PROCEEDINGS OF SCIENCE

Effects of atmospheric transparency on Telescope Array air shower analysis

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The Telescope Array (TA) experiment continues to observe Ultra High Energy Cosmic Rays (UHECRs) both with its original TA detectors as well as with the new TAx4 expansion detectors. These observations employ Fluorescence Detectors (FDs) to capture the air shower induced by the primary UHECRs. The FD observes fluorescence light emitted from atmospheric nitrogen molecules excited by air shower particles. Observation of the FD extends over tens of kilometers, and the fluorescence light is attenuated by scattering from atmospheric molecules and aerosols during the propagation process. Seasonal dependence was found when evaluating the attenuation of fluorescence by aerosols. We will report on the effects of this seasonal dependence on TA air shower analysis.

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1. Introduction

The Telescope Array (TA) experiment, located in Utah, USA, aims to observe Ultra-High Energy Cosmic rays (UHECRs) at energies above 10^{18} eV. TA consists of 507 Surface Detectors (SDs) and 3 Fluorescence Detector (FD) stations. Each FD station called as "Black Rock Mesa"(BR), "Long Ridge"(LR) and "Middle Drum"(MD) have been installed surrounding SD array.

The fluorescence light emitted from air showers is scattered and absorbed by atmospheric molecules and aerosols in the propagation process from the air shower to the FD. The distribution and amount of aerosols fluctuate in a short time due to wind and other factors, so we need to observe and estimate them.

In the TA experiment, we employ a variety of measurements for atmospheric monitoring, using laser systems. This laser system is located at the center of three FD stations, and the light scattered by the atmosphere is observed by each fluorescence detector station. This system is called CLF (Central Laser Facility) [1]. The laser is emitted vertically at the CLF, and the side-scattered light is captured by the FD to calculate atmospheric transparency. It has been reported that the Vertical Aerosol Optical Depth (VAOD) as the atmospheric transparency obtained from CLF observations has annual fluctuation in the last ICRC [2]. Figure 1 shows the median of VAOD at 5km and its error bars (1σ). The number shown above the error bar is the number of CLF events which is used for VAOD anlysis in that month. VAOD = 0.04 (blue horizontal line) is the yearly typical value. It appears that there are fluctuations up and down around the 0.04 line. It exhibits a tendency to rise during the summer and decline during the winter.

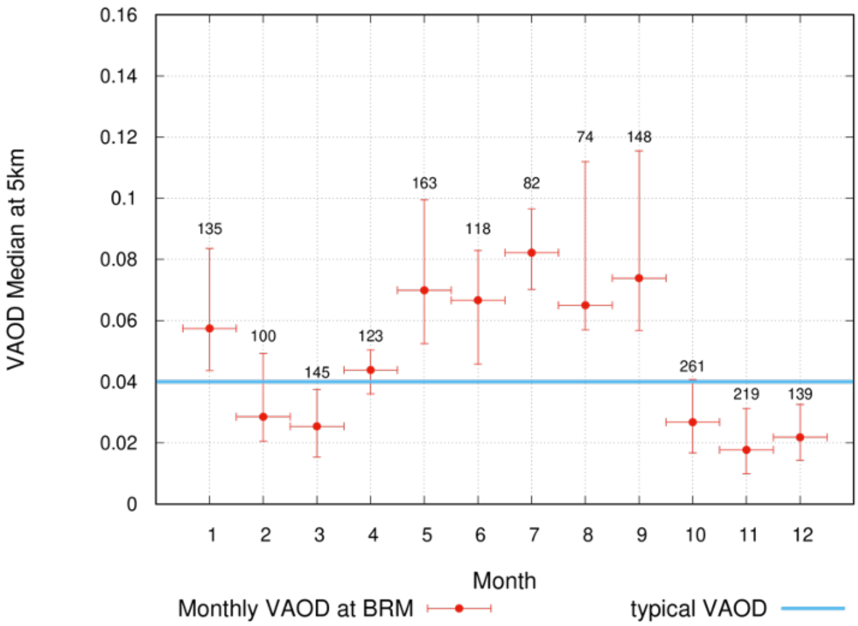

Figure 1: Median of VAOD and error bars indicate the range which is 1σ to the left and right from the median of its distribution for each month at BR

