Astrophys. Space Sci. Trans., 6, 27–30, 2010
www.astrophys-space-sci-trans.net/6/27/2010/
doi:10.5194/astra-6-27-2010

Astrophysics and Space Sciences Transactions

The Balloon-the-Shower programme of the Pierre Auger Observatory

B. Keilhauer[1] **for the Pierre Auger Collaboration**[2]

[1]KIT - Karlsruhe Institute of Technology, Germany
[2]Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina

Received: 6 September 2010 – Revised: 13 October 2010 – Accepted: 15 October 2010 – Published: 3 November 2010

Abstract. The southern part of the Pierre Auger Observatory in Argentina investigates cosmic rays with energies above about $5\cdot10^{17}$ eV. High-energy events which have been recorded with both detector components, surface water Cherenkov tanks and fluorescence telescopes, are crucial for the energy calibration of the entire detector system. Using this method, the energy reconstruction of extensive air showers relies on a proper fluorescence light reconstruction which depends on the knowledge of atmospheric conditions like pressure, temperature and water vapour. These properties of the atmosphere vary with altitude and in time. Therefore, a dedicated monitoring programme has operated since March 2009 to measure an actual atmospheric profile with meteorological radio soundings shortly after the detection of a high-energy air shower with $E_0 > 2\cdot10^{19}$ eV.

We will present the technical implementation of this programme as well as a reconstruction analysis using the data obtained. The reconstructed primary energy of air showers and the position of the shower maximum are compared with those results using either monthly models for the local atmospheric conditions or global meteorological models.

1 Introduction

The Pierre Auger Observatory investigates high-energy cosmic rays applying two complementary types of detector technique (Abraham, J. et al., 2004). The secondary particles of extensive air showers initiated by cosmic rays are sampled with an array of about 1660 water Cherenkov tanks when reaching ground. The fluorescence detector (FD) consists of 27 fluorescence telescopes arranged in 4 main fluorescence stations with 6 telescopes each and one enhancement station with 3 telescopes particularly for the detection of lower-energy events down to about 10^{17} eV. The Cherenkov tanks have a duty cycle of almost 100%, while the FD can be operated only during the nights about 1 week before and after new moon, resulting in about 13% observation time (Abraham, J. et al., 2010a). The energy reconstruction of air showers is almost model-independent using the fluorescence technique. Thus, the Auger Observatory uses its hybrid events, those which are observed by both detector components, to calibrate the large amount of air shower data which are obtained only with the tanks (Abraham, J. et al., 2009). However, an accurate reconstruction of air showers observed by fluorescence telescopes requires a sophisticated monitoring system to cope with unpredictable changes of atmospheric conditions (Abraham, J. et al., 2010b). The atmospheric monitoring programme at the southern Auger Observatory, located near Malargüe, Argentina, is designed to characterise atmospheric properties on fixed timescales. During FD shifts, aerosol conditions are recorded with hourly resolution using the Central Laser Facility (CLF), lidar stations, aerosol phase function (APF) monitors, and the Horizontal Attenuation Monitor (HAM) and ph(F)otometric Robotic Atmospheric Monitor (FRAM) telescopes (Valore, L. et al., 2009). Molecular scattering is calculated using atmospheric profiles from intermittent weather balloon flights and deduced monthly models (Abraham, J. et al., 2010b; Keilhauer, B. et al., 2005). Since March 2009, the system has been upgraded for a rapid monitoring programme to allow for triggering of instruments shortly after the detection of high-energy events and other showers of interest. During FD shifts, shower data are reconstructed by an automated online analysis. Showers that meet certain criteria are used to trigger dedicated measurements by the weather balloon, lidar, and FRAM subsystems.

