Rapid atmospheric monitoring after the detection of high-energy showers at the Pierre Auger Observatory

Bianca Keilhauer*, **for the Pierre Auger Collaboration**†

*Karlsruhe Institute of Technology (KIT),
Forschungszentrum Karlsruhe, Institut für Kernphysik, P.O.Box 3640, 76021 Karlsruhe, Germany
†Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina

***Abstract*. The atmospheric monitoring program of the Pierre Auger Observatory has been upgraded to make measurements of atmospheric conditions possible after the detection of very high-energy showers. Measurements of the optical transmittance due to aerosols and clouds are time-critical. Therefore, observations of atmospheric regions close to a shower track of interest are performed within ten minutes of a shower detection using LIDAR and telescope monitors. Measurements of the altitude dependence of atmospheric state variables such as air temperature, pressure, and humidity are performed within about two hours following the detection of a very high-energy event using meteorological radio soundings. Both programs are triggered using a full online reconstruction with analysis-level quality cuts. We describe the implementation of the online trigger, and discuss the impact of the monitoring data with high resolution on the analysis of air shower events.**

***Keywords*: rapid atmospheric monitoring, Pierre Auger Observatory, high-energy air showers**

I. Introduction

At the Pierre Auger Observatory [1], extensive air showers (EAS) induced by ultra-high energy cosmic rays are studied. The observatory consists of two detector types, a surface detector (SD) for secondary particles of EAS and fluorescence detector (FD) telescopes for UV-emissions by nitrogen molecules in the atmosphere. The fluorescence technique provides an almost calorimetric measurement of the primary energy of cosmic rays.

However, the constantly changing conditions of the atmosphere demand a sophisticated monitoring system [2]. The reconstruction of air showers from their UV-emission requires proper characterisation of atmospheric state variables such as pressure, temperature, and humidity, as well as the optical transmittance due to aerosol contamination and the presence of clouds [3]. The state variables of the atmosphere above the Pierre Auger Observatory are determined using meteorological radio soundings, while aerosol and cloud conditions are measured by two central lasers, four elastic LIDARs, and four cloud cameras [4].

The sounding data have been incorporated into monthly models, and aerosol and cloud data into an hourly database [4]. However, for events of particular physical interest, such as very high-energy showers, it is desirable to measure the properties of the atmosphere as accurately as possible. To improve the resolution of the atmospheric database for such events, dedicated radio soundings and LIDAR measurements can be triggered by an online event reconstruction. We will discuss the motivation for such measurements (Section II), the operation of the online trigger (Section III), and the use of dedicated atmospheric measurements in the offline reconstruction (Section IV).

II. Motivation for Rapid Monitoring

Between 2002 and 2005, radio soundings were performed at the observatory during dedicated measurement campaigns. Since mid-2005, the soundings have been performed approximately every fifth day. The measurements obtained by launching weather balloons provide altitude profiles of the air temperature, pressure, and relative humidity up to about 23 km above sea level. Due to the limited statistics of the measurements, the data have been incorporated into monthly models of conditions near Malargüe, Argentina, the site of the southern part of the Pierre Auger Observatory [4], [5].

Using monthly models instead of actual profiles introduces an uncertainty of the primary energy of $\Delta E/E = 1.5\% - 3\%$ for showers with energies between $\approx 10^{17.7}$ eV and 10^{20} eV, and a corresponding uncertainty $\Delta X_{\max} = 7.2 - 8.4$ g cm^{-2} of the position of the shower maximum. While it is not practical to perform a radio sounding every night, the reconstruction can be improved for a subset of the EAS data by concentrating the soundings in periods when high-quality events are observed. This subset of EAS events is particularly important because they contribute to the energy scale determination of the entire observatory [6].

