# Atmospheric Monitoring at a Cosmic Ray Observatory – a long-lasting endeavour

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**Abstract.** The Pierre Auger Observatory for detecting ultrahigh energy cosmic rays has been founded in 1999. After a main planning and construction phase of about five years, the regular data taking started in 2004, but it took another four years until the full surface detector array was deployed. In parallel to the main detectors of the Observatory, a comprehensive set of instruments for monitoring the atmospheric conditions above the array was developed and installed as varying atmospheric conditions influence the development and detection of extensive air showers.
The multitude of atmospheric monitoring installations at the Pierre Auger Observatory will be presented as well as the challenges and efforts to run such instruments for several decades.

## 1 Introduction

The Pierre Auger Observatory for detecting ultra-high energy cosmic rays was designed from its beginning as a so-called hybrid detector consisting of a surface detector (SD) array and a fluorescence detector (FD) [1]. The SD is built of 1660 water-Cherenkov tanks to record the secondary particles, produced in the extensive air shower cascade, at ground level. The duty cycle of this detector is almost 100% and provides data of cosmic ray events with high statistics. The FD is a set of 24 + 3 telescopes placed at four sites at the boundary of the SD array for collecting the light emission induced by the extensive air showers in the atmosphere. The duty cycle of this detector is only about 15%, but the data are essential for the energy determination of the cosmic ray events [2, 3] and for the determination of the position of the shower maximum [4].

Atmospheric conditions affect the development and detection of extensive air showers [5]. The atmospheric state variables – temperature, pressure, and humidity – alter the longitudinal and lateral development of extensive air showers [6–8] as well as the amount of fluorescence light emitted by the nitrogen molecules in the Earth's atmosphere while an extensive air shower develops through it and deposits energy [9–12]. The isotropically emitted fluorescence light is observed by telescopes in the wavelength range between about 300 and 420 nm. The telescopes are very sensitive and are operated only in dark, clear nights with only low moonlight so that extensive air showers of ultra-high energy cosmic rays can be observed evenatt distances of more than 30 km to the telescopes [1]. The condition of the atmosphere in terms of transmission properties between air shower and telescope has to be known for the reconstruction of cosmic ray events as well. Clouds are needed to be identified. The optical attenuation is given by absorption and scattering of light. The light absorption is neglible for the given wavelengths and the part of atmosphere observed which is up to about 8 km. However, the light scattering is a highly variable and important factor in the cosmic ray event reconstruction [5]. Light is scattered by atmospheric molecules and this process is described by analytic functions as Rayleigh scattering [13]. The more variable part of scattering is the light scattering by aerosols known as Mie scattering [14]. No general analytical solution for describing theses processes is available or strictly speaking, the behavior as a function of scattering angle is quite complex. The aerosol transmission factor depends on the vertical aerosol optical depth (VAOD), which has to be measured at the site of interests quite frequently, depending on the accuracy to be achieved. The angular distribution of light scattered by aerosols is strongly peaked in the forward direction and has only a small backscattering component. For the purpose of air shower reconstruction, this behavior can be approximated by a parameterization based on a Henyey-Greenstein function and a Legendre polynomial, see [5] and references therein. However, the parameters used in this function have also to be measured at the site of interest.

Since the Pierre Auger Observatory is aiming for high-precision data, the collaboration is operating a comprehensive set of instruments for monitoring the atmosphere above the 3000 km$^2$ array. A schematic view of the installations is given in Fig. 1. The different devices are used to measure different aspects of the atmospheric conditions,

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**Table 1.** Atmospheric measurements performed and the instruments that are used. The state variables are recorded continuously, but the aerosol and cloud information are collected only during FD data taking periods.

| Category | Variable | Frequency | Instrument(s) |
|---|---|---|---|
| State | At ground:<br>Pressure, Temp.,<br>Wind, Humidity | 5 min | Weather Stations |
| | Profile: Pressure,<br>Temp., Humidity | 3 hours | GDAS[a] |
| Aerosols | Vert. Optical Depth ($z$) | hourly | CLF, XLF + FD |
| | Phase Function | hourly | 2 APF units |
| | Ångström Coefficent | hourly | FRAM (HAM) |
| Clouds | Presence in FD pixels | 15 min | 4 Cloud Cameras |
| | Behind FD sites | 15 min | 4 lidar stations |
| | Along select tracks | avg. 1/night | FRAM, lidar |
| | Above CLF/XLF | hourly | CLF, XLF + FD |

[a]atmospheric model developed at the National Centers for Environmental Prediction, operated by NOAA; provided via READY - Real time Environmental Applications and Display sYstem.

so their frequency of data records are adjusted to the needs of the observatory, see Tab. 1.

