overlooking the central array of SD's. To the northeast is the Middle Drum 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 Block 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 $\sim$40% larger collecting area, leading to lower thresholds.

A. MD Data Acquision 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 subclusters of PMT's. Three tubes in each of two subclusters are required for the trigger. In addition, two of the three tubes in a subcluster must be adjacent and the subclusters themselves must be adjacent.

The analysis of this data is also identical to the used by HiRes-I. See reference [1] for details.

B. BRM & LR Data Acquision 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 a departure from previously observed mean and its variance. Every 12.8 μs, and 25.6 μs period
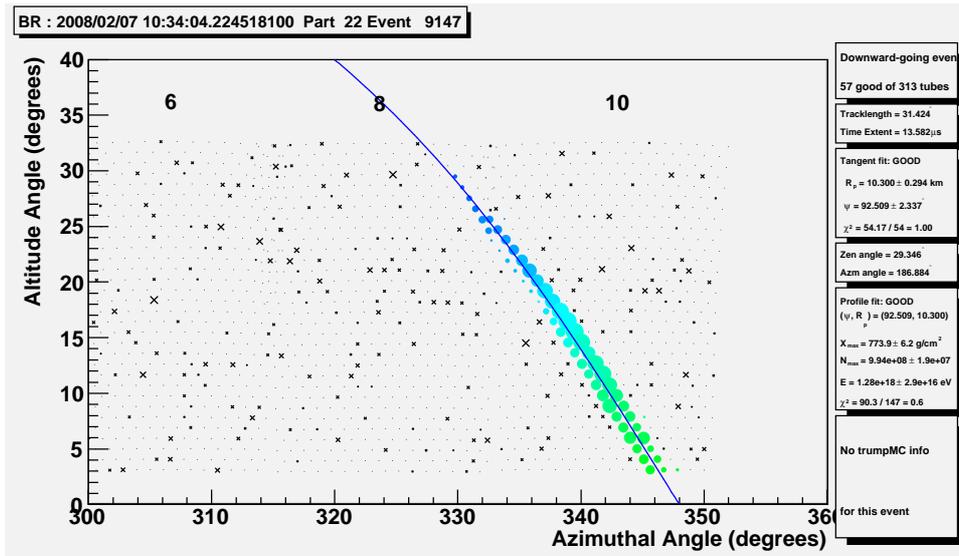
Fig. 1.   Sample event showing signal and noise PMT's and the best fit shower-detector plane.
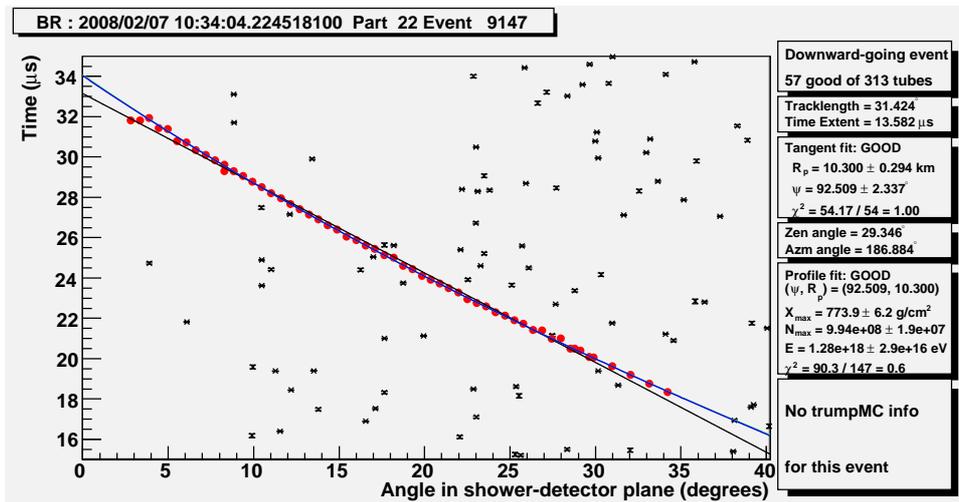

Fig. 2.   Sample event showing signal and noise tubes times vs. the angle from the horizon in the shower-detector plane and the best fit timing function.

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 PMT's aligned in both space and 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 1. 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 2.

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 input 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 in the flux of photons at the mirror for each 100 ns FADC slice. 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
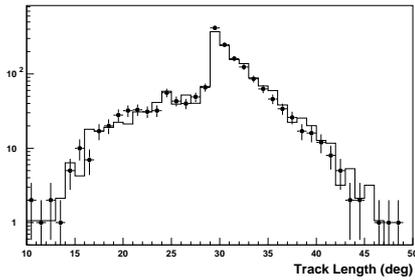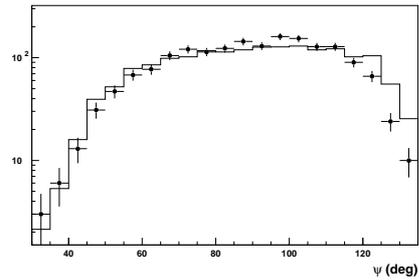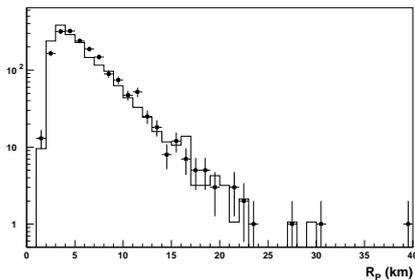
Fig. 3.   Data-MC comparison of shower track length.

Fig. 5.   Data-MC comparison of shower angle within SDP, ψ (deg).

Fig. 4.   Data-MC comparison of impact parameter, R_P (km).

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).

The number of observed events as a function of energy will be shown at the conference in Poland in July.

III. 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. Any shortcomings of the simulation become apparent in the comparisons of some observable distribution of data or they are not significant.

In the calculation of the aperture of fluorescence detector, comparisons of the track length 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 each of these distributions for the BRM site are shown in Figures 3–5.

The result of the MC calculation is the aperture of the experiment as a function of the energy. The aperture calculation for both MD and BRM will be shown at the conference in Poland in July.

IV. UHECR FLUX MEASUREMNTS

The spectrum of UHECR's 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 spectra from both MD and BRM will be shown at the conference in Poland in July.

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