2 Performance of the BtS programme

Using atmospheric profiles from monthly site models instead of data from meteorological radiosondes for the reconstruc-

Correspondence to: B. Keilhauer
(bianca.keilhauer@kit.edu)

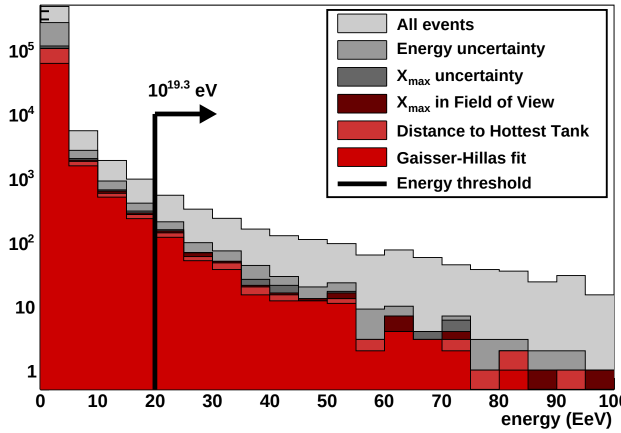

Fig. 1. Estimate of possible events for BtS based on all hybrid events collected between 2006 and 2009. The remaining events due to quality cuts and the energy threshold are shown.

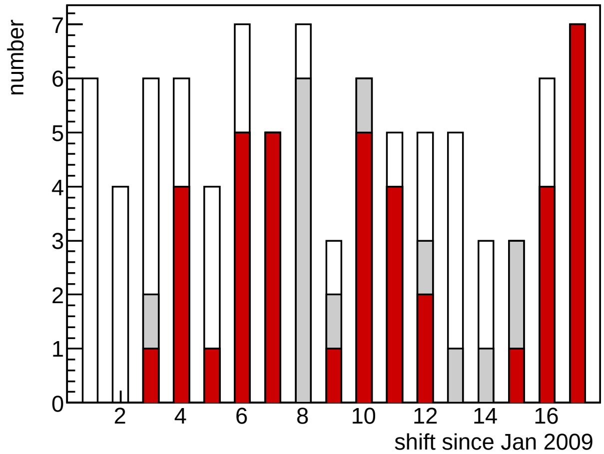

Fig. 2. Expected BtS triggers for the 17 FD shifts between 01/2009 and 05/2010 (white bars). In grey, the number of generated text messages is shown only for those expected events from 2009/2010. Shown in red is the number of events that were covered by a weather balloon launch. No visible white bar means that every interesting event was caught. No visible gray bar means that there was a launch for every text message.

tion of air showers affects the resolution of the reconstruction. Monthly site models worsen the accuracy in general and in particular for high-energy events. Overall, the monthly models contribute with $1.5-3\%$ to the energy resolution between $10^{17.7}$ eV and 10^{20} eV, and $7.2-8.4\,\mathrm{g\,cm^{-2}}$ to the $X_{\max}$ resolution of the hybrid reconstruction (Keilhauer, B. et al., 2009; Keilhauer, B. and Unger, M., 2009). However, the fluctuations can be up to 5% and $15\,\mathrm{g\,cm^{-2}}$, respectively. To reduce these uncertainties, the Balloon-the-Shower (BtS) programme was initiated to perform an atmospheric sounding within about three hours of the detection of a high-energy air shower.

2.1 Quality cuts

The BtS programme replaces regularly scheduled meteorological radio soundings. After an automated online reconstruction of incoming air showers, a script inspects every 15 min a set of reconstruction parameters. Only events passing dedicated cuts are selected and initiate a launch of a weather balloon. First of all, only events above an energy threshold of $E_{\min} \approx 2 \cdot 10^{19}$ eV are extracted. Further cuts assure that only those air showers are selected which are observed and reconstructed with high quality. These are a relative uncertainty of energy $\sigma_E/E < 0.2$, an uncertainty of the position of shower maximum $\sigma_{X_{\max}} < 40\,\mathrm{g\,cm^{-2}}$, the shower maximum has to be well inside the observed shower track and the Gaisser-Hillas fit to the shower profile has to meet certain criteria. The selected events trigger automatically a text message (SMS) which is sent to an on-site technician who performs a launch of a weather balloon. In Fig. 1, the performance of the quality cuts is shown for hybrid data collected between 2006 and 2009. The events that would have been selected for BtS are indicated by the red area above the energy threshold.

