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# A study of the systematic effects on the energy scale for the measurement of UHECR spectrum by the TA SD array

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We evaluated the systematic deviation of energy scales for the energy spectrum of the highest energy cosmic rays observed by the Telescope Array Surface Detector array due to differences in atmospheric fluorescence yield and missing energy estimation. The energy dependence on the energy scales is also investigated and observationally confirmed by the constant intensity cut method analysis. The results of these studies will be presented.

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## 1. Introduction

Compared to fluorescence detector (FD) observations, surface detector (SD) array observations have an advantage, especially in the measurement of energy spectrum that require observational statistics, due to their high duty cycle which is much greater than that of the telescopes. On the other hand, FD observations have an advantage in that the energy of primary cosmic rays can be estimated calorimetrically from air fluorescence photons of air showers. Therefore, the energy scale obtained based on FD observations is applied to the reconstruction of SD events.

Although the energy estimation from FD observations is calorimetric, two major systematic uncertainties exist. One is the estimation of the missing energy due to particles that do not emit air fluorescence photons. In the Telescope Array (TA) experiment, the missing energy is estimated by Monte Carlo simulations, but this method involves systematic uncertainties included in the Monte Carlo calculations. On the other hand, the Auger group estimates the missing energy experimentally which does not depend on Monte Carlo simulations.

The other is the choice of the fluorescence yield and its spectrum. Various measurements have been made at the laboratory level, and there is a freedom in choosing which of these results to use, which is a source of potential systematic errors.

Furthermore, the way in which the energy scale determined calorimetrically by FD is transferred to the SD data analysis is different for TA and Auger. In TA, for each shower event detected in the SD array, the energy $E_{\rm SD}$ is obtained by comparing an energy estimator obtained by shower reconstruction and the zenith angle $\theta$ with a look-up table previously obtained by Monte Carlo simulations. $E_{\rm SD}$ is then multiplied by an energy scale factor to correct it to a calorimetric energy[1]. In Auger, an energy estimator is converted to a calorimetric energy using a relation previously determined experimentally using the constant intensity cut (CIC) method[2].

It is known from the study of a working group composed of researchers from TA and Auger that there is a difference in the energy spectra presented by TA and Auger, which can be explained by a 9% difference in the energy scale, plus an energy-dependent shift corresponding to 20%/decade[3]. In this presentation, we will report the recalculation of the energy spectrum and the results to examine this difference. First we recalculated the energy scale using the exactly same fluorescence yield model and the missing energy used by Auger, At the same time, we also introduced the exactly same method as Auger, *i.e.*, the energy determination method based on the CIC method, using the exactly same fluorescence yield model and the missing energy. Using these methods, the energy-dependent shift is shown to be very small, and the energy spectra obtained using the recalculated energy determination methods are shown.

### 1.1 Telescope Array experiment

TA is the largest Ultra-High Energy Cosmic Ray (UHECR) observatory in the northern hemisphere. The TA detector consists of a surface array of 507 plastic scintillator SDs and three FD stations of fluorescence detectors. It is located in the desert, approximately 200 km south of Salt Lake City in Utah in USA. The SDs were deployed on a square grid with 1.2-km spacing, and the SD array covers an area of approximately 700 km$^2$. Each SD has two layers of 1.2-cm-thick scintillator with an area of 3 m$^2$. The full operation of SDs started in March 2008[4]. The duty cycle is approximately 95% on average. One northern FD station at the Middle Drum (MD) site uses 14 refurbished HiRes telescopes [5]. Two southern FD stations at the Black Rock Mesa (BRM) and Long Ridge (LR) sites were built newly each with 12 telescopes[6]. The MD FD views 3° - 31° and the BRM and LR FDs view 3° - 33° above horizon. All three FD stations started the observation in November 2007, and have duty cycles of approximately 10%.

### 1.2 Fluorescence yeild

The total yield used in TA was measured by Kakimoto et al[7]. and the relative emission spectrum is the results of FLASH[8]. In Auger, the measurements by AirFly[9][10][11] are used.

### 1.3 Missing energy

In the Telescope Array (TA) experiment, the missing energy is estimated by Monte Carlo simulations, but this method involves systematic errors included in the Monte Carlo calculations. On the other hand, the Auger group estimates the missing energy experimentally, and the value does not depend on Monte Carlo simulations.

