Atmospheric monitoring in Utah using the Back Scatter Lidar method

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Abstract.

We have installed a *lidar* (back scattering laser radar) system at the HiRes1 Observatory in Utah to measure the atmospheric transmittance in the Utah desert area and to evaluate this method of atmospheric monitoring for the HiRes observatory and the TA project.

This system is designed for the measurement of back scattered ultra violet laser light over long distance and low elevation angles. The atmospheric transmittance has calculated from observed data using Fernald's method. In this paper, we discuss the performance of the back scatter lidar system, the atmospheric transmittance in Utah, and its variation with time.

1 Introduction

Atmospheric fluorescence detection is a key method in UHE cosmic ray physics for current and future observations. It can measure the three dimensional development of air showers using plural stations, and therefore enables the accurate measurement of their shower axis, energies and X_{max} .

On the other hand, since this method uses the atmosphere as a scintillator and light transmission material from air shower to detector, we continuous have to monitor its condition. For example, the HiRes Observatory, which is the only current well-established fluorescence detector, has typically a few km to a few tens of km distance to observe UHE cosmic ray. The Telescope Array, which is the largest future fluorescence detector project, will have typically 10km to 50km distance. To estimate the transmittance of such depth of atmosphere, an active and speedy remote sensing technique is necessary.

We have installed a *lidar* (back scattering laser radar) system at the HiRes1 Observatory in Utah ($N40.2^{\circ}$, $W112.8^{\circ}$, Alt1597m) toward the north direction, for the purpose of developing the back scatter lidar technique as a low elevations



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Fig. 1. HiRes Observatory Map and Back Scatter Lidar direction

and long distances atmospheric monitor. This work is part of the HiRes and Telescope Array Project collaborations.

2 Detector

The back scatter lidar system consists of two parts. One is a steerable laser system for UV laser transmission, and the other is a back scattered UV light receiver system. These two systems are controlled individually, and communicate each other through a LAN.

2.1 Laser Transmitter

The HiRes1 steerable laser system can shoot a 355nm Nd:YAG laser toward any elevation and azimuth angle, with an energy several tens of mJ max and pulse frequency up to 10Hz. This laser system is also used for the multi-angle scatter lidar,

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Fig. 2. Illustration of the HiRes1 laser tower and the back scatter receiver mirror beside the HiRes mirror

combined with the HiRes2 detector. (L.R.Wiencke (1999)) For the measurement of back scatter lidar, it will shoot the laser beam toward two directions with elevation angles of 10° and 20° with two energies ($\sim 10mJ$ and $\sim 15mJ$) for 125 shots and 100 shots respectively, at a Hz frequency.

2.2 Back Scatter Receiver

The Back scatter receiver system locating at HiRes1 has a 1.5m diameter spherical fixed mirror and two PMTs with UV filters. Their fields of view are 10° and $20^{\circ} (\pm 0.5^{\circ})$ respectively in elevation angle with adjusted for typical elevation angles of HiRes and TA observations, and 105° in azimuth angle. The PMT signal waveform is recorded by digital oscilloscope with a 9 bits digitizer and 800ns sampling speed, corresponding to a 120m resolution in position.

3 Data Analysis

3.1 Period

The back scatter lidar was started in March 2001. The observation is carried out once in a hour with 450 laser shots on Moon-less nights, simultaneous with HiRes observation. Three months of data has been stored so far. Total observation time has reached 160 hours as at the end of May, 2001.



Fig. 3. Typical cloud signal: The cloud's peak can be seen at 13km and 23km for elevation 20° , 26km and 50km for elevation 10°

3.2 Cloud

Clouds make the estimation of transmittance very difficult since they have locally large cross section and increase multiple scattered light. They can be found by back scatter lidar easily as local peak of back scattered light signal as shown in Fig.3. March is one of the most cloudy seasons in Utah, and we exclude cloud-contained data prudently in this analysis. The clear sky ratio observed by the back scatter lidar system is shown in Table.1.

Table 1.	Clear	night	ratio	for eac	h month	of 2001
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Month	clear night time [hour]	clear night ratio [%]
March	16	25.0
April	13	28.9
May	21	41.2

3.3 Transmittance

3.3.1 Calculation Method

The back scatter lidar signal can be described using two components. aerosol and molecules.

$$P(z) = \frac{EC[\beta_1(z) + \beta_2(z)]T_1^2 T_2^2}{z^2}$$
(1)

where

z: distance from lase point P(z): return signal *E*: laser energy *C*: calibration constant $\beta_1(z)$: back scattering cross section of the aerosol $\beta_2(z)$: back scattering cross section of the molecules $T_1(z) = \exp[-\int_0^z \sigma_1(z)dz]$: aerosol transmittance $T_2(z) = \exp[-\int_0^z \sigma_2(z)dz]$: molecular transmittance

The solution of lidar signal has been discussed by many authors (G.J.Kunz (1983)) (F.G.Fernald (1984)) (J.D.Klett (1985)) (Y.Sasano (1985)). We use Fernald's method in this analysis, which assumes;



Fig. 4. 355nm UV light scattering coefficient in clear night sky.