2.2 Statistics

In Fig. 2, the statistics of hybrid events recorded between January 2009 and May 2010 which passed the quality and energy cuts can be seen. The shown events were reconstructed using the Offline Software Framework (Argiro, S. et al., 2007). Also the number of generated text messages that were sent after one of these events are shown. Only messages corresponding to one of the shown events are displayed. Note that the plot does not show all of the SMS notifications actually sent, because some of the events which passed the cuts during the online reconstruction do not pass when reconstructed offline. This is due to minor differences between the two versions of reconstruction. Furthermore, the number of events that either triggered an actual balloon launch or occurred while the data from a previous launch was still valid are displayed in Fig. 2.

Between March 2009 and May 2010, we performed 39 successful launches covering 51 selected air showers. The data from those atmospheric profiles can be used to reconstruct 69 FD profiles which passed all quality cuts.

3 Global Data Assimilation System (GDAS)

The Global Data Assimilation System is an atmospheric model developed at NOAA's[1] National Centers for Environmental Prediction (NCEP)[2] (M. Kanamitsu, 1989). An atmospheric model is a mathematical model that describes the

[1]National Oceanic and Atmospheric Administration
[2]Formerly known as National Meteorological Center (NMC)

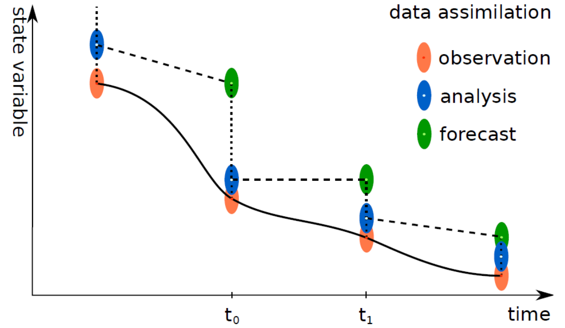

Fig. 3. Schematic principle of data assimilation: continuous line = real time course of a state variable; dotted line = analysis step; dashed line = forecast step (Epperlein, D., 2010), adapted from (Wergen, W., 2002).

atmospheric state at a given time and position. In meteorology and climatology, these models are used for decades and continually improved to estimate the current state of the system and form the basis of any weather forecast. Most atmospheric models apply a method called data assimilation (Wergen, W., 2002). It combines observations with results from a numerical weather prediction model. A schematic principle can be seen in Fig. 3. The numerical weather prediction model which is used in the GDAS as forecast is the Global Forecast System (GFS). The NCEP runs a series of computer jobs in regularly scheduled sequences where the last run, called the "final" analysis (FNL), is identical to the GDAS data as referred to in the next sections. The FNL uses all observation data including the latest arriving and delayed data to assimilate the best possible global analysis.

At NOAA's Air Resources Laboratory (ARL), meteorological GDAS data are archived and publicly available since 1997 every 6 hours, and since December 2004 every 3 hours (NOAA archive). The newer data provide atmospheric profiles for height, temperature, and humidity at 23 fixed pressure levels between 1000 and 20 hPa.

A detailed comparison of atmospheric profiles from radio soundings at the southern site of the Pierre Auger Observatory with corresponding profiles obtained from GDAS reveals a good description of the local atmospheric conditions for the site of the Auger Observatory by GDAS data.

4 Event reconstruction

In the following, we present a study of air shower reconstruction using the atmospheric conditions obtained by the BtS programme in the first case and using GDAS atmospheres in the second case. For both cases, a full weather-dependent fluorescence calculation (Arqueros, F. et al., 2008; Keilhauer, B. and Unger, M., 2009) based on AIRFLY data (Ave, M. et al., 2008) is used. The energy distribution of these events is presented in Fig. 4. We have investigated the effect of using

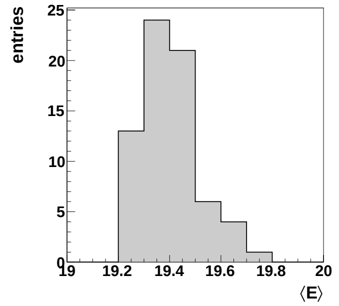

Fig. 4. Energy distribution of all 51 high-energy events which passed the BtS cuts, reconstructed with actual atmospheric profiles from the BtS programme.

