PROCEEDINGS OF SCIENCE

Measurement of the cosmic ray energy spectrum with the TA×4 SD array

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The TA×4 experiment aims to better understand the origin and nature of ultra-high energy cosmic rays (UHECRs) by expanding the observation area of the Telescope Array (TA) experiment by a factor of 4. This expansion will increase the statistics of UHECR events with energies greater than $10^{19.5}$ eV. The SD, which means the additionally deployed surface detectors (SD) for the TA×4 experiment, has been collecting data since 2019, and the analysis of this data is currently underway. In this presentation, we will report comparisons between the Monte Carlo simulation and the data obtained by the TA×4 SD array and highlight the agreement between the two. We will also report on the UHECR energy spectrum observed by the TA×4 SD array from October 2019 to September 2022.

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1. Introduction

The Telescope Array (TA) experiment, located around 39.30°N and 112.91°W in Utah in the U.S., observes cosmic-ray induced air showers with surface detectors (SDs) and fluorescence detectors (FDs). The observation area is about 700 km^2, which is the largest in the Northern Hemisphere. The TA experiment observed an indication of an intermediate scale anisotropy of arrival directions of cosmic rays with energies greater than 5.7×10^{19} eV (the so-called TA hotspot) with 3.4σ global significance [1]. This motivates us to investigate more about the highest energy events to better understand their source.

The TA×4 experiment is planned to accelerate the speed of the data collection, especially for cosmic rays with energies greater than 5.7×10^{19} eV by quadrupling the observation area including the original TA experiment. In 2019, 257 SDs were deployed with 2.08 km spacing, which is wider than the original TA SD spacing of 1.2 km, on square grids in the northern side and the southern side of the original TA SD array [2]. This expansion we have made so far is about half of the final plan, and the additional observation area is about 1,000 km^2. The TA×4 northern SD array and the southern SD array started stable observation in October 2019. In this paper, we present an energy spectrum of ultra-high energy cosmic ray (UHECR) greater than $10^{19.5}$ eV observed by the TA×4 SD, which hereafter means newly deployed 257 SDs, with 3 years of observation. The period is just before the implementation of the inter-tower trigger [3] in the TA×4 SD. This means that six sub-arrays that compose the TAx4 SD array operated independently during the period. The TAx4 SD energy spectrum combined with the 14 years of observation of the original TA SD array is also shown.

2. Reconstruction of air shower events observed by TA×4 surface detectors

The reconstruction method of the TA×4 SD is basically the same as the TA SD [4]. The only difference is energy estimation. Primary energies are estimated as a function of two reconstructed parameters: zenith angle θ and a signal density S_{800} at the lateral distance of 800 meters from shower axis. An energy estimation function was newly developed for the TA×4 SD based on Monte Carlo (MC) simulation. The MC simulation method is the same as the TA SD [5], and the details were described in the previous work [6]. It is noteworthy that showers were generated by CORSIKA code [7] using QGSJET II-04 [8] as a hadronic interaction model, and primary particles in the simulation are all protons. With the newly developed energy estimation, the bias of reconstructed energy greater than 10^{19} eV is less than 5%. The energy resolution greater than 5.7×10^{19} eV is about 25%.

3. Data/MC comparison

The MC simulation is used to calculate an exposure of the TA×4 SD array, determine energy estimation, and evaluate energy resolution and arrival direction resolution. Therefore, it is necessary to confirm that the MC simulation reproduces real observation data accurately. The distributions of reconstructed parameters were compared between MC simulated events and the observed events to this aim.

3.1 Event selection

Event selection criteria are the same as the previous work [6]. The following 7 selection criteria were required for both MC events and observed events: (1) at least 5 SDs are used in reconstruction, (2) the reconstructed core position is at least 400 meters away from the border of each array, (3) the reconstructed zenith angle is less than 55 degrees, (4) the reduced chi-square of the reconstruction fit is less than 4, (5) the uncertainty of reconstructed direction is less than 8 degrees, (6) the relative uncertainty of S_{800} is less than 0.5, and (7) the reconstructed energy without energy scaling is greater than 10^{19} eV. The Data/MC comparison and energy spectrum calculation were performed for events which passed the criteria.

