Toward a comparison of fluorescence energy scale and spectra between Telescope Array and the High Resolution Fly's Eye

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***Abstract*. One of the three fluorescence stations in the Telescope Array (TA) Experiment was constructed using refurbished telescopes from the High Resolution Fly's Eye (HiRes) Experiment. Specifically, the TA Middle Drum (MD) site is instrumented with detectors previously used at the HiRes-1 site. The inclusion of the MD site makes possible a direct comparison between the fluorescence energy scales and spectra between TA and HiRes. We will present a progress report on the analysis of the TA data collected by the MD site.**

***Keywords*: ultrahigh-energy spectrum comparison**

I. Introduction

The Telescope Array (TA) Experiment in the Western Central Utah Desert just northwest of the town of Delta, Utah. The TA collaboration includes a number of former member institutions of the Akeno Giant Air Shower Array (AGASA) [1] and of the High Resolution Fly's Eye (HiRes) Experiment [2]. New groups from South Korea and Russia have also recently joined TA.

II. The TA Detector Systems

The layout of the TA experiment is shown in Figure 1. The octagon in the interior shows the footprint of the ground array of 507 SD counters. The triangles show the locations of three FD sites. The fan-shaped wedges show the approximate coverage of the three fluorescence detectors for air showers of 10^{19} eV in energy. The circle in the center of the SD array is the Central Laser Facility (CLF). The CLF is placed so that it is equi-distant from the three FD stations. The telescopes are also arranged in such a way that vertical laser shots from the CLF are seen in the center of the field of view of each FD site.

Detailed descriptions of the TA SD array are given in reference [3]. New telescopes using 14-bit, 10 MHz FADC read-out systems with larger, segmented mirrors were constructed for the two southern FD sites. The details of these systems can be found in [4]. The northern FD site is located at Middle Drum (MD) and will be referred to by this name. The MD station, marked TA-FD2 in Figure 1, was constructed from the original 14 telescopes of the HiRes prototype detector that produced the HiRes-MIA spectrum and composition results in the 10^{17} – 10^{18} eV decade [5]. The same 14 telescopes

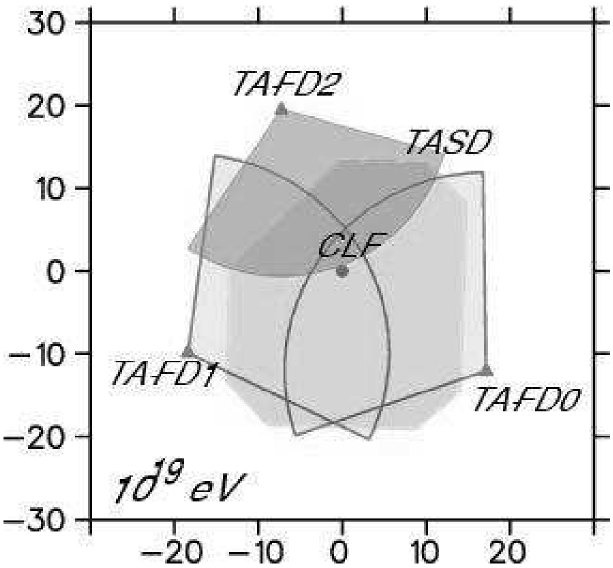

Fig. 1. Diagram showing the layout of the Telescope Array Experiment. The axis labels show distance in kilometers north/south and east/west of the Central Laser Facility.

also comprised 2/3 of the HiRes-1 detector site [6] that began observations in June of 1997. Monocular data from the HiRes-1 detector site also contributed most of the statistical power for the first observation of the Greisen-Zatsepin-K'uzmin (GZK) cut-off [7], [8], [9]. The performance of these 14 telescopes are well understood [10] and provide the possibility of a direct comparison to past HiRes results.