For aerosol measurements, the LIDAR stations conduct automated hourly sweeps of the atmosphere above the observatory to estimate the vertical aerosol optical depth, cloud height, and cloud coverage [7]. The hourly sweeps are sufficient to characterise changing aerosol conditions, but a more rapid response is necessary to identify moving clouds between shower tracks and the FD telescopes observing the event. To accomplish this, the LIDARs are capable of interrupting their hourly sweeps to scan interesting shower tracks for atmospheric non-uniformities [7], [8].

III. Online Trigger

To select events for monitoring with radio soundings and/or LIDAR scans, an online reconstruction is used to trigger balloon launches and the LIDAR hardware. As data are acquired from the FD telescopes and SD, they are merged by an event builder into hybrid event files, and passed to the reconstruction software. The software is the same as that used for $\overline{\rm Off}\underline{\rm line}$ event reconstruction [9], including the latest versions of the detector calibration databases. In this way, the LIDAR and balloon triggers can be constructed with the same quality as the offline physics analysis.

The reconstruction loop runs every 60–90 seconds, and reconstructs events between 2 and 10 minutes after their detection[1]. Events with reconstructible dE/dX longitudinal profiles are used to trigger LIDAR and sounding measurements following the application of basic quality cuts. The LIDARs trigger on showers with $E \geq 10^{19}$ eV in combination with given quality cuts on the reconstruction of the shape of the longitudinal profile. These events are typically of high quality and the rapid monitoring is to ensure that no atmospheric impurity has altered the reconstruction result. To allow the investigation of shower observations affected by clouds and other non-uniformities in the atmosphere for possible longitudinal profile corrections in the future, few events of lower quality with $E \gtrsim 10^{18.78}$ eV can also pass the trigger conditions. This yields up to one scan per night. A balloon launch is triggered for events with $E \geq 10^{19.3}$ eV and a profile fit χ^2/NDF < 2.5. All trigger conditions have in common that the position of shower maximum has to be well in the field of view and that the observed track has an expedient length.

The quality of the online reconstruction has been checked by comparing with results from the $\overline{\rm Off}\underline{\rm line}$ reconstruction. Even though some minor differences in the reconstruction chains are present, the reconstruction quality is excellent. Only some events are missed by the online reconstruction below 10^{18} eV, which is well below the required energy threshold for both rapid monitoring programmes. At primary energies of interest, the energy of the primary cosmic ray and the position of the shower maximum are reconstructed very well by comparison with the $\overline{\rm Off}\underline{\rm line}$ reconstruction: only below 1% difference for the energy and 2 g cm^{-2} in $X_{\rm max}$ are expected. The reconstruction cuts for triggering radio soundings yield a trigger rate of 3 to 13 radio soundings per shift[2] depending on season, see Fig 1. In practice, only one launch is performed within 5 hours resulting in about 2 to 6 launches per FD shift.

Triggers for the LIDAR systems are handled automatically by these stations: the hourly scans are halted and the LIDARs sweep into the field of view of the FD telescopes to probe the shower track [7]. To avoid triggering the telescopes with stray light, the FD data acquisition is vetoed for four minutes, the maximum duration of a dedicated scan. In contrast to the LIDAR, the balloon launches require human intervention. Therefore, a sounding trigger initiates a SMS text message to a technician in Malargüe. The technician then drives to the balloon launching facility and performs the sounding typically within two hours of the detection of the event. This measurement has no interference with any other data acquisition of the Pierre Auger Observatory.

[1]The delay is caused by buffering of station data from the SD.
[2]To infer these numbers, the EAS data sample from 2008 was analysed.

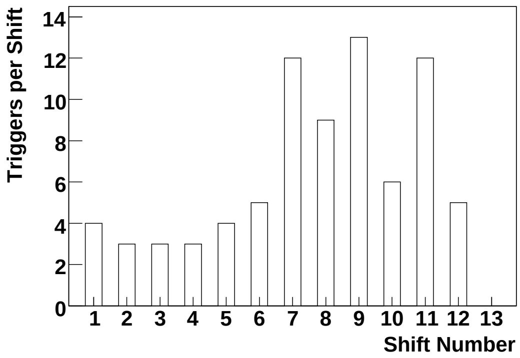

Fig. 1. All triggers for each FD shift in 2008 of events which would have passed the sounding trigger conditions. A seasonal effect due to longer nights in winter can be seen.

