32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

Atmospheric Calibrations for Air Fluorescence Observations in the Telescope Array Experiment by LIDAR system

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FOR THE TELESCOPE ARRAY COLLABORATION

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Abstract: Atmospheric calibrations are indispensable for understanding data gathered by air fluorescence detectors (FDs). UV fluorescence light generated by an air shower is scattered in propagating to the FD both by air molecules (Rayleigh scattering) and by aerosol particles in the air (Mie scattering). Because the influence of aerosols on scattering changes every day, it is necessary to measure aerosols on a regular basis. For the Telescope Array experiment (TA) atmospheric scattering is measured using a LIDAR system, and the systematic error of the calibration of atmospheric scattering is estimated by simulation. Here we report on the results of measurements of atmospheric scattering by LIDAR and the influence of the atmospheric calibration on FD observation.

Keywords: UHECR, fluorescence technique, Atmospheric, LIDAR

1 Introduction

The Telescope Array (TA) experiment was constructed in the desert southwest of Delta, Utah in the USA. TA observes ultra-high energy cosmic rays (UHECRs) using a surface detector (SD) array and three fluorescence detector (FD) stations. Atmospheric monitoring is important for observing UHECRs using the air fluorescence technique because the UV light generated by the air shower is scattered and lost along the path of transmission to the telescope. The optical depth from the air shower to FD affects the estimate of energy of the UHECR, and the distribution of transparency as a funtion of altitude affect the estimate of $X_{\rm Max}$.

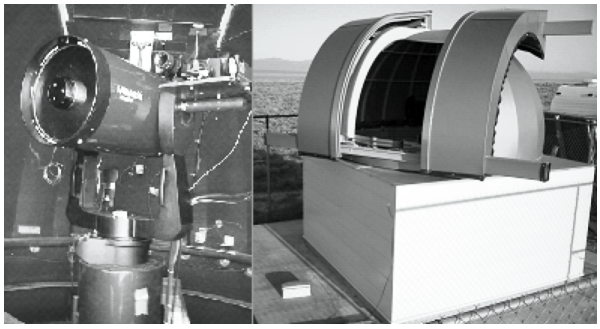

Figure 1: The LIDAR system. A left picture is LIDAR's system (telescope and laser, etc.). A right picture is the dome for protection of LIDAR.

The main scattering processes are Rayleigh scattering by air molecules, and Mie scattering by aerosols in the atmosphere.[1, 2, 3] The Rayleigh process is well understood and the scattering cross sections or atenuation lengths can be calculated using the Rayleigh scattering molecular cross section and the molecular density of the atmosphere. In order to calculate the molecular density, radiosonde data from Elko, Nevada are used to obtain temperature, pressure, and humidity near TA as a function of altitude. Sizes, shapes, and spatial distribution of aerosols around the site are not known and are variable with time. Therefore on-site monitoring of aerosols is essential for a fluorescence experiment.

In TA we make use of LIDAR for atmospheric monitoring.[4, 5] Our LIDAR system is installed near the Black Rock FD station which is to the southeast of our observation site. LIDAR observes the backscattered light from atmospheric scattering of a laser beam that is shot on

the same axis as the direction of the LIDAR observation. The extinction coefficient α is obtained from LIDAR observations. The atmospheric attenuation factor $T(x)$ (where x is the penetration range) is found as follows:

$$T(x) \quad = \quad \exp\left[-\int_0^x \alpha(x')\,\mathrm{d}x'\right]. \qquad (1)$$

A horizontal observation, a vertical observation and angles in between are done to understand the values of α from aerosols from ground level to about 7 km above the ground. Additionally, the vertical shots are done at two different laser energies to expand the range of measurements. The LIDAR is operated twice a night, once before the FD observation begin, and once after they end. We have analyzed about 500 measurements from Sept 2007 to Oct 2009.