III. TA Middle Drum Fluorescence Detector

Figure 2 shows a photograph of the Middle Drum detector site. The telescopes are instrumented with 2 m diameter mirrors each made from four clover-leaf segments. Subtracting obscuration from the camera, the mirrors each have an effective light collection area of 3.7 m^2. Each camera consists of 256 two-inch photomultiplier tubes (PMT) arranged in a row-wise hexagonal close-pack configuration. Each PMT pixel views a one-degree cone in the sky, and each camera has a $16°$(azimuth) $\times 14°$ (elevation) field-of-view (FOV). The viewing directions of the telescopes are shown in figure Figure 3, which also display of a vertical xenon flasher event.

Fig. 2. Photograph of the Middle Drum FD mirror building before PMT cameras were installed. The 14 mirrors are pointed alternately at 10° and 24° to provide overall coverage between 3°–31° in elevation and 114° in azimuth toward the SD array.

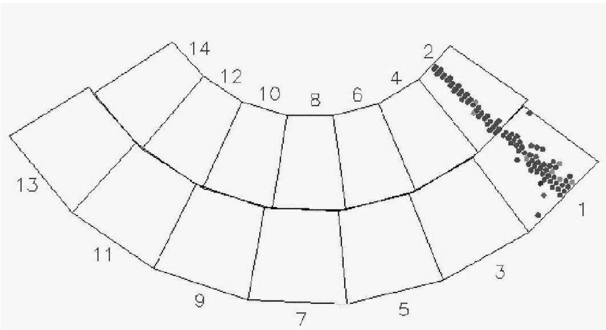

Fig. 3. The diagram of the two-layer layout of the Middle Drum telescopes. The telescopes on the left of the diagram are pointing south. The lower and upper edges of the telescope coverage are at 3° and 31°, respectively. The two right most telescopes are displaying an event from a vertical xenon flasher.

The PMT cameras and readout electronic systems were retrieved from the HiRes-1 site in the spring of 2007 and were refurbished during the summer. The construction of the Middle Drum site was completed in the fall. The only major upgrade made to the system were (a) a new central timing system that provides GPS synchronization replacing an older system, (b) a new twisted-pair LAN replacing a 10-base2 coaxial cable network, and (c) A satellite-based WAN connection. The first shake-down run of the site took place during the October–November dark period. The first production-quality data were taken in December of 2007.

IV. Data Collection and Calibration

For presentation at the 2009 ICRC, the analysis of the Middle Drum data will be based mostly on the first year of data taken between December 2007 and December 2008. During this one year period, the Middle Drum FD station was operated for about 965 hours, accumulating 785 hours of good weather data These corresponds to 11.0% and 9.0% duty cycle, respectively.

The energy scale of the reconstruction and aperture calculation are critically dependent on the correct photometric scale, precise tracking of the detector thresholds, and real-time measurement of the aerosol content during data-taking. The photometric scale is monitored using a combination of a system of UV flashing LED that tracks the gain variations of the telescopes through the course of a month, and a high-stability, roving xenon flasher (RXF) that is used to illuminate one telescope at a time. The RXF is also used to obtain a primary cross-calibration between the three FD stations. At the time of writing of this article the energy scale for the reconstructed events is still being refined and has a systematic uncertainty at about the 20% level.

The detector thresholds at the Middle Drum are read-out once per minute. In general they vary slowly and track very well with the changes measured quantum efficiencies of the PMT cameras (mostly due to temperature variations) over long periods of time. These are dependent on the ambient background light levels and were not expected to be correlated to that of the HiRes sites. In fact the running thresholds at Middle Drum were on average about 25% lower than at HiRes-1 with the same set of telescopes. The correct input threshold is crucial in the accurate determination of the detector aperture.

