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Cosmic ray energy spectrum in the 2nd knee region measured by the TALE-SD array

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The Telescope Array Low energy Extension (TALE) experiment in Utah, U.S.A., consists of 10 atmospheric fluorescence telescopes and 80 Surface Detectors (SDs) spread over an area of 21 km^2. The SD array consists of 40 SDs at 400 m spacing and 40 SDs at 600 m spacing. The TALE-SD was completed in February 2018 and has been in steady operation since then, triggering at a rate of about 30 air shower events in 10 minutes. We have developed the software to measure the energy spectrum of cosmic rays from the data obtained by TALE-SD. The performance of the software was evaluated by using air shower events generated by Monte Carlo simulation. We estimate that when the energy of the primary cosmic ray is $10^{18.0}$ eV, the accuracy of energy determination is 20%, the accuracy of arrival direction determination is 1.5°, and the aperture is 16 km^2 sr. We also compared the MC and Data to see if they were consistent. In this presentation, we will report these results.

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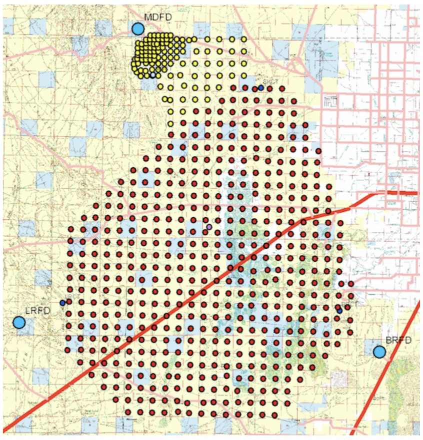
1. Introduction

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. There are 507 surface detectors with about 700 km^2 effective detection area and The three TA FD stations, which are called Black Rock Mesa (BRM), Long Ridge (LR), and Middle Drum(MD). These TA FD telescopes are viewing 3 ° to 31 ° in elevation. A map of the detectors is shown in left Figure 1.

The Telescope Array also has an extension to lower the experiment's energy threshold allowing us to study cosmic rays with energies down below $10^{16.0}$ eV. This extension is known as the Telescope Array Low Energy extension (TALE) shown in right Figure 1. In the TALE experiment, 10 Fluorescence detectors, which observes at a higher elevation angle than the TA-FD, and 80 surface detectors, which is installed at a higher density than the TA-SD, are installed next to the TA experiment. The full details of the detectors are found in [1] [2] .



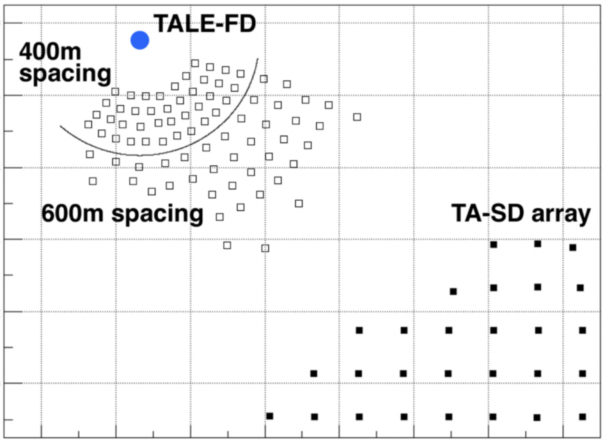


Figure 1: Map of Telescope Array and TALE detectors. Left : Locations of the scintillator Surface Detectors (SD) are shown as red points and the locations of the three Fluorescence Detector (FD) stations are indicated by the blue points. Locations of the scintillator Surface Detectors for TALE are shown as yellow points.
Right : Locations of the scintillator Surface Detectors and the TALE Fluorescence Detector (TALE-FD) stations are shown as white points and blue points respectively. Locations of the scintillator Surface Detectors for TA are shown as balck points. The area closest to the TALE-FD station have 40 SDs with a spacing of 400 m, and the outer area have 40 SDs with a spacing of 600 m. TALE-SD array is arranged in a fan shape instead of a grid shape in order to optimize the hybrid observation with TALE-FD.

The goal of the TALE experiment is to measure the energy spectrum and mass composition in the energy range from $10^{15.0}$ eV to $10^{20.5}$ eV and identify some interesting spectral features such as the second knee and even the knee. For this analysis, we focus on the 2nd knee region (primary energy is around $10^{17.5}$ eV), and utilize a reconstruction of the shower events by the TALE Surface Detectors (TALE-SD).

