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Measurement of atmospheric aerosols in southeast Colorado using backscatter LIDAR and a shadow-band solar radiometer

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Knowledge of atmospheric aerosol optical properties is a key element for operation of cosmic ray detectors using the Nitrogen air fluorescence technique. We have measured the horizontal attenuation length and vertical profiles of atmospheric aerosols on a number of nights above the Pierre Auger Observatory northern site in southeast Colorado using a backscatter LIDAR. The LIDAR operates at 337nm with a horizontal beam and beams at elevation angles up to the vertical. We compare the LIDAR measurements to daytime total vertical optical depth measurements at 332 nm made every three minutes for more than a year at the same site using a shadow-band solar radiometer. We discuss the LIDAR data in the context of a simple model for atmospheric aerosols and we analyze them using Fernald's solution.

1. Introduction

Ultra high-energy cosmic rays incident on the Earth's atmosphere produce showers containing upwards of 10^{10} particles, mostly electrons, positrons and gamma rays. Near the dense central core of such a shower the Nitrogen in the air fluoresces, and the resultant UV light, in the range 300nm to 400nm, can be observed and related to the energy of the primary cosmic ray through the peak brightness of the shower or via the total integral of the light[1]. There are three main issues to understand to measure the fluorescence light: production in the Nitrogen fluorescence[2]; propagation of the light from the shower to the detector[3]; and absolute calibration of the detector[4].

Propagation of light through the air requires knowledge of two atmospheric components: the pure molecular atmosphere and the aerosol content. This paper presents measurements of the aerosols at the Pierre Auger Observatory northern site in southeast Colorado, USA.

2. Instrumentation and Techniques

We used two independent instruments to measure the aerosols: a shadow-band radiometer operating in the daytime using the Sun as a standard candle, and a backscatter LIDAR operating at night.

Two shadow-banded radiometers were supplied by the USDA UV-B Monitoring and Research Program (UVMRP)[5]. One, the Visible Multi-Filter Rotating Shadowband Radiometer (VIS-MFRSR), is a 7 channel, 10 nm full-width half-maximum (FWHM) instrument that measures total and diffuse irradiance, and by subtraction and dividing by the cosine of the solar zenith angle, the direct normal irradiance at 415, 500, 610, 665, 860 and 960 nm nominal wavelengths (Yankee Environmental Systems, Turners Falls, Massachusetts). The second instrument, an Ultraviolet Multi-Filter Rotating Shadowband Radiometer (UV-MFRSR) made by the same manufacturer, is a seven channel ultraviolet version of the visible VIS-MFRSR. The UV-MFRSR contains 2 nm FWHM filters at 300, 305, 317, 325, 332 and 368 nm nominal wavelengths.

Measurements for the VIS-MFRSR (UV-MFRSR) were made every 15 (20) s and averaged to record three minute averages. In addition to measuring UV irradiances, the UV-MFRSR is used extensively by the UVMRP in their 35 site network for air quality[6,7,8]. One may determine aerosol vertical optical depths[7] (AVOD), Angstrom exponent, and single scattering albedo[9]. Instruments are calibrated using a time series of Langley voltage intercepts[8,9].

The LIDAR mechanical system is based around a Meade LX200 14-inch reflector telescope (Meade Instrument Corp., 6001 Oak Canyon, Irvine, CA 92618 www.Meade.com). The telescope mirrors were initially coated to enhance reflectivity in the visible range, but eliminate reflectivity in the UV. In order to allow for UV reflectivity we had the mirrors re-aluminized and coated with a quartz protective layer (Spectrum Coatings, Inc., 1165 Ring Street, Deltona, FL 32725) giving 90 to 95% reflectivity down to approximately 300nm. The system uses a Laser Science, Inc (LSI) model VSL 337ND-S Nitrogen cartridge laser (Laser Science, Inc. 8E Forge Pkwy Franklin, MA. 02038 host.theeditors.com/laserscience/).

Backscattered light is collected using the standard optical path of the telescope (three mirrors, recoated as stated above). At the position of the eyepiece, the collected light passes through a UV filter and a 2cm aperture into a photomultiplier tube (EMI 9214B—Electron Tubes, LTD 100 Forge Way Unit F, Rockaway, NJ 07866). The high voltage distribution base for the tube was tapered to optimize linearity across 4 orders of magnitude of light intensity. The laser is mounted on the telescope body, and the laser light is reflected as it exits the laser by two 45^o flat mirrors that are optimized for 337 nm (CVI, Inc 200 Dorado SE Albuquerque, NM 87123). This provides a 1-meter transverse offset of the laser beam parallel to the optic axis of the telescope insuring that the laser beam enters the field of view a few hundred meters from the telescope; at this distance the PMT is not saturated by the signal.

The PMT-filter-aperture assembly attaches to the lens mount of the telescope and is easily removed. This allows us to use the telescope optics to align the laser beam parallel to the telescope optical axis. The PMT is read out into a PICO Technology ADC-212 card (PICO Technology, The Mill House, Cambridge Street, PE19 1QB, United Kingdom). The laser provides a 4-nsec pulse, and we read out 3200 samples (separated by 20nsec) per laser pulse; this provides a possible range of 9.6 km for the LIDAR measurements, but typically the signal was too weak beyond 5-6 km for the duration of data taking at any one elevation angle. The laser repetition rate was approximately 2 Hz, and we recorded all 3200 samples for each laser pulse, usually taking 1000 pulses at a given elevation angle.

