



Energy Calculation of Ultra High Energy Cosmic Rays in MD Hybrid Mode with Telescope Array

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Abstract: The Telescope Array experiment studies ultra high energy cosmic rays at energies $> 10^{18}$ eV using a hybrid detector. Fluorescence telescopes measure the longitudinal development of the extensive air shower generated by a primary cosmic ray particle. Meanwhile, scintillator surface detectors measure the lateral distribution of secondary particles that hit the ground, the "footprint" of the shower. The Middle Drum (MD) fluorescence detector is one of three telescope observatories overlooking the array of 507 scintillator detectors. It is located at the northwest corner of the Telescope Array and consists of 14 refurbished telescopes from the High Resolution Fly's Eye experiment (HiRes). Since the MD site reuses telescopes from the HiRes experiment, it provides a direct link back to the HiRes experiment and data. Using the scintillator surface detector data in conjunction with the MD telescope data improves the geometrical reconstruction of the showers, and hence, provides a more accurate reconstruction of the energy of the primary particle. A comparison of hybrid energy to monocular energy will be presented as well as a link between this experiment and the HiRes experiment.

Keywords: Telescope Array, Hybrid

1 Telescope Array

Telescope Array (TA) is an international collaboration between universities from U.S., Japan, Korea, Russia and Belgium. The experiment has been fully operational since 2008. TA is a hybrid experiment designed to measure spectrum, composition and anisotropy of Ultra High Energy Cosmic Rays (UHECR). The TA experiment is comprised of 38 telescopes spread over three fluorescence detector (FD) sites. These three sites are situated at the periphery of a surface detector (SD) array of 507 scintillation counters spread over ~ 750 km². The two southern FD sites, equipped with newly designed and constructed FADC read out and 3 m² mirrors, are located at Black Rock Mesa (BRM) and Long Ridge (LR). The northwestern site is located at Middle Drum (MD), and is equipped with 14 refurbished telescopes from the HiRes-1 site of the High Resolution Fly's Eye (HiRes) experiment.

1.1 Middle Drum Hybrid

The use of the refurbished HiRes-1 telescopes at Middle Drum served to reduce the construction cost and development time of TA. More importantly, the use of the same equipment that provided most of the event statistics of the first observation of the GZK cut-off [1] gives TA a direct link and cross-calibration to the HiRes experiment. The monocular energy spectrum based on one year of data from

the MD detector was shown at the 31st International Cosmic Ray Conference in Poland [2].

The MD monocular analysis used the same profile constrained fit (PCF) that was previously used for the HiRes monocular spectrum [1][3]. In fact, the same HiRes simulation and reconstruction code was used for MD. Therefore, a direct comparison between Middle Drum and HiRes can be performed [4]. Logically, the next step in this process is to link the MD analysis to the SD array. The hybrid analysis of the Middle Drum data can be directly compared to the hybrid results from the BR and LR detectors [5], leading to a link between HiRes and the full TA experiment. In this paper, we report on the progress of the MD hybrid studies, with the immediate goal of producing a hybrid energy spectrum using MD data. In the longer term, MD hybrid data will also be used for composition and anisotropy studies.

2 Middle Drum Hybrid Data and Reconstruction

The Middle Drum detector has been making routine observations since December, 2007. The surface array has been operational since May, 2008. The hybrid analysis uses the data collected between May, 2008 and September, 2010. Hybrid events were identified by comparing the trigger times of MD FD triggers to those of the SD. Coincident events between the two detectors within a microsecond window were selected. The time-matching yielded a

total of 905 hybrid events during this observation period. The hybrid reconstruction algorithm is described in reference [5]. A shower detector plane (SDP) is reconstructed from the pointing direction of triggered photomultiplier tubes (PMTs). Within the SDP, the shower axis is obtained from a fit of the PMT trigger times (timing-fit) assuming the shower front propagates at the speed of light. But in addition, the trigger time of an SD counter near the SDP, and the shower core location determined from the SD data, are used to constrain the FD timing-fit.

