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Calibration of the TA Fluorescence Detectors and Systematic Uncertainties in UHECR Analysis

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Accurate calibration of the Telescope Array Fluorescence Detector (TA-FD) and the atmosphere is crucial for precise analysis of Ultra High Energy Cosmic Rays (UHECRs) using the atmospheric fluorescence method. This paper focuses on two key aspects of calibration: the pointing direction of the TA-FD and the atmospheric transparency as measured by the Vertical Aerosol Optical Depth (VAOD). The pointing direction of the TA-FD was analyzed with an accuracy of ±0.03 degrees using the Opt-copter, a drone-mounted LED light source. The impact of this pointing accuracy on cosmic ray analysis, including the biases and systematic uncertainties it introduces, is estimated. Additionally, the TA experiment continuously observes UHECRs with the FD, capturing air showers induced by primary UHECRs. Monthly VAOD values, determined through Central Laser Facility (CLF) operation, exhibit a seasonal dependence. Incorporating this seasonal variation into air shower analysis can improve the accuracy of primary energy and Xmax measurements, along with the associated systematic uncertainties.

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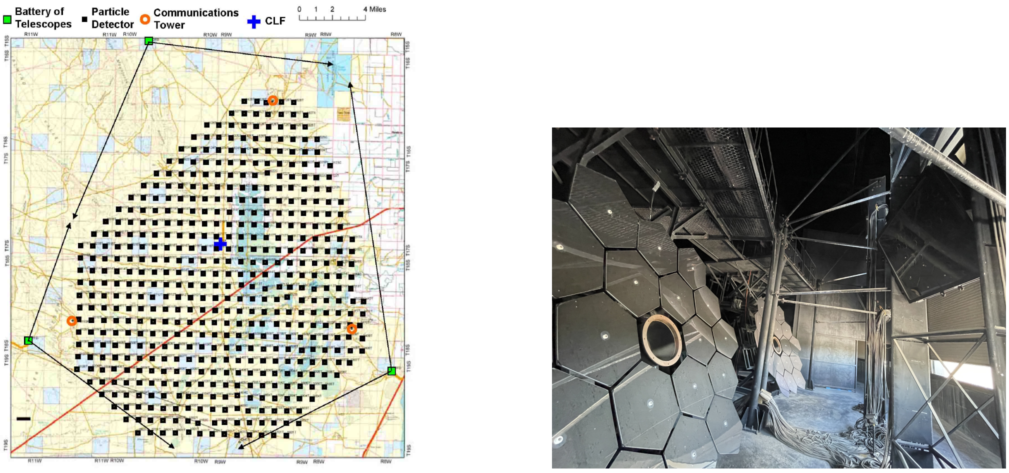
1. Introduction

The Telescope Array (TA) experiment, located in Utah, USA, has been continuously observing ultra-high-energy cosmic rays (UHECRs) with energies exceeding 10^{18} eV for nearly 20 years. The experiment employs several methods to detect UHECRs. We have 507 surface detectors (SD) to detect particles that reach the surface of the ground directly. Additionally, it operates three fluorescence detector (FD) stations to capture the fluorescence emitted by the atmosphere from an air shower. Figure 1a shows the site map of the TA experiment. Figure 1b shows the appearance of TA-FD. Accurate calibration of the telescopes and atmospheric conditions is essential when estimating



(a) Site map of the TA.

(b) The appearance of TA-FD

Figure 1: Left: Site map of the TA. Black squares show the surface detectors. Green squares show the florescence detectors. Blue cross show the central laser facility. Right: The appearance of florescence detector.

the energy or composition of the primary particles using FD. The TA experiment requires more accurate analysis using FD to resolve the differences between TA and other experiments and to reduce the systematic uncertainties among FD stations. For this reason, we analyzed the optical properties of the FD in greater detail of FD and developed a monthly atmospheric transparency model with higher time resolution.

In this proceedings paper, we apply the new calibration factors, the telescope pointing direction and monthly model of the atmospheric transparency, to the cosmic ray analysis. We evaluate the impact of each calibration on the cosmic ray analysis using simulations.