2. Event reconstruction and selection

About 4 months of data from October 2019 to January 2020 were analyzed for the cosmic ray spectrum. Total detector on-time is ~3600 hours. In this analysis, the events are reconstructed by the equation for the geometric reconstruction of the event,

$$t^{\mathrm{FIT}} = T_0 + \frac{l}{c} + \tau$$

where t^{FIT} is arrival time of air shower to SD, T_0 is arrival time of the shower core to the surface, c is the speed of the light and τ is time delay in the arrival time of the particle from the shower plane due to the curvature of the shower surface. This τ is a parameterization of the equation obtained by Linsley as a function of zenith angle θ for the TA experiment[3][4] [5] . Next reconstruction step, the particle density obtained from each detector is fitted with the following lateral distribution function from Akeno Giant Air Shower Array (AGASA) experiments [6]

$$\begin{aligned}
\rho^{\mathrm{FIT}} &= A\left(\frac{s}{91.6[m]}\right)^{-1.2}\left(1+\frac{s}{91.6[m]}\right)^{-(\eta(\theta)-1.2)}\left(1+\left(\frac{s}{1000[m]}\right)^{2}\right)^{-0.6} \quad [/m^2] \\
\eta(\theta) &= 3.97 - 1.79(\sec\theta - 1)
\end{aligned}$$

where A is the normalization, s is the distance to the shower axis, θ is the zenith angle.

The TALE-SD uses two reconstructed parameters to determine the primary energy. One is the particle density at 600 m from the shower axis (S600) and the other is the zenith angle (θ). The primary energy is determined using these parameters and the energy table for TALE-SD array obtained from the air shower Monte Carlo simulation as shown Figure2. This energy estimation table assumes a pure proton, and is made using the quality cuts shown below table1. Also, to obtain good resolution and Data/Monte Carlo comparisons, quality cuts were performed on the reconstructed showers as summarized in 1.

Variable	cut condition
# of SDs	≥ 5
zenith angle [°]	$< 45°$
D_{border} [m]	< 100 m
χ^2_{G} / d.o.f	< 4
χ^2_{L} / d.o.f	< 2
$(\sigma^2_\theta + \sin^2\theta\sigma^2_\phi)^{1/2}$ [°]	$< 2.5°$
σ_{S600} / S600	< 0.25

Table 1: Quality Cuts Applied in this study

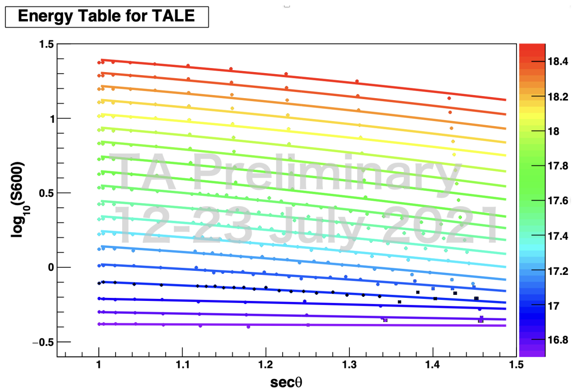


Figure 2: Energy Estimation Table for TALE-SD array. This energy estimation table assumes a pure proton. At this study, the energy range that can be estimated is from $10^{16.7}$ eV to $10^{18.5}$ eV.

3. Monte Carlo simulation

We generate cosmic ray showers using the CORSIKA-based MC simulation code developed for TA [7]. The Monte Carlo simulation procedure consists of two parts. One is an air shower simulation with the hadron interaction model QGSJET-II-04 [8] , and the other is the TALE surface detector simulation. In this analysis, we assume that the primary particle is proton. These showers were thrown from $10^{16.95}$ eV to $10^{18.55}$ eV with the spectral index of 3.0. The Monte Carlo simulated an isotropic distribution in the azimuthal angle, and zenith angle was thrown up to 65 °. And core position is randomly chosen within a circle of radius 5.5 km, which is enough to cover the entire TALE-SD array.

