PROCEEDINGS OF SCIENCE

The Cosmic Ray Energy Spectrum above 2 PeV measured by the TALE Fluorescence Telescopes

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The Telescope Array (TA), deployed in the desert of central Utah, is the largest hybrid cosmic ray detector in the Northern Hemisphere. It was initially designed to observe ultra high energy cosmic rays with energies $> 10^{18}$ eV. To lower the energy threshold of the experiment, TA added an extension, known as the Telescope Array Low-energy Extension (TALE), consisting of high elevation-angle telescopes and a dense graded array of scintillator surface detectors to the existing main array. Including TALE telescopes, the TA Middle Drum (MD) site has a field of view 114° in azimuth and 3-59° in elevation. In this work, I will present a measurement of the cosmic ray energy spectrum using data collected by the TALE telescopes in monocular mode with energy above 2 PeV.

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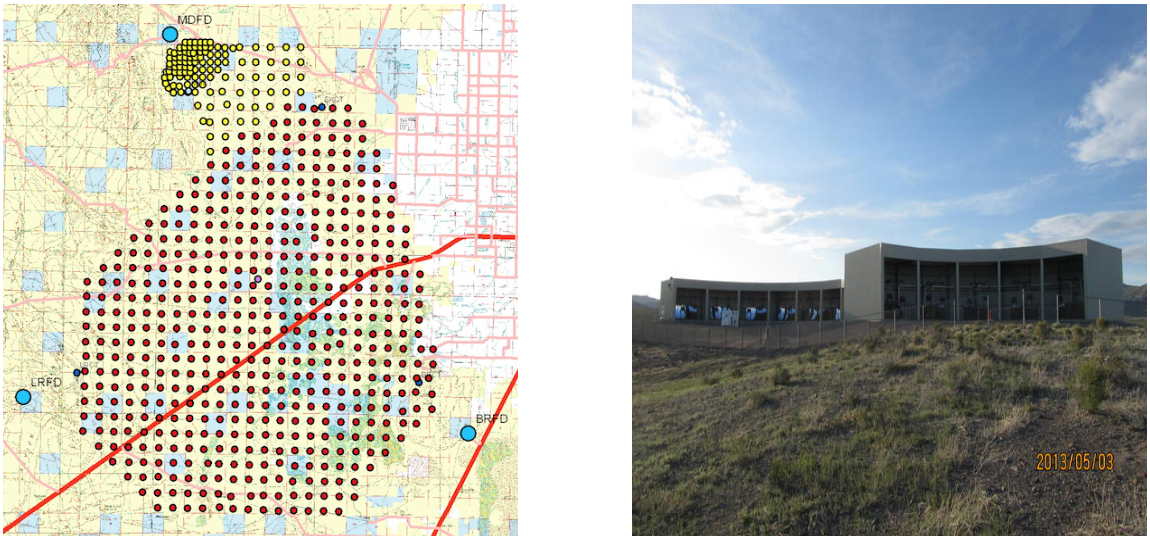
1. Introduction

The Telescope Array (TA) is deployed in Millard County, Utah, USA. It mainly observes Ultra High Energy Cosmic Rays (UHECRs), using both fluorescence telescopes and scintillator surface detectors. A map of the detectors is shown in Figure 1a. Using the fluorescence telescopes, we measure the scintillation light isotropically emitted by air molecules during the development of air shower created by cosmic rays. Three telescope stations overlook the scintillator array. The Middle Drum (MD) station [1] is in the northern most location of the TA and the Black Rock and Long Ridge fluorescence stations [2] are located in the southeast and the southwest, respectively. Additionally, an array of 507 scintillator surface detectors [3] is deployed in a square grid with 1.2 km spacing. The scintillator surface detector array, at the same time, is used to observe the footprint of the development of the air shower by sampling the density of shower particles arriving at the ground. In addition to the detectors, the Central Laser Facility (CLF) is located equidistant (20.85 km) from each fluorescence stations to monitor the atmosphere at the observatory.