IV. Analysis

During the March – April 2009 FD shift, the rapid monitoring with radio soundings was activated for the first time. We had two nights with successful triggers for the radio soundings. In the second night, it was a stereo event. Both radio soundings could be performed within 1.5 hours after the high-energy air shower. The first trigger was sent at the end of March and the second one at the beginning of April. In Fig. 2, the difference between the actual measured atmospheric profiles from the radio soundings and the monthly models for the area of the Auger Observatory valid for that month are displayed for the temperature, atmospheric depth, and vapour pressure. For the event in March, the differences between the measured temperature and atmospheric depth profiles and the monthly average model are small. However the considerable amount of water vapour in the lower atmosphere indicates possible distortions of the longitudinal shower profile compared with a reconstruction using the adequate monthly model. A reconstruction of the first event with the actual atmospheric profiles compared with that using monthly models yields a $\Delta E/E$ of +0.9% and a $\Delta X_{\rm max}$ of +6 g cm^{-2}. For the event in April, the water vapour content is nearly the same as in the corresponding monthly model. However, the higher temperature close to ground resulting in lower atmospheric depth values will change the reconstructed air shower event. The same two versions of reconstruction as for the first event yield a $\Delta E/E$ of -0.5% and -1.0% for the two different FD

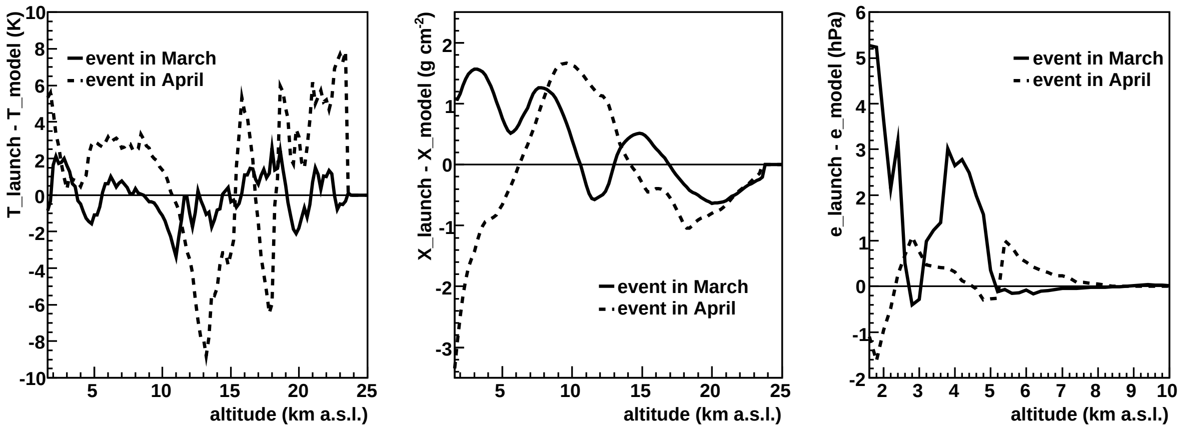

Fig. 2. Difference between two actual measured atmospheric profiles in March and April 2009 from the radio soundings and the corresponding monthly models for the area of the Auger Observatory. Left: Temperature. Middle: Atmospheric Depth. Right: Vapour Pressure.

stations which observed this stereo event and a $\Delta X_{\max}$ of +4 g cm^{-2} and +3 g cm^{-2}.

In the second shift running this programme, we had 10 triggers in 6 nights. The first one was again a stereo event and in the fourth night, there were 3 triggers within 2.5 hours. The fifth night also provided two triggers in 2.5 hours, and in the last night there were 2 triggers within 1 hour. In total, we had 5 radio soundings initiated by high-energy air shower events, because the SMS during the last night were lost.

