(1) SHINSHU UNIVERSITY (2) OECU 大阪電気通信大学 Osaka Electro-Communication University (3) CHUBU UNIVERSITY AICHI JAPAN (4) ICRR Institute for Cosmic Ray Research University of Tokyo (5) KU (6) UTAH TELESCOPE ARRAY PROJECT

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

Takayuki Tomida[1], Daiki Sato[1], Kota Mizuno[1], Aoi Matsuzawa[1], Yuichiro Tameda[2], Katsuya Yamazaki[3], Keitaro Fujita[4], Daisuke Ikeda[5], John Matthews[6] and for the Telescope Array collaboration

Contact : tomida@cs.shinshu-u.ac.jp

Abstract 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 presentation focuses on two key aspects of calibration: the pointing direction of the TA-FD and the atmosphere 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-board LED light source. We estimate the impact of this pointing accuracy on cosmic ray analysis, including the biases and systematic uncertainties it introduces. Additionally, the TA experiment continuously observes UHECRs with the FD, capturing air showers induced by primary UHECRs. Monthly VAOD values, determined through CLF operation, exhibit a seasonal dependence. We will discuss how incorporating this seasonal variation into air shower analysis can improve the accuracy of primary energy and Xmax measurements, along with the associated systematic uncertainties.

Telescope pointing direction

Opt-copter

The "Opt-copter" is calibration device for telescope pointing direction, equipped with a UV-light source and the RTK-GPS for positioning on the drone. 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 imaged 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 by alignment of the center PMTs on the cameras).

	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

Table 1. The results of FD pointing analysis at BRM station (2018)

Effect of the telescope pointing direction

We should use the FD pointing obtained by "Opt-cotper" for cosmic ray analysis because it is analyzed with greater accuracy than the starlight analysis. We apply the FD pointing direction obtained by the Opt-copter analysis and those obtained by the starlight analysis for the reconstruction. Figure 1 is the reconstruction X_{max} with the two FD pointing directions from the same simulation. X_{max} using the FD pointing obtained by the Opt-copter analysis is deeper than X_{max} using those obtained by the starlight analysis because the FD pointing direction obtained by the Opt-copter is lower in angle than those obtained by the starlight analysis. Figure 2 is difference reconstructed X_{max} of the same event for the effect on a single event. This effect results +1.2 to +3.5 g/cm^2 over the energy range of $10^{18.5}$ to $10^{20.0}$ eV.

