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The atmospheric transparency of Telescope Array observation site by the CLF

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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. The 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 assessing the attenuation of fluorescence by aerosols. We also captured the weather characteristics. We report on the effect of aerosols on the atmospheric transparency of the TA sites.

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1. Introduction

The Telescope Array experiment keeps observing Ultra High Energy Cosmic Ray(UHECR) from the beginning of 2008 to the present. The TA uses two air shower detection techniques of fluorescence detection technique and particle surface detection technique to observe UHECRs[1][2]. A layout of TA experiment site is shown in Figure 1. The 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.

Fluorescence light witch is generated by the air shower. FD observes cosmic rays indirectly by detecting these fluorescence light. Atmospheric monitoring is necessary for observing UHECRs using the air fluorescence technique because the fluorescence light is scattered by the atmosphere in their path of transmission to the FD. Mainly, two types of scattering are considered the atmospheric molecules and the aerosol. Rayleigh scattering that the atmospheric molecules causes can estimate from information of the temperature and the atmospheric pressure obtained from the GDAS[3]. Scattering caused by an aerosol has significant effect on energy of cosmic rays because the shape, the amount and the composition of the aerosol are varied by the atmospheric and ground situation. Moreover, they changes time by time.

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), that overview is shown in Fig. 2[4]. In the last ICRC, We have been reporting on the Vertical Aerosol Optical Depth (VAOD) as the atmospheric transparency obtained from CLF observations. Since the VAOD from the previous analysis did not consider the annual fluctuation of atmospheric molecules, the influence of the annual fluctuation of atmospheric molecules was removed in this work. In this the paper, we report about system, analysis and obtained

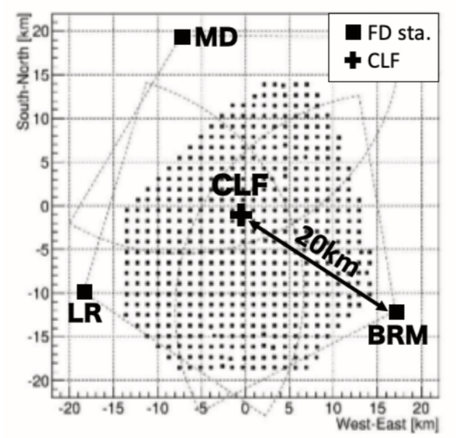

Figure 1: A layout of the TA experiment site. Black small squares are SDs, and three FD stations are shown by BR, LR, and MD with large square. CLF is located at the center of them.

Figure 2: The CLF system. The piture is appearance of the CLF container.

atmospheric transparency of the CLF.

2. Analysis Method

In order to analyze the laterally scattered light of the vertical laser by the CLF and obtain atmospheric attenuation only by aerosol, we compare it with the state where the aerosol is extremely low, that is, the state where atmospheric scattering by atmospheric molecules is dominant. We have selected data similar to ideal observations in which atmospheric molecules have a dominant effect on all atmospheric scattering. The details will be described later, but it was decided that the observation with the largest amount of light received from the altitude where the weather is sunny and the aerosol is thin is similar to the ideal observation situation.

2.1 Vertical Aerosol Optical Depth

Using the CLF system, we can obtain Vertical Aerosol Optical Depth (VAOD) by considering Rayleigh scattering and the detection efficiency of FD. The VAOD $\tau_{\rm AS}$ is a value equal with the integration value of α to H km from 0 km(2). α is extinction coefficient which is the reciprocal of the attenuation length as a function of height h.

$$\tau_{\rm AS}(\rm H) = \int_0^{\rm H} \alpha_{\rm AS}(h)dh. \tag{1}$$

The VAOD obtained by CLF reflects accurately the total amount of aerosols because the photon passes at a low altitude during the propagation period from the air shower to FD(see Figure 3). Thus, we can calibration factor of the atmosphere every 30 minutes within the FD observation time.

2.2 Solution policy

Overview of the laser path in the analysis is shown in Figure 3. The number of photons Np_0 at laser burst is attenuated by atmospherical molecules and aerosol. The attenuation factor $T(\rm H)$ for photons which vertically propagate in the atmosphere at height H is given by Equation 3.1

$$T_{\rm AS}(\rm H) = \exp[-\tau_{\rm AS}(\rm H)]. \tag{2}$$

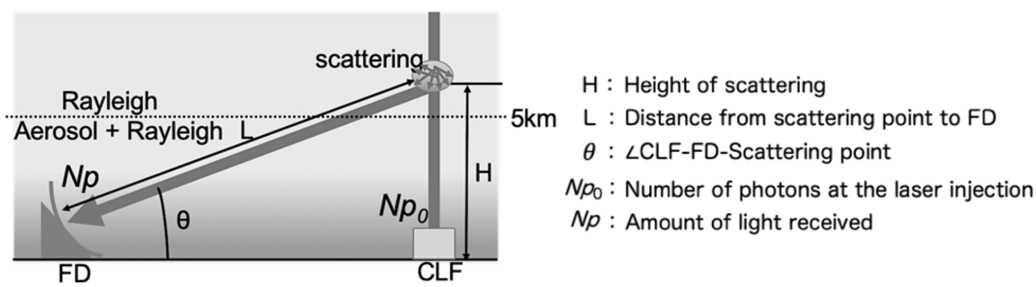

Figure 3: Overview of the laser path in the analysis.

