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Abstract

The Pierre Auger Observatory has led to significant advances in our understanding of ultra- high-energy cosmic rays. These new insights have driven a major upgrade of the Observatory, known as AugerPrime, through which the experiment has entered its Phase II, a new period of data collection. A key part of the upgrade is adding surface scintillator detectors (SSD) on top of the existing water-Cherenkov detectors (WCD). The main goal is to leverage their different responses to the electromagnetic and muonic shower components, enhancing the reconstruction of the primary cosmic-ray mass. In this contribution, we present the methods that involve analyzing peak and charge distributions of atmospheric muons for accurate calibration during extensive air-shower event reconstruction, along with the development of a rate-based algorithm for independent calibration. We also show the performance of the SSDs with Phase-II data, including PMT reliability and stability of key parameters, such as gain and signal-to-noise ratio.

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Calibration and Performance of the Surface Scintillator Detector of the Pierre Auger Observatory

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The Pierre Auger Observatory has led to significant advances in our understanding of ultra-high-energy cosmic rays. These new insights have driven a major upgrade of the Observatory, known as AugerPrime, through which the experiment has entered its Phase II, a new period of data collection. A key part of the upgrade is adding surface scintillator detectors (SSD) on top of the existing water-Cherenkov detectors (WCD). The main goal is to leverage their different responses to the electromagnetic and muonic shower components, enhancing the reconstruction of the primary cosmic-ray mass. In this contribution, we present the methods that involve analyzing peak and charge distributions of atmospheric muons for accurate calibration during extensive air-shower event reconstruction, along with the development of a rate-based algorithm for independent calibration. We also show the performance of the SSDs with Phase-II data, including PMT reliability and stability of key parameters, such as gain and signal-to-noise ratio.

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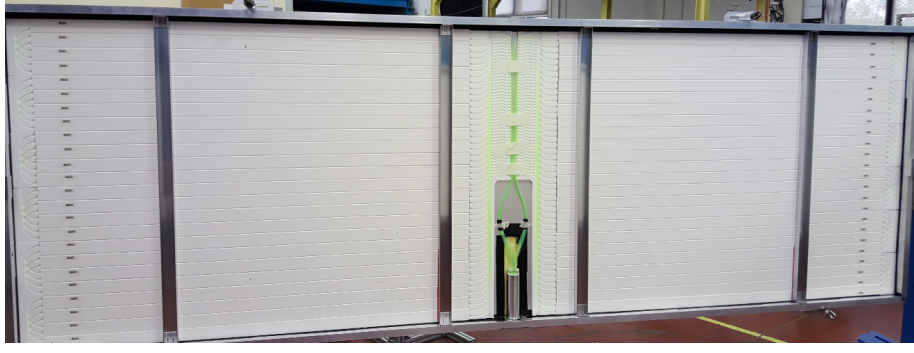


Figure 1: Photograph of an open SSD at the construction phase.

1. Introduction

The Pierre Auger Observatory, located in Malargüe, Argentina, is the world’s largest cosmic ray detector, combining a surface array of over 1600 Water-Cherenkov Detectors (WCDs) with 27 fluorescence telescopes. Its hybrid design enables precise measurements of extensive air showers from ultra-high-energy cosmic rays (UHECRs). Over the years, the Observatory has produced key results on the energy spectrum, anisotropy, and mass composition of cosmic rays.

To enhance its capabilities, the Observatory has undergone a major upgrade – AugerPrime – which includes the addition of Surface Scintillator Detectors (SSDs) above each WCD. These detectors improve the separation of electromagnetic and muonic components, enhancing mass composition studies. In this contribution, we present the SSD calibration methods based on atmospheric muons, including a novel rate-based algorithm, and evaluate the detector performance using Phase-II data.

2. The Surface Scintillator Detector

The SSD module consists of two scintillator panels composed of plastic scintillator bars, encased in an aluminium box, with a photomultiplier (PMT) housed between the panels. The total active area of the scintillators in a module is 3.84 m^2 . The active part of each of the scintillator panels is composed of 24 scintillator elements (bars) of 1.6 m length, 5 cm width, and 1 cm thickness. Each bar houses two horizontal holes through which wavelength-shifting (WLS) fibers are guided. The fibers are bundled and glued with optical cement in a PMMA (poly(methyl methacrylate)) cylinder, a so-called “cookie” whose front window is connected to the PMT, a bi-alkali Hamamatsu R9420, 1.5-inch diameter, with 18% quantum efficiency at a wavelength of 500 nm [1]. The picture of open SSD assembled in the laboratory is shown in Fig. 1.

