Atmospheric transparency at TA site using Central Laser Facility

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Abstract. The Telescope Array (TA) experiment has three fluorescence detector (FD) stations to measure fluorescence light emitted from extensive air showers, especially produced by Ultra High Energy Cosmic Rays (UHECRs). These fluorescence light is attenuated and decreased by aerosols in the atmosphere during their propagation to the FD. Measuring and calibrating the atmospheric attenuation is necessary to estimate energy of primary cosmic rays. The central Laser Facility (CLF) consists of a laser of wavelength of 355 nm, and emits beam vertically with 10 Hz, every half-hour. The atmospheric transparency in terms of the Vertical Atmospheric Optical Depth (VAOD) is measured with the CLF every 30 minutes during FD observation. The CLF is located at the center of three FD stations and observes the atmospheric transparency of the TA site. We calculated VAOD $\tau_{AS}(5\text{km})$ at the BR station using 1853 events of the CLF laser from January 2012 to September 2016. We found that the median of VAOD at 5 km height from the ground is $0.043^{+0.025}_{-0.015}$. We also found a seasonal variation of VAOD using the same data.

1. Introduction

\textbf{Figure 1.} Left figure shows a layout of the TA experiment site. Three FD stations are shown by BR, LR, and MD with large square. CLF is located at the center of them. Right figure shows an outside view of CLF container.

Atmospheric monitoring is important to observe Ultra High Energy Cosmic Rays (UHECRs) using the air fluorescence technique, because the fluorescence light is scattered by the atmosphere.
in their propagation to the FD. Scattering caused by aerosol has significant effect on energy estimation of primary cosmic rays because distribution, amount and composition of the aerosol are varied by the atmospheric and ground condition. In the TA experiment, we employ a variety of measurements for atmospheric monitoring, using two laser systems. The first laser system is Mie-LIDAR (LIght Detection And Ranging), which observes the back-scattered light of the laser. Mie-LIDAR is widely used in ground-based aerosol measurements. The Mie-LIDAR system at BR is operated at just before and after and FD observation, twice a night. The second laser system is located at the center of three FD stations (Figure 1). Vertically emitted laser beam from the system is scattered by the atmosphere, and the scattered photons are observed by each fluorescence detector. This system is called CLF (Central Laser Facility)[1], and UV laser light is vertically burst from the CLF every 30 minutes during FD observations.

2. Atmospheric transparency analysis

We can measure Vertical Aerosol Optical Depth (VAOD) using CLF by considering Rayleigh scattering and the detection efficiency of FD. $\tau_{AS}(H)$ at a given altitude $H$ is defined by an integral,

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

where $\alpha$ is extinction coefficient which is the reciprocal number of the attenuation length as a function of height $h$, and $h$ is the height from the ground.

2.1. Analysis method

![Figure 2. Overview of the laser path in the analysis.](image)

Overview of the laser path in the analysis is shown in Figure 2. The number of photons $N_{p0}$ at a laser shot is attenuated by atmospherical molecules and aerosol. The attenuation factor $T(H)$ for photons which vertically propagate in the atmosphere to height $H$.

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

Here the suffix "AS" means for "Aerosol". The laser photons that survived the atmospheric attenuation (2) are then scattered at the altitude $H$, and some of the photons are observed by an FD at the distance of $L$ from the scattering point. The number of photons to be observe by the FD is calculated as

$$N_{p}(H) = N_{p0}T_{Ray}(H)T_{AS}(H)\left(S_{Ray} + S_{AS}\right)T_{Ray}(L)T_{AS}(L). \quad (3)$$

where $S_{Ray}$ and $S_{AS}$ are the scattering coefficients of photons towards the FD. Here the suffix "Ray" means for "Rayleigh". Assume the amount of light received by FD with no scattering by aerosol $N_{p}'$. It assumed $T_{AS}(H) = T_{AS}(L) = 1$ and $S_{AS} = 0$ and $N_{p}'$ is calculated as

$$N_{p}'(H) = N_{p0}'T_{Ray}(H)S_{Ray}T_{Ray}(L). \quad (4)$$

Also, we assume following two conditions in our analysis. First, we analyzed CLF waveforms of higher than 5 km of height data because scattering by aerosol is negligible at that height[2].
Therefore, we can assume $S_{AS} = 0$. 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 $T(L) = T(H) / \sin \theta$. $\theta$ is determined from the light receiving timing recorded by PMTs of FD. Based on these two assumptions, VAOD $\tau_{AS}$ is obtained by comparing $N_p$ with $N_p'$ (Equation (5)).

$$\frac{N_p(H)}{N_p'(H)} = \frac{N_p_0}{N_p'_0} \exp\left[-\tau_{AS}(H) \frac{\sin \theta + 1}{\sin \theta}\right]. \quad (5)$$

2.2. Analysis result

We calculated VAOD $\tau_{AS}(5\text{km})$ at the BR FD station using 1853 events of CLF laser from January 2012 to September 2016(Figure 3). We divided the period by the maintenance of the equipment etc., and reliable three periods that each has one year and analyzed by each period.

The median of VAOD and $(1\sigma)$ width of the distribution that an one-sided 34 % tile is $0.043^{+0.025}_{-0.015}$. The VAOD obtained by the Mie-LIDAR system, which is another atmospheric monitor of TA, is $0.035^{+0.019}_{-0.013}$[2]. If this analysis is statistically evaluated under the same conditions (VAOD $\leq 0.10$) as the Mie-LIDAR system, VAOD by our analysis is $0.037^{+0.016}_{-0.011}$. The present results 0.043 and 0.035 are in agreement within the quoted errors. Figure 4 shows the variation of VAOD in 1 year. The VAOD tends to be high in summer (Jun-Sep) and low in winter(Nov-Feb). These were also seen in the Mie-LIDAR system.

![Figure 3. The distribution of VAOD for 3 years.](image)

![Figure 4. Variation of VAOD in 1 year.](image)

3. Conclusion and Near feature

The CLF measures the atmospheric transparency which called Vertical Aerosol Optical Depth. We have found that the median of VAOD at 5 km from the ground is $0.043^{+0.025}_{-0.015}$ using CLF. Moreover, the seasonal dependence was confirmed at variation of VAOD in 1 year from the VAOD analysis result with 3-years data. Near future, we will proceed the analyses to all the data in order to get atmospheric transparency and we will modelize seasonally and hourly variation of VAOD. After that, we plan to estimate the effect on the reconstructed energies on the FD analysis by calibrating the atmospheric transparency.

References

[1] S. Udo et al., Proceedings of the 30th International Cosmic Ray Conference in Merida, 5(2007) 1021.