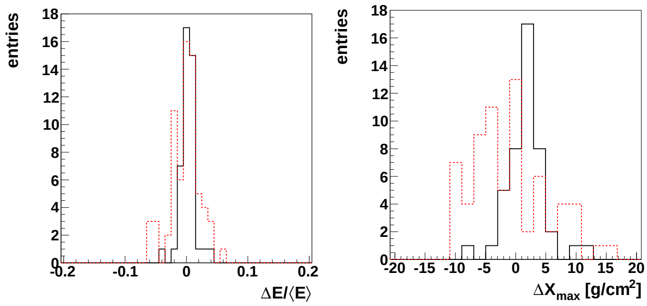

Fig. 5. Difference between reconstructed events using monthly site models and using BtS atmospheric profiles in red together with reconstructions using GDAS compared with using BtS atmospheric conditions in black. Left: Energy; black histogram - Mean 0.3%, RMS 1.2%, red histogram - Mean -0.2%, RMS 2.4%. Right: Position of shower maximum; black - Mean 1.7 $\mathrm{g\,cm^{-2}}$, RMS 3.2 $\mathrm{g\,cm^{-2}}$, red - Mean -0.8 $\mathrm{g\,cm^{-2}}$, RMS 6.1 $\mathrm{g\,cm^{-2}}$.

different atmospheric profiles in the offline reconstruction, in particular with regard to changes in the reconstructed energy E and the position of shower maximum X_{max}. The differences between reconstructions using monthly site models and using BtS atmospheric profiles together with the difference between reconstructions using GDAS profiles and using BtS profiles are displayed in Fig. 5, left for E and right for X_{max}.

The agreement in energy reconstruction is very good. Only some air showers are mis-reconstructed by about 7% at most. The small X_{max} offset with GDAS is due to a small offset in pressure values compared with BtS atmospheres. However for X_{max}, individual air showers are mis-reconstructed by up to 17 $\mathrm{g\,cm^{-2}}$. The broader distribution with monthly site models can be explained by the intrinsic width of these models trying to cover all conditions within a full calendar month.

Furthermore, some systematics are studied. The reconstruction differences for E and X_{max} are investigated with respect to primary energy, vertical position of shower maximum and seasonal effects. For the former two, no dependences were found. The seasonal effects are shown in Fig. 6. The reconstructed energy does not reveal any seasonal effects. Only a small dependence for the X_{max} reconstruction can be seen while using monthly site models compared with

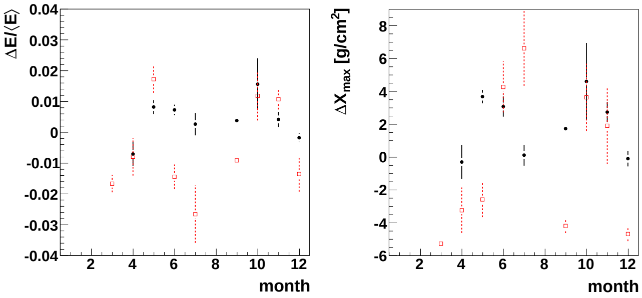

Fig. 6. Reconstruction differences for E (left) and X_{max} (right) in dependence on calendar month to check for seasonal effects. Colours are as in Fig. 5. Further details are described in the text.

BtS profiles, red squares in right part of Fig. 6. The dependence becomes more evident ignoring September results, this bin just contains two entries. It appears that during austral winter, the use of monthly site models leads to a systematically smaller reconstructed X_{max} when compared to the use of BtS profiles. While the statistics are admittedly small, this might be a real effect due to differences in vapour pressure profiles between sounding data and monthly models.