2. VAOD anomaly in January

CLF operation was conducted from 2010 to 2018, and about three of those years are used in the VAOD analysis. "Entries" in Table 1 shows the number of laser shots. "Days" in Table 1 shows the number of days in which laser shots were conducted during the about three years period. The values in this table indicates that the VAOD analysis is unbiased. However, the median value "0.057" in January seems to be high. This is because some observations in January were attenuated at low altitudes (1 to 3 km). Figure 2 shows that the distribution of number of photon when attenuation occurs at low altitude altitude and when it does not. This specific waveform is responsible for the increase in VAOD. We suspect that the attenuation at low altitudes may be caused by fog.

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Median VAOD	0.057	0.029	0.025	0.044	0.070	0.067	0.082	0.065	0.074	0.027	0.018	0.022
Entries	135	100	145	123	163	118	82	74	148	261	219	139
Days	15	21	16	19	27	21	15	15	24	34	27	19

Table 1: The median of VAOD at each month, the number of CLF events which is used for VAOD anlysis in that month and the number of days used for analysis in about three years

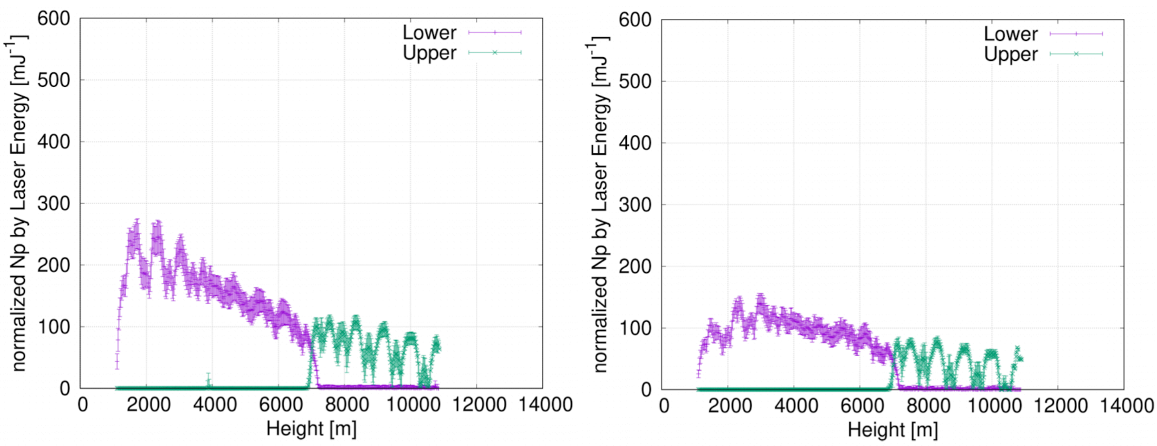

Figure 2: Distribution of the number of photon captured by FD
Left : Normal waveform, Right : waveform with attenuation at low altitude

3. Effects of atmospheric transparency seasonal dependence on air shower analysis

Currently, we use the yearly VAOD which is the constant throughout the year for atmospheric calibration. In contrast, we can get the monthly VAOD (Figure 1) which is the different for each month due to the CLF analysis. In this section, we estimate the systematic error when the monthly VAOD is applied.

3.1 Analysis Method

We evaluate the systematic error of primary energy due to the aerosols utilizing monthly VAOD data obtained from CLF through a Monte-Carlo (MC) technique. In addition, we also evaluate that systematic error using yearly VAOD data for comparison. In this analysis, we use the mono analysis of BR FD [3]. To assess the impact of VAOD on shower reconstruction, we simulate a shower using VAOD data acquired from CLF and subsequently reconstruct it using the same VAOD, yearly value, and monthly value. As for the geometry, the result is a fix to the simulation. The conditions used in the simulation, atmospheric conditions in reconstruction and quality cuts are as follows tables.

