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Performance of the Fluorescence Detectors of the Pierre Auger Observatory

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Fluorescence detectors of the Pierre Auger Observatory have been operating in a stable manner since January 2004. After a brief review of the physical characteristics of the detectors, the associated atmospheric monitoring, the calibration infrastructure and the detector aperture, we will describe the steps required for the reconstruction of fluorescence event data, with emphasis on the shower profile parameters and primary energy.

1. Introduction

The Pierre Auger Observatory has been designed with an order of magnitude increase in collecting power over previous experiments, coupled with an unprecedented ability to study detection and reconstruction systematics. This combination of statistics and data quality will surely lead to new discoveries regarding the origin of the highest energy cosmic rays, through measurements of the energy spectrum, mass composition and arrival directions. A unique feature of the Auger observatory is its "hybrid" nature, where showers are observed by surface and fluorescence detectors.

The fluorescence detectors (FD) are distributed in 4 stations around the perimeter of the surface detector (SD) array, and view the atmosphere above the array on moon-less or partially moon-lit nights. Details of the surface and fluorescence detectors are given in [1]. The full southern Auger array will contain 1600 water Cherenkov detectors spread over 3000 km^2, and currently more than half of the array is in operation [2]. High quality data are being collected, including "hybrid" events described in an accompanying paper [3]. Here we discuss the fluorescence detector performance.

2. The Fluorescence Detectors

At the present time three of the four fluorescence sites have been completed and are in operation. Two of them, Los Leones and Coihueco, have been collecting data since January 2004, with Los Morados beginning data taking in March 2005. The fourth site at Loma Amarilla will be in operation in the second half of 2006.

A fluorescence site contains six identical fluorescence telescopes. The telescope design incorporates Schmidt optics. Fluorescence light enters the telescope through a 1.10 m radius diaphragm, and light is collected by a 3.5 m $\times$ 3.5 m spherical mirror and focused onto a photomultiplier (PMT) camera. The camera contains 440 hexagonal (45 mm diameter) PMTs, each PMT covering a 1.5° diameter portion of the sky. The optical spot size on the focal surface has a diameter of approximately 15 mm (equivalent to 0.5°) for all directions of incoming light. To reduce signal losses when the light spot crosses PMT boundaries, small light reflectors ("mercedes stars") are placed between PMTs. The field of view of a single telescope covers 30° in azimuth and 28.6° in elevation and an entire fluorescence site (six telescopes) covers 180° in azimuth and 28.6° in elevation. The fluorescence telescopes have been installed with an uncertainty of 0.1° in their nominal pointing directions. However, observations of stars crossing the field of view of the telescopes can improve this precision, to 0.01°.

An optical filter matched to the fluorescence spectrum (approximately 300 nm to 400 nm) is placed over the telescope diaphragm to reduce night-sky noise. In addition, the diaphragm contains an annular corrector lens as part of the Schmidt telescope design, with an inner radius of 0.85 m and outer radius of 1.10 m. The effect of the lens is to allow an increase in the radius of the telescope diaphragm from 0.85 m to 1.1 m (increasing the effective light collecting area by a factor of two) while maintaining an optical spot size of 0.5° [4].

3. Detector Calibration

One of the goals of the FD is to measure air shower energies with an uncertainty smaller than 15%. In order to achieve this goal the fluorescence detectors have to be calibrated with a precision of about 8% and the calibration stability needs to be monitored on a regular basis. An absolute calibration of each telescope is performed three or four times a year, and relative calibrations are performed every night during detector operation.

The Absolute Calibration: To perform an absolute end-to-end calibration of a telescope, a large homogeneous diffuse light source was constructed for use at the front of the telescope diaphragm. This diffuse light source has the shape of a drum, and has a diameter of 2.5 m. The light flux emitted by the drum at the diaphragm is known from laboratory measurements [5]. The ratio of the drum intensity to the observed signal for each PMT gives the required calibration. At present, the precision in the PMT calibration using the drum is about 12% [5], and is performed at a single wavelength of 375 nm. The precision will be improved and calibrations will be performed at other wavelengths. The drum is also used to adjust gains for uniform response of the pixels.

Relative Calibration: Optical fibers bring light signals to three different diffuser groups for each telescope: (a) at the centre of the mirror to illuminate the camera; (b) along the lateral edges of the camera body facing the mirror; (c) facing two reflecting Tyvek foils glued on the inner side of the telescope shutters. The total charge per pixel is measured with respect to reference measurements made at the time of absolute drum calibrations. This allows the monitoring of short and long term stability, the relative timing between pixels and the relative gain of each pixel [6]. The relative calibration information is not yet incorporated in the reconstruction system. However, the average detector stability has been measured and a corresponding systematic uncertainty of 3% has been introduced to account for this. This contributes to the overall 12% systematic uncertainty in the FD calibration.

Cross-check of the End-to-End Calibration: Cross-checks of the FD calibration can be made by reconstructing the energy of laser beams that are fired into the atmosphere from various positions in the SD array. Laser beams are fired to the sky with known geometry and energy. Part of the laser light is scattered by the atmosphere (Rayleigh and aerosol scattering) and this scattered light is detected by the FD telescopes. Using the measured signal and knowledge of the scattering parameters, it is possible to estimate the laser energy for comparison with the real laser energy. The observed difference between the reconstructed energy and the real laser energy is of the order of 10% to 15% [8], consistent with the current level of uncertainty in calibrations and knowledge of the atmosphere.

