Atmospheric Monitoring at the Pierre Auger Observatory – Status and Update

KARIM LOUEDEC[1] FOR THE PIERRE AUGER COLLABORATION[2]
[1]*Laboratoire de l'Accélérateur Linéaire, Univ Paris Sud, CNRS/IN2P3, Orsay, France*
[2]*Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*
(Full author list: http://www.auger.org/archive/authors_2011_05.html)
auger_spokespersons@fnal.gov
DOI: 10.7529/ICRC2011/V02/0568

Abstract: Calorimetric measurements of extensive air showers are performed with the fluorescence detector of the Pierre Auger Observatory. To correct these measurements for the effects introduced by atmospheric fluctuations, the Observatory operates several instruments to record atmospheric conditions across and above the detector site. New developments have been made in the study of the aerosol optical depth, the aerosol phase function and cloud identification. Also, for cosmic ray events meeting certain criteria, a rapid monitoring program has been developed to improve the accuracy of the reconstruction. We present an updated overview of performed measurements and their application to air shower reconstruction.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, air fluorescence technique, atmospheric monitoring, aerosols, clouds

1 Introduction

The Pierre Auger Observatory detects the highest energy cosmic rays with over 1600 water-Cherenkov detectors arranged as a triangular array. It is surrounded by the fluorescence detector (FD) which consists of 27 telescopes grouped at four locations. The telescopes measure UV light emitted by nitrogen molecules after having been excited by electrons produced in the extensive air showers. Since the fluorescence light is proportional to the energy deposited by the shower, the primary cosmic ray energy can be estimated if the fluorescence yield is known. The FD telescopes are also used to reconstruct the slant depth of shower maximum ($X_{\max}$) which is sensitive to the mass composition of cosmic rays.

The Auger Observatory uses the atmosphere as a giant calorimeter. Light is produced and transmitted to the FD detector through an atmosphere with properties which change through the day. Thus, it is necessary to develop a large atmospheric monitoring program [1]. The production of fluorescence and Cherenkov photons in a shower depends on the atmospheric state variables such as temperature, pressure and humidity. When a photon travels from the shower to the observing telescopes, it can be scattered from its original path by molecules (*Rayleigh scattering*) and/or aerosols (*Mie scattering*).

In Fig. 1, the different experimental setups installed at Malargüe to monitor the atmosphere are listed. The state variables of the atmosphere are recorded at ground level

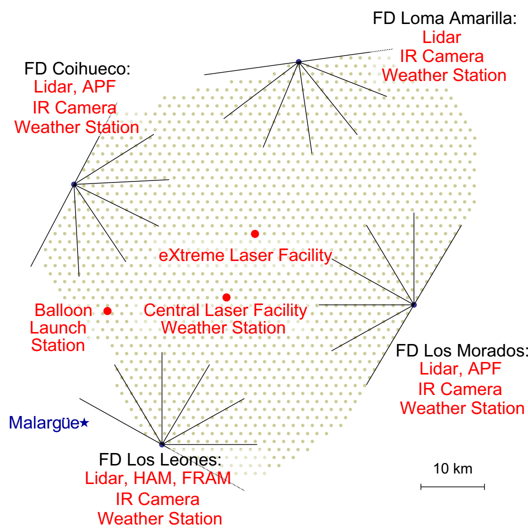

Figure 1: **Map of the Pierre Auger Observatory located close to Malargüe, in Argentina.** Each FD site hosts several atmospheric monitoring facilities.

using five weather stations. Above the Pierre Auger Observatory, the height-dependent profiles have been measured using meteorological radio-sondes launched from a helium balloon station. The balloon flight program ended in December 2010 after having been operated 331 times. The most recent monthly models of atmospheric state variables derived from these flights were developed from data between August 2002 and December 2008. Additionaly, a meteorological model has been implemented by the Auger Collaboration for air shower reconstruction [2] based on the Global Data Assimilation System (GDAS) developed by the National Oceanic and Atmospheric Administration (NOAA) which combines observations with results from a numerical weather prediction model.