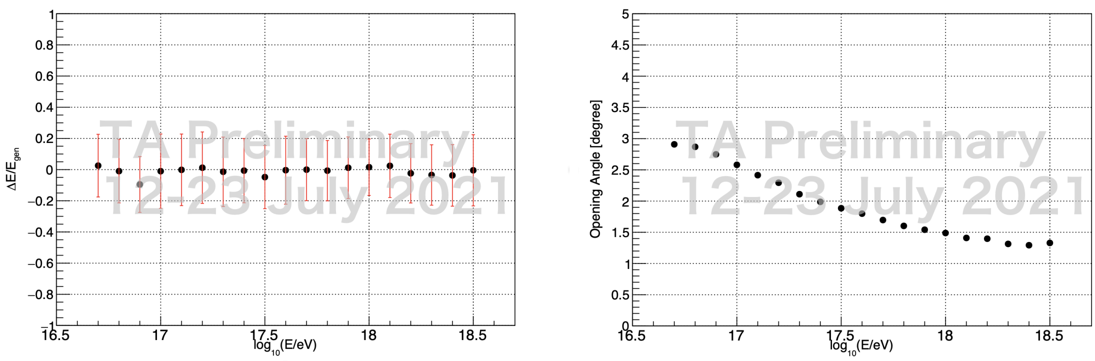


Figure 3: Resolution studies using Monte Carlo events. Left: primary energy.The Gaussian fit is used to determine the detector bias and resolution. Right: Opening angle at 68% of the number of events at a given energy.

Figure 3 show the resolution of important parameters from reconstruction. We evaluate the resolutions of ~20%, shown as the red bars, in primary energy range from $10^{16.7}$ eV to $10^{18.5}$ eV, and as for the resolution of the arrival direction, 3 ° for events with energy $10^{16.7}$ eV, and 1.5 ° for events with energy $10^{18.5}$ eV.

In the future, to evaluate the energy spectrum, it is necessary to calculate the aperture of the TALE-SD array. The aperture cannot be calculated with simple geometric factor because it depends on the performance of the surface detectors and also on the primary particles. Therefore, these dependencies are taken into account by MC simulation to estimate the aperture of the detector. However, note that in this analysis we assume pure proton in the MC. The aperture is calculated as follows

$$A\Omega(E) = A_{\mathrm{GEN}}\Omega_{\mathrm{GEN}} \cdot \mathrm{N}_{\mathrm{recon}}(\mathrm{E})/\mathrm{N}_{\mathrm{thrown}}(\mathrm{E}) \tag{1}$$

where E is the primary energy of cosmic ray, $A_{\mathrm{GEN}}\Omega_{\mathrm{GEN}}$ is the thrown aperture region of MC simulation, N_{recon} is the number of reconstructed events and N_{thrown} is the number of thrown events.

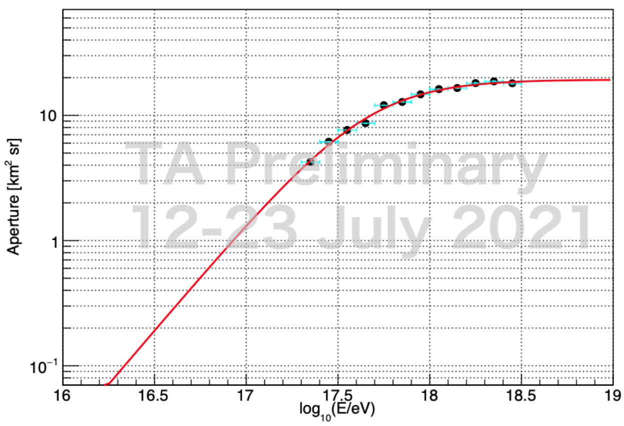


Figure 4: The aperture assuming a pure proton for the TALE-SD array. The red line is a fitted data point.

4. Data/MC Comparisons

To check if the Monte Carlo reasonably represents the data, measurable parameters' distributions were plotted. The Monte Carlo and Data (from October2019 to the end of January 2020) were applied the same quality cuts to be compared in energy range from $10^{17.5}$ eV to $10^{18.5}$ eV. Figure 5 shows Data and Monte Carlo comparisons for primary energy E, azimuthal angle ϕ, zenith angle θ, the particle density at 600 m from the shower axis S600, core position in X and core position in Y. Blue data points and red Monte Carlo histogram are consistent.