3.2 Energy scale

The energy estimation possibly has biases associated with hadronic interaction models and SD spacing. For the original TA SD array, the bias was evaluated using events well-reconstructed by both SD and FD because FD measures the energy of air showers calorimetrically and therefore has better measurement accuracy than SD. Assuming proton primaries using the QGSJET II-03 hadronic interaction model, the energies reconstructed by SDs are estimated by 27% higher than those by FDs [4].

For the TA×4 SD, however, the number of events reconstructed by both SD and FD is not yet sufficient because the TA×4 SD is focused on observing UHECRs, especially greater than $5.7{\times}10^{19}$ eV. In this study, therefore, we determined the energy scale for the TA×4 SD with QGSJET II-04 proton to reproduce the energy spectrum measured by the TA SD 11 years of observation [9].

3.3 Comparison of distributions of reconstructed parameters

Comparisons of distributions of various reconstructed parameters between observed events and simulated events are shown in Fig. 1, and the p-value of chi-square test for each parameter is listed in Table 1. The number of simulated events is normalized to match the number of events expected from the energy spectrum measured by the TA SD 11 years of observation [9]. There is no inconsistency between the observed data and simulated data. The energy scale factor was measured to be 1.36 as a preliminary from the top left panel of Fig. 1.

4. Energy spectrum

4.1 Energy spectrum with the TA×4 northern SD array and southern SD array

We calculated the cosmic ray energy spectrum for energies greater than $10^{19.5}$ eV with the observational data acquired by the TA×4 SD array from October 2019 to September 2022. The energy spectrum is obtained by the following equation:

$$J(E_i) = \frac{N_{rec}^{Data}(E_i^{rec})}{A\Omega T \times Rec.Eff.(E_i^{rec}, E_i^{gen}) \times \Delta E_i^{gen}} \tag{1}$$