2. Telescope pointing direction

2.1 Opt-copter

The "Opt-copter" is a calibration device for determining the telescope's pointing direction, equipped with a UV-light source and the RTK-GPS for positioning on the drone. Figure 2 shows the appearance of the Opt-copter. This device is flown within the field of view of the telescope, and the light source mounted on the drone is observed with the telescope to analyze the optical properties of the FD. The position accuracy of the RTK-GPS is typically 10 cm, which corresponds to a directional accuracy of 0.02 degrees. The FD pointing is analyzed by comparing the position of the light source on the drone and center of gravity of the imaged captured by FD. Table 1 shows the shift of BRM-FD's pointing direction from the starlight analysis (previous analysis). The uncertainty of this analysis is ±0.03 degrees (RTK-GPS resolution + Systematic error due to the alignment of the center PMTs on the cameras).[1] [2]

Figure 2: The appearance of the Opt-copter

Table 1: The pointing shift of the telescope at BRM station analyzed using the Opt-copter. The uncertainty of the Opt-copter analysis is 0.03 degrees.

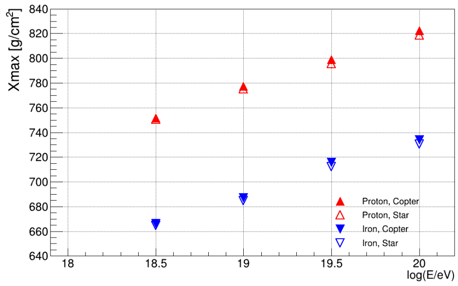
	FD00	FD01	FD02	FD03	FD04	FD05	FD06	FD07	FD08	FD09	FD10	FD11
ΔAzimuth [deg.]	0.05	0.00	0.04	0.04	0.04	0.02	0.01	-0.04	0.01	-0.05	-0.02	0.01
ΔElevation [deg.]	0.11	-0.04	0.02	-0.03	-0.04	-0.12	-0.05	-0.14	-0.12	-0.19	-0.14	-0.15

2.2 Effect of the telescope pointing direction

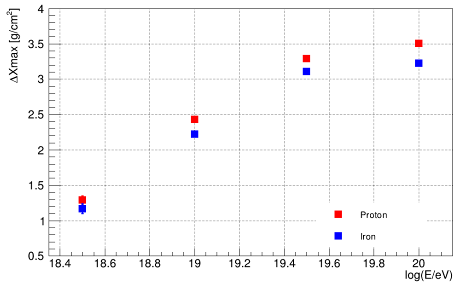
The FD pointing direction obtained using the Opt-copter has greater accuracy than that determined through starlight analysis. In the Opt-copter analysis, the difference was as large as -0.19 degrees which exceeds the analysis error assumed in the starlight method. Therefore, it is necessary to perform cosmic ray analysis using the geometry derived from the Opt-copter. We estimate the effect of changing the telescope pointing direction on X_{max}. We apply the FD pointing direction obtained by the Opt-copter analysis and those obtained by the starlight analysis to the reconstruction. We also use the Opt-copter geometry in the simulation to replicate actual FD observations. Figure 3a is the reconstruction X_{max} with the two FD pointing directions from the same simulation. The X_{max} obtained with the Opt-copter-based pointing direction is deeper than that obtained with the starlight-based direction because the Opt-copter's pointing direction is at a lower angle. Figure 3b is the reconstructed X_{max} difference ($X_{max}^{copter} - X_{max}^{star}$) of the same event for the effect on a single event. This effect results in a shift +1.2 to +3.5 g/cm^2 over the energy range of $10^{18.5}$ to $10^{20.0}$ eV.

2.3 Bias and systematic uncertainty by the pointing direction

We estimate the reconstruction bias and the systematic uncertainty in X_{max} using the FD pointing obtained by the Opt-copter analysis. Figure 4a shows the reconstruction bias, represented as the average of the histogram of the difference $X_{max}^{recon} - X_{max}^{simu}$ for each FD pointing direction. The



