Abstract. Telescope Array (TA) experiment is the largest hybrid detector to observe ultra-high energy cosmic rays (UHECRs) in the northern hemisphere. In the TA experiment, we newly designed and constructed 24 fluorescence detectors (FDs) located at two stations. We report the energy spectrum of UHECRs with energies above \(10^{17.5}\) eV from analyzing data collected by the new FDs during the first 3.7 years in monocular mode.

1 Telescope Array experiment

Origins of cosmic rays are still unknown during a century. Telescope Array (TA) experiment is the largest hybrid detector toward understanding origins of ultra-high energy cosmic rays (UHECRs) [1]. TA consists of 507 surface detectors (SDs) deployed with 1.2 km spacing for covering an effective area of about 700 km² and of three stations of fluorescence detectors (FDs) looking inward over the SD array, as shown in Fig. 1. A full operation of TA has been started in March 2008.

2 Data Set and Reconstruction Procedure

We explain a data set and an analysis procedure of the FDs in monocular mode which is the method to reconstruct primary cosmic ray information from data measured by only one FD station. Using this monocular analysis, we report the broad energy spectrum of UHECRs above \(10^{17.5}\) eV observed by the newly constructed FDs.

One of the stations located at north-west of the array has 14 FDs transported from HiRes experiment[2], so called the Middle Drum station (MD), and the other 24 FDs located at two stations are newly designed and constructed for the TA experiment, named as the Black Rock Mesa (BRM) and the Long Ridge (LR) station, with new calibrations and atmospheric monitors[3][4][5][6][7]. FD observations detecting atmospheric fluorescence photons emitted by molecules excited by extensive air showers (EAS) provides simulation-independent determinations of primary energies, because productions and energy losses of electro-magnetic components of EASs which are dominant components contributing fluorescence photon emissions are less dependent on hadron interaction models.

When the geometry of EASs is determined, a longitudinal development of EAS is estimated by an inverse Monte Carlo method[10]. The inverse Monte Carlo is the way to search an optimum solution of the shower development using Monte Carlo (MC) simulations with changing longitudinal development parameters.

\[
t_i = t_{\text{core}} + \frac{1}{c} \frac{\sin \Psi - \sin \alpha_i}{\sin(\Psi + \alpha_i)}
\]
The geometrical and the longitudinal fittings are con-

\( \frac{709.9}{27} = 18 \)

The reconstructed core location is within a circle with

\( \Omega \)

The maximum depth of EAS is observed inside the field

\( X_eV \), the aper-

The reconstructed zenith angle of the EAS is less than

\( \Omega + \Phi \)

\( E_{\text{max}} \), it is independent

\( N_{\text{max}} \), is the last one.

Moreover, the following quality cuts are applied in

the monocular analysis because faint shower signals with

short tracks are difficult to reconstruct to determine their geometries. Thus, short tracks and small time extent events were removed under following quality cuts.

- The geometrical and the longitudinal fittings are con-
  verted.
- The number of selected PMTs is larger than 10.
- The track length is larger than 10°.
- The time extent is larger than 2 µs.
- The reduced \( \chi^2 \) for the geometrical fitting is less than
  20.
- The maximum depth of EAS is observed inside the field
  of view (FOV) of FD, \( X_{\text{start}} < X_{\text{max}} < X_{\text{end}} \) where \( X_{\text{start}} \) is
  the first slant depth where emitted photons are measured by
  FD, \( X_{\text{end}} \) is the last one.
- The reconstructed core location angle of the EAS is less than
  55°.
- The reconstructed core location is within a circle with
  25 km radius from the location of CLF.

3 Performance of TA FD

Using the reconstruction methods, we evaluate resolutions of the monocular analysis by MC simulated events before analyses of observed data. At first, we generate artificial data calculated by MC simulations of primary protons generated by QGSJet-II-03 model of CORSIKA simulation[11]. Secondly, we reconstructed this simulated data in monocular analysis, and finally compare reconstructed results with true ones.

The distributions of the difference between simulated and reconstructed values on arrival directions and primary energies of EASs are shown in Fig. 3. The resolution of arrival direction in monocular mode is 7.4 degree as defined within 68% region. Because of such low geometrical resolution, energy estimation of monocular analysis has a systematic bias. Thus, we corrected this bias which is +3% at

\( 10^{18.5} \ eV \) and +7% at \( 10^{19.5} \ eV \) with a energy dependence. As the result, a root-mean-square of the distribution of the histogram is 23%.