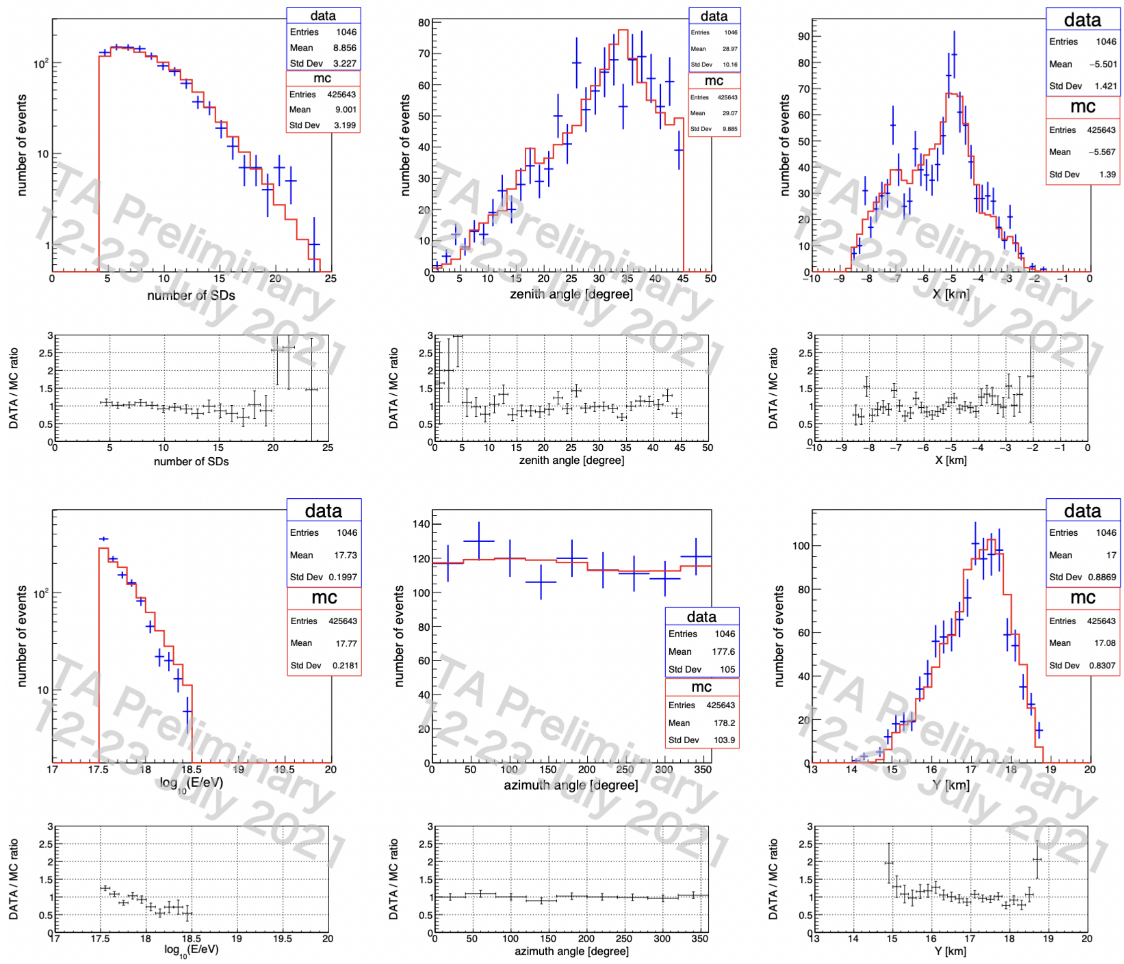


Figure 5: Data/Monte Carlo comparisons. Top left: the shower energy E. Top middle: the zenith angle, θ. Top right: the azimuthal angle, ϕ. Bottom left: the particle density at 600 m from the shower axis, S600. Bottom middle: the shower core position in X, x. Bottom right: the shower core position in Y, y. 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. Conclusion

The TALE SD array has been in operation since February 2018 with 80 SDs. The TALE-SD array DAQ is now running stably. We evaluate the energy resolutions of 20%, in energy range from $10^{16.7}$ eV to $10^{18.5}$ eV,and as for the resolution of the arrival direction, 3 ° for events with energy $10^{16.7}$ eV and 1.5 ° for events with energy $10^{18.5}$ eV. And we evaluated the preliminary aperture assuming a pure proton. We also compared the MC and Data. There were no big differences. In the future, we plan to obtain the energy estimation table, the aperture by considering the composition of cosmic rays.

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