- Single elastic scattering with two components of Rayleigh and Mie scattering process
- Only Rayleigh component appears at the high altitude calibration point, Z_c
- Extinction-to-Backscattering ratio for molecule is constant $S_2 = \frac{\sigma_2}{\beta_2} \sim \frac{8\pi}{3}$
- Extinction-to-Backscattering ratio for aerosol is also constant $S_1 = \frac{\sigma_1}{\beta_1}$ (typical value $30 \sim 70$)

The solution is;

$$\sigma_1(I-1) + \frac{S_1}{S_2}\sigma_2(I-1) =$$
(2)

$$\frac{X(I-1)\exp(A(I-1))}{\frac{X(I)}{\sigma_1(I) + \frac{S_1}{S_2}\sigma_2(I)} + (X(I) + X(I-1)\exp(A(I-1))\Delta Z}$$
(3)

where

I: the distance bin number

 $X(z) = P(z)z^{2}$ $A(I) = (S_{1} - S_{2})[\beta_{2}(I) + \beta_{2}(I+1)]\Delta Z$

3.3.2 Result

The result of volume scattering coefficients are shown in Fig.4, 5 and 8-10. The input value for S1 is 30, and the error caused by changing this constant $30 \sim 70$ is $\sim 5\%$. The calibration altitude are 6.5km for elevation 20° and 4.5km for 10° . The data used in Fig.4 are the clearest two days in observation period, and Fig.5 are the haziest two days. The two lines are the expected values from the pure Rayleigh scattering (A.Bucholtz (1995)), and a simple atmospheric model using aerosol density distribution,

$$\rho_a(h) = \exp(-h/H_a) \tag{4}$$

where h is height, H_a is scale height for aerosol vertical distribution, and 1.2km are used here. The input value of horizontal extinction length is 11.7 km for the aerosol component



Fig. 5. 355nm UV light scattering coefficient in hazy night sky.

at the ground level. The circle plots show elevation angle 10° and square plots show 20° , the open plots show laser energy $\sim 10mJ$ and closed plots show $\sim 15mJ$ respectively.

Fig.6 shows the atmospheric transmittance from the 14km point to the 7km point in distance along with laser track as illustrated in Fig.7. The "+" plots and "×" plots are the extrapolated data of the atmospheric transmittance from the 14km point to the observation point for 10° and 20° respectively. This extrapolation is assumed that $\sigma_1(z)$ is constant below the altitude 2.7km for elevation 10° , and 3.2km for 20° .

4 Discussion

Fig.6 shows the atmospheric transmittance in Utah with typical elevation angles and distances in the HiRes observation. It can be seen clearly that the time variation of atmospheric transmittance is bigger in elevation angle 10° than 20° since lower air contains much aerosols. The standard deviation of atmospheric transmittance from 14km to the observation point using extrapolation is $\sim 20\%$ for elevation angle 10° . We can't help occurring cosmic ray energy estimation error due to this deviation of atmospheric transmittance, if we use a time-constant atmosphere model. But if we select well stable data, March and May in this case, the estimation error can be kept less than 8% for elevation 10° with proper timeconstant atmosphere model.

In the case of TA, typical distance will be $10 \sim 50 km$, and 8%, 20% error will be increased up to $\sim 20\%$, $\sim 50\%$ respectively. Therefore dynamic atmosphere model is essential to TA, and all sky transmittance monitor is necessary on every hour.

5 Summary

We have installed a back scatter lidar system in the HiRes1 Observatory as part of the HiRes and TA collaborations. We have monitored the atmospheric transmittance in the Utah



Fig. 6. Transmittance in distance between 7 - 14km, and their extrapolation to observation point.



Fig. 7. back scatter lidar elevation angle and data area for transmittance calculation.

desert area during moonless nights over three months. Clouds are the main cause of variance in atmospheric transmittance over this period, and this back scatter lidar system shows good performance in active cloud sensing up to a 50km distance, which is same as the typical TA observation field for a single station.

The lidar equation has been solved for clear sky data using Fernald's method, and atmospheric transmittance data have been plotted. The clearest data show they can be explained by almost Rayleigh scattering alone. On the other hand, the haziest data show it is difficult to explain by simple exponential atmosphere model.

The average volume scattering coefficient distribution is shown in Fig.8 for each month.

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Fig. 8. volume scattering coefficient in clear night sky for March, April, May 2001

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