The analysis of LIDAR data has two parts. The first part involves a simple model of the atmosphere, which includes the standard molecular atmosphere[10] and a three-parameter model for the aerosols. The aerosol model assumes a uniform aerosol layer starting at the ground; this part has two parameters, the (uniform) extinction length and the height up to which the uniform layer extends. The third parameter is an exponential fall-off length to describe a smooth reduction of the aerosols from the top of the uniform layer as altitude increases. We analyze the LIDAR signal from all elevation angles (typically 2.5º, 10º, 30º, and 80º on a given night) and adjust the three parameters of the model (and overall signal normalization) until it approximately describes the data. The simple model is used only as a starting point for the second part of the LIDAR analysis, which is an inversion following Fernald[11]. The integral of the Fernald inversion yields the AVOD up to the range limit of the LIDAR signal, typically about 5-6 km, beyond which the LIDAR makes no measurement.

3. Data and Results

The solar radiometer has been taking data daily from late December 2003. The LIDAR data are from six nights in late 2004 and early 2005. Figure 1 shows the result of the Fernald inversion and the simple model for LIDAR data taken on May 4, 2005. Figure 2 displays the daytime shadow-band monitor AVOD results at 332nm for the twelve days on either side of the six nights of LIDAR data talking. Also shown on Figure 2 are the results of the integral of the LIDAR Fernald inversion for the night between the two days of solar monitor results. In the clearer time of year the daytime and nighttime measurements agree better than they do as the atmosphere worsens. In spring, the night appears significantly clearer than the day – at least for the few nights of LIDAR data in this study, or perhaps there are aerosols or residual clouds above the 5-6 km LIDAR range that are measured in the daytime by the shadow band radiometer.

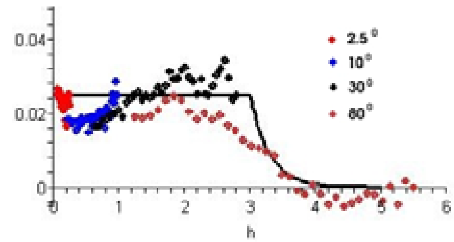

Figure 1. Plotted points show the Fernald inversion results for LIDAR data taken at elevation angles 2.5, 10, 30 and 80 degrees on the night May 4-5, 2005. The horizontal aerosol attenuation length is approximately 40km, which compares well to the 13.8km attenuation length for pure air at the altitude of the site. The model for aerosols is shown as the smooth curve. The integral of the plot is the aerosol vertical optical depth up to about 6 km.

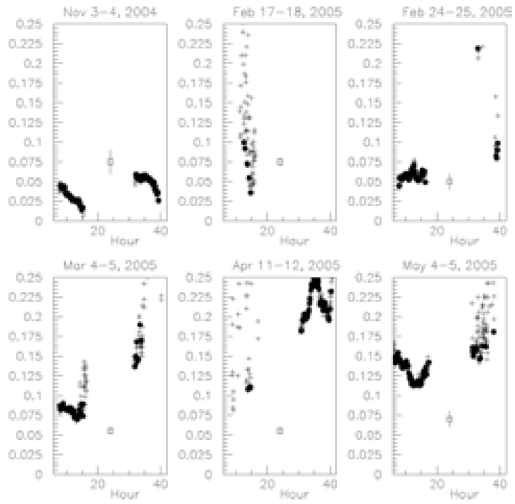

Figure 2. Aerosol vertical optical depth versus time for solar radiometer results (at 332 nm) bracketing six nights of LIDAR data (at 337 nm). The horizontal axis in each plot is the hour after midnight on the first day. The LIDAR results are plotted in the night between the two days. The optical depth of the molecular atmosphere up to 5 km above the site is approximately 0.26, so these aerosol vertical optical depths indicate relatively clear nights.

Daytime clouds attenuate the sunlight reaching the solar radiometer making the raw solar radiometer measurement the total vertical optical depth of the clouds plus the aerosols. Clouds typically produce a quickly varying optical depth, as evidenced on some of the days in Figure 2. In order to remove some of the effect of the clouds so as to measure only the aerosols, we put a cut on the derivative of the radiometer optical depth as a function of time. Solid points in Figure 2 show measurements that pass the requirement, crosses show ragged, quickly-changing vertical optical depth associated with passing clouds. The algorithm is not perfect, and it errors on the side of allowing contributions from clouds to the ostensibly aerosol-only optical depth.

We have taken monthly averages of the daytime radiometer optical depth (passing the cloud cut), and they are shown in Figure 3, where the LIDAR optical depths are re-plotted. A seasonal variation is clear.

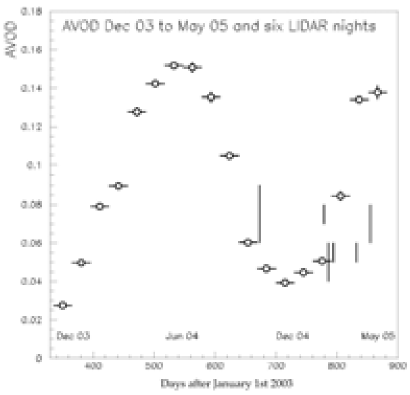

Figure 3. Points show the monthly average aerosol vertical optical depth (332nm) from the solar radiometer. The six vertical bars represent the integral of the LIDAR (337nm) Fernald inversion, that is, the aerosol vertical optical depth up to 5-6 km. The length of the vertical bar is a measure of the systematic error in the LIDAR measurement.

4. Summary and Conclusion

We have measured atmospheric aerosols at the Auger Observatory site in southeast Colorado, USA. A clear seasonal variation in the daytime aerosol vertical optical depth is observed. The nighttime optical depth appears to be lower than the daytime measurement in the spring when the atmosphere is less clear than in colder times of the year. Overall measurements indicate that the location has a good atmosphere for observation of ultra-high energy cosmic rays using the air fluorescence technique.

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