Conditions used in the simulation

- Primary particle : Proton
- Interaction model : QGSJETII-04
- log(E/eV) : 18.0, 19.0
- Zenith angle : 0 - 65 °
- Azimuth angle : 0 - 360 °
- Core positon (log(E/eV)=19) : within 25km from CLF
- Core positon (log(E/eV)=18) : Fan shape centered on BR (17.5km radius)
- Number of events : Number of CLF data per month × 500

Atmospheric conditions in reconstruction

- Thrown VAOD
- Yearly VAOD
- Monthly VAOD

Quality cuts

- Number of PMTs > 10
- time extent > 2 μs
- track length > 10 °
- Xmax in the field of view of FD
- Zenith angle < 55 °

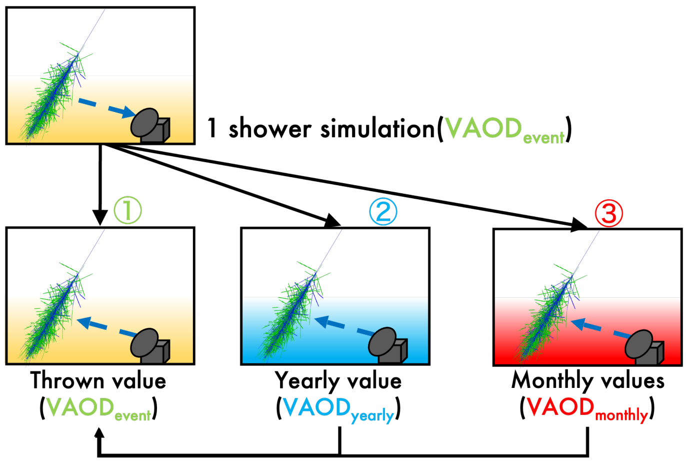

Figure 3: Model diagram showing reconstruction under three atmospheric conditions for one air shower simulation

Figure 3 shows the model diagram showing reconstruction under three atmospheric conditions for one air shower simulation. We compare these three reconstructed energy results. When we reconstruct events that have been collected over an entire year, using the values of VAOD that is relevant for each event, there is no bias due to atmospheric effects. We assume that E_{event} is the ideal result in this analysis and evaluate by making comparisons between E_{event} and E_{yearly} or E_{monthly}. The diffrence between E_{event} and E_{yearly} or E_{monthly} is due to the atmospheric effects. By evaluating these differences, we can assess the systematic errors that would result from using each atmospheric model. ΔE_Y is the diffrence between E_{event} and E_{yearly}. And also, ΔE_M is the diffrence between E_{event} and E_{monthly}.

3.2 Results

We estimated the ΔE_{Y} and ΔE_{M} for each month. In this analysis, we evaluate the differences of energy as a ratio by dividing them by E_{event}. Figure 4 shows the ΔE histgrams of the sum of all months at 10^{19} eV. These two results are not significantly different. The mean and standard deviation were evaluated using Gaussian fitting, resulting in $\Delta E_{\text{Y}} = 0.8 \pm 11.4\%$ and $\Delta E_{\text{M}} = 0.4 \pm 9.2\%$. Both of them have no bias. These results mean that previous results using yearly VAOD are not wrong.

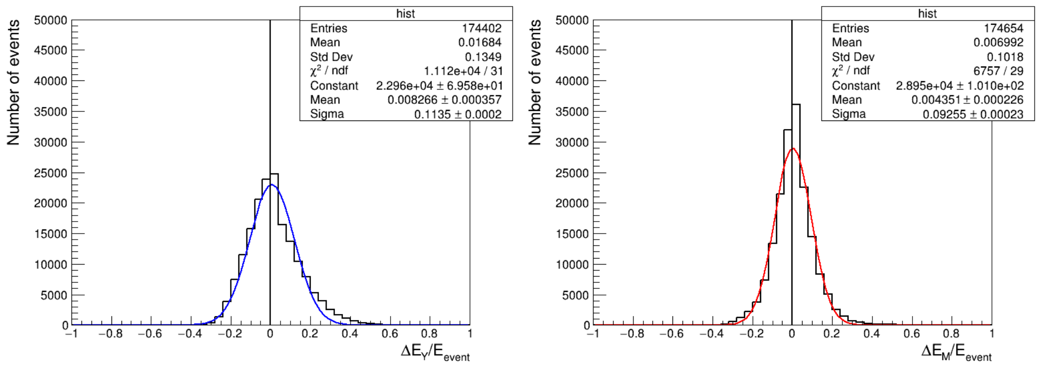

Figure 4: Results for 10^{19}eV : sum of all months. Left:using yearly VAOD, Right:using monthly VAOD