## 2. Energy scale evaluation

In the TA experiment, an energy scale factor of 1/1.27 has been observably obtained and used to convert $E_{\rm SD}$, the energy determined with the SD array for an event to $E_{\rm FD}$, the calorimetric energy determined from the FD measurements of the same event[1]. Specifically, the following equation, $E_{\rm FD} = E_{\rm SD}/1.27$ is used for the conversion. In this analysis, the fluorescence yield used in the FD hybrid reconstruction is changed to the AirFly model, and in addition, for the missing energy in these reconstructions the same value used by the Auger experiment is used. After making these changes, the energy scale factor was re-calculated. The procedure is exactly the same as the previous procedure described in the reference[1]. The data used to recalculate the energy scale factor are the 11.8 years of simultaneous detection events in both the SD array and FDs. The events were reconstructed and selected by performing hybrid analysis and quality cuts on these data using exactly the same treatment used in the previous Xmax study[12]. In addition, the SD array data were analyzed using exactly the same method as in the energy spectrum study[1].

The energy scale factor obtained after recalculation with the different fluorescence yield and the missing energy was 1/1.35. This value was used to correct $E_{\rm SD}$, and the scatter plot compared to $E_{\rm FD}$ is shown on the left in Figure 1. Fitting this with a power law function of energy yields an index of 0.998, which is not unity, but the energy dependence is very small at $-0.4\%$/decade.

## 3. Energy estimation with the constant intensity cut method

In this section, the constant intensity cut method used by the Auger collaboration to obtain the energy spectrum of cosmic rays [2] is precisely applied to the data from the TA experiment to obtain primary energies of cosmic rays and the energy spectrum.

Here, we used the same selected data set as in the previous section of the study. In addition, only events with energies greater than $10^{19}$ eV are used. This energy threshold guarantees that the detection efficiency of the SD array is 100%. As an energy estimator, we followed the previous procedure with Auger and used the particle number density in terms of VEM at a certain core distance.

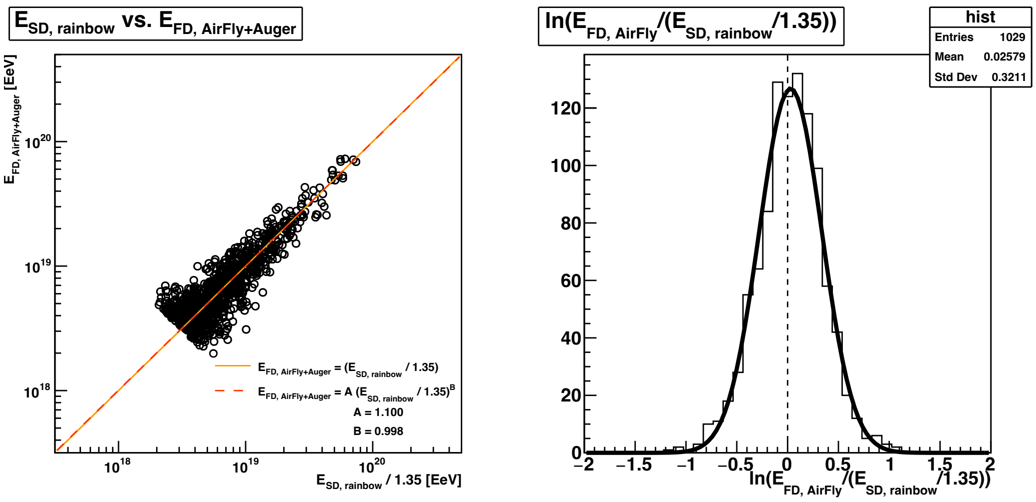


**Figure 1:** *left:* The scatter plot comparing $E_{\rm FD}$ with $E_{\rm SD}/1.35$. The fitting with a power law function and the best fit values are shown in the figure. *right:* The histogram of $E_{\rm FD}$ to $E_{\rm SD}/1.35$.

As the core distance, we chose 800 m, which is also used in the standard energy determination of the TA experiment, but we also tried 1300 m. This was because there was some discussion in the spectrum working group that 800 m might not be an optimized distance for energy determination and that 1300 m might be more appropriate[3]. The particle number densities at core distances of 800 m and 1300 m were converted to values for an air shower incident at a zenith angle of 35 degrees and expressed as $S_{35}(s800)$ and $S_{35}(s1300)$, respectively. The relationships between these $S_{35}$ and $E_{\rm FD}$ were then determined. The results are shown in Figure 2. By fitting these relationships with a power law function, we obtained the functions to determine the energy from the energy estimators, $s800$ and $s1300$. The functions for these relations are also written to fit Figure 2.

A scatter plot showing the relationship between $E_{\rm SD,rainbow}$, the energy obtained by the standard method of TA experiments, converted by the energy scale factor obtained in the previous section, and $E_{\rm SD,CIC(s800)}$ the energy obtained by converting the energy estimator, $s(800)$, to energy using the function obtained in this section is shown in Figure 3 left. The plot when energy estimator, $s(800)$, is changed to s1300 is also shown in Figure 3 right. Fitting these relationships with a power law functions, the indices are not unity, but these energy dependences, in terms of energy-dependent shift, are small and corresponds to $-2.7\%$/decade for $s800$, $-1.4\%$/decade for $s1300$.