## 2 Atmospheric monitoring devices

The knowledge of atmospheric state variables is a fundamental ingredient for the cosmic ray event reconstruction. As described above, the state variables influence the development of extensive air showers and the amount of light emission, but they are also needed for the analyses of aerosol and cloud measurements. A simple and robust measurement of the state variables is done with ground-based weather stations. These weather stations are typically commercial products designed for long-term operation in remote and harsh environments. The data are provided with high precision and recording rates, but only at ground level. For receiving vertical profiles of state variables in the atmosphere, the Auger Observatory performed manual radio soundings during the early years. The systems are also commercial products with high accuracy, but each launch of a weather balloon has to be done manually and can be done only rarely compared to the continuous changes of the atmosphere [15, 16]. Thus, performing local radio soundings cannot be the appropriate tool for a cosmic ray observatory. At the Auger Observatory, the alternative application of a global atmospheric model has been investigated and implemented in the process for cosmic ray event reconstruction [6]. The Global Data Assimilation System (GDAS) [17] is a model developed at NOAA's National Centers for Environmental Prediction. 3-hourly data are available in 23 constant pressure levels up to about 26 km and are published once a week. For the Auger Observatory, we have setup automated scripts for converting the data to the Auger-required format and to provide the data in dedicated databases.

Measuring the aerosol content in the atmosphere is a much more difficult procedure. Several techniques have been developed, mainly by meteorologists, but typically hardly any instruments are commercially available and thus, own designs and constructions have to be used. A widely used technique are elastic and Raman lidars measuring the backscattering signal of laser pulses. They provide information about the optical extinction due to aerosols and air molecules. In sophisticated analyses, vertical aerosol optical depth (VAOD) profiles can be derived. Another technique, developed by astroparticle physicists, makes use of the fluoresence telescopes of the cosmic ray observatory. Also here, laser pulses are shot into the atmosphere, but the scattered light in the line of sight towards the FD is recorded. These laser facilities are typically placed in the center of cosmic ray observatories with FD and therefore called Central Laser Facility (CLF). For the installations at the Auger Obervatory, a technical description can be found in [1] with more details about the Raman lidar in [18] and about the CLF in [19, 20]. Another device developed for the Auger Observatory is FRAM [21], a ph(F)otometric Robotic Atmospheric Monitor that measures starlight to determine the wavelength dependence of Rayleigh and Mie scattering, but is also used to derive total optical depth data [22, 23]. The central laser facilities are quite robust devices and only regular scheduled maintenance intervalls are needed. The operation during FD data taking is also highly automated so that FD shift personnel needs to check only for some data output, but no active operation of the system is required. The later analysis of data has to be done more manually and input of FD calibration data is needed. The CLF data provide the standard VAOD information at the Auger Observatory for the cosmic ray event reconstruction. Operating elastic and Raman lidars is more challenging. Lidars are delicate devices in terms of optical alignment and laser operation. For cosmic ray observatories, a balance between laser activities for lidar operation and FD data taking has to be found since the lasers are too bright for the FD telescopes in their field of view. The FRAM is a passive device, not interfering with FD data taking. However, typically only the total aerosol profile can be recorded independent of the field of view of the FD telescopes or actual positions of cosmic ray events.

In addition to these information, clouds have to be detected. At the Auger Observatory, infrared cameras are operated at each of the FD stations [24, 25]. An image of the entire hemisphere is taken every 15 minutes during FD data taking and every 5 minutes, the cloud monitors scan the sky in the field of view of each of the FD telescopes for identifying the cloud cover. The cloud measurements do not affect any FD data taking and are done fully automated. This cloud information is used to set quality cuts during the analysis of cosmic ray events since no cloud altitudes can be derived from these observations. The cloud base height can be obtained from elastic lidar measurements in the same field of view. Since the FD data taking time has to be maximized, cloud base heights are measured behind the field of view of each FD station at the Auger Observatory. Also the use of satellite data about clouds are investigated [26, 27]. These data provide a useful cross-check, but the resolution is currently too low for the needs of the Auger Observatory.