The Telescope Array has added an extension to lower the experiment's energy threshold allowing us to study cosmic rays with energies down below 10^{16} eV. This extension is known as the Telescope Array Low Energy extension (TALE) shown in Figure 1b. High-elevation-angle telescopes and a graded infill array of more closely packed scintillator surface detectors at the TA Middle Drum (MD) station were added to help make measurements of lower energy cosmic ray



(a) Map of Telescope Array and TALE detectors.

(b) MD/TALE buildings.

Figure 1: Map of Telescope Array and TALE detectors. (a) Locations of the scintillator Surface Detectors (SD) are shown as red points and the locations of the three Fluorescence Detector (FD) stations are indicated by the blue points. Locations of the scintillator Surface Detectors for TALE are shown as yellow points. The purple point indicates the location of the CLF. (b) The lower building on the left is the main TA building which contains 14 telescopes viewing 3-31° elevation. The taller building on the right has 10 TALE telescopes viewing 31-59° elevation above the main TA telescopes.

showers. While the TA MD telescopes view only 3°-31° in elevation, the TALE extension telescopes view the sky above the MD telescopes and increase the elevation viewing angle up to 59° which makes it possible to observe Cherenkov events. This enables us to observe the full development of lower-energy showers which starts higher in the atmosphere. With a larger field of view, we can see longer tracks and this gives us additional information about shower geometry and profile.

The goal of the TALE spectrum analysis is to determine the flux of cosmic rays down to 10^{15} eV and identify some interesting spectral features such as the second knee and even the knee. One such feature, called as the second knee, may imply a composition transition from galactic to extra-galactic cosmic rays above 10^{17} eV. The TALE energy spectrum can be directly compared to satellite-based cosmic rays measurement and connected to the TA high energy cosmic ray energy spectrum measurement. For this analysis, we utilize a monocular reconstruction of the shower energy of events observed by the TALE telescopes.

2. Event reconstruction and selection

About 4 years of data from June 2014 to November 2018 were analyzed for the cosmic ray spectrum. Total detector on-time is 2633.33 hours and this data set of the cosmic ray spectrum from $10^{15.3}$ to $10^{18.3}$ eV contains a mixture of Cherenkov and fluorescence events. At the lowest energies, events are mostly by Cherenkov events and in energy between $10^{16.5}$ and $10^{17.5}$ eV, events are typically composed of a mix of both Cherenkov and fluorescence events which is called mixed signal events. In this analysis, fluorescence-dominant events were excluded in order to match event selection criteria used for the TALE composition analysis.

The events are reconstructed in monocular mode with the geometry determined by the equation

$$t_i = t_0 + \frac{R_p}{c} \cdot \tan\left(\frac{\pi - \psi - \chi_i}{2}\right), \tag{2.1}$$

where t_i and χ_i are the trigger time and pointing direction of tube i, respectively; ψ is the in-plane angle; R_p is the impact parameter of the shower; c is the speed of the light; and t_0 is the time when the shower is calculated to be at R_p.

The profile of the shower is fitted using the Gaisser-Hillas parameterization formula [4]

$$N(x) = N_{\max} \cdot \left(\frac{x - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\lambda}} \cdot e^{\frac{X_{\max} - x}{\lambda}}, \tag{2.2}$$

where $N(x)$ is the number of charged particles at a given slant depth, x, in g/cm^2; $X_{\max}$ is the slant depth where the number of secondary particles reaches the maximum; $N_{\max}$ is the maximum number of particles at $X_{\max}$; X_0 is a fit parameter associated with the depth of the first interaction; and λ is 70 g/cm^2 fixed, explaining the width of the shower profile. The low energy events, however, have too short track lengths in order to carry out geometry reconstruction alone. For this case, the profile-constrained geometry fit is applied to reconstruct events for a combined fit to shower geometry and shower profile.

