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Telescope Array atmospheric monitoring system at Akeno Observatory

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Abstract. We have developed an atmospheric monitoring system for the Telescope Array experiment at Akeno Observatory. It consists of an Nd:YAG laser with alt-azimuth shooting system and a small receiver. This system is installed in an air conditioned weather-proof dome. All parts: the dome, laser, shooter, receiver and optical devices are fully controlled by a personal computer running the Linux operating system. It is now operated as a backscattering LIDAR system. For the Telescope Array experiment, to estimate energy reliably and to obtain the shower development profile correctly, we need to calibrate the light transmittance of the atmosphere to high accuracy. Based on the observational results using this monitoring system, we consider this LIDAR to be a very powerful technique for Telescope Array experiments. The details of this system and the atmospheric monitoring technique will be discussed.

1 Introduction

The air fluorescence technique for air shower observation has many advantages (for example: direct measurement of shower longitudinal development, stereo geometrical reconstruction with multiple eyes). These advantages will bring technical breakthroughs in EHE Cosmic Ray physics. On the other hand, in this technique we measure the light yielded from air showers after transmission through the 10 $\sim$ 60 km atmosphere. The atmosphere can be considered as the part of the detector. Therefore, the calibration of the transmittance of the atmosphere is essential for air fluorescence experiments.

The Telescope Array(TA) detector will observe air showers which flash at distance of more than 50 km from the detector. According to simulation studies, the energy resolution of TA is less than 6 % and the resolution of X_{max}, the position of the shower maximum, is 20 g/cm^2 (as far as we know atmospheric transmittance). To realize this high resolution, we have to monitor the transmittance of atmosphere to better than few percent on accuracy. TA and High Resolution Fly's Eyes are challenging and developing various methods for the purpose of this atmospheric monitoring which use lasers or flashers.

One of the well known techniques for atmospheric monitoring is LIDAR. This technique is a kind of remote sensing which has developed for environmental science. Atmospheric conditions can be monitored remotely by measuring back scattered light from a pulsed laser beam.

For the purpose of atmospheric monitoring for TA, we are developing a steerable LIDAR system. In this paper, we will report details of this system and discuss how to accurately measure the transmittance of the sky.

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2 Experiments

The steerable LIDAR system is being developed at Akeno Observatory in Yamanashi Prefecture, Japan(900 m a.s.l., $138.5°$ N, $35.78°$ E). In this observatory, there are many cosmic ray detectors including AGASA and fluorescence detectors. Using these detectors, hybrid observation of cosmic rays are on going.

This system is constructed on the roof of the Akeno Main laboratory and consists of laser, optical table, shooting system, infrared camera, light receiver, data acquisition system and an astro-dome which house the system. The system is illustrated in Fig.1.

The third harmonic of a Nd:YAG laser is transported to the shooting system after phase conversion by a circle polarizer. The wave length of this laser beam is 355 nm, maximum pulse energy is 7 mJ and maximum repetition rate is 10 Hz. An Alt-azimuth mount has been adopted for the shooting system. A parabolic mirror of 16 cm diameter is mounted on the elevation axis as a receiver. A one inch PMT is located at the focus. The field of view of this receiver system is about 1 degree. Because the shooting and receiving mirror are mounted

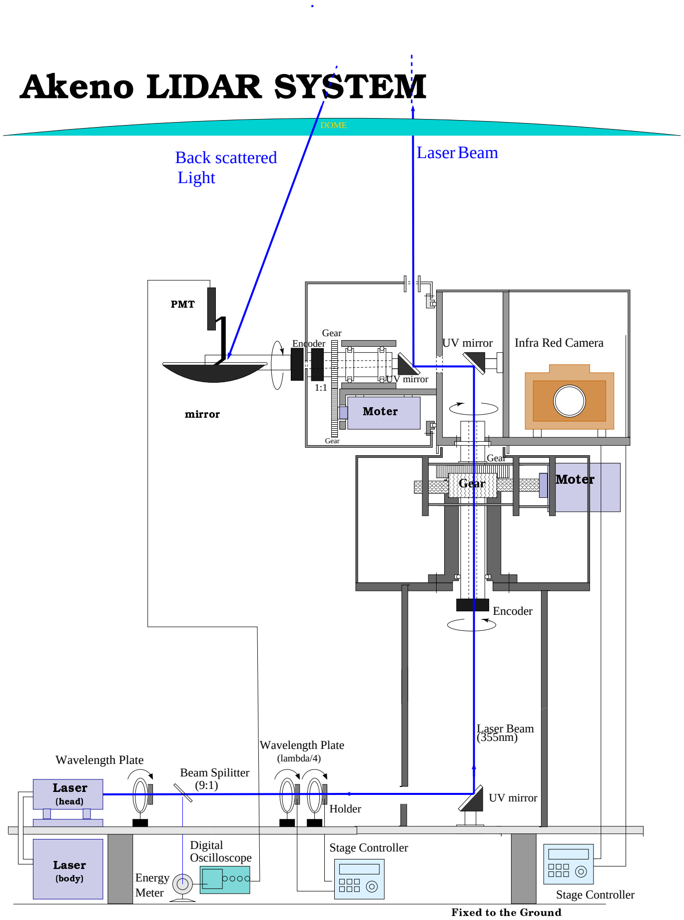

Fig. 1. Diagram of the LIDAR system developed at Akeno observatory.

on the same part, laser beam and receiver can be simultaneously controlled.

