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The atmospheric transparency measured with a LIDAR system at the Telescope Array experiment

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ABSTRACT

An atmospheric transparency was measured using a LIDAR with a pulsed UV laser (355 nm) at the observation site of Telescope Array in Utah, USA. The measurement at night for two years in 2007–2009 revealed that the extinction coefficient by aerosol at the ground level is $0.033^{+0.016}_{-0.012}$ km^{-1} and the vertical aerosol optical depth at 5 km above the ground is $0.035^{+0.019}_{-0.013}$. A model of the altitudinal aerosol distribution was built based on these measurements for the analysis of atmospheric attenuation of the fluorescence light generated by ultra high energy cosmic rays.

1. Introduction

Ultra High Energy Cosmic Rays (UHECRs) interact with the cosmic microwave background and produce a cutoff structure in their energy spectrum (GZK cutoff) at the energy around $10^{19.8}$ eV as predicted by Greisen et al. [1,2]. The HiRes group reported that there is a GZK cut-off in their observed energy spectrum at the energy it was predicted [3,4]. A similar suppression in the energy spectrum is reported by the Auger experiment in the Southern Hemisphere [5]. However, the AGASA experiment observed a spectrum which continued unabatedly with 11 events beyond the GZK cutoff [6,7]. To understand this discrepancy, the Telescope Array (TA) experiment was constructed in the desert area near the town of Delta in Utah, the USA. It is a hybrid detector consisting of Surface Detector (SD) array and three Fluorescence Detector (FD) stations. It measures the energy spectrum, anisotropy and composition of UHECRs to identify their origin. The TA has three FD stations called "Black Rock Mesa" (BR), "Long Ridge" (LR) and "Middle Drum" (MD), which have been installed surrounding the SD array. The BR site (1404 m a.s.l.) is located at the southeast corner of the SD array while the LR site (1554 m a.s.l.) is to the southwest. The BR and LR stations each have 12 telescopes. The MD site (1610 m a.s.l.) is located at the northwest, and has 14 telescopes. The FD stations overlook an array of 507 SDs (Fig. 1).

The UV fluorescence light generated by an air shower is scattered and lost along the path of transmission to the telescope. The main scattering processes are Rayleigh scattering by molecules and scattering by aerosols in the atmosphere. The Rayleigh scattering process is well understood and the attenuation length can be calculated using the Rayleigh scattering cross-section and the molecular densities of the atmosphere [8–10]. In order to calculate the molecular densities of the atmosphere, radiosonde data from Elko(Nevada) are used to obtain temperature, pressure and humidity around the TA observatory as a function of height. Sizes, shapes and spatial distribution of aerosols around the site

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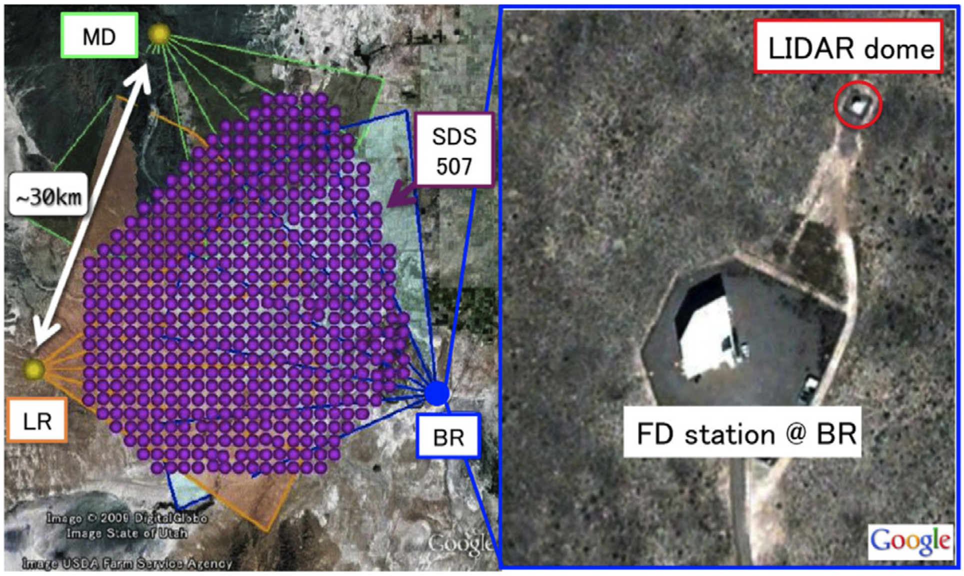

Fig. 1. Location of the LIDAR system. A left figure is a map of the TA experiment. Little black points are SDs, and three FD stations are shown by BR, LR, and MD. A right picture shows the positions of BR-station and LIDAR dome. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are not known, and are variable with time. Therefore, on-site monitoring of aerosols is essential in a fluorescence experiment.