The PMT is connected to the acquisition electronics, with the anode read out by a 12-bit FADC operating at 120 MHz. This results in a time binning of approximately 8.33 ns. To interpret the digital readings from the FADCs, it is necessary to define a unit that characterizes the energy deposited by minimum-ionizing particles (MIP). This approach is analogous to the one already adopted for the WCD, where signals are expressed in terms of the equivalent charge produced by vertical-centered through-going muon referred to as VEM (vertical-equivalent muon).

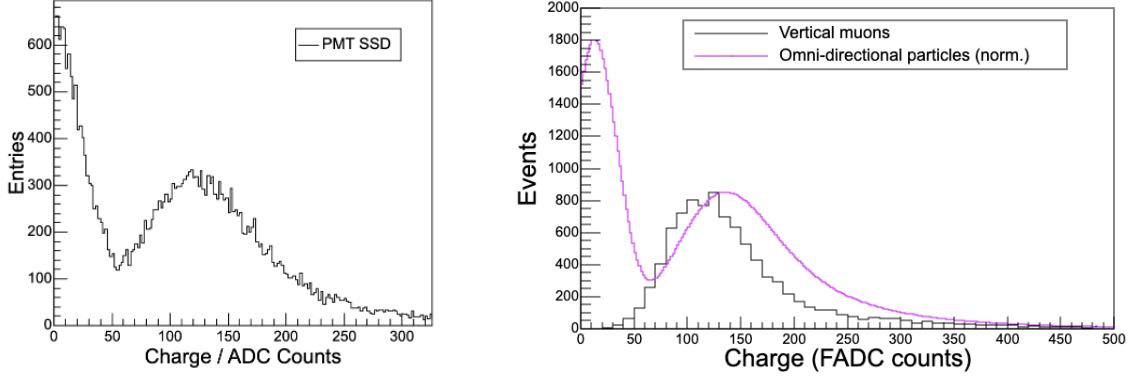


Figure 2: *Left:* Example of calibration histograms for the PMT of one scintillator. *Right:* Estimation of the correction factor from omnidirectional to vertical muon distribution.

The 3 WCD and the SSD PMTs signals are divided into four high-gain and four low-gain signals, respectively. The gain ratio is set by the electronics design to 128 for the SSD channel and to 32 for the WCD PMTs [2]. This configuration extends the dynamic range above 20 000 MIP, in line with the increased dynamic range of the WCD achieved through the addition of the small PMT (see section 4.4).

3. Calibration methods

3.1 Histogram Based Calibration

Calibration of MIP and VEM in ADC counts is based on atmospheric muons, which are abundant and energetic. For the WCD, where vertical muons cannot be isolated, charge spectra from muons arriving at all angles are continuously collected as calibration histograms.

A similar method is used for the SSD, selecting only events where a WCD PMT detects a muon-like signal, improving sample purity by exploiting the distinct response of WCD to muons and electromagnetic particles. Histograms are recorded every 61 seconds and used to estimate calibration units. An example of charge calibration histogram for the SSD is shown in the left plot of Fig. 2.

Since inclined particles deposit more energy in the SSD, a correction factor – derived from simulations and a dedicated setup using RPCs to select vertical muons – is applied to convert omnidirectional (OD) MIP values to vertical equivalents (VE), see right plot in Fig. 2. The correction factor estimated with the latter method is

$$Q_{\text{OD}}^{\text{peak}} / Q_{\text{VE}}^{\text{peak}} = 1.19 \pm 0.07, \quad (1)$$

where the quoted uncertainty of 6% is a conservative estimate, obtained by adding in quadrature the contributions from PMT instability (4%) and bar-to-bar light-yield variability (5%). Further details on the experimental setup are available in Ref. [3].

