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Atmospheric aerosol monitoring at the Pierre Auger Observatory

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For a ground based cosmic-ray observatory the atmosphere is an integral part of the detector. Air fluorescence detectors (FDs) are particularly sensitive to the presence of aerosols in the atmosphere. These aerosols, consisting mainly of clouds and dust, can strongly affect the propagation of fluorescence and Cherenkov light from cosmic-ray induced extensive air showers. The Pierre Auger Observatory has a comprehensive program to monitor the aerosols within the atmospheric volume of the detector. In this paper the aerosol parameters that affect FD reconstruction will be discussed. The aerosol monitoring systems that have been deployed at the Pierre Auger Observatory will be briefly described along with some measurements from these systems.

1. Introduction

The fluorescence signal emitted by a cosmic-ray induced extensive air shower (EAS) is in principle a good calorimetric measure of the primary particle energy. The fluorescence signal is relatively independent of the primary particle species and assumptions about the high energy particle interactions in the EAS. If this is to be exploited, the efficiency of fluorescence light production and subsequent transmission to an FD need to be well understood. In particular the aerosol content of the atmosphere, in the form of clouds, dust, smoke and other pollutants, needs to be well characterized. The aerosol content of the atmosphere can be variable on short time-scales necessitating the routine monitoring of light transmission conditions in the atmospheric volume above the Pierre Auger Observatory.

To account for possible horizontal non-uniformities in the aerosols the area enclosed by the observatory is divided into 5 sub-regions within which only the vertical characteristics of the aerosols are described. Within each region the aerosols are characterized in vertical slices of 200 m thickness, up to a height of 10 km. The aerosol parameters that are important for EAS reconstruction are:

VAOD(h): vertical aerosol optical depth as a function of height

α(h): aerosol scattering coefficient as a function of height

$d\sigma/d\Omega$: aerosol differential scattering cross-section

The wavelength dependence of these parameters in the 300 - 400 nm sensitivity range of the FDs is also measured. Aerosol parameters are updated hourly for the periods of FD operation.

2. Aerosol monitoring systems

Backscatter LIDARs

An elastic backscatter LIDAR will be located near each of the FD sites. Currently 2 of these LIDARs are operational, a third is being built and the fourth will be installed when the fourth FD is completed. These LIDARs detect the elastic backscatter signal from pulsed UV lasers. The backscatter signal is detected by

photo-multiplier tubes (PMTs) at the foci of three 80 cm diameter parabolic mirrors. The laser and mirrors are mounted on a steering frame that allows the LIDAR to be pointed to almost any direction in the sky.
The PMT signals are recorded by a commercial LIDAR transient digitizer (Licel model TR40-160) with 12 bit resolution at 40 MHz sampling rate. The digitizer has a 16 kByte trace length and can also record the arrival times of single photons with a 250 MHz counting system.
The dynamic range of the LIDAR systems is increased by repetitive sampling of the laser backscatter signals. To reduce data collection time the laser systems are being upgraded to high repetition-rate 351 nm diode pumped lasers (Photonics Industries model DC30-351). The backscatter trace recording rate, limited by the Licel DAQ, is 300 Hz. Within a 2-3 second period the LIDARs can record a good quality backscatter signal at distances in excess of 25 km. More details of the LIDAR systems can be found in [1] and [2].
During FD operation the LIDAR systems perform a routine scan of the sky over each FD providing an hourly measurement of aerosol conditions. If an FD detects a cosmic-ray track it can send the shower-detector plane information to its local LIDAR system to request a "shoot-the-shower" procedure. The LIDAR software connects to the surface detector (SD) data acquisition system to see if a cluster of tanks triggered at the same time as the FD event. If this is confirmed the LIDAR will interrupt its routine operation and scan the shower-detector plane providing real-time clarity information.
As part of the backscatter LIDAR program a single Raman LIDAR detector has been installed on one of the elastic backscatter LIDARs. This detector measures backscatter light that has been frequency shifted by Raman scattering from atmospheric nitrogen and oxygen. The Raman LIDAR technique allows for a more accurate reconstruction of aerosol transmission, which is limited for elastic backscatter LIDARs by uncertainties in the aerosol backscatter cross-section. Due to the small Raman scattering cross-section this technique requires large numbers of high power laser shots. This would result in an unacceptable level of light pollution if the FDs were operating, so the Raman LIDAR is run during non data-taking periods and will be used to cross-check the accuracy of the VAOD(h) measurements made with the elastic backscatter LIDARs.