2 Analysis of Atmospheric Transparency

2.1 The Extinction Coefficient

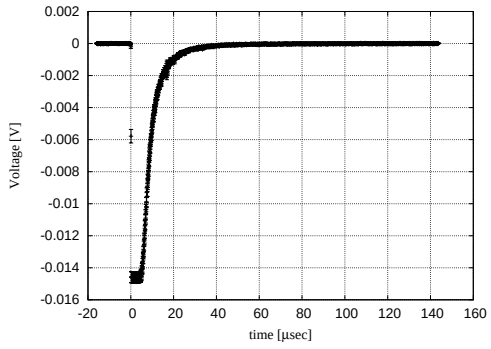

Figure 2: The detected signals by LIDAR observation.

The detected signal $W(t)$ from LIDAR is the voltage output by the PMT in the LIDAR observing the backscattered light as a function of time after the laser shot. The backscattered light intensity F(x) as a function of distance from the LIDAR is found as follows:

$$F(x) = W(t)x^2, \;\; x = t\frac{c}{2}, \qquad (2)$$

where c is the speed of light.

The extinction coefficient $\alpha(x)$ at a distance x is related to $F(x)$ by the LIDAR equation:

$$\frac{1}{F(x)}\frac{\mathrm{d}F(x)}{\mathrm{d}x} = \frac{1}{\beta(x)}\frac{\mathrm{d}\beta(x)}{\mathrm{d}x} - 2\alpha(x) \qquad (3)$$

where β is the back scattering coefficient. The factor 2 of α indicates round trip photon propagation. The α at ground level is analyzed by the slope method that assumes that $\mathrm{d}\beta(\mathrm{x})/\mathrm{dx} = 0$ for a horizontal shot (i. e., atmospheric scattering in the penetration range of the laser is constant). In this case, the relation given in Eq.3 becomes Eq4:

$$\frac{1}{F(x)}\frac{\mathrm{d}F(x)}{\mathrm{d}x} = -2\alpha(x). \qquad (4)$$

The $\alpha(h)$ as a function of height "h" above the ground is given by Klett's method that assumes the relation between α and β is β goes as α^κ. This assume there is no height dependance of the differential scattering cross section in the atmosphere.

$$\alpha(x) = \frac{F(x)^{\frac{1}{\kappa}}}{\frac{F(x_c)^{\frac{1}{\kappa}}}{\alpha(x_c)} + \frac{2}{\kappa}\int_x^{x_c} F(x')^{\frac{1}{\kappa}}\mathrm{d}x'}, \quad (x = h) \qquad (5)$$

where x_c is height of the boundary condition. κ is 1.00 for a pure molecular atmosphere, and is known to be between 0.067 and 1.30 for an atmosphere heavily loaded by aerosol or with rain or snow.[7, 8, 9] For the typical desert atmosphere of the TA site, we have found κ approaches 1.0 at high altitudes and can reach 1.14 near the ground.

In Figure 3, observed $\alpha(0\mathrm{km})$ is shown by the closed circle, and the crosses show the observed α every 250 m in altitude. The solid line shows the extinction coefficient for Rayleigh scattering calculated from the radiosonde data. The open squares show the extinction coefficient α of aerosol scattering calculated by subtracting the Rayleigh scattering coefficient from the observed coefficient.

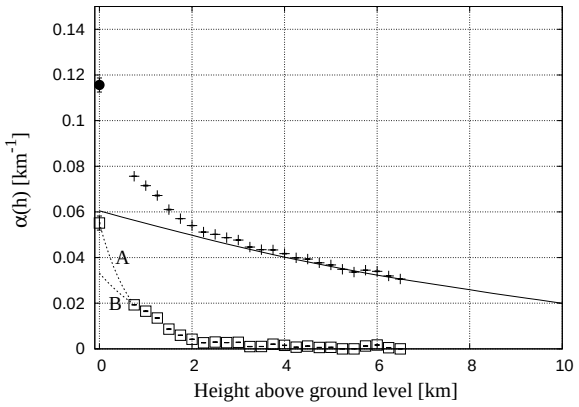

Figure 3: The extinction coefficients α as a function of height from ground level obtained by the LIDAR system.

We only use data from above 750 m altitude for vertical shots because the detected light signal is saturated by the strong scattering from closer distances. A pulsed LED is used synchronously with the laser firing, and is used to calibrate the PMT gain linearity. This linearity check shows us that the systematic error of observed $\alpha(0\mathrm{km})$ is +0%/-7% and that of $\alpha(h)$ is +0%/-2%. In addition we estimate by iteration that the systematic error of $\alpha(h)$ is +5%/-0% from the assumption that $\kappa = 1$ for Klett's method.