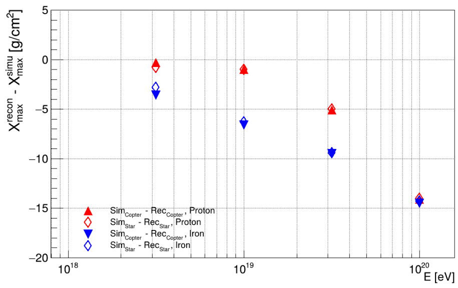
(a) Reconstructed X_{max} average



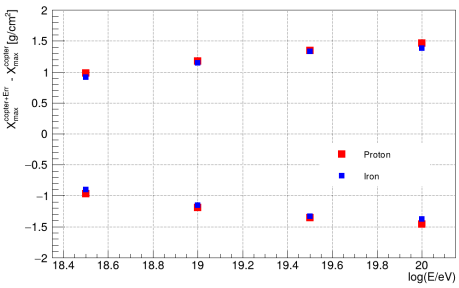
(b) ΔX_{max} average

Figure 3: Left: The reconstructed X_{max} average using Opt-copter geometry and star geometry. Right: Effect of the telescope pointing direction for X_{max}. The average value of reconstructed $X_{max}^{copter} - X_{max}^{star}$.

current bias using the starlight-based geometry is nearly the same as that using the Opt-copter-based geometry. Figure 4b shows the systematic uncertainty in X_{max} due to pointing accuracy (±0.03 degrees). This is the difference between the reconstructed X_{max} values obtained from the Opt-copter analysis with the FD pointing and those obtained when accounting for the pointing accuracy. This effect results in an uncertainty of ± 0.9 to ± 1.5 g/cm^2 over the energy range of $10^{18.5}$ to $10^{20.0}$ eV.



(a) Reconstruction bias of X_{max} using each telescope geometry



(b) Systematic uncertainty of X_{max} from the telescope pointing accuracy

Figure 4: Left: Result of the reconstruction bias using the Opt-copter geometry and the bias using the star geometry. Right: Result of the systematic uncertainty of the X_{max} from the telescope pointing accuracy in the energy range of $10^{18.5}$ to $10^{20.0}$ eV. The telescope pointing accuracy is ±0.03 degrees.

3. Atmospheric Transparency

3.1 Central Laser Facility

A laser system is located at the center of three FD stations in TA site, and the light scattered by the atmosphere is observed by each FD station. This system is called CLF.[3] Figure 5 shows the appearance of the CLF system. The laser is emitted vertically at the CLF, and the side-scattered light is captured by the FD to calculate atmospheric transparency. The Vertical Aerosol Optical Depth (VAOD) represents the atmospheric transparency obtained from CLF operations.

Figure 5: Appearance of the CLF container.

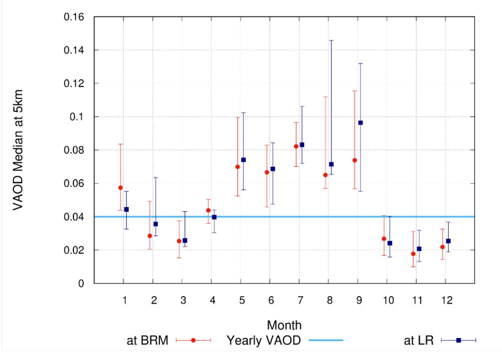
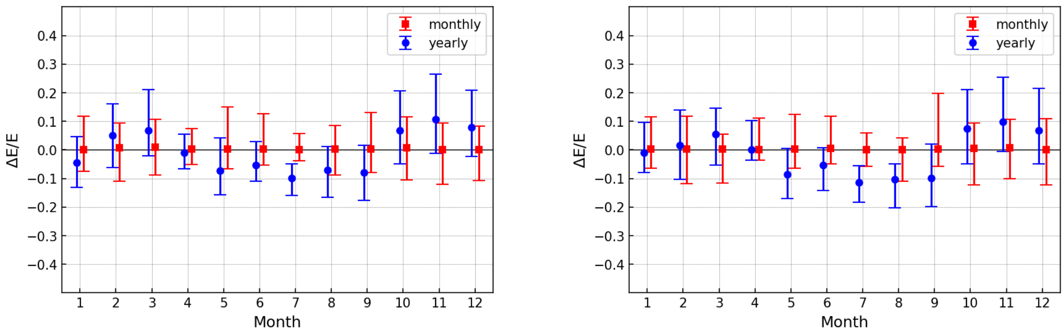


Figure 6: Median of VAOD with error bars indicate the range which is 1σ to the left and right from the median of its distribution for each month.