An infrared camera is also mounted on this shooting system as a cloud monitor. The transmittance and cloud can be monitored at the same time by using this infrared camera. Details of this cloud monitoring system will be reported in another paper in this conference.

The signal from the PMT is acquired by a Digital Oscilloscope which measures the time profile of the back scattered light. Time resolution is 200 nsec which corresponds to ∼30 m space resolution. An average of 16 shots are recored on the local computer. 1024 shots in the vertical direction and 256 shots for every 5 degrees in zenith angle are measured with this system.

The system can be controlled by remote computer via the network, and observation is fully automated. If it begins to rain during the observation, the system automatically shuts down.

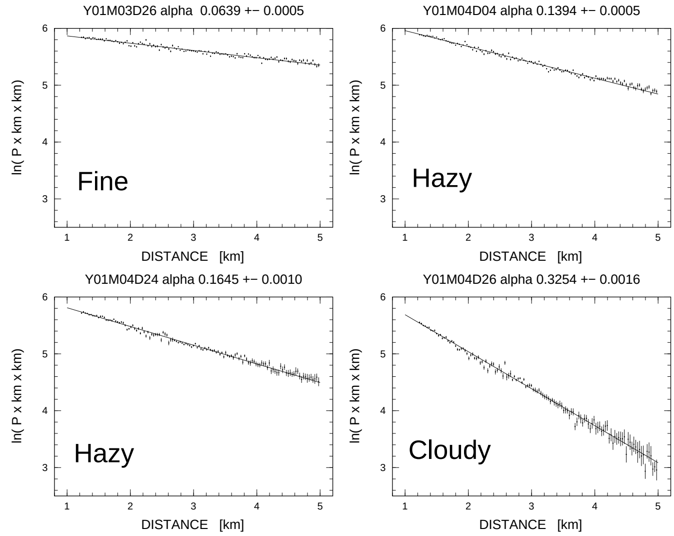

Fig. 2. Horizontal measurement. x-axis is distance from LIDAR, and y-axis is S(R). Region from 1.2 km to 5 km are plotted. The up left panel is clearest night, and right down panel is cloudy night. Solid line is result of fitting by straight line. The extinction coefficient α can be measured by the slope of this line.

3 Analysis

3.1 LIDAR equation

In general, the intensity of the back scattered light detected by LIDAR is calculated using following equation, so called LIDAR equation,

$$P(R) = \frac{P_0 \kappa A (c\tau/2) \beta(R) T^2(R) Y(R)}{R^2} + P_b \tag{1}$$

$P(R)$: intensity of the detected light
P_0 : LASER intensity
P_b : intensity of back ground photons
c : light velocity
R : distance from LASER to target
τ : integration time
$Y(R)$: geometrical efficiency of the beam track and receiver
A : aperture of receiver
κ : detector efficiency
β : back scatter coefficient
$T(R)$: transmittance (=$exp(-\int_0^R \alpha dr)$)
α : extinction coefficient (=1/attenuation length)

We define the following parameters for convenience.

$$P_0 \kappa A \frac{c\tau}{2} Y(R) \equiv C \tag{2}$$

$$X(R) \equiv R^2 (P(R) - P_b) \tag{3}$$

$$S(R) \equiv ln(X(R)) \tag{4}$$

The LIDAR equation can then be written as follows.

$$\frac{dS(R)}{dR} = \frac{1}{\beta(R)} \frac{d\beta(R)}{dR} - 2\alpha(R) \tag{5}$$