2.2 The Vertical Aerosols Optical Depth

We define the vertical aerosol optical depth (VAOD) "τ_{AS}" by the integration of $\alpha_{\mathrm{AS}}(h)$ from 0 to h as follows:

$$\tau_{\mathrm{AS}}(h) \quad \equiv \quad \int_0^h \alpha_{\mathrm{AS}}(h')\,\mathrm{d}h'. \qquad (6)$$

The systematic error of VAOD due to the linearity calibration of the PMT is +0%/-17% and that due to the estimation "$\kappa = 1$" in Klett's method is +2%/-0%. When we calculate VAOD, there is no data in the low altitude ranges due to saturation of the PMT signal. We estimate the behavior of α at low altitudes in two different ways: For curve "A" in Figure 3 we simply define an exponential curve that uniquely connects $\alpha_{\rm AS}(0)$ and $\alpha_{\rm AS}(h_{\rm min})$ ($h_{\rm min}$ =750 m). For curve "B", we extrapolate the single exponential curve that best fits the lowest five points (excluding the point at 0 height). The systematic error from missing data points at low height is estimated to be $\pm$9% from the range between the dotted lines in Fig.3.

The total systematic error of VAOD is +9%/-18%.

3 Typical of Atmospheric Transparency

We use the typical altitudinal distribution of median $\tau_{\rm AS}(h)$ for analysis of air showers. This distribution is obtained from LIDAR data that pass quality cuts of $h_{\rm min}$=0.75 km, and the highest measured data is above 5.0 km.

A typical plot of $\tau_{\rm AS}(h)$ is a function of height is shown in figure 4. The open squares are the median values of $\tau_{\rm AS}(h)$, and the error bars are 1 σ. The solid line shows a fit to the median $\tau_{\rm AS}(h)$ by integrating Eq.7, a two exponential functional form for $\tau_{\rm AS}(h)$.

$$\alpha_{\rm AS}^{\rm Typical}(h) = 0.019\exp(-\frac{h}{1.9}) + 0.021\exp(-\frac{h}{0.2}). \quad (7)$$

The systematic error in using this form to calculate atmospheric extinction is +84%/-36%. The total systematic error of a typical $\tau_{\rm AS}$ is +84%/-40%.

The dotted line in figure 4 is a fit of Eq.8 to the data; a simplified single exponential form for $\tau_{\rm AS}(h)$.

$$\alpha_{\rm AS}^{\prime\rm Typical}(h) = 0.04\exp(-\frac{h}{0.9}). \quad (8)$$

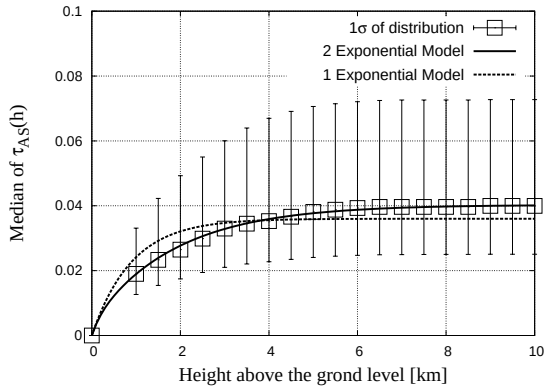

Figure 4: The distribution of typical VAOD (τ_{AS}) as a function of height from ground level. At each height, The open squares show a median of typical VAOD, error bars indicate the range (1σ) of its distribution.

Table 2: Comparison of results of reconstruction by atmospheric conditions in daily and atmospheric model.