3.2 Rate Based Calibration. An online estimation of the MIP Peak.

The offline calibration of the SSD detector follows the same model used for the calibration of the PMTs in the WCD, both in terms of the charge distribution (MIP Charge or Q_{SSD}) and the

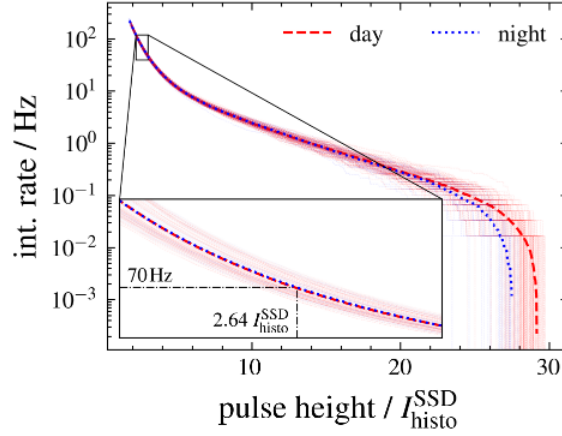


Figure 3: Integral rate of events with a peak height $\geq I_{\text{SSD}}$. The rate remains stable across day/night cycles and different local station hardware. A trigger rate of 70 Hz is achieved for a threshold of $T_{70} = 2.64 I_{\text{SSD}}$.

signal peak (MIP Peak or I_{SSD}). While the WCD employs an online procedure primarily to set the detector trigger thresholds, a similar approach is not used for the scintillator. This is due to hardware limitations at the local station level and because the scintillator operates in slave mode. However, implementing an online estimate would enable real-time monitoring of the detector performance.

To this end, a rate-based model has been developed. The method employs a single-bin threshold trigger with a variable threshold T_{70} , measured in ADC counts. The number of events n in the SSD that satisfy this trigger condition is counted over an integration window t_{cal} . After each t_{cal} interval, the threshold is adjusted by a value δ , following the steps described in details in Ref. [4]. Assuming constant electronic gain, this algorithm guarantees a stable estimate of T_{70} . To relate T_{70} to the MIP peak I_{MIP} , peak histograms are collected under the condition of a coincident signal in the WCD. The pulse height spectrum I in the SSD is measured for various stations and times of day. Using knowledge from these coincidence histograms, the pulse height spectrum is expressed in units of $I_{\text{SSD}}^{\text{histo}}$, and the integral event rate is calculated for thresholds of 1, 2, etc., times $I_{\text{SSD}}^{\text{histo}}$.

This analysis, carried out across all stations and different times of day, reveals no significant dependence on hardware or temperature. The resulting average rate-threshold relationship is shown in Fig. 3. Notably, a 70 Hz trigger rate can be achieved by applying a fixed threshold (in units of I_{MIP}), leading to the rate-based estimator of the MIP peak $I_{\text{SSD}}^{\text{rate}} = 2.64 T_{70}$. It is worth noting that the 70Hz rate is currently used as a test value; further studies are ongoing to determine the optimal trigger rate for implementing an online estimator of the MIP peak.

4. Performance

The Surface Scintillator Detector (SSD), part of the AugerPrime upgrade, was fully installed in 2023, with over 1400 units deployed and operational. This marked a transition phase in the data acquisition of Pierre Auger Observatory, aimed at integrating the new instruments introduced by the upgrade. Known as Phase II, this period includes all data collected with the SSDs since their deployment. This section evaluates the SSD stability based on operational parameters and early data.

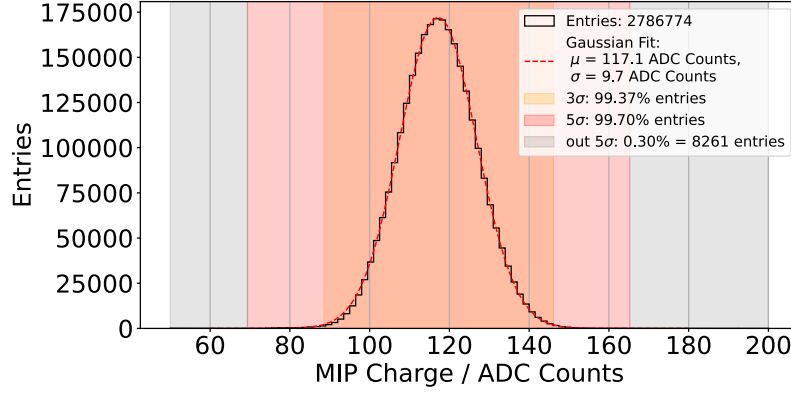


Figure 4: MIP charge distribution for SSD signals collected in Phase-II data.