Central Laser Facility (CLF)

The CLF is located in the middle of the Pierre Auger Observatory SD array, at distances that range from 26 to 39 km from the FDs. A 355 nm laser at this facility produces laser pulses with a width of 7ns and a maximum energy of around 7 mJ. The laser beam can be steered to any part of the sky to an accuracy of $0.2°$. A more detailed description of the CLF can be found in [4]. Scattering of photons out of the laser beam by the atmosphere produces tracks that are detected by the FDs. For every hour of FD operation several hundred laser shots are fired with different directions and laser energies. The tracks made by the CLF have a wide range of uses, including testing the geometrical reconstruction accuracy of the FDs. Using an optical fiber a fraction of the laser light can be injected into a nearby SD tank allowing systematic studies of the hybrid geometry reconstruction accuracy.
The main purpose of the CLF is to measure the aerosol content of the atmosphere. For a vertical laser track, viewed by the FDs at scattering angles of near $90°$, scattering from the beam is dominated by well known molecular scattering processes. The predictable intensity of light scattered from the beam at each height can be used to measure the aerosol attenuation from the beam to the FDs providing a measurement of VAOD(h). In Figure 1. the distribution of VAOD measured between FD altitude and 4500 m above sea level (a.s.l) is shown. These low-lying aerosols, often consisting of wind-driven dust, have a strong effect on the transmission of light from EAS. The altitude difference in the FDs can be seen in figure 1. where the VAOD measured at the Los Leones FD is systematically larger than at the Coihueco FD. The Coihueco FD (altitude 1690 m a.s.l) is located on a high ridge, while the Los Leones FD (altitude 1416 m a.s.l) is at about the same altitude as the plane that contains the SD.

Horizontal Attenuation Monitors (HAMs)

The HAMs measure the attenuation length at near ground level between the FDs. Each HAM system consists

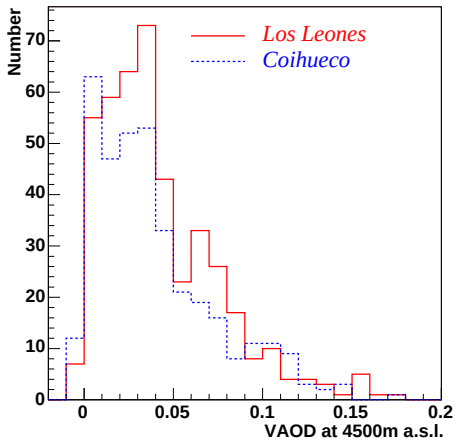

Figure 1. The distribution of VAOD from FD level to 4500m above sea level (a.s.l) reconstructed from CLF laser shots (January 2004 - February 2005). As described in the text, the VAOD measured at different FDs is expected to be slightly different.

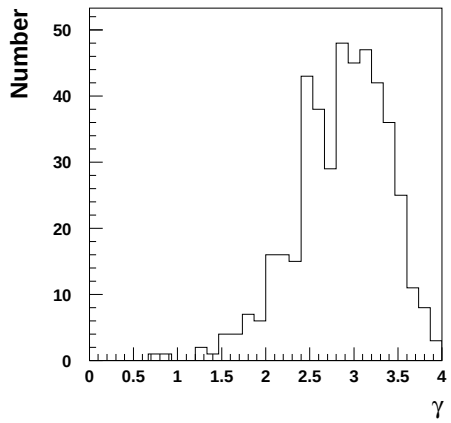

Figure 2. Distribution of the aerosol attenuation wavelength dependence parameter, γ, measured by the first HAM system. For a pure molecular atmosphere we would expect γ to be close to 4.

of a DC light source, located at one FD, and a receiver located at another FD. Currently one HAM is operational which monitors the aerosols between the Los Leones and Coihueco FDs. Two more systems are planned that will monitor other regions of the Pierre Auger Observatory aperture.