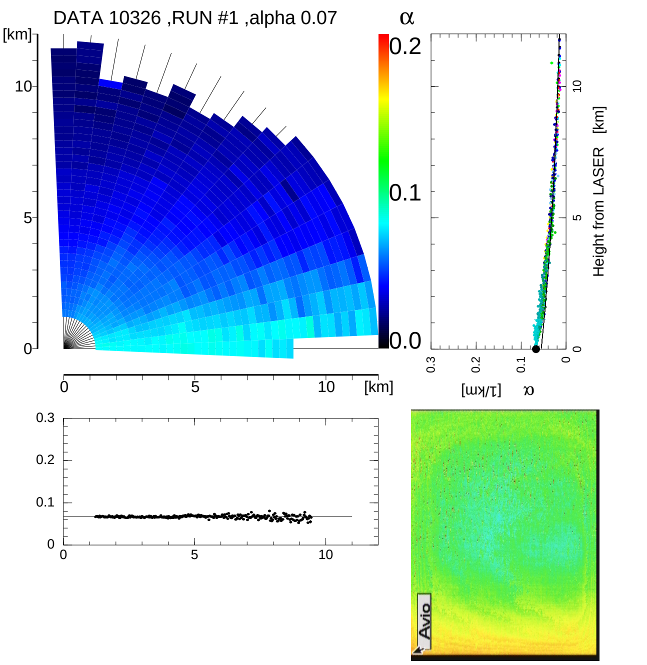

Fig. 3. An example of estimated extinction coefficient α. Upper left panel shows a two dimensional map of α inside a 12 km radius circle from LIDAR. Estimated α from horizontal measurement is indicated in title. Upper right panel shows the estimated extinction coefficient as a function of altitude from the observation point at each zenith angle. Different colors correspond to different zenith angles. The black dot at altitude 0 indicates the measured value in horizontal shots. The solid line indicates the expected value from Rayleigh scattering. Lower left panel shows the estimated extinction coefficient for horizontal shots. Lower right panel shows an image from the infrared camera. It was very clear night.

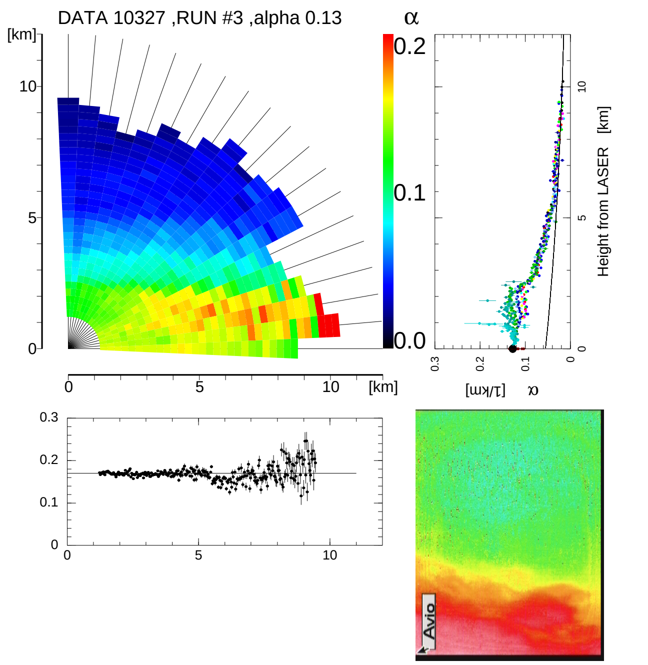

Fig. 4. The next night's data. The expression is the same as the previous figure. It was hazy at low altitude.

There are two variable parameters in this LIDAR equation: One is the extinction coefficient α that represents the amount of scattered photons in a scattering volume. This value corresponds to the reciprocal of attenuation length. The other parameter is back scattering coefficient β that represents the amount of scattered photons in the backward direction. Because the LIDAR equation has two variables, it can not be solved in general.

3.2 Horizontal measurement

One of the simplest solutions of the LIDAR equation is horizontal measurement. If the atmosphere depends only on altitude, the parameter β is constant at a given altitude. Because of $d\beta/dR = 0$, equation(5) can be written as follows

$$\alpha = -\frac{1}{2}\frac{dS}{dR} \tag{6}$$

Using this equation, the transmittance of the atmosphere same level as the detector can be measured. Fig.2 shows examples of this horizontal measurement. The data which is comparatively near the detector is used. Four examples are shown. It can be seen that the attenuation depends clearly on the weather. It can also be confirmed that the atmosphere is uniform in this region. This method approve to be very convincing and accurate.

3.3 Klett's method

As mentioned before, the LIDAR equation can not be solved without any assumption because it has two variable parameters. If we assume a relationship between α and β, the variable parameter can be reduced. For this purpose, an empirical relationship is proposed:

$$\beta = const \cdot \alpha^k \tag{7}$$

In this assumption, k depends on the atmospheric condition and wave length. It is generally in the interval 1 $\sim$ 0.6. Klett proposed a stable solution using this relationship (J.D.Klett 1981). Substituting this relationship into equation(5) and adopting the critical value at further point R_C, we obtain

$$\alpha(R) = \frac{X(R)^{1/k}}{\frac{X(R_c)^{1/k}}{\alpha(R_c)} + \frac{2}{k}\int_R^{R_c} X r^{1/k} dr} \tag{8}$$

Using Klett's method, we can estimate α if we can put certain values to the parameter 'k' and the critical value $\alpha(R_c)$. To determine these parameters, we consider simple assumptions as follows,

- In the measurement in the vertical direction, the smallest α corresponds to the value expected from Rayleigh scattering. If there is no cloud, this value can be estimated at the highest point.
- In the measurement of a different direction, smaller α (it means the value at the region of no cloud) corresponds

to the α which is measured at a direction of ± 5 degrees at the same altitude.