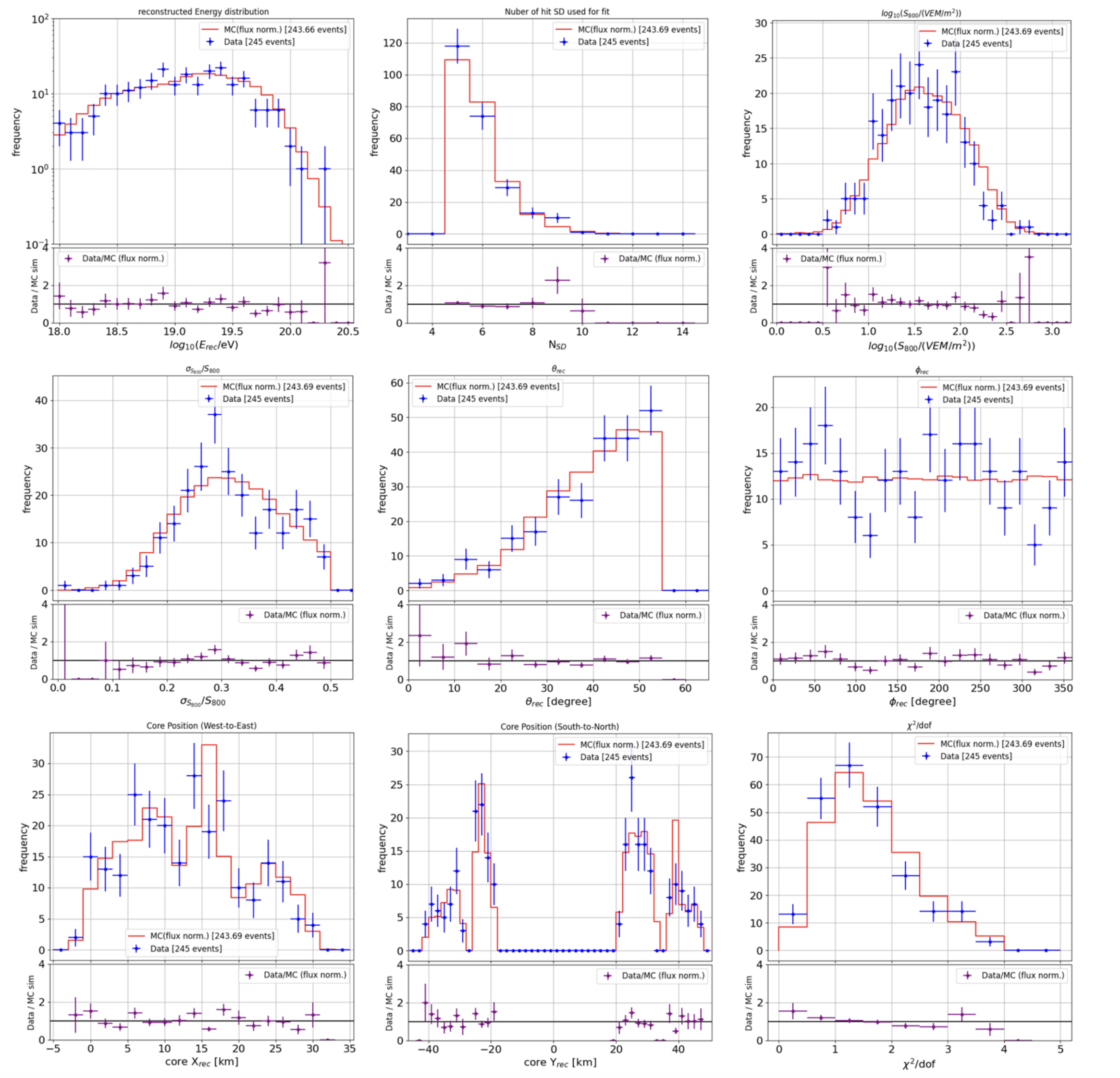


Figure 1: Comparisons between observed events (blue points) and simulated events (red histogram). The MC simulation histograms are normalized to the expected number of events from the TA SD 11 years of observation [9] by 1.36 energy scale. Chi-square test p-values of the parameters are listed in Table 1. The compared parameters are reconstructed energy, the number of SDs used for the combined fit of geometry and lateral distribution, S_{800}, $\sigma_{S_{800}}/S_{800}$, zenith angle, azimuthal angle, core positions (west-east direction and south-north direction) and χ^2/ndof of the combined fit.

Table 1: chi square test p-value for parameters.

parameter	p-value
Energy	0.774
The number of SD	0.524
S_{800}	0.634
Relative uncertainty of S_{800} ($\sigma_{S_{800}}/S_{800}$)	0.041
Zenith angle (θ)	0.646
Azimuthal angle (ϕ)	0.294
Core position (west-east)	0.101
Core position (south-north)	0.301
χ^2/ndof of fit	0.347

where $N_{rec}^{Data}(E_i^{rec})$ is the number of observed events in each reconstructed energy bin, A and Ω are the area and the solid angle of showers generated in the MC simulation, respectively. T is the observation period, ΔE_i^{gen} is the bin width of each energy bin, and $Rec.Eff.(E_i^{rec}, E_i^{gen}) = N_{rec}^{MC}(E_i^{rec})/N_{gen}^{MC}(E_i^{gen})$ is reconstruction efficiency considering bin-to-bin migration effects. The denominator of the efficiency is the number of thrown events in the MC simulation, and the numerator is the number of reconstructed events that pass the event selection in the MC simulation. The total effective exposure and the number of observed events of the TA×4 SD were calculated by taking the sum of the six sub-arrays because an inter-tower trigger system, which enables to obtain cosmic-ray events around the boundaries between sub-arrays, was not yet implemented in this period. Each sub-array operated independently and had different aperture and different on-time. This calculation method is the same as the calculation method of the TA SD. The effective aperture and the effective exposure considering bin-to-bin migration effects are shown in Fig. 2.