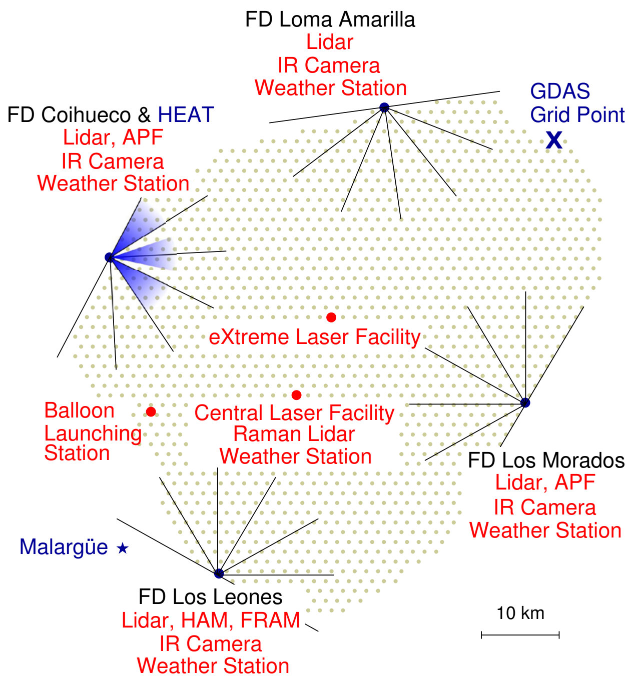


**Figure 1.** Schematic overview of the atmospheric monitoring devices installed at the Pierre Auger Observatory [1]. At each FD site, there is a lidar station, a ground-based weather station, and an infrared camera for cloud cover detection. In addition, there are devices for measuring the Aerosol Phase Function (APF) at FD Coihueco and Los Morados, a Horizontal Attenuation Monitor (HAM) at FD Los Leones, and a ph(F)otometric Robotic Atmospheric Monitor (FRAM) also at Los Leones. A steerable backscatter elastic lidar system is installed at each of the 4 FD sites to measure aerosols and the positions of clouds near each site. At central positions within the surface detector array, two laser facilities are installed (CLF and XLF). These instruments, together with the FD, are used to measure VAOD as a function of height in the line of sight of each FD telescope 4 times per hour. In April of 2013 the CLF was upgraded with a Raman lidar receiver. Near the western boundary of the array, the Balloon Launching Station (BLS) was assembled together with a weather station as a base unit for an electric field meter. From this launch station, the weather balloons were typically carried across the entire array by westerly winds.

## 3 Conclusions

For cosmic ray observatories as the Pierre Auger Observatory, atmospheric monitoring is an important task to ensure the required accuracy of data. The atmosphere at the site of the observatory is part of the detector system and thus has to be monitored and recorded with the same elaborateness as other devices for the detection of cosmic rays. The atmospheric monitoring system at the Pierre Auger Observatory is a comprehensive set of different devices, all serving for tracking different conditions of the atmosphere with required accuracy in time and quality, with some devices having a partial overlap in information for cross-checking different devices and their long-term stability.

Typical cosmic ray observatories run for many years up to few decades, this includes also the atmospheric monitoring systems. The collaborations have to ensure that the used systems are designed for long-term operations, for low staff assignment during continuous operation, and for low maintenance effort. In the designing phase of an observatory, the requirements for the atmospheric monitoring have to be defined carefully: What data are needed in what precision, format, and which time intervalls? How fast have these data to be available for cosmic ray data analyses? How much of redundancy is aimed for? Is the planning, installation, and design of analyses procedures of atmospheric monitoring systems fast enough to meet the needs of the observatory?

It is recommended to rely on robust, most simple, and sufficiently automized atmospheric monitoring systems for use at cosmic ray observatories, because of their long-term operation at typically quite remote sites.

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