An important check to ascertain that the thresholds are set correctly in the Monte Carlo (MC) simulations is to make comparisons between data and MC distributions of key quantities. In Figure 4 we show a comparison of the distribution of the average number of photo-electrons per photo-tube associated with an air shower. We refer to these as ”good tubes” to exclude random PMT hits from night-sky fluctuations. Figure 5 shows a similar comparison for the data and MC distributions of the reconstructed impact parameter of the air showers from the Middle Drum site. Both comparisons show excellent agreement between the data and the simulation. We display here the comparison in the $10^{18.0} - 10^{19.0}$ eV which represents the bulk of the data to be included in the first spectrum. Similar data–MC agreement is seen also at both higher ($> 10^{19}$ eV) and lower energies ($10^{17.5} - 10^{18.0}$ eV).

The measurement of aerosol concentrations is done using a combination of a mono-static LIDAR located at the Black Rock Mesa FD site (TA-FD0), and vertical shots from an energy-tripled YAG laser (550 nm) located at the CLF. Preliminary studies have shown reasonable agreement between the LIDAR and the CLF results. While these measurements are still being refined and will be reported independently[11], the average vertical aerosol optical depth (VAOD) is not expected to deviate much from the 0.04 observed for good weather nights by the HiRes experiment [12] which had been located only about 100 km north of the TA stations.

Assuming horizontal uniformity in the aerosol concentration near the ground, the vertical laser shots from the CLF should produce equal light fluxes from a given elevation. Shot-to-shot comparison of the observed laser

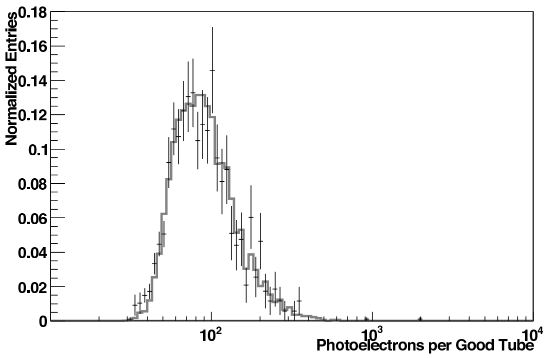

Fig. 4. Data–MC comparison for events reconstructed between $10^{18.0} - 10^{19.0}$ eV of the distribution of the average number of photo-electron per "good" tube. In this context a "good" tube is one that is in spatial and temporal correlation with the cosmic ray event, and not a random hit from night-sky fluctuations. The data points with error bars correspond to the data distribution.

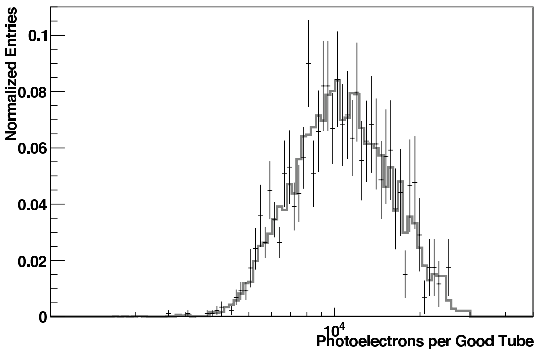

Fig. 5. Data–MC comparison for events reconstructed between $10^{18.0} - 10^{19.0}$ eV of the distribution of reconstructed impact parameter, R_P (in km). Again the data points with error bars correspond to the data distribution.

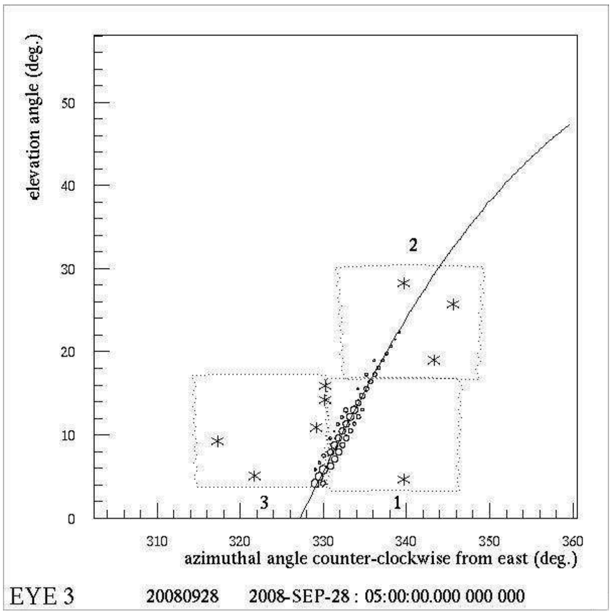

Fig. 6. Display of a Middle Drum Event reconstructed at 3×10^{19} eV. crossing three telescopes.