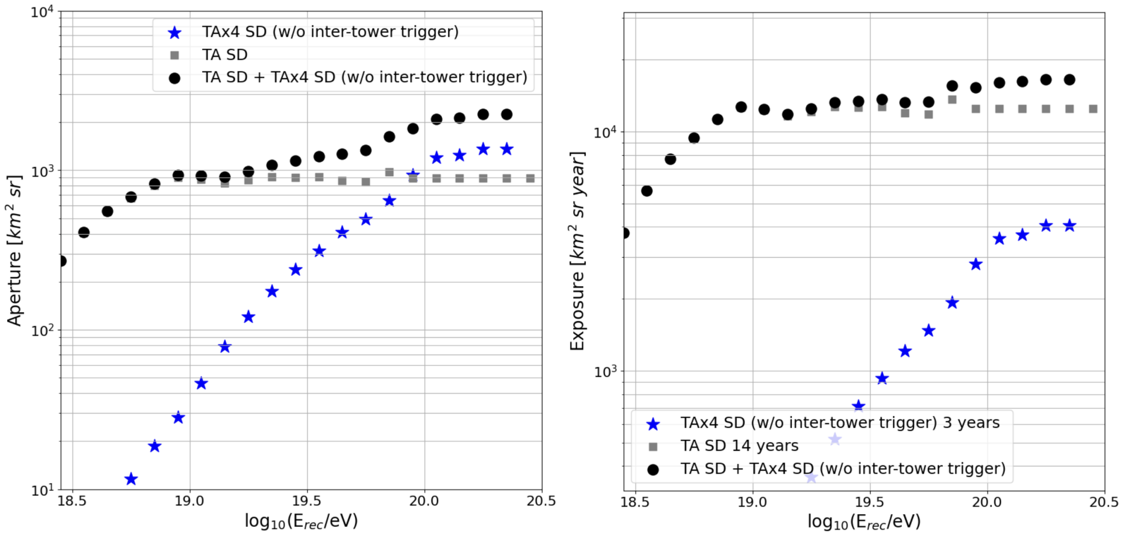
Fig. 3 shows the calculated cosmic ray energy spectrum along with a fit result with a broken power law function:

$$J(E) = K[\theta(E_{break} - E) \times (E/\mathrm{EeV})^{p_1} + \theta(E - E_{break}) \times (E_{break}/\mathrm{EeV})^{p_1 - p_2} \times (E/\mathrm{EeV})^{p_2}] \quad (2)$$

where $\theta(E)$ is a step function. p_1 and p_2 are slopes of the power law before and after the break point E_{break}, respectively. The fit was performed with events greater than 10^{19} eV. The fit results are listed in Table 2. The cutoff structure in the energy spectrum was also measured by the TA×4 SD, and the energy spectrum is consistent with that measured by the TA SD [10]. The expected number of events with energies greater than $10^{19.8}$ eV considering bin-to-bin migration effect on the assumption that there is no cut off in the energy spectrum is 30.94, and the observed number of events is 16. This corresponds to a significance of 2.8σ.

4.2 Combined energy spectrum

Fig. 4 shows the cosmic ray energy spectrum calculated with 14 years of the TA SD data and 3 years of the TA×4 SD data. The TA×4 SD data with energy greater than $10^{19.5}$ eV were used for the combination. The calculation method is the same as the method described in 4.1.



(a) Effective aperture. **(b)** Effective exposure.

Figure 2: Effective aperture (left) and effective exposure (right) of the TA×4 northern SD + the TA×4 southern SD (blue stars). Those of the TA SD (gray squares) and the combined aperture (black dots) are also shown.