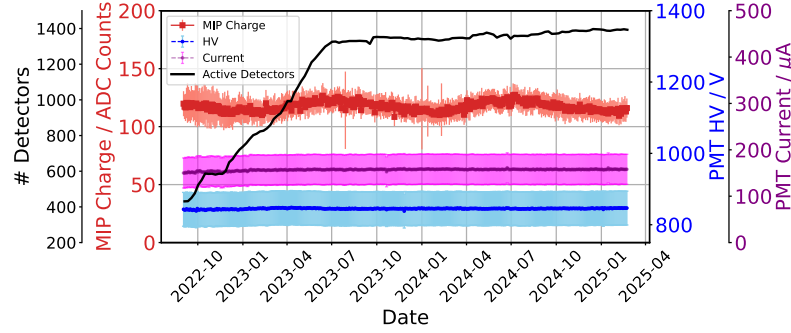


Figure 5: Monitoring data for HV and current for the SSD. The averages among all the detectors are showed with relative standard deviation. In red the average daily MIP charge distribution.

4.1 MIP Charge Distribution

The stability of the large number of detectors deployed in the field is essential to ensure a uniform response of the SSD array. The calibration analysis performed over the first years of data shows that the distribution of the MIP charge is well described by a Gaussian, with mean and standard deviation as shown in Fig. 4. Among all calibrated signals associated with events reconstructed by the surface detector, only 0.30% fall outside a 5σ interval from this distribution. These outliers are mainly attributed to a small subset of detectors that, for limited periods of time, operated under conditions different from the expected working point. In most cases, these deviations are associated with PMTs biased by high voltage values lying outside the typical range of 760 to 980 V.

In addition to the calibration performance, the monitoring system allows us to evaluate the long-term stability of the detector in terms of high voltage and current, as shown in Fig. 5 [5]. While the MIP charge exhibits seasonal variations – discussed in the following sections – the detector demonstrates excellent stability in terms of operating point for the active and functioning units. The plot also shows the number of detectors that were active over time, highlighting the progressive development of the array towards its full data-taking capacity in Phase II.

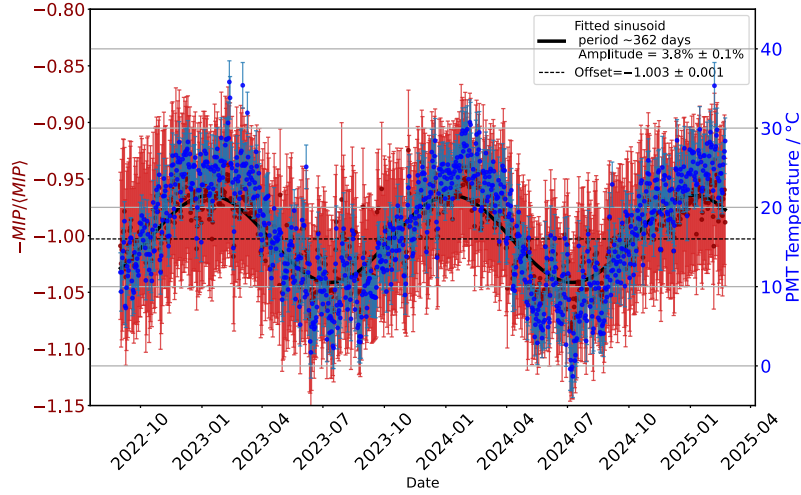


Figure 6: Seasonal variation of the relative MIP charge (red) and the average PMT temperature (blue).