Aerosol monitoring is performed using two central lasers (CLF/XLF), four elastic scattering lidar stations, two aerosol phase function monitors (APF) and two optical telescopes (HAM/FRAM). Also, a Raman lidar currently used in Colorado (USA) is scheduled to be moved to the Auger Observatory for the Super-Test-Beam project [3]. For cloud detection, a Raytheon 2000B infrared cloud camera (IRCC) is installed on the roof of each FD building.

2 Extracting the Aerosol properties

Most of the aerosols are present only in the first few kilometers above the ground level. The aerosol component is highly variable in time and location. Two main physical quantities have to be estimated to correct the effect of the aerosols on the number of photons detected by the telescopes. These are the aerosol attenuation length, linked to the aerosol optical depth, and the aerosol scattering phase function.

2.1 Aerosol attenuation

Unlike molecular scattering, aerosol attenuation does not have an analytical solution. Aerosol optical depths are measured in the field at a fixed wavelength λ_0, chosen more or less in the centre of the nitrogen fluorescence spectrum. To evaluate the aerosol extinction at another incident wavelength, we use the power law

$$\tau_a(h,\lambda) = \tau_a(h,\lambda_0) \times (\lambda_0/\lambda)^{\gamma}\,, \tag{1}$$

parameterized empirically, where $\tau_a(h,\lambda)$ is the vertical aerosol optical depth between the ground level and an altitude h, and γ is known as the Angström coefficient. Its value was estimated in the Auger Observatory by two facilities. The Horizontal Attenuation Monitor (HAM) displays a wavelength dependence with $\gamma = 0.7 \pm 0.5$ [4]. The small value of the exponent suggests a large component of large aerosols, i.e. aerosols larger than around 1 μm at least. This result is confirmed by the FRAM, the (F/Ph)otometric Robotic Atmospheric Monitor, a robotic optical telescope located about 30 m from the FD building at Los Leones [5]. In addition, an aerosol sampling program at ground level is being developed to study chemical composition and size distribution [6]. When enough statistics are accumulated, cross-checks between optical and direct measurements will be possible.

Vertical aerosol optical depth profiles are measured hourly by two lasers, the CLF and the XLF, located at sites towards the centre of the Auger array (see Fig. 2(a)). The incident wavelength is fixed at $\lambda_0 = 355$ nm and the mean energy per pulse is around 7 mJ, more or less the amount of fluorescence light produced by a shower with an energy of 10^{20} eV. More than six years of hourly data accumulated with the CLF is currently used to correct events for aerosol attenuation. The four lidars can also be used to estimate the optical depth and the horizontal attenuation for the four FD sites.

2.2 Angular dependence of aerosol scattering

The FD reconstruction of the cosmic ray energy must account not only for light attenuation between the shower and the telescopes, but also for direct and indirect Cherenkov light contributing to the recorded signal. Therefore, the scattering properties of the atmosphere need to be well estimated. The angular dependence of scattering is described by a phase function $P(\theta)$, defined as the probability of scattering per unit solid angle out of the beam path through an angle θ. Whereas the molecular component is described analytically by Rayleigh scattering, the Mie scattering does not provide a basic equation for the aerosol component. In the Auger Collaboration, the aerosol phase function (APF) is usually parameterized by the Henyey-Greenstein function

$$P_a(\theta|g) = \frac{1-g^2}{4\pi}\frac{1}{(1+g^2-2\,g\,\cos\theta)^{3/2}}, \tag{2}$$

where $g = \langle\cos\theta\rangle$ is the asymmetry parameter. It quantifies the scattered light in the forward direction: a larger g value means a stronger forward-scattered light.

In the Auger Observatory, the goal is to monitor the APF by estimating the g parameter. Up to now, the phase function was measured by the APF monitors located at Coihueco and Los Morados [7]. Recently, a new method based on very inclined shots fired by the CLF was developed (laser shots with zenith angles higher than 86$^{\text{o}}$). Following the same idea as before, knowing the geometry of the laser shot and the signal recorded by the pixels, it is possible to extract the g parameter. The advantage of this technique is that a g parameter can be estimated for each FD site, and it can cover lower scattering angles (the angular range where larger aerosols could be detected). The two techniques give a similar value for the g parameter, around 0.55 (see Fig. 2(b)).