The DC light sources emit a broad spectrum of wavelengths including in the 300 - 400 nm range where the FDs are sensitive. The light detectors consist of UV enhanced CCD arrays (Starlight Xpress model MX5-16) at the focus of 15 cm diameter mirrors. A filter wheel in front of the CCD allows for monitoring at different wavelengths (365, 404, 436 and 542 nm). A measurement of the horizontal attenuation length at these wavelengths is made for each hour of FD operation. The principle measurement made by the HAMs is the wavelength dependence of the horizontal attenuation length described by a power law index, γ. The distribution of γ for total attenuation (molecular and aerosol) from measurements made during the period December 2004 until March 2005 is shown in figure 2.

Aerosol Phase Function Monitors (APFs)

Cosmic-ray induced EAS generate approximately equal numbers of Cherenkov and fluorescence photons over the life of the cascade. The Cherenkov photons are strongly forward beamed, but do contaminate the fluorescence signal directly and through atmospheric scattering. The scattering properties of the molecular atmosphere are well known, but the aerosol scattering properties depend on the specific characteristics of the aerosols.

The APFs [3] are designed to measure the aerosol differential scattering cross-section ($d\sigma/d\Omega$). The measurement is made by firing a horizontal, collimated beam of light from a xenon flashlamp across the front of an FD. The track that is generated contains a wide range of light scattering angles from the beam (30° to 150°). The APFs include narrow band filters to monitor the wavelength dependence of $d\sigma/d\Omega$.

One APF has been installed at the Coihueco FD and has been generating hourly data since September 2004. A second APF is currently being commissioned at the Morados FD site.

Cloud cameras

Clouds can have very large optical depths and can therefore have a dramatic effect on the scattering and transmission properties of the atmosphere. Although some of the other atmospheric monitors, notably the LIDARs and the CLF, are sensitive to the presence of clouds they do not provide a detailed all-sky map of cloud distributions. This information is collected by the cloud cameras. These consist of finely pixelated infrared cameras (Raytheon model 2000B, 7 μm - 14 μm wavelength range) which are sensitive to the temperature differences between the clear sky and clouds. The cameras, with a FOV of 46° x 35°, are on steerable mounts so that they can survey the entire sky. It is planned to have one camera per FD site and currently 2 are installed, at the Los Leones and Coihueco FDs. The cloud cameras scan the FOV of the FDs every 5 minutes, and also generate a full sky scan every 15 minutes. An analysis effort is underway to provide a clear/cloudy flag for each FD pixel updated every 5 minutes during FD observing periods.

Star monitors

By viewing the attenuation of starlight it is possible to measure the total optical depth from observation level to the top of the atmosphere. This measurement can then be used as a cross-check of the total optical depth inferred from the laser-based monitoring systems. Two star monitors have been deployed - one fixed and one steerable. The fixed system uses a CCD with a wide FOV lens (95° x 95°) to monitor star images from an elevation of 10° to zenith. Attenuation measurements are made by tracking star images through the FOV at different slant optical depths. The steerable system uses narrow FOV CCDs at the focus of a 20 cm diameter mirror mounted on a telescope steering mechanism. The telescope can be steered to measure the light flux from individual stars, or to look at the light from the HAM system. A flip mirror can be activated to direct the light to a photometer that can make high precision measurements of light flux. The steerable star monitor has a range of wide and narrow band filters to allow monitoring over a range of wavelengths. The star monitors will be able to check that the aerosol attenuation wavelength dependence, measured at ground level by the HAMs, is also valid for aerosols that are distributed vertically.

3. Conclusions

The Pierre Auger Observatory has a network of monitoring systems designed to measure the aerosol parameters that are of relevance to cosmic-ray observation. The aerosol parameters that most strongly affect FD data interpretation are monitored by multiple systems. This redundancy allows for important cross-checks and better understanding of the uncertainties in the reconstruction of cosmic-ray data. Many of the aerosol monitoring systems are already operational and providing data that are being used in the analysis of cosmic-ray events.

References

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