– α at a point of lower than 100 m can be estimated as the α obtained in the horizontal measurement.

With these assumptions, we can determine parameter 'k' and the critical value. Examples of result of this analysis are shown in Fig.3 and Fig.4. Fig.3 is the result for a very clear night. The atmosphere of this night was uniform as is illustrated. It can be clearly seen that statistical error is very small at all points. For example, the transmittance between detector and a 10 km distance in the vertical direction is estimated to be 73.27% with statistical error of 0.05%. Fig.4 shows the result measured on the next night to the previous figure. It was hazy and the atmosphere was not uniform at lower altitudes. The transmittance between detector and 10 km distance in the vertical direction is 57.91% with statistical error of 0.07%. It take measurement time as about 20 minutes these case.

3.4 Systematic errors

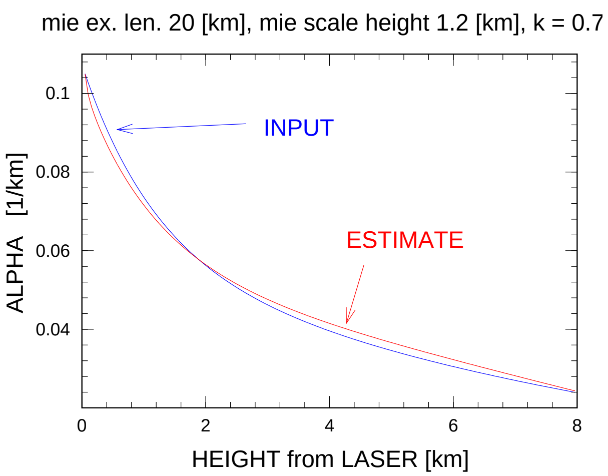

Fig. 5. Simulation of LIDAR. Blue line is inputed atmospheric model. The horizontal attenuation length and scale height of mie scattering is indicated on the title. This is typical value on the desert. Red line is estimated α using Klett's method described in the section3.3.

The systematic error in the present analysis based on Klett's method has been investigated using a simple Monte-Carlo simulation (John A. J. Matthews 2001). Fig.5 shows an example of this simulation. Attenuation length and scale height of Mie scattering is assumed to be a typical value as indicated in the figure. Elevation angle is 10 degrees. The estimated α is slightly different from true value, however the transmittance from detector to 30 km is 48% and the systematic error is only 2%. We conclude that this technique is accurate enough for our purposes. This systematic error can be reduced using more sophisticated method (F.G.Fernald 1984). This method will be described in another paper in this conference.

The detector constants (for example: mirror reflectivity, PMT gain, beam intensity and so on) do not contribute to the systematic errors in this analysis except for the linearity of the PMT. The effect of multiple scattering is ignored in this measurement. The most significant systematic error is caused by the uncertainty in the critical value. The altitude of 10 km, where we gave the boundary condition, may not enough to ignore the effect of mie scattering. This problem can be solved if we use larger mirror or higher intensity laser.

4 Summary

We have developed a steerable LIDAR system for atmospheric monitoring for the Telescope Array. The system consists of a 5 mJ pulse laser and a 16 cm diameter mirror. Using this system, a technique for atmospheric monitoring was developed.

Firstly, the extinction coefficient α at the level of the detector is measured. Then α is estimated at all directions using Klett's method. The transmittance of the night sky to a distant of 10 km can be measured successfully. The statistical error in this analysis is less than 2% under a clear sky. It takes 20 minutes to measure one azimuthal direction.

Based on this observational result, we are considering about future plans for atmospheric monitoring for the Telescope Array. Signal to noise ratio is in proportion to beam intensity, mirror diameter and square root of observation time. 5 mJ $\times$ 16 cm $\times$ $\sqrt{20min}$ = 358 $[mJ \cdot cm \cdot min^{1/2}]$ is required to measure to a distant of 10 km. To measure more than 50 km, we need 358 $\times$ 5^2 = 8950$[mJ \cdot cm \cdot min^{1/2}]$. This means a 21 mJ laser is necessary for 3m diameter mirror if we want to measure one azimuthal direction in 2 minutes. This is probably the most realistic design for Telescope Array atmospheric monitoring.

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