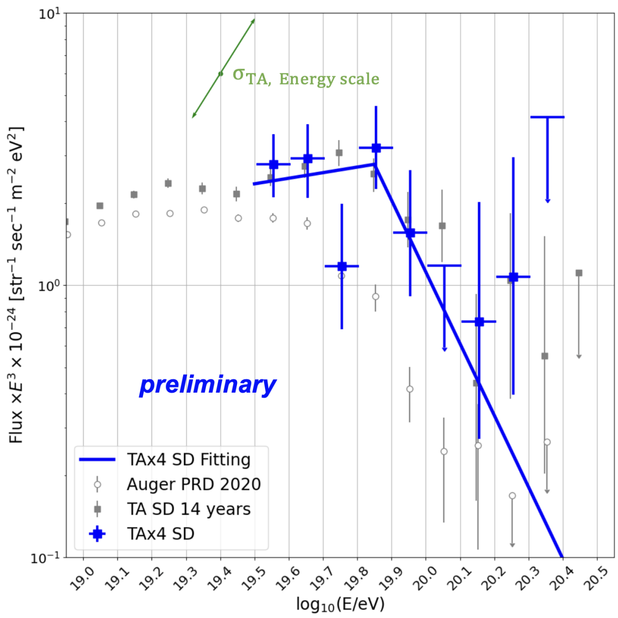


Figure 3: The cosmic ray energy spectrum measured with the TA×4 SD (blue squares). The blue solid line represents the fit result for the TA×4 SD energy spectrum. The fit results are listed in Table 2. For comparison, the TA SD energy spectrum [10] (gray squares) and the Auger energy spectrum [11] (open circles) are also shown. The green arrow indicates the systematic uncertainty due to the uncertainty of the energy scale ∼21% almost independent of energy [12].

Table 2: Fit result with a broken power law function.

K [sr^{-1}s^{-1}m^{-2}eV^{-1}]	$1.16^{+1.21}_{-0.60} \times 10^{-31}$
p_1	$-2.80^{+0.21}_{-0.15}$
p_2	$-5.63^{+1.70}_{-2.16}$
E_{break} [eV]	$10^{19.85^{+0.09}_{-0.22}}$

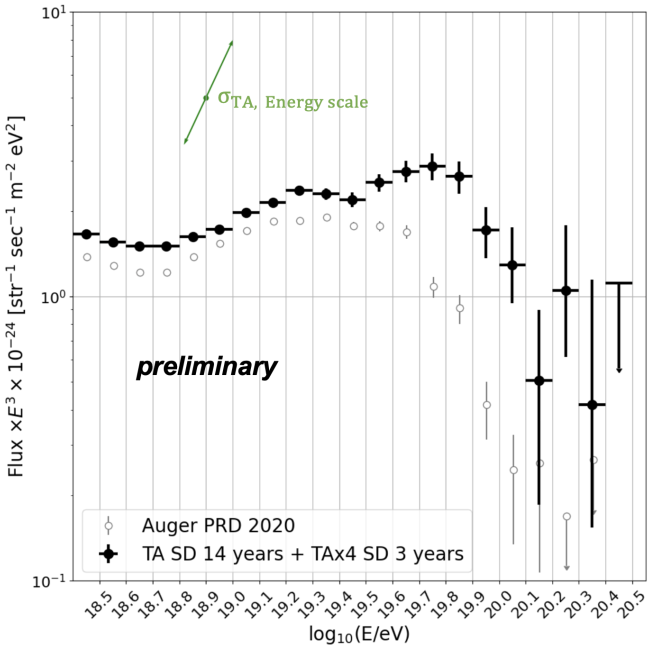


Figure 4: The black dots indicate the combined spectrum and open circles represent Auger energy spectrum [11]. The green arrow indicates the systematic uncertainty due to the uncertainty of the energy scale of the TA experiment [12].

5. Summary

The TA×4 SD started stable observation in October 2019 with 257 surface detectors covering about 1,000 km^2. In this work, we showed the cosmic ray energy spectrum greater than $10^{19.5}$ eV using the first 3 years of data obtained by the TA×4 SD. The high energy cutoff structure was measured by the TA×4 SD as well. The energy spectrum is consistent with the TA SD energy spectrum. We also presented the combined cosmic ray energy spectrum using 14 years of the TA SD data and 3 years of the TA×4 SD data. The TA×4 SD enhances the number of UHECR events, especially those greater than $10^{19.5}$ eV.

During the initial 3 years from October 2019 to September 2022, the inter-tower trigger was not yet implemented in the TA×4 SD. The inter-tower trigger further increases the aperture of the TA×4 SD [3], and the data analysis is ongoing.

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