3 Cloud Detection

Cloud coverage has an influence on the FD measurements: it biases the estimation of the $X_{\max}$ by producing bumps or dips in the longitudinal profiles and it decreases the real flux of cosmic ray events. Thus, an event is reconstructed only if the cloud fraction is lower than 25%. Around 30% of the events are rejected due to cloudy conditions. During the recent years, the Auger Collaboration has developed several methods to monitor the clouds all through

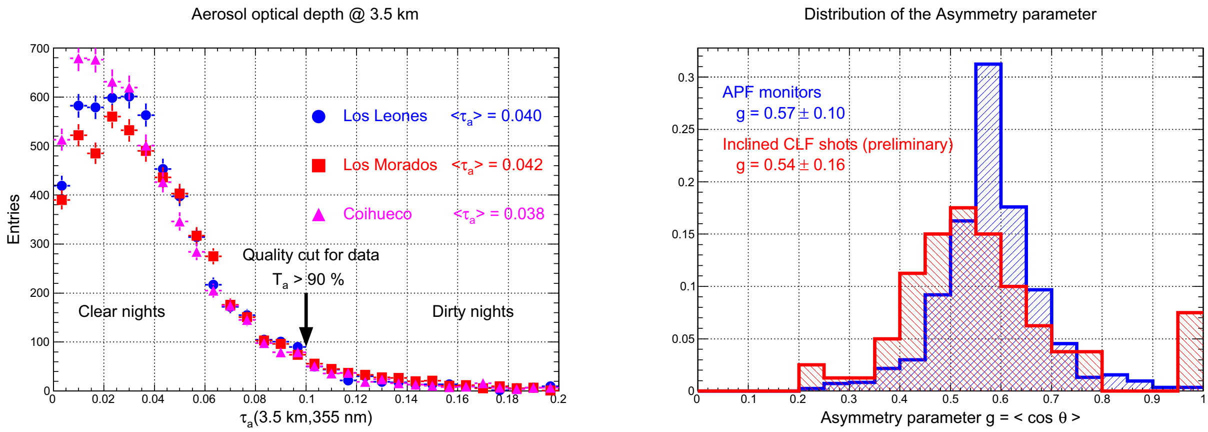

Figure 2: **Aerosol measurements.** *(a)* Vertical aerosol optical depth at 3.5 km above the fluorescence telescopes measured between January 2004 and December 2010. The transmission coefficient is defined as $T_a = \exp{(-\tau_a)}$. *(b)* Asymmetry parameter distribution measured by the APF monitor between June 2006 and June 2008, and the inclined CLF shots during 2008.

the night. During FD data acquisition, each IRCC records 5 pictures of the FD field-of-view every 5 minutes: the raw image is converted into a binary image (white: cloudy / black: clear sky), then the fraction of cloud for each pixel of the FD cameras is calculated producing the so-called FD pixels coverage mask. Different filters are applied in succession to remove camera artifacts and to get the clear sky background as uniform as possible. The cloud information for each pixel is updated every 5-15 minutes. These cloud masks are stored in a database and are now used as quality cuts after the air shower reconstruction. Fig. 3(a) gives an example of cloud mask overplotted on a telescope camera, with the corresponding longitudinal profile showing dips and bumps typical of a cloud.

A new method of identifying clouds over the Auger Observatory using infrared data from the imager instrument on the GOES-12/13 geostationary satellite is also used [8]. It obtains images using four infrared bands every 30 minutes. A brightness temperature T_i is assigned to the i-th band. The whole Auger array is described by 360 pixels: the infrared pixels projected on the ground have a spatial resolution of ~ 2.4 km horizontally and ~ 5.5 km vertically. The cloud identification algorithm uses the combination of $T_2 - T_4$ and T_3 to produce cloud probability maps (see Fig. 3(b)). Data from the satellite indicate clear conditions (cloud probability lower than 20%) during $\sim 50\%$ of FD data acquisition and cloudy (cloud probability higher than 80%) during $\sim 20\%$.