## 4. Energy spectra

The results obtained by analyzing 14 years of data from TA in exactly the same way as in previous energy spectrum studies are shown in Figure 6. The case with the conventional energy scale factor of 1/1.27 is shown in black, and the case with the value of 1/1.35, which is the value recalculated by this study, is shown in red. At the same time, Auger's result[2] is shown for comparison.

First, focus on the energy region below $10^{19.5}$ eV. The difference between the previous TA and Auger results was +9% on the energy scale, but using the recalculated energy scale, the difference

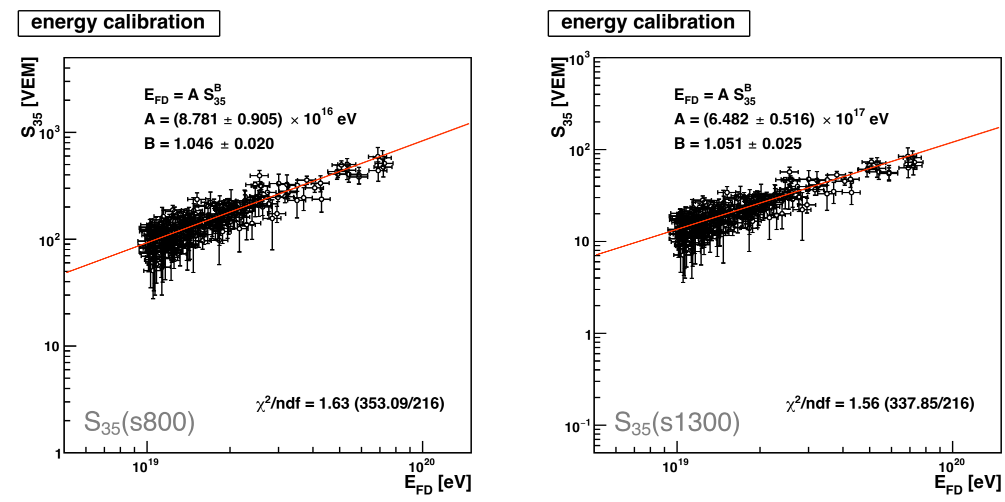


**Figure 2:** The relationships between these $S_{35}$ and $E_{\rm FD}$, and *left* is for $s800$ and *right* is for $s1300$.

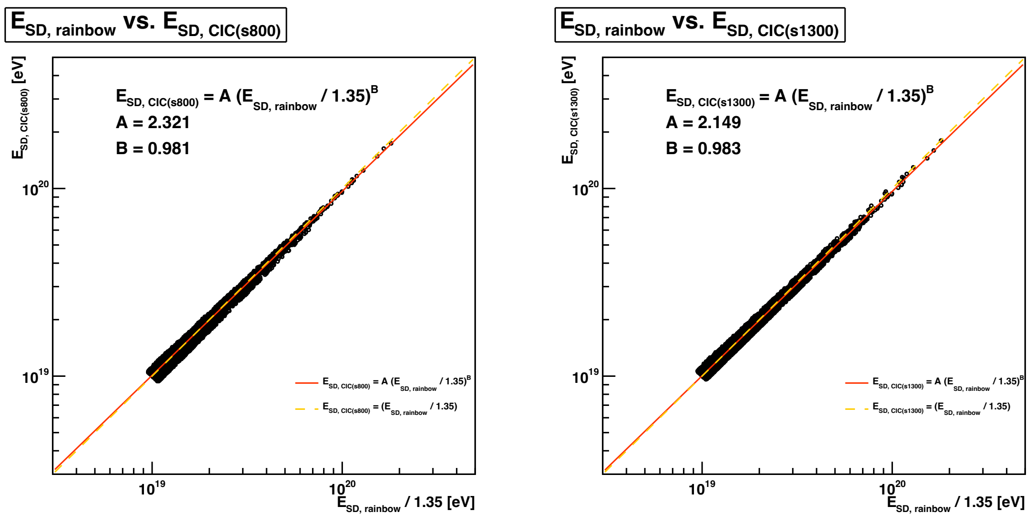


**Figure 3:** These are comparisons of $E_{\rm SD,rainbow}$, the energy obtained by the standard method of TA using the energy scale factor obtained in this study, and $E_{\rm SD,CIC}$, the energy obtained using the relations in Figure 2 obtained with the CIC method.

was reduced to +1%. This is due to the use of the AirFly model and Auger's missing energy, which were off by about -14% and about +7%, respectively.