5 Conclusions

The BtS programme of the southern Pierre Auger Observatory runs very successfully since March 2009. Actual atmospheric conditions can be obtained shortly after the detection of high-quality, energetic air showers observed in hybrid mode. In parallel, global atmospheric models are tested and the GDAS represents a suitable source of very frequent, well-fitting atmospheric descriptions for the Auger Observatory. Within the next months, it will be investigated to replace local radio soundings entirely by applying GDAS data in air shower reconstruction.

Acknowledgements. The successful installation and commissioning of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe.

We are very grateful to the following agencies and organizations for financial support which are listed at http://www.auger.org/contact/agencies.html.

Edited by: H. Fichtner
Reviewed by: two anonymous referees

References

Abraham, J. et al. (Pierre Auger Collab.): Properties and performance of the prototype instrument for the Pierre Auger Observatory, Nucl. Instr. Meth., A 523, 50–95, 2004.

Abraham, J. et al. (Pierre Auger Collab.): The Cosmic Ray Energy Spectrum and Related Measurements with the Pierre Auger Observatory, in: Proc. 31st ICRC, Lodz, Poland, arXiv:0906.2189[astro-ph], 2009.

Abraham, J. et al. (Pierre Auger Collab.): The fluorescence detector of the Pierre Auger Observatory, Nucl. Instr. Meth., A 620, 227–251, 2010a.

Abraham, J. et al. (Pierre Auger Collab.): A study of the effect of molecular and aerosol conditions in the atmosphere on air fluorescence measurements at the Pierre Auger Observatory, Astropart. Phys., 33, 108–129, 2010b.

Argiro, S. et al.: The offline software framework of the Pierre Auger Observatory, Nucl. Instr. Meth., A 580, 1485–1496, 2007.

Arqueros, F., Hörandel, J., and Keilhauer, B.: Air fluorescence relevant for cosmic-ray detection - Summary of the 5th fluorescence workshop, El Escorial 2007, Nucl. Instr. Meth., A 597, 1–22, 2008.

Ave, M. et al. (AIRFLY Collab.): Temperature and humidity dependence of air fluorescence yield measured by AIRFLY, Nucl. Instr. Meth. A 597, 50–54, 2008.

Epperlein, D.: Untersuchung der Anwendbarkeit eines globalen Atmospherärenmodells für das südliche Pierre-Auger-Observatorium, Diplomarbeit, KIT Karlsruher Institut für Technologie, 2010.

Kanamitsu, M.: Description of the NMC Global Data Assimilation and Forecast System, Weather and Forecasting, 4, 335–342, 1989.

Keilhauer, B. for the Pierre Auger Collab.: Atmospheric Profiles at the Southern Pierre Auger Observatory and their Relevance to Air Shower Measurement, in: Proc. 29th ICRC, Pune, India, 7, 123–126, arXiv:astro-ph/0507275, 2005.

Keilhauer, B. for the Pierre Auger Collab.: Rapid Atmospheric Monitoring After the Detection of High-Energy Showers at the Pierre Auger Observatory, in: Proc. 31st ICRC, Lodz, Poland, arXiv:0906.2358[astro-ph], 2009.

Keilhauer, B. and Unger, M.: Fluorescence emission induced by extensive air showers in dependence on atmospheric conditions, in: Proc. 31st ICRC, Lodz, Poland, arXiv:0906.5487[astro-ph], 2009.

NOAA archive: READY - Real-time Environmental Applications and Display sYstem, http://ready.arl.noaa.gov.

Valore, L. for the Pierre Auger Collab.: Atmospheric Aerosol Measurements at the Pierre Auger Observatory, in: Proc. 31st ICRC, Lodz, Poland, arXiv:0906.2358[astro-ph], 2009.

Wergen, W.: Datenassimilation – ein Überblick, Deutscher Wetterdienst DWD, promet 27, No. 3/4, 142–149, 2002.

Addendum

A full author list of the Pierre Auger Collaboration as of August 2010 is available at: http://www.auger.org/archive/authors_2010_08.html.