Thanks to the IRCC and the data satellite, cloud coverage can be followed through the night. However, they cannot determine the cloud heights. In the Auger Observatory, this information is provided by the CLF/XLF and the lidars. The maximum height of clouds detected by these two techniques is between 12 km and 14 km, depending on the FD site. A cloud positioned along the vertical laser track scatters a higher amount of light, producing a peak in the recorded light profile. On the other hand, a cloud located between the laser and the FD site produces a local decrease in the laser light profile. Finally, the lidar telescopes sweep the sky during a 10-min scan every hour. Clouds are detected as strong light scatter regions in the backscattered light profiles recorded by the mirrors. The height of a cloud is deduced from the arrival time of the detected photons. These measurements have identified two cloud populations located at about 2.5 km and 8.0 km above sea level.

4 Rapid Atmospheric Monitoring

During FD data acquisition, showers meeting certain criteria are used to trigger dedicated measurements by the weather balloon, lidar and FRAM to get a detailed description of the atmosphere in the vicinity of the shower track. The rapid monitoring system occurs as follows: a hybrid reconstruction using all the detectors and calibration data available is performed on shower data measured at most 10 min after their detection. Only events passing a list of quality cuts activate the rapid monitoring procedure.

The *Balloon-the-Shower* (BtS) program was dedicated to perform an atmospheric sounding within about three hours after the detection of a high-energy event. The measurements obtained by launching weather balloons provide altitude profiles of the air temperature, pressure and humidity up to about 23 km above sea level. Such a delay is mostly conformable with the validity of the balloon data, since the fluctuations in the atmospheric profiles are usually low within a single night. Between March 2009 and May 2010, 39 launches were performed covering 51 selected events. Using monthly models instead of BtS profiles introduces an uncertainty on the energy $\Delta E/E = (-0.2 \pm 2.4)\%$ and on the position of the shower maximum $X_{\max} = (-0.8 \pm 6.1)$ g cm^{-2}, for showers with energies between $10^{19.3}$ eV and $10^{19.7}$ eV [9]. The balloon