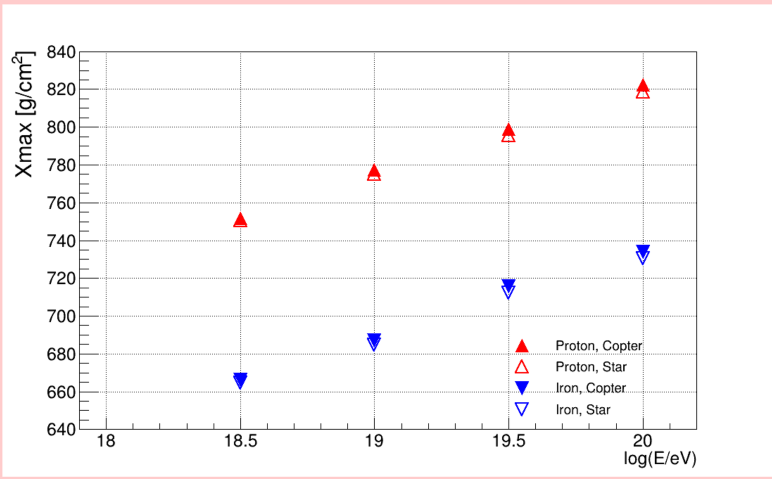


Figure 1. Reconstructed X_{max} values

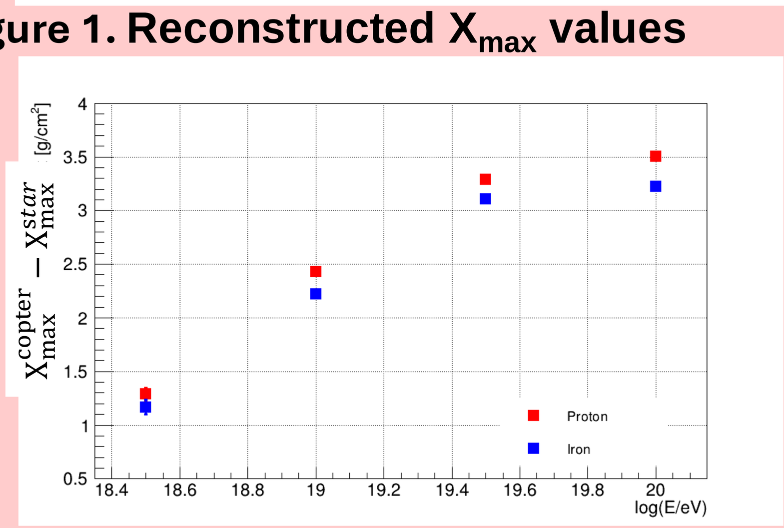


Figure 2. Mean of histogram of difference $X_{max}^{copter} - X_{max}^{star}$ for reconstructed event

Bias and systematic uncertainty by the pointing direction

We estimate the bias and the systematic uncertainty in X_{max} using the FD pointing obtained by the Opt-copter analysis. Figure 3 is the average of the histogram of the difference $X_{max}^{recon} - X_{max}^{simu}$ in each the FD pointing direction. Figure 4 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 of the Opt-copter analysis that includes 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.

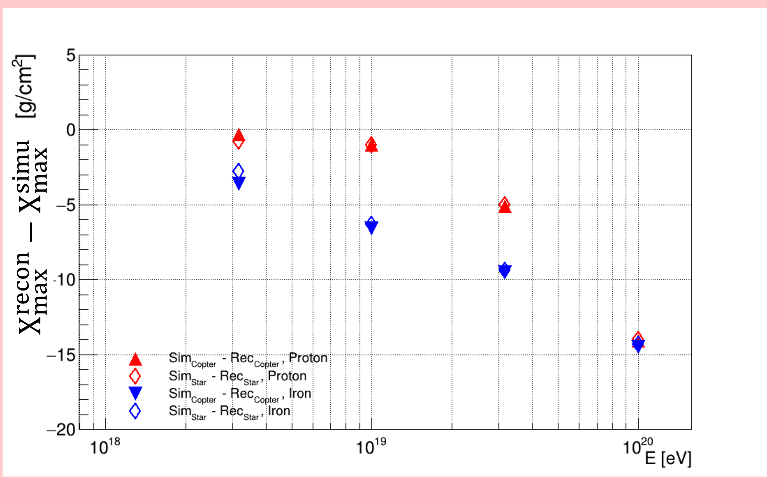


Figure 3. Bias of X_{max}

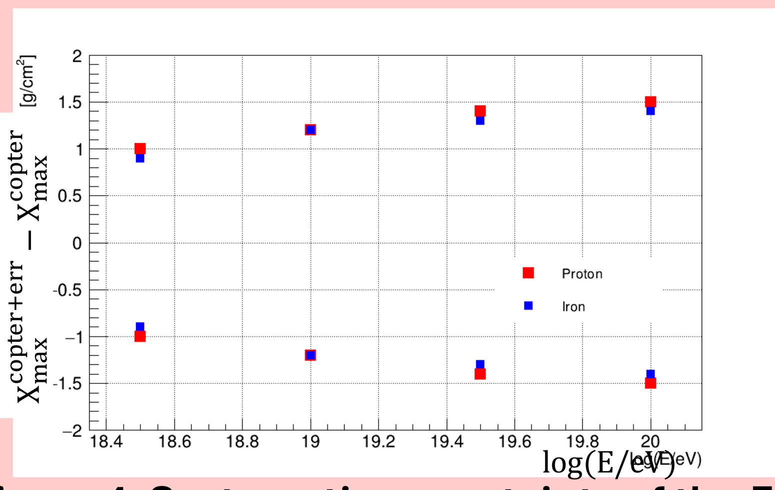
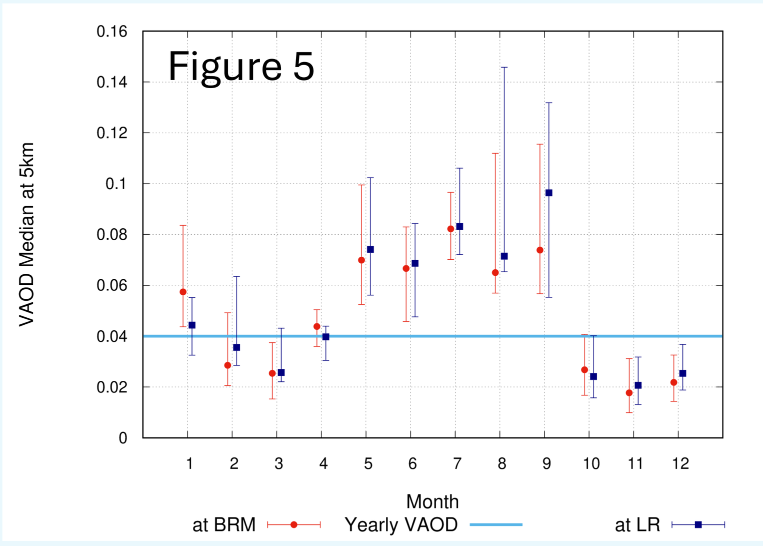