Suffix "AS" means for "Aerosol", and "Ray" means for "Rayleigh" scattering. After attenuated from the ground to height H and scattered, the amount of light heading to the FD can be calculated from the scattering coefficient S. S is a coefficient including scattering cross-section and angle. The received light amount of FD is shown in Equation 3.

$$Np(\mathrm{H}) = Np_0 T_{\mathrm{Ray}}(\mathrm{H}) T_{\mathrm{AS}}(\mathrm{H}) \Big(S_{\mathrm{Ray}} + S_{\mathrm{AS}} \Big) T_{\mathrm{Ray}}(\mathrm{L}) T_{\mathrm{AS}}(\mathrm{L}). \tag{3}$$

Assuming the amount of light received Np' in the atmosphere without aerosol at the clear night, there is no scattering by aerosol. Therefore, The number of photons Np'_0 at laser burst is scattered by only atmospherical molecules at the clear night. Np' at the clear night is shown in Equation 4 where it assumed $T_{\mathrm{AS}}(H) = T_{\mathrm{AS}}(L) = 1$ and $S_{\mathrm{AS}} = 0$.

$$Np'(\mathrm{H}) = Np'_0 T'_{\mathrm{Ray}}(\mathrm{H}) S'_{\mathrm{Ray}} T'_{\mathrm{Ray}}(\mathrm{L}). \tag{4}$$

With this taken into consideration, we analyze assuming the following three conditions.

- Use scattered at higher than 5 km height data in measured waveform (atmospherical molecule dominant)
- Assume the atmospheric parameters are constant in horizontal direction
- We assumed that the effects of annual fluctuations in atmospheric molecules would be negligible. That is shown as following:
  $T_{\mathrm{Ray}}(H) = T'_{\mathrm{Ray}}(H)$, $T_{\mathrm{Ray}}(L) = T'_{\mathrm{Ray}}(L)$ and $S_{\mathrm{Ray}} = S'_{\mathrm{Ray}}$.

First, Mie-LIDAR by TA experiment has found that aerosols do not exist at a height of 5 km or more from the ground at the TA site[4]. In this analysis, it is analyzed CLF waveforms of higher than 5 km of height data because scattering by aerosol is negligible at that height. Therefore, we can assume $S_{\mathrm{AS}} = 0$. Second, assume that the lateral aerosol distribution for each altitude at the TA experiment site is constant. Thus, attenuation factor T(L) is calculated by $T(\mathrm{L}) = T(\mathrm{H})$ / sinθ. θ is determined from the light receiving timing recorded by PMTs of FD. Based on these two conditions, VAOD τ_{AS} is obtained by comparing Np with Np' at the clear night(Equation 5).

$$\frac{Np(\mathrm{H})}{Np'(\mathrm{H})} = \frac{Np_0}{Np'_0} \exp\Big[-\tau_{\mathrm{AS}}(\mathrm{H}) \frac{\sin\theta + 1}{\sin\theta} \Big]. \tag{5}$$

Solving this equation as a solution for τ_{AS} gives:

$$\tau_{\mathrm{AS}}(\mathrm{H}) = -\frac{\sin\theta + 1}{\sin\theta} \ln\Big[\frac{Np'_0}{Np_0} \frac{Np(\mathrm{H})}{Np'(\mathrm{H})} \Big]. \tag{6}$$

This solution assumes that atmospheric molecules do not fluctuate over the years. However, the optical depth of atmospheric molecules from the ground to 5 km above the ground at ELKO near the TA experimental site varies by 8 % annually, and the extinction coefficient α_{Ray}(5km) at a surface altitude of 5 km fluctuates by 3%. Since we thought that the effects of scattering due to annual fluctuations of atmospheric molecules should be fully considered, we sought a solution that took into account the effects of atmospheric molecules. Therefore, we newly added the following conditions: $T_{\mathrm{Ray}}(H) \neq T'_{\mathrm{Ray}}(H)$, $T_{\mathrm{Ray}}(L) \neq T'_{\mathrm{Ray}}(L)$ and $S_{\mathrm{Ray}} = S'_{\mathrm{Ray}}$.

$$\frac{Np(\mathrm{H})}{Np'(\mathrm{H})} = \frac{Np_0}{Np'_0}\exp\left[-\tau_{\mathrm{AS}}(\mathrm{H})\frac{\sin\theta+1}{\sin\theta}\right]$$

$$\exp\left[-\tau_{\mathrm{Ray}}(\mathrm{H})+\tau'_{\mathrm{Ray}}(\mathrm{H})\right]\exp\left[\frac{-\tau_{\mathrm{Ray}}(\mathrm{H})+\tau'_{\mathrm{Ray}}(\mathrm{H})}{\sin\theta}\right]\exp\left[(-\alpha_{\mathrm{Ray}}+\alpha'_{\mathrm{Ray}})\Delta\mathrm{H}\right]. \quad (7)$$