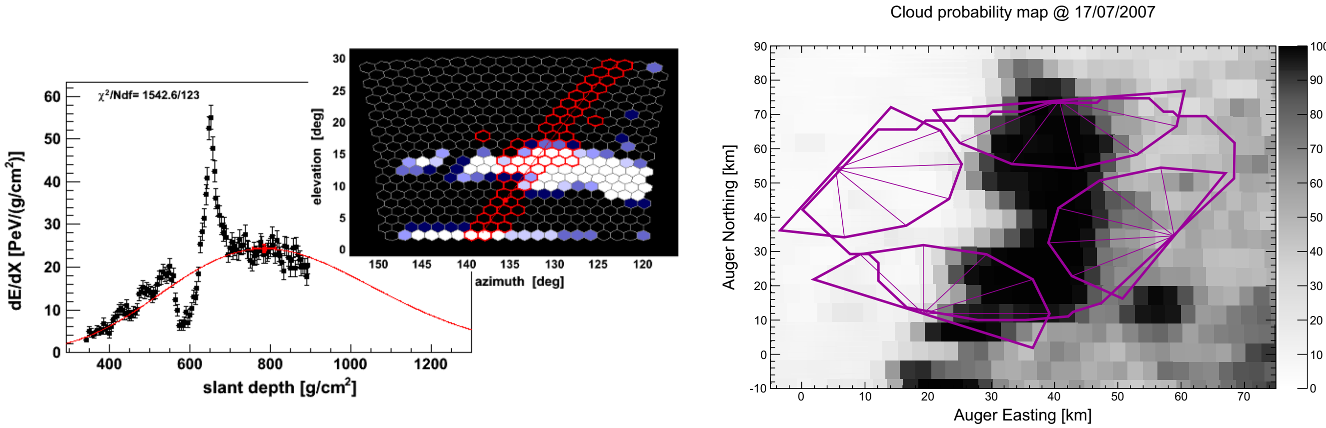

Figure 3: **Cloud coverage.** *(a)* Display of an event recorded by a FD camera, with index of cloud coverage for each pixel (lighter pixels mean higher cloud coverage). Pixels with no cloud are in black. The associated longitudinal profile is also shown. *(b)* Cloud probability map for 17/07/2007 at 01:09:24 UT. Pixels and their cloud probability are colored in accordance with the scale to the right of the map.

program, including BtS, ended in December 2010 and is now replaced by numerical meteorological profiles [2].

The motivation of the *Shoot-the-Shower* (StS) program is to identify non-uniformities – especially clouds or aerosol layers – that affect light transmission between the shower and detector. The StS shooting sequence, or lidar scan, goes from the ground to the top of the FD field of view, all along the shower track. Each shooting direction is separated from the previous one by 1.5°. Between January 2009 and July 2010, 70 hybrid events passed the online quality cuts and triggered a StS scan. 9 out of 70 StS were aborted because of various hardware issues, reducing the sample to 61 events. The StS scans were analyzed and clouds were detected in 20 of the 61 events.

FRAM can be programmed to scan the shower path, recording images with a wide-field CCD camera mounted on the telescope. For each event passing the different cuts and being close to Los Leones, a sequence of 10 to 20 CCD images is produced. The CCD images can be analyzed automatically, and an atmospheric attenuation is obtained for each image. This goal is achieved using the photometric observations of selected standard, i.e. non-variable, stars. From January 2010 to July 2010, 173 successful observations were done. These observations permitted detection of the presence of clouds or aerosol layers and images corresponding to an attenuation coefficient higher than expected for a clear sky.

5 Conclusion & Future Plans

Thanks to a collection of atmospheric monitors, the Pierre Auger Observatory has accumulated a large database of atmospheric measurements. This huge effort significantly reduced the systematic uncertainties in the air shower reconstruction. The rapid monitoring, focused on the highest energy events, also reduced uncertainties due to atmospheric effects. The program can be easily extended to incorporate new instruments as the Raman lidar, expected to be installed close to the CLF in 2011 for the Super-Test-Beam project. Also, a design study for new elastic scattering lidars has been undertaken. The goals are a more compact lidar with better mechanical stability and weatherproofing.

Recently, a public conference took place at Cambridge, UK, where interdisciplinary science at the Pierre Auger Observatory (IS@AO) was discussed [10]. During this meeting, scientists from a variety of disciplines talked about the potential of the Observatory site and to exchanged ideas exploiting it further. Among them, we can cite the possible connection between clouds, thunderstorms and cosmic rays, a larger aerosol sampling program and the detection of atmospheric gravity waves.

References

[1] The Pierre Auger Collaboration, Astropart. Phys., 2010, **33**: 108-129
[2] M. Will, for the Pierre Auger Collaboration, paper 0339, these proceedings
[3] L. Wiencke, for the Pierre Auger Collaboration, paper 0742, these proceedings
[4] S. BenZvi et. al., for the Pierre Auger Collaboration, Proc. 30th ICRC, Mérida, México, 2007, **4**: 355-358
[5] P. Trávníček et. al., for the Pierre Auger Collaboration, Proc. 30th ICRC, Mérida, México, 2007, **4**: 347-350
[6] M.I. Micheletti et. al., *private communication*
[7] S. BenZvi et. al., Astropart. Phys., 2007, **28**: 312-320
[8] https://events.icecube.wisc.edu/indico/contributionDisplay.py?contribId=22&sessionId=11&confId=30
[9] B. Keilhauer, for the Pierre Auger Collaboration, Astrophys. Space Sci. Trans., 2010, **6**: 27-30
[10] http://www.ncas.ac.uk/isATao