An example of the data event triggered by the TALE telescope is shown in Figure 2. It shows typical one telescope Cherenkov event observed by the TALE detector. The right hand side panel shows an event display with PMT pixels, the middle panel shows a reconstructed shower profile

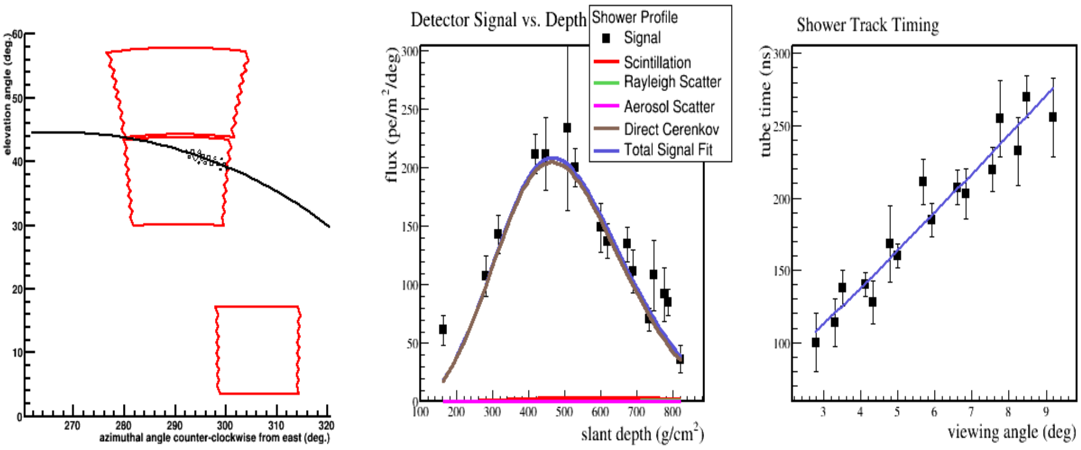


Figure 2: An example of the data event triggered by the TALE telescope [5].

with contributions of variety of light production mechanisms, and the left hand side panel shows time versus angle fitting. As can be seen from the figure, most of the signal come from the direct Cherenkov light. Also note, this event has about 7° long track within 200 ns duration.

To obtain good resolution and Data/Monte Carlo comparisons, quality cuts were performed on the fully reconstructed showers. These cuts were optimized for the Cherenkov-dominant and mixed signal events observed by TALE station. An event is retained if:

- An event is successfully reconstructed.
- Observed $X_{\max}$: Cherenkov-dominant events and mixed signal events should be between 435 to 920 g/cm^2.
- Geometry: track length must be $> 6.1^\circ$. Cherenkov-dominant events are defined if events have more than 55% of direct Cherenkov contribution out of the total signal and mixed signal events are defined if events have more than 35% of direct Cherenkov contribution out of the total signal.

3. Monte Carlo simulation

`CONEX` simulated shower library with EPOS-LHC for proton, helium, CNO, and iron primaries was used. These showers were thrown from 1×10^{15} to 3×10^{18} eV with the spectral index of 2.92. The Monte Carlo simulated an isotropic distribution in the azimuthal angle, the impact parameter, R_p, was thrown up to about 36 km, and zenith angle, θ, was thrown up to 70°. For all four primaries, the equal number of events were thrown. The atmospheric profiles are implemented from the GDAS database which is provided every three-hour-long and a value of the atmospheric vertical aerosol optical depth is fixed with 0.04.