To evaluate the energy spectrum of UHECRs, it is essential to calculate an aperture of FD. The aperture can not calculate a simple geometrical factor because it depends on not only the energies, but also the performance of FD, atmospheric models, PMT gains and primary shower species. Thus, we estimate the aperture of FD using MC simulations including these dependences. The aperture of FD, \( A\Omega \), is calculated from a ratio between the number of reconstructed events with the quality cuts and the number of thrown ones[2].

\[
A\Omega(E) = A\Omega^G \cdot \frac{N_{\text{reco}}(E)}{N_{\text{thrown}}(E)}
\]

where \( A\Omega^G \) is the thrown aperture region of MC simulation, \( N_{\text{reco}} \) is the number of reconstructed events, \( N_{\text{thrown}} \) is the number of thrown events.

Since TA was designed stereo observation mode for showers above \( 10^{19.0} \ eV \), we define the combined aperture of the BRM and the LR stations in each monocular mode. When a energetic shower is reconstructed by the both stations, we select one result with a larger number of photoelectrons than another station to avoid the double counting of high energy showers. Using these reconstructed events by both the BRM and the LR combined mode, we estimate the combined aperture of BRM and LR stations with primary protons and irons of the QGSJet-II hadron interaction model as shown in Fig. 4.

In the low energy region less than \( 10^{18.5} \ eV \), the aperture is dependent on the primary species. In contrast, in the high energy region above \( 10^{19.5} \ eV \), it is independent of them.

4 Data Analysis

Analyzing the observed data during by the same analysis processes, we obtained histograms of reconstructed energies as shown in Fig 5. There are three types of histograms, BRM (red), LR (blue) and combined (green) energies, respectively.

As further enhancement of our reliability in our analysis, the distributions of the several parameters obtained from the reconstructions of the observed data are compared with the expected ones estimated from MC simulations. A couple of parameters for data and MC comparisons are shown in Fig. 6. In these figures, the black
Figure 4. The combined aperture of BRM and LR stations evaluated by MC simulations for primary protons (green solid-line) and irons (black dotted line) in monocular mode.

Figure 5. Histograms of reconstructed energies in monocular analysis. The BRM, LR and combined ones are indicated as red, blue and green lines, respectively.

Figure 6. The distributions of energies, impact parameters and angles in a shower detector plane between observed data (plot) and MC simulations for primary protons (red) and irons (blue) at the BRM (left column) and the LR stations (right column).

Figure 7. Distributions of difference of reconstructed energies at the BRM and the LR stations. The peak energy of reconstructed 234 showers is $10^{18.6}$ eV. The plot is observed data, the histogram is estimated from our MC simulation.

Air showers reconstructed by both stations in monocular mode are useful to confirm an accuracy of reconstructed energies independently for Monte Carlo simulations. Assuming both FD stations have the same resolution, $\sigma$, a root-mean-square of distributions of difference of reconstructed energies at the BRM and the LR stations are equivalent to $\sqrt{2}\sigma$. Thus, we estimate the accuracy of our FD monocular analysis from distributions of difference of reconstructed energies at the BRM and the LR stations. In this data set, we found 234 events reconstructed by both stations in monocular mode, and a distribution of these difference is shown in Fig. 7. Converted to a linear value based on Fig. 7, the resolution of FD is estimated as 40%.

Finally, we calculate the energy spectrum based on the apertures, the live times and the number of reconstructed showers, as discussed previously. An exposure of FD is giving from the apertures and the live times by

$$\omega(E) = A\Omega(E) \cdot t$$  \hspace{1cm} (3)

where $t$ indicates the live time and aperture, $A\Omega(E)$, is already estimated in Fig. 4. Moreover, a flux is evaluated by

$$J(E) = \frac{N(E)}{\omega(E) \cdot \Delta E}.$$  \hspace{1cm} (4)
5 Conclusions

The newly constructed fluorescence detectors for Telescope Array experiment have a steady observation of UHECRs from 2008. Analyzing the data collected during 3.7 years by the monocular analysis located at the BRM and the LR station, we estimate the energy spectrum with a broad energies above $10^{17.5}$ eV. The obtained energy spectrum is consistent with spectra measured by the TA surface detectors, the Middle Drum FD and the HiRes experiment.

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