Energy Spectrum Measured by the Telescope Array Surface Detectors

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Abstract. Located in the west desert of Utah, USA, the Telescope Array experiment is the largest ultra-high energy cosmic ray observatory in the northern hemisphere. It consists of two types of detectors: scintillator surface detectors (SDs) and air fluorescence detectors (FDs). A total of 507 SDs consisting of two-layer plastic scintillation counters is deployed with 1.2 km spacing, making measurements over an area of approximately 700 km². There are 3 FD stations, having 38 fluorescence telescopes viewing 3°–31° in elevation, overlooking the SD array. In this work, we update the Telescope Array energy spectrum as measured by the SD array for 14 years. We verify the linearity in TA SD energy reconstruction using three different energy comparisons: Monte Carlo comparison, FD/SD comparison, and Constant Intensity Cut method. The spectral features of ankle, softening, and GZK cutoff are seen in 14 years of TA SD data. Also, we consistently observe that the cutoff energy depends on declination.

1 Introduction

Ultra-high energy cosmic rays (UHECRs), extremely energetic \( E > 10^{18} \) eV charged particles flying into Earth’s atmosphere from outer space, have been investigated as a window of exploring the Universe. The traditional main observables of UHECRs are mass composition, arrival direction, and energy spectrum. Comprehensive understandings of those observables all together are necessary to elucidate the nature and origin of UHECRs. It is essential to investigate the energy spectrum of UHECRs since the spectral features of cosmic rays contain information about the sources and about cosmic ray propagation. The high energy cutoff at \(~10^{19.8}\) eV, the energy predicted by Greisen, Zatsepin, and Kuzmin (GZK) [1, 2], was first observed by the High Resolution Fly’s Eye experiment (HiRes) [3] and later confirmed by Telescope Array (TA) experiment [4]. In the southern hemisphere, the Pierre Auger Observatory (Auger) [5] observed the cutoff at a slightly lower energy. Although the GZK cutoff mechanism is pion photoproduction due to cosmic microwave background photons striking cosmic ray protons, the high energy cutoff might be caused by the maximum energy of sources. The ankle, a hardening of the spectrum at \(~10^{18.7}\) eV, can be interpreted as due to \( e^+ e^- \) pair production [6] if cosmic rays are protons. In the southern hemisphere, the Auger collaboration has a different interpretation [7]. In this work, we investigate energy spectrum features using the most up-to-date data measured by the TA surface detector array.

2 Telescope Array Experiment

The Telescope Array (TA) experiment [8, 9] is the largest UHECR observatory in the northern hemisphere, which is designed to observe the extensive air shower induced by a primary particle hitting Earth’s atmosphere. It is located near the west desert of Utah, USA (39.3° N, 112.9° W, 1400 m above sea level). We deployed a total of 507 surface detectors (SDs) consisting of two-layer plastic scintillation counters with 1.2 km spacing, making measurements over an area of approximately 700 km². This SD array is overlooked by three fluorescence detector (FD) stations having a total of 38 fluorescence telescopes viewing 3°–31° in elevation above the SD array. The deployment layout is depicted in Figure 1.

3 Reconstruction of Events Observed by Surface Detectors

When a primary particle of UHECRs collides a nucleus of Earth’s atmosphere, a cascade of millions of subatomic particles, an extensive air shower (EAS), is initiated and develops along the track of the primary particle. The profile of the EAS is reconstructed as follows. First, we locate the core position and determine the arrival direction of the primary particle using SD counter position and timing by using the modified Linsley shower-shape function fit [10]. Next, we fit counter signal size to find its lateral distribution [11, 12]. The signal size at 800 m, S800, is the density of shower particles at a lateral distance of 800 m from the shower axis is used as an energy estimator. Using S800 and zenith angle, the energy of the primary particle is determined from the look-up table, \( E_{\text{TBL}} \), which is produced from the SD Monte Carlo simulation using CORSIKA

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software package [13] with the QGSJetII-03 hadronic interaction model assuming proton primaries [14]. Lastly, we compare these Monte Carlo determined energies with FD’s calorimetric energies using hybrid events. The scale factor is found to be 1.27, and the final energy is obtained by 

\[ E_{\text{Final}} = E_{\text{TBL}} / 1.27. \]

## 4 Descriptions on Dataset

In this work, we used a dataset measured by the TA SD array from May 11, 2008 up to May 10, 2022; i.e. 14 years of SD data. The selection criteria employed in this analysis are as follows: 1. Each event must include at least five SD counters.

2. The reconstructed primary zenith angle must be less than 45°.

3. The reconstructed event core must be more than 1200 m from edge of the array.

4. Both the geometry and lateral distribution fits must have \( \chi^2 \) of degree of freedom value less than 4.

5. The angular uncertainty estimated by the geometry fit must be less than 5°.

6. The fractional uncertainty in S800 estimated by the lateral distribution fit must be less than 25%.

Monte Carlo based on CORSIKA software package is used for resolution and exposure calculations. The energy and angular resolutions of 14 years of TA SD data are summarized below.