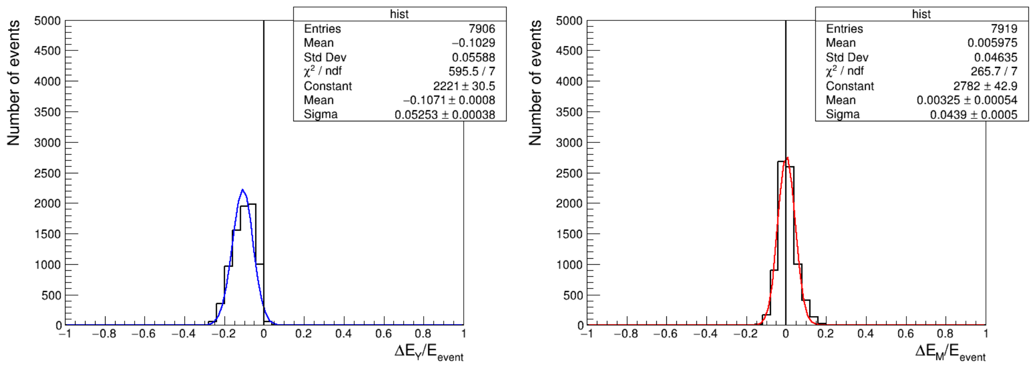

Figure 5: Results for 10^{19}eV in July. Left:using yearly VAOD, Right:using monthly VAOD

There is a clear difference in the distribution of ΔE separately for each month. Figure 5 shows the ΔE distribution in July which has the highest median of VAOD. Results are $\Delta E_{\text{Y}} = -10.7 \pm 5.3\%$

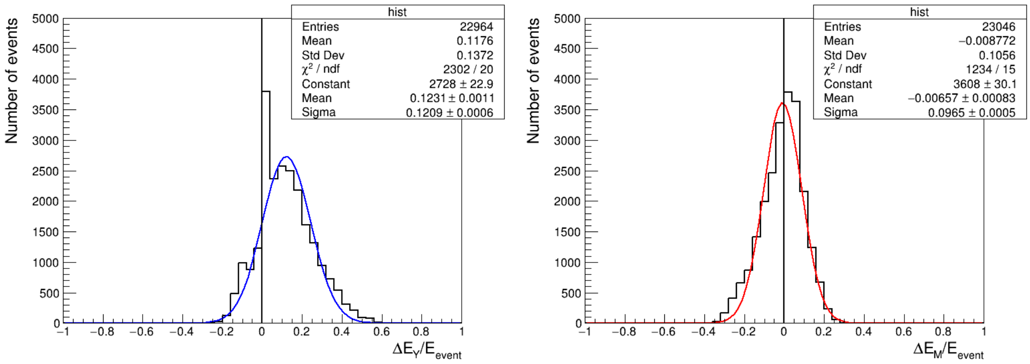

Figure 6: Results for 10^{19}eV in November. Left:using yearly VAOD, Right:using monthly VAOD

and $\Delta E_{\mathrm{M}} = 0.3 \pm 4.4\%$ in July. These results mean that reconstructed energy tends to be estimated lower when using yearly VAOD in July. On the other hand, reconstructed energy using monthly VAOD has no bias. Figure 6 shows the ΔE distribution in November which has the lowest median of VAOD. Results are $\Delta E_{\mathrm{Y}} = 12.3 \pm 12.1\%$ and $\Delta E_{\mathrm{M}} = -0.7 \pm 9.7\%$ in November. Energy is estimated to be higher using yearly VAOD in November. This indicates that if the amount of aerosol is larger than expected, the energy is estimated to be greater and vice versa.