Turning now to the region above $10^{19.5}$ eV, there is a clear difference between the TA and Auger results. Since it is known that the difference between TA and Auger in this energy region is smaller using data from the common declination band[3], the excess on the TA spectrum above $10^{19.5}$ eV is considered to represent the declination dependence on the energy spectrum.

The energy spectra obtained using $E_{\rm CIC}$ are shown in Figure 5, where the difference between TA and Auger is +3%, reflecting the +2% larger than $E_{\rm SD,rainbow}/1.35$.

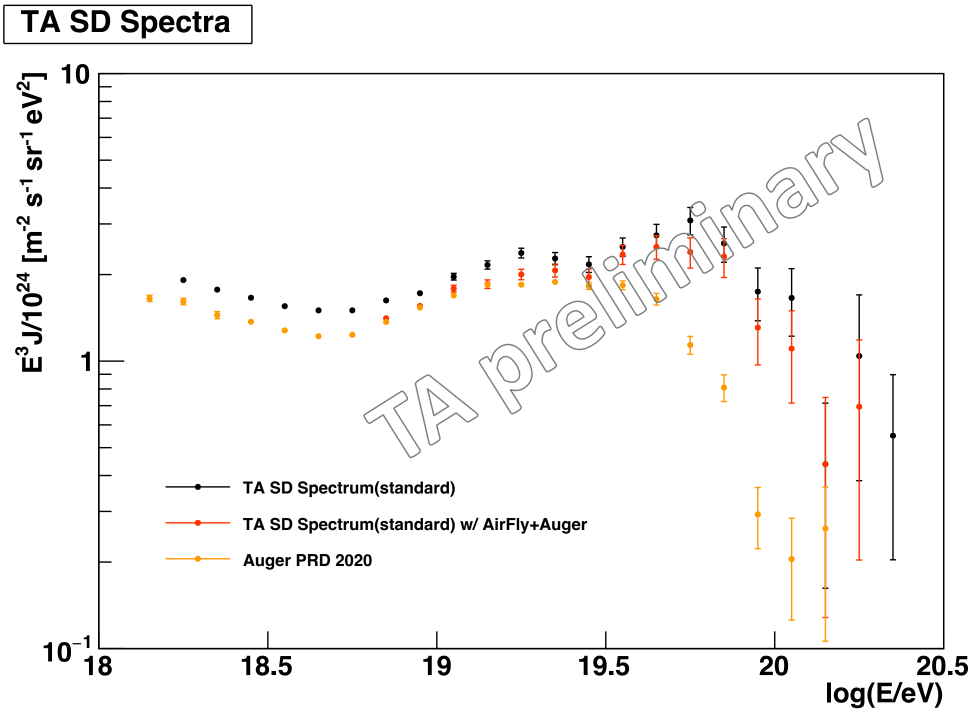


**Figure 4:** Some energy spectra are shown. The spectrum in black is data from 14 years of TA analyzed in the standard way, using the conventional energy scale factor of 1/1.27. Red is the same data as the black one, but analyzed with the energy scale factor of 1/1.35 obtained by the recalculation described in this presentation. Orange is the result of the measurement by Auger[2].

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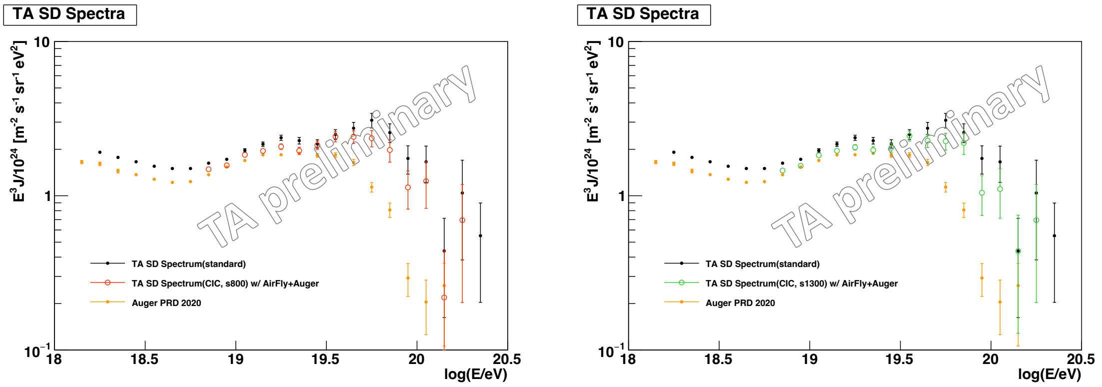


**Figure 5:** Same as Figure 4 for black and orange. On the left is the result of obtaining the energy spectrum based on the energy obtained using s800 as the energy estimator and the relationship in Figure 2 *left*. On the right is the case with s1300.

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