Figure 3 and 4 show the resolution of important parameters from reconstruction for the TALE monocular spectrum analysis. In figures, all Cherenkov-dominant and mixed signal events were included regardless of energy and primary. We evaluate the resolutions of 1° in ψ angle, 7% in R_p, 17% in energy, and 46 g/cm^2 in $X_{\max}$. For events with energy less than $10^{16.0}$ eV, we obtain

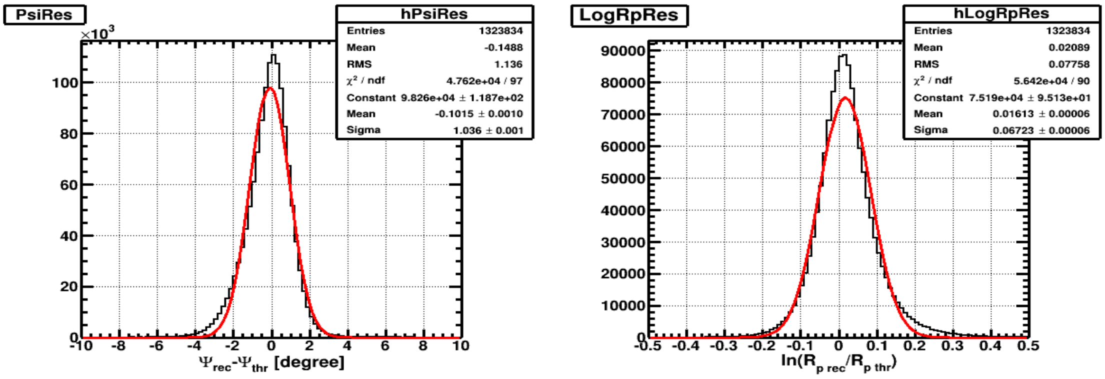


Figure 3: Resolution studies using Monte Carlo events. Left: the in-plane angle, ψ. Right: the impact parameter, R_p. The Gaussian fit is used to determine the detector bias and resolution.

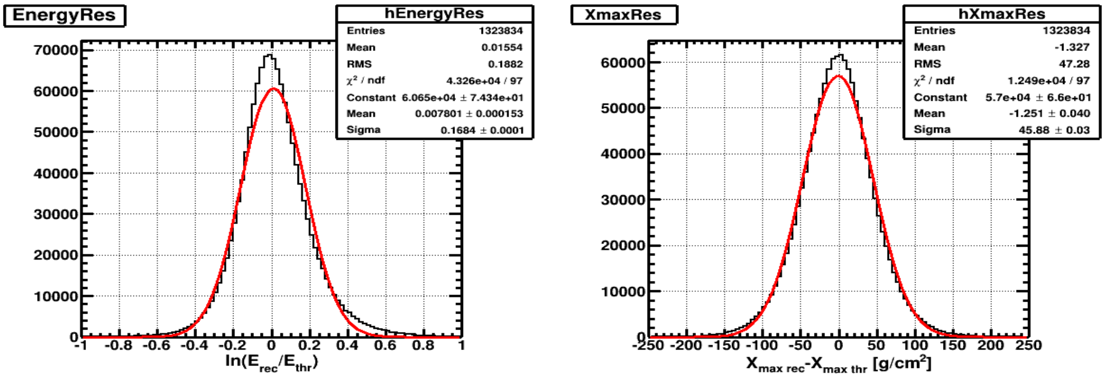


Figure 4: Resolution studies using Monte Carlo events. Left: the total energy. Right: the shower maximum depth, $X_{\max}$. The Gaussian fit is used to determine the detector bias and resolution.

the resolutions of 1° in ψ angle, 8% in R_p, 19% in energy, and 49 g/cm^2 in $X_{\max}$. For events with energy greater than $10^{16.0}$ eV, the resolutions are better: 1° in ψ angle, 4% in R_p, 13% in energy, and 41 g/cm^2 in $X_{\max}$.

4. Data/MC Comparisons

To check if the Monte Carlo reasonably represents the data, measurable parameters' distributions were plotted. The Monte Carlo and Data were applied the same quality cuts to be compared. Among measurable parameters, the impact parameter and zenith angle parameter are important to determine the aperture. Figure 5 shows Data and Monte Carlo comparisons for in-plane angle (ψ), impact parameter (R_p), azimuthal angle (ϕ) and zenith angle (θ). Black data points and red Monte Carlo histogram are in good agreement.