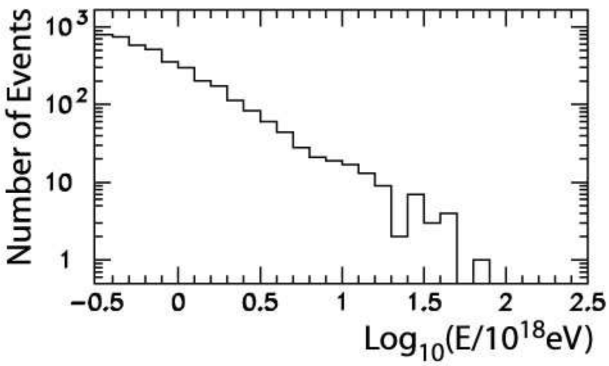

Fig. 7. Distribution of reconstructed $\log_{10}\left(E/10^{18}\mathrm{e}V\right)$ for events above $10^{17.5}$ eV, seen my the TA Middle Drum FD station.

tracks provides an end-to-end cross-calibration of the photometric scales between the three FD stations.

V. Preliminary Analysis of Middle Drum data

The data set from Dec 2007 to Dec. 2008 represents an overall exposure at 10^{20} eV comparable to just under 1/2 that of the AGASA experiment, or about 1/10 that of HiRes. In this preliminary analysis, where the energy scale uncertainty is at the 20% level, a total of about 1100 events were reconstructed above 10^{18} eV, and 56 events were seen above 10^{19} eV. An example of an event reconstructed at about 3×10^{19} eV is shown in Figure 6.

The reconstruction and detector simulation codes were previously used for the HiRes-1 monocular reconstruction used for the GZK analysis. The only changes made were that (a) the detector geometry was altered to reflect the two-ring configuration at Middle Drum, and (b) the detector thresholds in the simulation were changed to match the lower thresholds for operations at MD.

The distribution of reconstructed energies is shown in Figure 7. No events were seen above 10^{20} eV. At the time of writing of this report, work is under way to generate a full Monte Carlo set for the calculation of the detector aperture needed to generate an energy spectrum.

VI. Toward a direct comparison between HiRes and Telescope Array

A primary goal of the TA experiment is to resolve the difference between the AGASA and HiRes results. For this purpose, the experiment is designed to have coincident measurements of showers between the FD and SD arrays. The MD site is however 8 km from the nearest SD counter. The coincident event sample between the MD fluorescence detector and the SD array is therefore smaller than those of the other two stations.

The SD array started data taking a few months later than the MD site, and initial operation was restricted to running the array as three separate sub-arrays. These factors further limit the coincidence data volume for now. Furthermore, the MD-SD coincident data set is dominated by low energy events below 10^{18} eV. The SD array becomes fully efficient only just below 10^{19} eV. So these represent a biased low-energy data sample with abnormally deep showers that trigger the surface array.

For a direct comparison between TA and HiRes we will initially rely mainly on a comparison of the spectra measured by the three FD stations, and using hybrid events seen between the two southern FD stations and the SD array. Direct photometric cross-calibrations will be provided both by the RXF calibration and by co-incident observations of the vertical CLF laser shots. Data have been collected for both methods, and analysis efforts are under way to produce both FD and SD spectra. These will be reported elsewhere [13], [14].

For the longer term, a full-array trigger has been in operation since the start of 2009, and a hybrid trigger will be implemented that will enable of small events in time coincidence with FD triggers. These will improve the statistics of coincidence events and will permit hybrid reconstruction of events at the MD fluorescence detector.

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