As with the equation 6, the solution for $\tau_{\mathrm{AS}}(\mathrm{H})$ is as follows.

$$\tau_{\mathrm{AS}}(\mathrm{H}) = -\frac{\sin\theta+1}{\sin\theta}\ln\left[\frac{Np'_0}{Np_0}\frac{Np(\mathrm{H})}{Np'(\mathrm{H})}\right]+\left((\tau'_{\mathrm{Ray}}(\mathrm{H})-\tau_{\mathrm{Ray}}(\mathrm{H}))+\frac{\sin\theta+1}{\sin\theta}(\alpha'_{\mathrm{Ray}}-\alpha'_{\mathrm{Ray}})\Delta\mathrm{H}\right). \quad (8)$$

3. Result and Discussion

We calculated the VAOD $\tau_{\mathrm{AS}}(5\mathrm{km})$ at the BR station using CLF by 1853 events from January 2012 to September 2016. We divided the period by the maintenance of the equipment etc., and secured three periods and analyzed by each observation period. Figure 4 shows the monthly transition of the median VAOD for three years. It shows the results of previous and this work. The effect in summer was remarkable, and a 5∼10% increase in VAOD was confirmed. The median and distribution (1 σ) of VAOD in three years by each of previous and this work are $0.044^{+0.025}_{-0.017}$ and $0.045^{+0.026}_{-0.018}$. This statistic is evaluated with a distribution with a VAOD that is less than 0.02. This distribution is shown in Fig. 5.

The obtained VAOD was a change within the distribution on average over 3 years. However, the effect was confirmed depending on the season. In the future, the seasonal dependence of aerosols should be considered in the FD analysis of TA experiments.

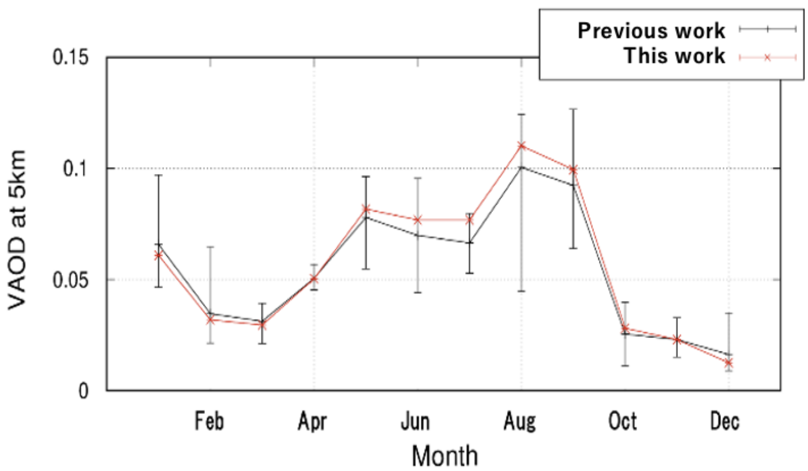

Figure 4: Median of the VAOD for monthly transition.

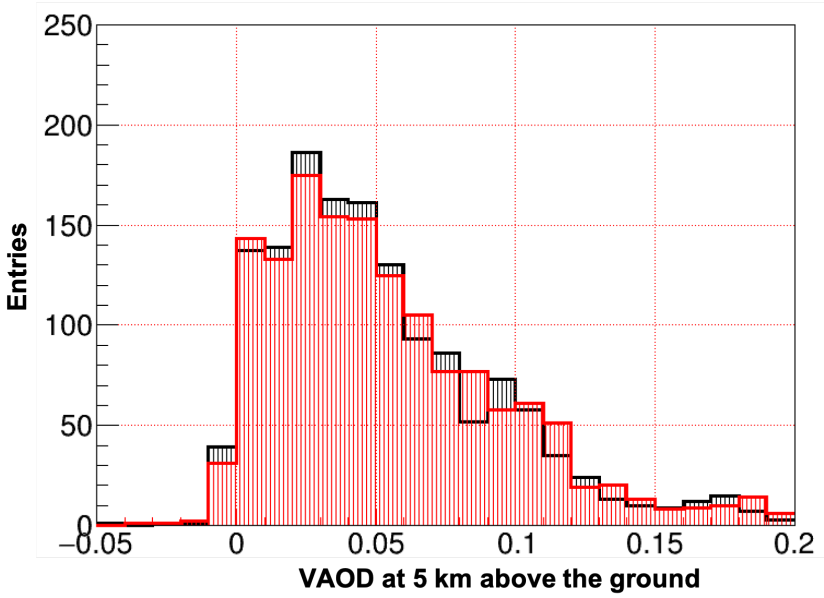

Figure 5: Distribution of VAOD for 3 years.

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