In the TA, we employ a variety of measurements for atmospheric monitoring, using two laser systems and a cloud camera. The first laser system is the LIDAR (LIght Detection And Ranging, we call LIDAR) installed near the BR station, which injects a pulsed laser light in the atmosphere and observes the back-scattered light at the same location. LIDAR is widely used in ground based aerosol measurement. The LIDAR system is operated before the beginning and after the end of an FD observation, twice a night. The second laser system is located at the geographical center of the three FD stations. It fires a vertical laser beam of 355 nm and the scattered light by the atmosphere is observed by each fluorescence detector station. This system is called CLF (Central Laser Facility) [11,12]. We are shooting 300 shots of laser at 10 Hz from the CLF every 30 min during FD observation. In addition, we installed an infrared CCD camera for cloud monitoring near the LIDAR system, and take pictures of the night sky every hour during FD observation [13]. Furthermore, the weather monitors are installed in each of the FD stations and at the CLF to obtain the atmospheric status at the ground level.

In this paper, we report on the LIDAR system (Section 2), the data set and the analysis method (Section 3), the determination of the Rayleigh scattering by the radiosonde data (Section 4), the result of aerosol scattering by the LIDAR data (Section 5), and a model of atmospheric transparency at the TA site (Section 6).

2. LIDAR system

A photograph of the LIDAR system is shown Fig. 2(a). The LIDAR is composed of five basic system blocks. Those are (1) a laser, (2) a steerable telescope, (3) a photo-multiplier tube, (4) a digital oscilloscope, and (5) a control system as shown in Fig. 2(b). We use an air cooled Nd:YAG laser (Orion model by New Wave Research) with a third harmonic oscillation module (355 nm). The laser fires a pulse with the width of 4–6 ns at 1 Hz. The maximum energy of the laser pulse is 4 mJ. A MEADE LX200GPS-30 telescope with a diameter of 305 mm and a focal length of 3048 mm is used with a photo-multiplier tube (HAMAMATSU R3479) mounted at the focus of the telescope. A linear range of the PMT was checked by simultaneously firing a series of UV-LED pulses at the telescope overlaying with the laser shot, and confirming that the overlaid signal has the same charge as the LED-only signal without the laser shot. The laser is attached to the telescope mount, therefore the direction control of the laser-telescope-PMT system can be simply accomplished by commands to the telescope mount. The back-scattered photons from the laser are collected by the telescope, detected by the PMT, and the signals are digitized with a digital oscilloscope (Tektronix 3034B) [11,14]. In addition, a portion of each laser shot is picked off for measurement by an energy monitor.

By measuring the time structure of the back-scattered photons, we can determine the atmospheric conditions including aerosol distributions along the path of the laser beam. The operation of the LIDAR is composed of horizontal shots in the north and vertical shots. The vertical operation was made in high (~ 4 mJ) and low (~ 1 mJ) energies in order to measure the extinction coefficient α over a large range. The horizontal operation uses only the high energy. In each vertical and horizontal operation, 500 laser pulses are shot and recorded. A total of 1500 shots composed one LIDAR operation. The pedestal level is measured in between each shot and is subtracted from the laser shot data in order to account for the background. In the following analysis, we use an average of the PMT signal profiles in order to reduce shot-to-shot fluctuations.

3. Data set and analysis method

A waveform $W(t)$ is obtained by averaging the PMT signal for 500 laser shots. A range corrected power return $F(x)$ of the LIDAR is defined by the waveform $W(t)$ as a function of the distance x from the LIDAR:

$$F(x) = W(t)x^2, \quad x = t\frac{c}{2} \tag{1}$$

where c is the speed of light and t is the time from the laser shot. The solid angle correction is taken into account in the definition of $F(x)$. An example of $W(t)$ and $F(x)$ is shown in Figs. 3 and 4.