4. Atmospheric Monitoring

As part of the reconstruction process, the detected light at the telescope must be transformed into the amount of fluorescence light emitted at the shower axis as a function of atmospheric depth. For this it is necessary to have a good knowledge of local atmospheric conditions. We need to account for both Rayleigh and aerosol scattering of light between the shower and the detector, so we must understand the distribution of aerosols and the density of the atmosphere at different heights. In addition, the temperature distribution with height is needed since the fluorescence light yield is a (slow) function of temperature. Finally, the detector volume must be monitored for the presence of clouds.

Atmospheric Aerosols: Aerosols in the atmosphere consist of clouds, smoke, dust and other pollutants. The aerosol conditions can change rapidly and are known to have a strong effect on the propagation of fluorescence light. The Observatory has an extensive network of atmospheric monitoring devices. These include LIDAR systems, cloud cameras and star monitors. We have also deployed systems to monitor the wavelength dependence and differential scattering properties of the aerosols. More details of these systems can be found in [7]. A steerable laser system, located near the centre of the Auger array is used to generate tracks that are seen by the fluorescence detectors [8]. These tracks also provide a sensitive measure of the aerosol content of the atmosphere within the aperture of the Observatory. In addition to these monitoring devices, the FD background signal itself is used to measure the aerosol and cloud conditions [9]. Presently, only the aerosol information obtained from observing the laser tracks is incorporated in the shower energy reconstruction algorithm.

Molecular Atmosphere: The atmospheric characteristics at different heights above the surface array have been studied in a number of campaigns with meteorological radiosondings and with continuous measurements by ground-based weather stations. In addition, studies have been made of routine radiosondings performed at different places in Argentina. Monthly variations are compared to daily variations as well as year-to-year fluctuations of the monthly average profiles. The uncertainty in the currently applied monthly atmospheres in the Auger reconstruction introduce an uncertainty in the atmospheric depth at ground of about 5 g cm^{-2} [10].

Cloud Coverage: Customized infra-red (7–14 μm) cloud cameras have been installed at each fluorescence site. The cloud camera scans the FD field of view every 5 minutes and the entire sky every 15 minutes, producing sky cloud pictures. The pictures are then processed and a database table is filled. The data base indicates which PMTs have their field of view free of clouds at a given time.

5. Detector Aperture

The response of the Auger fluorescence telescopes has been simulated in detail and the detector aperture has been estimated as a function of energy, atmospheric conditions and primary mass [11, 12]. These fluorescence and hybrid apertures were estimated for a fully built detector (four fluorescence detectors and a 3000 km^2 surface array) and for a detector configuration corresponding to October 2004 [12]. For a fully built detector, the hybrid apertures for cosmic rays with energies of $10^{17.5}$ eV, 10^{18} eV, $10^{18.5}$ eV and greater than 10^{19} eV are approximately 900, 3200, 6400 and 7400 km^2 sr respectively.

6. Shower Geometry Reconstruction

Reconstruction of the shower geometry begins with determination of the plane containing the shower axis and the FD, the shower-detector plane or SDP [1]. The uncertainty in the reconstructed SDP depends on the size of each PMT field of view ($1.5°$ here), the observed angular track length, and on the width of the shower image. For a typical shower (23° track length) the estimated uncertainty (from Monte Carlo) in the normal to the reconstructed SDP is about 0.3°.

The shower axis within the SDP is defined by the impact parameter R_p, and the angle to the horizontal χ_0. Reconstruction of these parameters using the FD alone is prone to difficulty, especially if the angular extent of the track is small, since a range of R_p and χ_0 values may fit the measured angular speed in the FD camera. This degeneracy may be broken with the addition of timing information from a single tank in the surface array, and the uncertainty of the reconstructed shower axis is dramatically reduced to approximately 50 m in the core location and to 0.5° in the shower axis orientation [13].

7. Shower Profile and Energy Reconstruction

The signal detected at the FD cameras is converted to the number of 375 nm-equivalent photons arriving at the telescope diaphragm as a function of time [1]. The systematic error in this transformation is currently 12% [5].

The amount of light emitted at the shower track is calculated using the shower geometry, the known atmospheric conditions, the spectrum of the light and the detector's relative wavelength response. Using an iterative procedure we take account of the direct and scattered Cherenkov light measured by the FD [14]. The resulting fluorescence light at the shower track is converted to the energy deposited by the shower by applying the expected fluorescence efficiency at each depth. The overall uncertainty in the transformation from photons at the detector to emitted fluorescence photons is of the order of 12%. The application of the fluorescence yield currently includes a systematic uncertainty on the absolute yield of 13% [15], and systematics related to the pressure (4%), temperature (5%) and humidity (5%). The integral of the shower energy deposit profile provides a calorimetric measure of the cosmic ray energy. A small correction is made for unseen energy - an energy-dependent correction of 5-15% with a systematic uncertainty of about 3% [16].

8. Conclusions

Two of the Auger fluorescence detector sites have been operating in a stable manner since January 2004 and a third site began operation in March 2005. Absolute calibration of the FDs has been performed with a precision of 12%, with improvements planned to reduce this uncertainty to 8%. The atmospheric conditions are constantly monitored and their contribution to the uncertainties in the reconstructed shower parameters have been evaluated. The estimated systematic uncertainty in the reconstructed shower energy is currently 25%, with activity underway to reduce this significantly.

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