Once the shower geometry has been calculated, the pointing directions of the triggered PMTs are projected onto the reconstructed shower axis. The integrated pulse areas are then converted to shower profile: the number of photons per track length per collection area vs. shower slant depth. The profile is then fitted to a Gaisser-Hillas parametrization of the number of charged particles vs. depth [4]. The calorimetric energy of the shower is then determined from the integral of this curve, and the energy of the primary particle is determined by applying missing energy correction to the calorimetric energy to account for the invisible energy carried off by energetic neutral particles in the shower.

3 Middle Drum Hybrid Monte Carlo

Monte Carlo (MC) simulations are used to determine how well the reconstruction programs perform. The MC data set generated for this analysis assumed an isotropic distribution and was sent through the same processing and reconstruction programs that were performed on the data. The input energy for the simulated event set was thrown with a spectral index of 3.25 below $10^{18.65}$ eV and 2.81 above $10^{18.65}$, between $10^{17.9}$ eV and $10^{21.0}$ eV. These spectral indices were taken from the HiRes monocular spectrum [1], and included 25,727 MC events that triggered both the Middle Drum detector and the surface array. This is approximately 25 times the number of data events that were analyzed in hybrid mode.

3.1 Resolution

Resolution plots show the distribution of the difference (fractional where applicable) between the thrown and the reconstructed energy and geometrical parameters for the MC events. This is a good indicator of how well the reconstruction programs perform. The three primary parameters that show the quality of the reconstruction are impact parameter, R_P (figure 1), the in-plane angle, Ψ (figure 2), and the energy. In comparison with Middle Drum monocular reconstruction, the improvement in hybrid is an order of magnitude in both R_P and Ψ . The energy is improved by a factor of 2. Here it is shown in energy range of $10^{18.5-19.0}$ eV (figure 3), which is the range in which hybrid performs the best energy reconstruction.

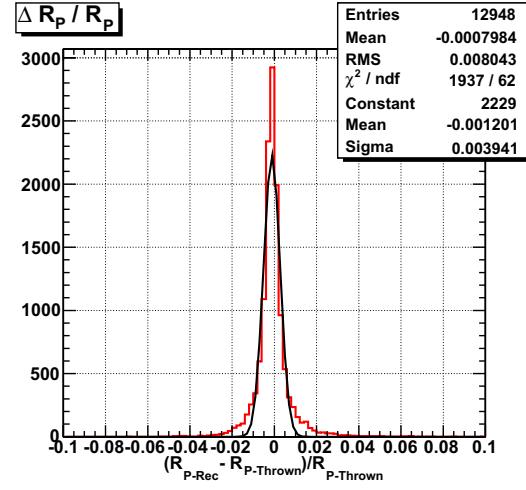


Figure 1: Middle Drum Impact Parameter, R_P , Resolution. Shown is the normalized difference between the reconstructed and thrown R_P for each event. The red histogram shows the Monte-Carlo data, and the black line shows the gaussian fit to the data.

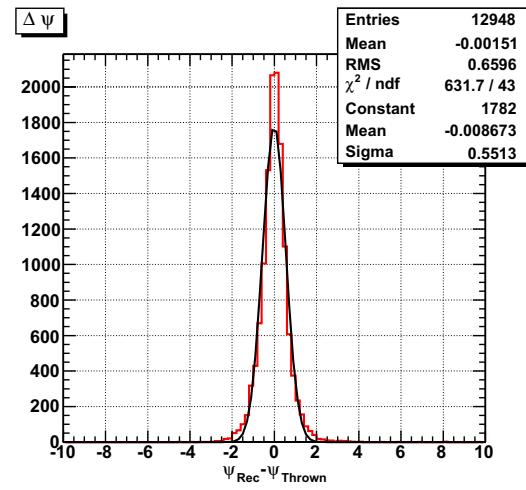


Figure 2: Middle Drum In-Plane Angle, Ψ , Resolution. Shown is the difference between the reconstructed and thrown Ψ angle for each event. The red histogram shows the Monte-Carlo data, and the black line shows the gaussian fit to the data.