Figure 7 shows the ΔE distribution for each month at 10^{18} and 10^{19} eV. The results using the yearly value has annual fluctuation at both energies. This fluctuation tends to increase as energy increases. The trend of this fluctuation is consistent with the distribution of monthly median of VAOD (Figure 1). This means that energy tends to be estimated lower in summer and higher in winter. Each month has a positive or negative bias. The result of summing these biases is shown in Figure 4. Using the monthly values, this fluctuation is not seen.

4. Summary

The atmospheric transparency : VAOD used for TA air shower reconstruction is the constant throughout the year. On the other hand, the monthly VAOD is revealed by operating CLF. Therefore, we used these two models to estimate effects on energy reconstruction. When comparing the results as sum of one year data, there was no significant difference between the two models. This result means that previous results using yearly VAOD are not wrong. However, when comparing the results for each month, there was significant impact on the models. Average value of reconstructed energy in July and November are biased when using yearly VAOD. In the case of 10^{19} eV, energy is estimated about 11% lower in July and about 12% higher in November. In contrast, there is no bias in both months when using monthly VAOD. We found seasonal dependence of VAOD on energy reconstruction, and we succeeded to calibrate the dependency by using monthly VAOD.

In the future, we will continue to estimate the effects of the LR FD.

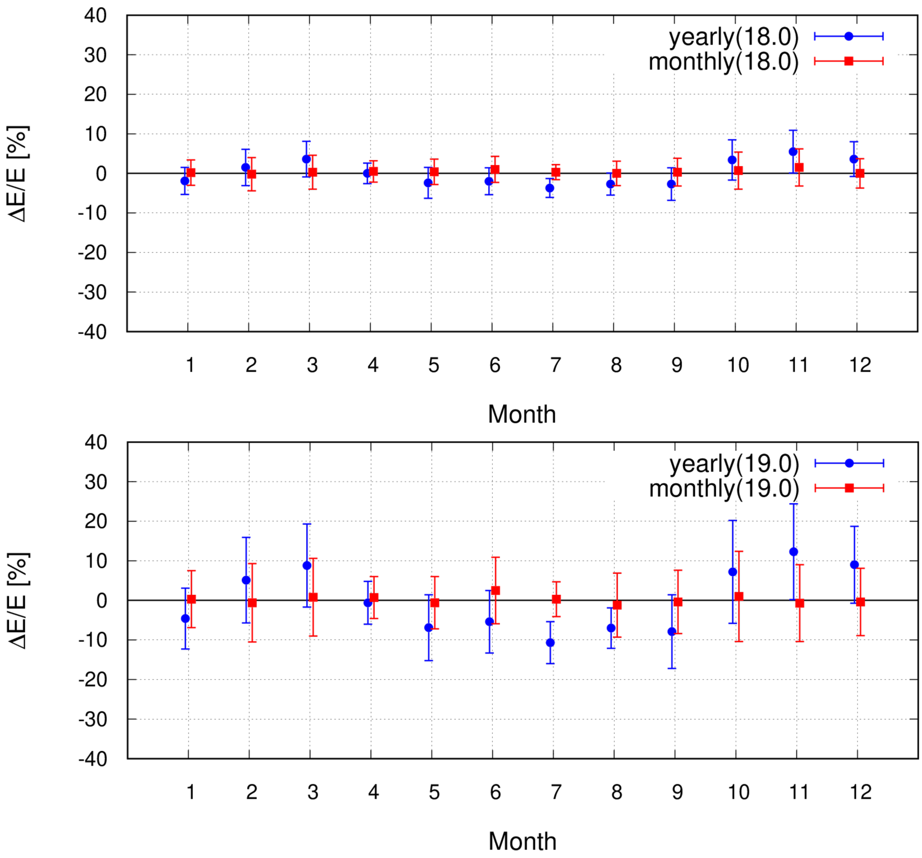

Figure 7: ΔE distribution for each month. Upper figure is at 10^{18} eV. Lower figure is at 10^{19} eV. The mean and standard deviation evaluated using Gaussian fitting on the histgrams of the $\Delta E/E_{\text{event}}$ at each month are plotted.

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