All events have been reconstructed using two different configurations. The first one represents the status of currently best knowledge, so using the actual atmospheric profiles from the radio soundings in combination with descriptions of fluorescence emission [10] and transmission taking into account all temperature, pressure, density, and humidity effects. The second reconstruction relies on the same descriptions but uses the monthly models for the site of the Pierre Auger Observatory which provide also profiles of water vapour. In Fig. 3, the resulting differences of the reconstruction procedures are shown for all events during March and April 2009. The stereo events have been reconstructed independently for the two FD stations which observed the extensive air shower. The primary energies of these events vary from the threshold energy up to almost $10^{19.7}$ eV and for the position of shower maximum, values between 654 and 924 g cm^{-2} slant depth are observed. The given differences are between reconstruction with actual atmospheric profiles and that with monthly models. For the primary energy, we expect an uncertainty of $\pm$ 2.5% at $E_0 = 10^{19.3}$ eV while using monthly models. The differences between reconstructions using sounding data and the monthly models fit these expectations (Fig. 3 left). For the position of shower maximum, the expected uncertainty at $E_0 = 10^{19.3}$ eV is $\pm$ 8 g cm^{-2}. The reconstruction with monthly models nearly matches these expectation but is biased to one direction for this season (Fig. 3 right).

The rapid monitoring with LIDARs started in February 2009 and through the beginning of May 2009, the four LIDAR stations at the Pierre Auger Observatory were triggered 29 times. The intention is to investigate atmospheric conditions for those high-energy showers that fail strict analysis cuts due to distortions caused by clouds and aerosols.

For high-energy showers of high reconstruction quality, the LIDAR scans can be used to verify the quality of the atmosphere. In this manner, the scans allow for the investigation of atmospheric selection effects on the highest energy showers. Of the 29 showers probed by dedicated LIDAR scans, 17 passed the strict quality cuts used in the analysis of FD data. The energies of these showers ranges from 10^{19} to $10^{19.52}$ eV. The observed shower maxima are between 678 and 808 g cm^{-2}.

In nearly all cases, the profile fit is of high quality, and the LIDAR data do not indicate the presence of large amounts of aerosols or heavy cloud coverage. One exception is shown in Fig. 4, in which the light from the upper segment of a shower track is blocked by a thick cloud layer. The backscattered light from the LIDAR scan shows a strong echo near 8 km above ground level, or 650 g cm^{-2} slant depth along the shower track, confirming the presence of a cloud.

At present, the rapid monitoring with LIDARs is mainly used as a check of the quality of the atmosphere after the observation of high-energy showers. This is quite important for analyses that rely on unusual features in shower tracks, such as exotic particle searches. The LIDAR shots can also be used to remove obscured or distorted sections of a shower track from the analysis. Once sufficient statistics have been collected, it should be possible to use the LIDAR data to correct observed shower tracks for inhomogeneities in the atmosphere.