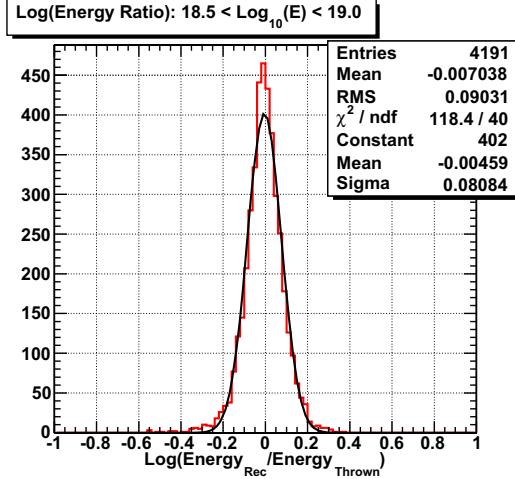


Figure 3: Middle Drum Energy resolution for events with energy between $10^{18.5}$ and $10^{19.0}$ eV. Shown is the log of the ratio of the reconstructed and thrown energy for each event. The red histogram shows the Monte-Carlo data, and the black line shows the gaussian fit to the data.

3.2 Data-MC Comparison

In order for the resolutions obtained above to be meaningful, the MC simulation must give a good representation of the data. It is therefore important to compare the actual distributions of the same key geometrical parameters: R_P and Ψ . The distribution of these parameters also define the FD acceptance. The fidelity of the simulation of the acceptance is of particular importance to the eventual measurement of the energy spectrum.

To establish that our hybrid MC gives a good account of the hybrid MD data, we make data-MC comparisons, where we compare directly the distributions of the reconstructed events in the MC to that obtained from real data. Unlike the resolution plots, here we are not making an event-by-event comparison of the reconstructed quantity to the thrown within the MC. Instead, the distributions of the reconstructed R_P and Ψ are compared between data and MC. The plots of the data-MC comparison for R_P and Ψ are shown in figures 4 and 5, respectively. In each case, the MC is normalized to the total number of data events. While the statistics are small for the data, the simulated distributions are in good agreement with the data in both parameters.

4 Summary

We have shown that hybrid reconstruction of the FD data from the TA Middle Drum site significantly improves the geometrical and energy resolutions over that of the monocular reconstruction. An energy spectrum from MD hybrid data will be completed in the near future. Study of the X_{max} reliability and resolution will begin soon with the goal of making a composition measurement.

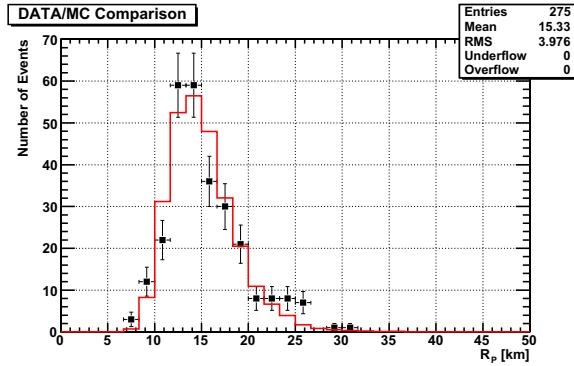


Figure 4: Middle Drum Impact Parameter, R_P , Data-MC comparison. Black points indicate the real data, and the MC is shown in the red histogram.

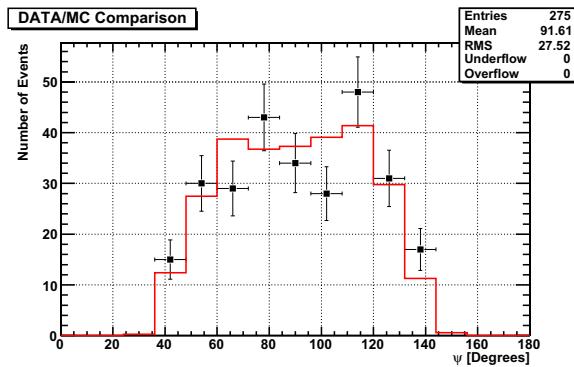


Figure 5: Middle Drum In-Plane Angle, Ψ , Data-MC comparison. Black points indicate real data, and the MC is shown in the red histogram.

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