Figure 4. Systematic uncertainty of the FD pointing

Atmospheric Transparency

Central Laser Facility : CLF

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



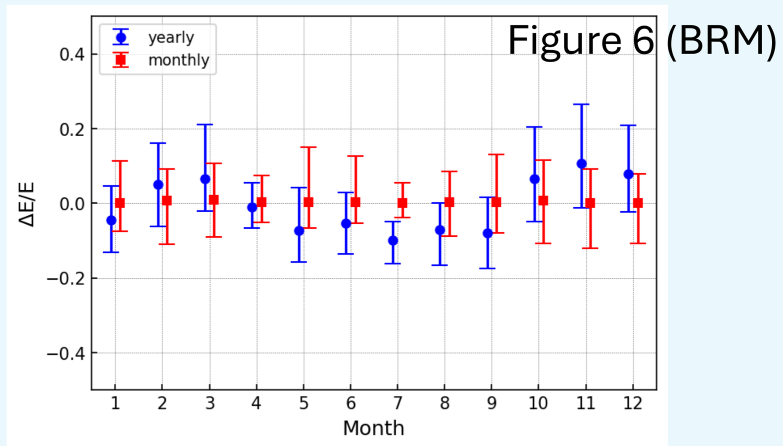
Monthly variation of VAOD

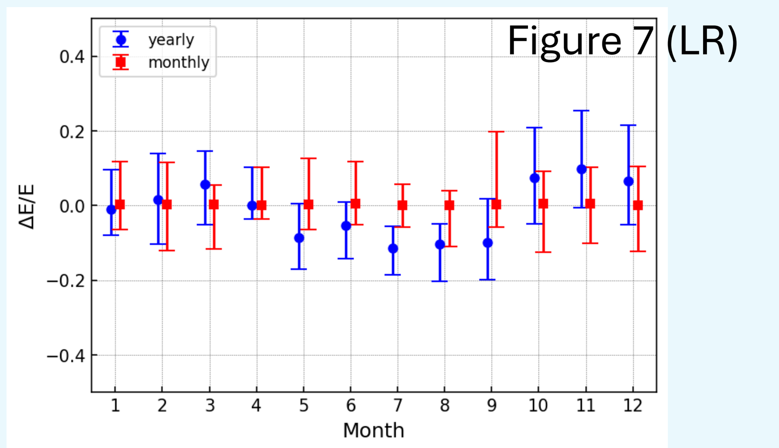
Fig. 5 shows the median of VAOD at 5km above the ground with 1σ error bars at BRM and LR stations. VAOD = 0.04 (blue horizontal line) is the yearly average value. VAOD in July is the highest, and VAOD in November is the lowest. It appears that there are fluctuations up and down around the 0.04 line.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

Systematic uncertainty in each month

We apply yearly VAOD and monthly VAOD to reconstruct the primary energy and compare their results with event-by-event results to estimate the systematic uncertainty. Fig. 6 and Fig.7 show 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 yearly VAOD at both stations. This seasonal dependence is removed when using monthly VAOD.

CLF





Systematic uncertainty at each energy

We estimate the systematic uncertainty in primary energy by adding results each month. Fig. 9 and Fig.10 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 yearly VAOD, and the red plots are with monthly VAOD. The systematic uncertainty with yearly 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 primary energy due to aerosols across all energy regions.