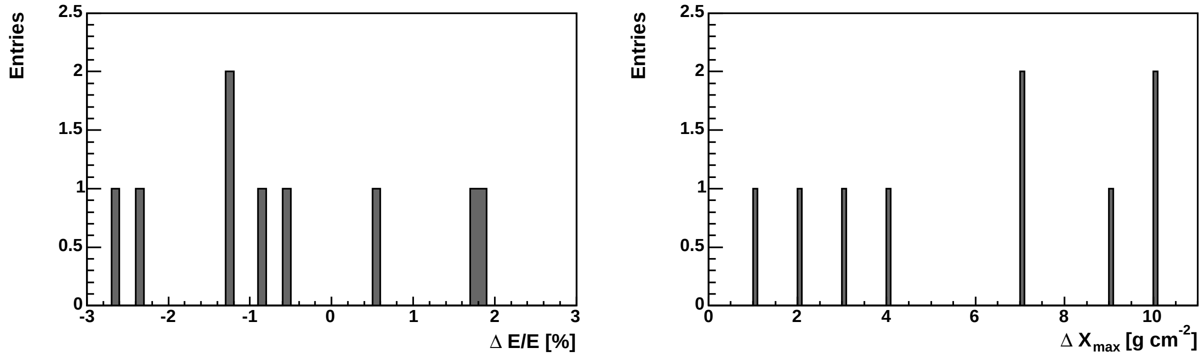

Fig. 3. Comparison of two different versions of reconstruction for air shower events observed in March and April 2009. The first reconstruction uses actual atmospheric profiles from radio soundings performed shortly after the detection of the EAS. The second one uses monthly models developed for the site of the Pierre Auger Observatory.

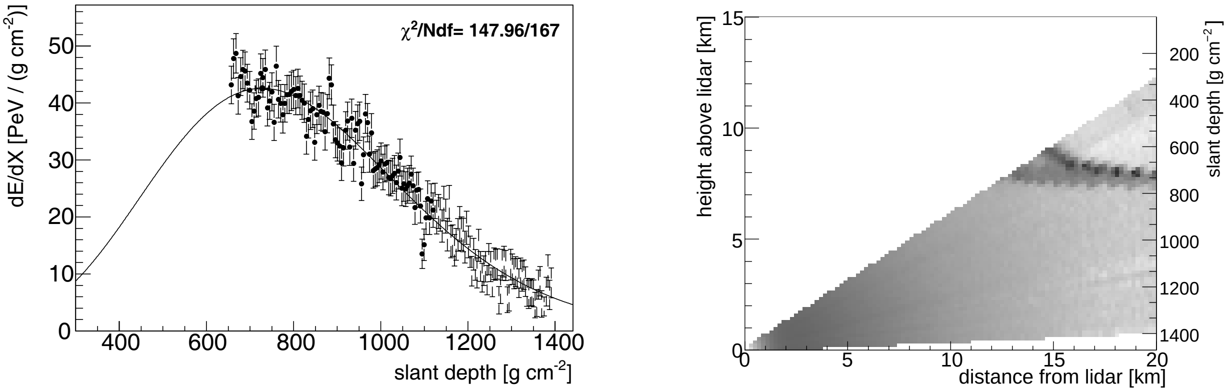

Fig. 4. Left: A $10^{19.48}$ eV shower profile obscured below 650 g cm^{-2} by a cloud. The backscattered light from a LIDAR scan of the shower-detector plane (right) confirms the presence of a cloud layer (the dark horizontal band) in the telescope field of view.

REFERENCES

[1] J. Abraham *et al.* [Pierre Auger Collab.], Nucl. Instr. Meth. **A523** (2004) 50

[2] S. BenZvi for the Pierre Auger Collab., Proc. 31st Int. Cos. Ray Conf. Lodz, Poland, (2009)

[3] L. Valore for the Pierre Auger Collab., Proc. 31st Int. Cos. Ray Conf. Lodz, Poland, (2009)

[4] J. Abraham *et al.* [Pierre Auger Collab.], *A Study of the Effect of Molecular and Aerosol Conditions on Air Fluorescence Measurements at the Pierre Auger Observatory*, submitted to Astropart. Phys. (2009)

[5] J. Blümer *et al.* for the Pierre Auger Collab., Proc. 29th Int. Cos. Ray Conf. Pune, India, **7** (2005) 123

[6] J. Abraham *et al.* [Pierre Auger Collab.], PRL **101** (2008) 061101

[7] S.Y. BenZvi *et al.*, Nucl. Instr. Meth. **A574** (2007) 171

[8] J. Boyer et al. for the HiRes Collab., Proc. 28th Int. Cos. Ray Conf. Tsukuba, Japan, 1 (2003) 481

[9] S. Argiro *et al.*, Nucl. Instr. Meth. **A580** (2007) 1485

[10] B. Keilhauer, M. Unger, Proc. 31st Int. Cos. Ray Conf. Lodz, Poland, (2009)