4.2 Seasonal effects

The charge distribution of the photomultiplier is affected by temperature, with more stable operation observed at lower temperatures compared to higher ones. In colder conditions, the signal-to-noise ratio improves, the gain is enhanced, and the MIP charge tends to increase relative to the average level. This effect, already visible in Fig. 5, is further highlighted in Fig. 6, where a clear anti-correlation with the average PMT temperature is observed. To study the behavior of all detectors in the array over time, the MIP charge is normalized as follows:

- A dimensionless normalized MIP charge (mip) is calculated for the k^{th} detector ($k = 1, \dots, N_{\text{SSD}}$) over the full dataset as

$$mip_i^k = \left(\frac{MIP_i^k}{\text{ADC Counts}} \right) \left/ \left(\frac{1}{N} \sum_{j=1}^N \frac{MIP_j^k}{\text{ADC Counts}} \right) \right. \quad (2)$$

- A daily, array-level relative MIP charge is then defined to track collective variations,

$$\frac{MIP}{\langle MIP \rangle}(\text{day}) \equiv \frac{1}{\sum_{k=1}^{N_{\text{SSD}}} N_{\text{entries}}^k(\text{day})} \sum_{k=1}^{N_{\text{SSD}}} \sum_{i=1}^{N_{\text{entries}}^k(\text{day})} mip_i^k \quad (3)$$

The plot in Fig. 6 shows the evolution of the quantity defined in Eq. (3), inverted in sign to display the oscillation in phase with the temperature. The dominant oscillation period is found to be approximately 362 days, with an amplitude stable within about 4% on average. The uncertainty is computed as the standard deviation of the $MIP/\langle MIP \rangle$ distribution, and accounts for detector-to-detector fluctuations as well as daily thermal variations, which will be discussed in the next section.

4.3 Daily temperature correlation

Following the same approach used for the seasonal analysis of the MIP charge fluctuations over time and its correlation with the daily average PMT temperature in the scintillator detectors,

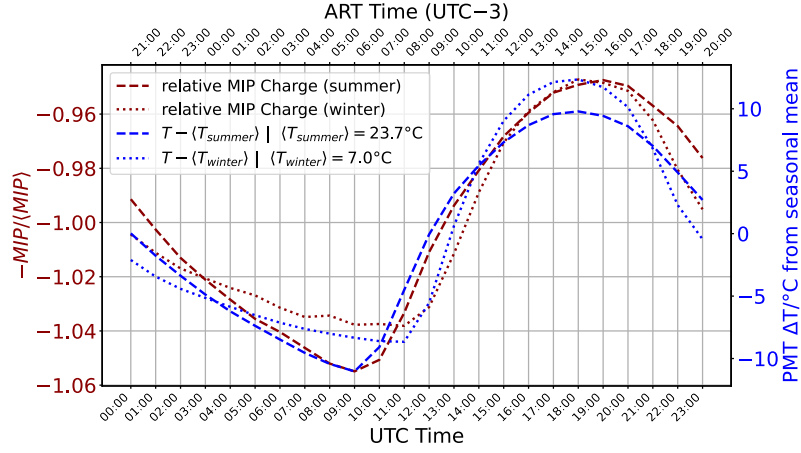


Figure 7: Daily variation of the MIP charge (red) and the average PMT temperature (blue), for two different periods: summer (dashed) and winter (dotted). The two horizontal axes display the time in UTC and local Argentinian time, respectively.