3.2 Monthly Variation of VAOD

Figure 6 shows the median of VAOD at 5km above ground level with 1σ error bars at BRM and LR stations. VAOD = 0.04 (blue horizontal line) is the constant average value. VAOD in July is the highest, and VAOD in November is the lowest. It appears that there are fluctuations up and down around the 0.04 line. It tends to rise during summer and fall during winter.[4]



(a) Systematic uncertainty in each month using BR station

(b) Systematic uncertainty in each month using LR station

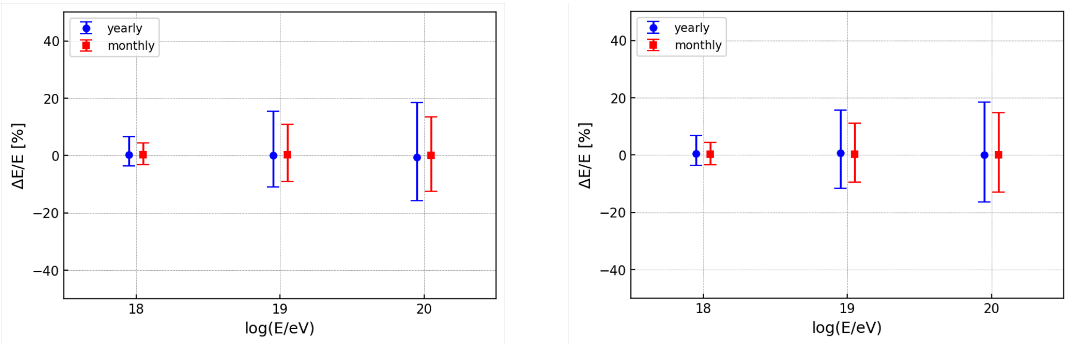
Figure 7: Results of the systematic uncertainty in each month of primary energy in 10^{19} eV. The blue plots are with the constant VAOD and the red plots are with the monthly VAOD.

3.3 Systematic uncertainty at each month

We applied both constant VAOD and monthly VAOD to reconstruct the primary energy and compared the results with event-by-event results to estimate the systematic uncertainty. Figure 7 shows the systematic uncertainty in each month of primary energy in 10^{19} eV at BRM and LR stations. There is a bias of approximately +12% in November and -11% in July when using constant VAOD at both stations. This seasonal dependence is removed when using monthly VAOD.

3.4 Systematic uncertainty at each energy

We estimate the systematic uncertainty in primary energy by adding results each month. Figure 8 show the result of the systematic uncertainty at three kinds of primary energy (10^{18} eV, 10^{19} eV, 10^{20} eV) at BRM and LR stations, respectively. The blue plots are with constant VAOD, and the red plots are with monthly VAOD. The systematic uncertainty with constant VAOD in 10^{19} eV are $0.0^{+15.4}_{-10.9}$ % (BRM) and $0.0^{+14.9}_{-12.2}$ % (LR), respectively, and the systematic uncertainty with monthly VAOD are $0.0^{+10.6}_{-9.3}$ % (BRM) and $0.0^{+10.9}_{-9.7}$ % (LR), respectively. We confirmed that using monthly VAOD reduces the systematic uncertainty in each primary energy due to aerosols across all energy regions.



(a) Systematic uncertainty at each energy using BR station

(b) Systematic uncertainty at each energy using LR station

Figure 8: Results of the systematic uncertainty at three kinds of primary energy (10^{18} eV, 10^{19} eV, 10^{20} eV). The blue plots are with the constant VAOD and the red plots are with the monthly VAOD.

4. Summary

The pointing direction of the FD was analyzed with higher accuracy. We evaluated the effect of the FD pointing direction on cosmic ray analysis, the reconstruction bias using the copter geometry and the systematic uncertainty due to the pointing accuracy (±0.03 degrees) of the FD. When we use the copter geometry, X_{max} shifts deeper by +1.2 to +3.5 g/cm^2. The systematic uncertainty due to the pointing accuracy of the FD is about ±1 g/cm^2.

A monthly atmospheric transparency model with higher time resolution was also developed. We estimated the bias and systematic uncertainties when using this model. Compared to conventional analysis, we find that the analysis could be performed without bias throughout the year, and the systematic uncertainties are also reduced.

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