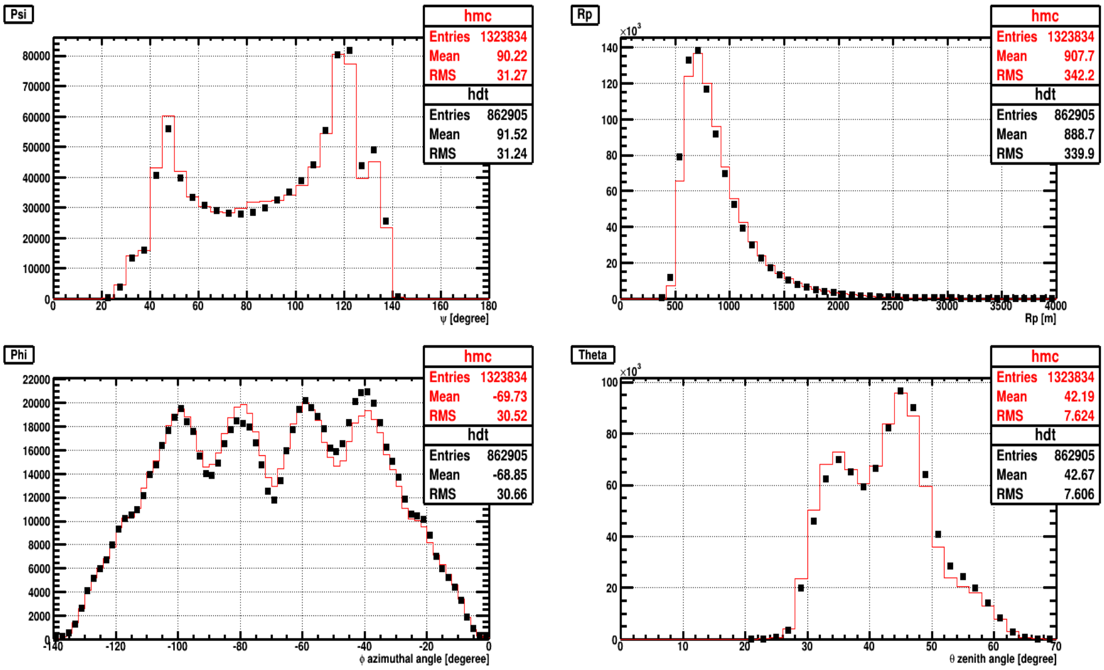


Figure 5: Data/Monte Carlo comparisons. Top left: in-plane angle, ψ. Top right: the impact parameter, R_p. Bottom left: the azimuthal angle, ϕ. Bottom right: the zenith angle, θ. The black points with error bars show the data, while the Monte Carlo is shown by the red histogram. The Monte Carlo has been normalized to the same number of events as the data.

5. Results and Discussion

The Telescope Array has been extended to lower the experiment's energy threshold, allowing for the study of cosmic rays with energies below 10^{16} eV. The extension is called the Telescope Array Low Energy extension (TALE). The Telescope Array and TALE together enable the observation of the full development of lower-energy showers which initiate higher in the atmosphere and observe cosmic rays covering four decades in energy using the same suite of detectors. For this analysis, we analyze about 4 years of data from June 2014 to November 2018 and use a monocular reconstruction of the TALE telescope data with Cherenkov-dominant and mixed signal events. The resolution of the shower energy and geometric variables shows good agreement between the thrown and reconstructed values. Data and Monte Carlo comparisons for energy and geometrical variables are in good agreement. The composition dependence of the aperture was taken into account during the aperture calculation. The cosmic ray energy spectrum measured by the TALE telescopes from $10^{15.3}$ to $10^{18.3}$ eV will be shown and the spectral features will be discussed in the conference.

References

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