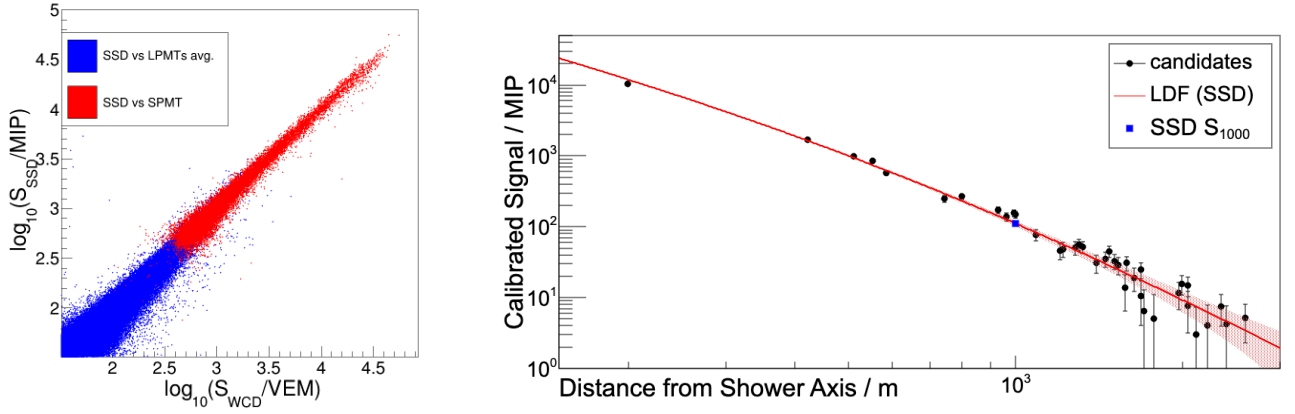


Figure 8: *Left:* Dynamic range. *Right:* Lateral Distribution Function fit of an SD event using the SSD signals.

this section investigates daily thermal effects by analyzing variations over the course of a day. Two periods were selected: summer (2024-12-01 to 2025-02-01) and winter (2024-07-01 to 2024-09-01). The same quantity defined in Eq. (3) is now computed hourly instead of daily.

Fig. 7 shows its evolution, plotted with inverted sign to highlight the anti-correlation with PMT temperature. The left vertical axis indicates the average PMT temperature, expressed as deviation from the seasonal mean ($\langle T_{\text{summer}} \rangle = 23.7^\circ\text{C}$ and $\langle T_{\text{winter}} \rangle = 7.0^\circ\text{C}$), to align the curves. Dashed and dotted lines represent summer and winter data, respectively.

A MIP charge variation of up to 6% is observed, with a peak-to-peak difference of $\sim 10\%$, more pronounced in summer. This suggests greater calibration stability during colder months, when PMTs operate at lower temperatures.

4.4 Dynamic range and SSD Reconstruction

The upgrade of the surface detector stations has significantly extended the dynamic range, enhancing the ability to accurately measure signals near the shower core and reducing signal saturation. This issue was especially common in high-energy showers, where the three large PMTs (LPMTs) in the water-Cherenkov detectors often saturated.

To mitigate this, a small PMT (SPMT) was added at the center of each tank, expanding the dynamic range [6]. The scintillator detectors were similarly designed to match the SPMT range. As shown in the left panel of Fig. 8, the Phase-II configuration can handle signals up to several tens of thousands of VEM/MIP before saturation, compared to just a few thousand with LPMTs alone.

Finally, the right panel of Fig. 8 shows an event reconstructed using SSD signals. Station responses are plotted as a function of distance from the shower axis, based on the geometry from standard WCD reconstruction. The reconstructed event has a primary energy of $E = (49.4 \pm 1.6) \text{ EeV}$ and a zenith angle of $\theta = (51.73 \pm 0.04)^\circ$. The data are fitted with a modified NKG function, defined as

$$S(r) = S(r_{\text{opt}}) \left(\frac{r}{r_{\text{opt}}} \right)^\beta \left(\frac{r + r_s}{r_{\text{opt}} + r_s} \right)^{\beta+\gamma}. \quad (4)$$

Since the SSDs are co-located with the WCDs, the same parameters were chosen: $r_{\text{opt}} = 1000 \text{ m}$ and $r_s = 700 \text{ m}$, while the parametrization of the shape parameters β and γ in terms of the shower size and zenith angle is described in Ref. [7]. As in the case of the WCD, the SSD-based reconstruction allows for the determination of a shower size parameter, S_{1000} , defined as the signal at 1000 meters from the shower core, obtained from the fit.

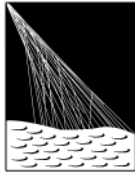
5. Conclusions

The installation of over 1400 SSDs as part of the AugerPrime upgrade has significantly enhanced the capabilities of Pierre Auger Observatory. We presented calibration methods based on atmospheric muons, including a rate-based approach for real-time monitoring. Performance studies show stable operation across the array, with MIP charge variations well correlated with temperature. The extended dynamic range enables accurate signal reconstruction even near the shower core. These results confirm the SSD reliability and its key role in improving mass composition analyses in Phase-II data.

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