E_0[eV]	#eve.	Atmos.	ΔE_0[%]	$\Delta X_{\rm Max}$[g/cm^2]
$10^{18.5}$	501	1 exp.	1.7± 6.4	4.6±7.1
	502	2 exp.	-2.4±6.3	-3.6±8.8
$10^{19.0}$	917	1 exp.	1.3±8.6	4.5±7.7
	919	2 exp.	-4.2±8.6	-5.0±8.6
$10^{19.5}$	1200	1 exp.	1.4±11.1	4.9±9.3
	1210	2 exp.	-0.6±10.6	0.2±7.6

4 Systematic error by Calibration of Atmospheric Transparency

We estimate the systematic error of using the atmospheric models obtained by LIDAR to determine shower parameters by a monte-carlo (MC) technique. A shower is simulated using the daily data for each day where there is good LIDAR data, then reconstructed using the same data, and both of the the typical atmospheric models. Comparison between the MC inputs to the shower and the reconstructed values allows one to determine the error. The conditions of and quality cuts used the in the simulation are as follows:

- Primary energy : logE= 18.5, 19.0 and 19.5 eV
- Zenithal in direction : between 0 $\sim$ 60 $^\circ$ (the isotropic)
- Azimuthal in direction : between 0 $\sim$ 360 $^\circ$ (the isotropic)
- Core position : within 25 km of the CLF (center of TA SD array).
- Number of event : 20 events at each energy for each of 136 good LIDAR runs.
- Quality Cuts on reconstruction : Reconstructed $X_{\rm Max}$ in field of view of FD.
- Atmospheric conditions : reconstruct using data from that run, and also using single exponential fit and double exponential fit.

The results of the reconstruction are summarized in Table1.

The $\Delta E0$ and $\Delta X_{\rm Max}$ are evaluated as follows:

$$\Delta E_0/E_0^{\rm sim} = (E_0^{\rm rec} - E_0^{\rm sim})/E_0^{\rm sim} \quad (9)$$

$$\Delta X_{\rm Max} = X_{\rm Max}^{\rm rec} - X_{\rm Max}^{\rm sim} \quad (10)$$

Even when we use the same atmospheric model in simulation and reconstruction, the table shows a systematic bias in primary energy and $X_{\rm Max}$. To remove the reconstruction bias, in Table 2 we show a comparison of results between showers reconstructed using the daily model, and the same shower reconstructed using the one exponential and two exponential models.

5 Conclusion

The atmospheric transparency used to reconstruct air shower in TA is measured by using LIDAR. The extinction

Table 1: Comparison of results of reconstruction by atmospheric conditions in daily and atmospheric model.

E_0[eV]	#sim.	#trig.	Atmos.	#rec.	#sel.	$\Delta E_0[\%]$	$\Delta X_{\rm Max}[{\rm g/cm^2}]$
$10^{18.5}$	2720	593	daily	556	505	1.94 $\pm$ 4.86	0.87 $\pm$ 14.11
			1 exp.	553	502	4.63 $\pm$ 10.05	5.61 $\pm$ 17.9
			2 exp.	553	502	0.28 $\pm$ 9.60	2.02 $\pm$ 19.31
$10^{19.0}$	2720	1112	daily	1060	930	2.78 $\pm$ 5.02	3.86 $\pm$ 14.40
			1 exp.	1057	919	5.34 $\pm$ 11.94	8.36 $\pm$ 17.70
			2 exp.	1056	919	0.38 $\pm$ 11.01	0.62 $\pm$ 18.72
$10^{19.5}$	2720	1543	daily	1459	1221	3.19 $\pm$ 5.19	6.39 $\pm$ 15.13
			1 exp.	1457	1206	3.30 $\pm$ 16.35	11.33 $\pm$ 20.11
			2 exp.	1460	1224	1.58 $\pm$ 15.21	4.93 $\pm$ 18.96

coefficient α is obtained from LIDAR observation, then the VAOD $\tau_{\rm AS}(h)$ is defined as the integration of α from the ground to height h. The systematic error of VAOD from one observation is +9%/-18%. A model of the change of $\alpha_{\rm AS}$ with altitude was found by fitting two years of LIDAR observations. The range of variation of the daily data from the model is +83%/-36%. When an $10^{19.5}$ eV air shower is reconstructed using the model function, the systematic uncertainty of energy is shown to be about 11%, and the systematic uncertainty of $X_{\rm Max}$ to be about $9{\rm g/cm^2}$by comparing MC simulation data.

Acknowledgement

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) "Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays", and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions and the University of Utah Center for High Performance Computing (CHPC).

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