- \( E \geq 10^{19.0} \text{ eV} \): 20% in energy and 1.4° in angular.
- \( 10^{18.5} \text{ eV} \leq E < 10^{19.0} \text{ eV} \): 29% in energy and 2.1° in angular.
- \( 10^{18.0} \text{ eV} \leq E < 10^{18.5} \text{ eV} \): 34% in energy and 2.4° in angular.

## 5 Results

### 5.1 Linearity in Energy Reconstruction

Figure 2 shows the linearity in energy reconstruction with three different approaches. The left panel shows the ratio between reconstructed energy and thrown energy in Monte Carlo simulation. The same reconstruction program for data analysis is used for this analysis. The linearity is observed in this comparison. The middle panel shows the ratio between reconstructed energy measured by SD and FD as a function of energy. For higher energy bins the number of events is not sufficient but linearity is observed. The right panel shows the comparison of energies determined by the TA’s standard SD reconstruction method and the Constant Intensity Cut method [15]. The result agrees within ~3% level at the TA’s highest energy [16]. The results from these three different approaches are consistent with each other showing the linearity in the energy reconstruction above \( 10^{19} \text{ eV} \).

### 5.2 Energy Spectrum and Features

Figure 3 shows the energy spectrum derived from the 14 years of TA SD data with the selection criteria described in Section 4. The data is represented by black points with error bars and a fit to the broken power law is shown with the black solid line. Here, we fit to the broken power law having two breakpoints. The first break point, the ankle feature, is found at \( E_{\text{Ankle}} = 10^{18.6\pm0.01} \text{ eV} \) with spectral indices of \( \beta_1 = -3.27 \pm 0.02 \) before the ankle and \( \beta_2 = -2.69 \pm 0.02 \) after the ankle. The second break point, the GZK cutoff feature, is obtained at \( E_{\text{GZK}} = 10^{19.78\pm0.04} \text{ eV} \) with the spectral index of \( \beta_3 = -4.47\pm0.41 \) after the GZK cutoff.

It is known that there are differences in the cutoff energies depending on declination in TA’s filed of view from the previous energy spectrum analysis results [17]. Using the 14-year TA SD dataset, we confirm that the cutoff energy depends on declination. In the lower declination band, between -15.7° and 24.8° (the band seen by both TA and Auger), the cutoff energy is fit to be \( 10^{19.65\pm0.02} \text{ eV} \). In the upper declination band, \( \delta \geq 24.8° \), the cutoff energy is fit to be \( 10^{19.84\pm0.02} \text{ eV} \). This energy difference has a local significance of about 5σ. The declination dependence feature is shown in the right panel of Figure 3.

Recently, Auger reported evidence for a new spectral feature, a softening of the energy spectrum at \( 10^{19.11\pm0.03} \text{ eV} \) [18]. Following that, we searched for the new feature in the northern hemisphere data, including HiRes, TA FD, and TA SD. The same softening feature in the northern hemisphere has been observed but at the energy of \( 10^{19.25\pm0.05} \text{ eV} \) [19]. Here, we investigate this feature using the 14 years of SD data. The softening feature is consistently observed, and the fit to the broken power law shows the softening feature appears at energy of \( 10^{19.22\pm0.08} \text{ eV} \). The probability to observe such a feature in the spectrum by chance is excluded at 4.0σ level. The detailed results of spectral features using three break points are shown with the black fitting line in Figure 4.
Figure 2. Linearity in energy reconstruction. The ratio between reconstructed energy and thrown energy in Monte Carlo simulation (left), the ratio between reconstructed energy measured by SD and FD (middle), and the comparison of energies determined by the TA's standard SD reconstruction method and the Constant Intensity Cut method (right) as a function of energy show consistent results of the linearity in the energy reconstruction.

Figure 3. Energy spectrum using 14-year SD data and declination dependence. (Left) The data is represented with the black points with error bars, and a fit to the broken power law is shown with the black solid line. Here, we fit to the broken power law having two breakpoints, where \( p_1, p_2 \) are the spectral indices before and after the ankle, respectively, \( E_{\text{ankle}} \) is the energy of the ankle, \( E_{\text{GZK}} \) is the energy of the GZK cutoff, and \( p_3 \) is the spectral index after the GZK cutoff. (Right) The data in the lower declination \((-15.7^\circ \leq \delta < 24.8^\circ)\) are marked with the red dots overlaid with the red fitting line. The data in the higher declination \((\delta \geq 24.8^\circ)\) and its fitting result are shown with the open black circles superimposed and the black line, respectively.

Figure 4. Softening spectral feature in 14-year SD data. The data is represented with the black points with error bars, and a fit to the broken power law having three break points is shown with the black solid line. The detailed results are written on the energy spectrum, including spectral indices and break energies.
6 Summary

The TA SD array has been steadily collecting data since May 11, 2008. In this work, we used 14 years of TA SD data and derived energy spectrum. First, we validated Monte Carlo simulation carefully by comparing it with the distribution of the data. We concluded that TA SD energy reconstruction is robust from three different energy comparisons: FD/SD comparison, Monte Carlo, and Constant Intensity Cut method. The TA SD energy spectrum shows three spectral features—ankle, softening (instep/shoulder), and GZK cutoff—with 14 years of data. In addition, the declination dependence of the cutoff energy was consistently seen in the up-to-date dataset.

References