PROCEEDINGS OF SCIENCE

A Novel Tool for the Absolute End-to-End Calibration of Fluorescence Telescopes – The XY-Scanner

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The Pierre Auger Observatory uses 27 large-aperture wide-angle Schmidt telescopes to measure the longitudinal profile of air showers using the air-fluorescence technique. Up to the year 2013, the absolute calibration of the telescopes was performed by mounting a uniform large-diameter light source on each of the telescopes and illuminating the entire aperture with a known photon flux. Due to the high amount of work and person-power required, this procedure was only carried out roughly once every three years, and a relative calibration was performed every night to track short-term changes. Since 2013, only the relative calibration has been performed. In this paper, we present a novel tool for the absolute end-to-end calibration of the fluorescence detectors, the XY-Scanner. The XY-Scanner uses a portable integrating sphere as a light source, which has been absolutely calibrated. This light source is installed onto a motorized rail system and moved across the aperture of each telescope. We mimic the illumination of the entire aperture by flashing the light source at ~1700 positions evenly distributed across the telescope aperture. For the absolute calibration of the light source, we built a dedicated setup that uses a NIST-calibrated photodiode to measure the average photon flux and a PMT to track the pulse-to-pulse stability. We present the laboratory setups used to study the characteristics of the employed light sources and discuss the inter-calibration between selected telescopes.

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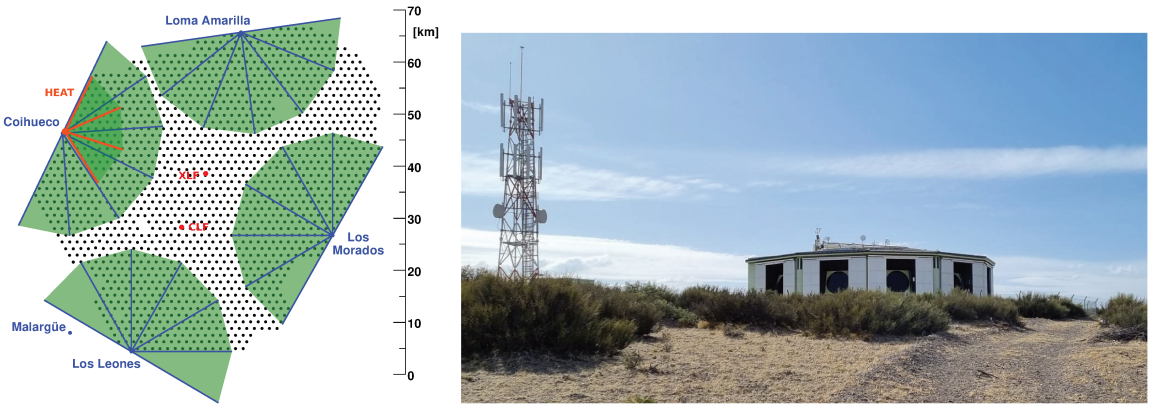

Figure 1: *Left:* Illustration of the Pierre Auger Observatory. Black dots represent SD stations. The field-of-view of the 27 FD telescopes are marked in green. *Right:* Photograph of the Coihueco FD building hosting six telescopes. Communication tower is visible in the left.

1. Introduction

The Pierre Auger Observatory [1] is constructed as a hybrid cosmic-ray observatory combining a surface-detector array (SD) with a system of air-fluorescence telescopes (FD) [2]. The SD employs 1660 self-sufficient water-Cherenkov detector stations distributed across an area of ~3000 km^2. Each black dot on the left side of Fig. 1 represents one SD station. On the edge of the SD array 27 large-aperture fluorescence telescopes are installed on four different sites. These telescopes build the FD. The edges of the field of views of the individual telescopes are marked by the blue lines in the illustration on the left side of Fig. 1. While the SD samples particle reaching the ground, we use the FD to observe the fluorescence light emitted by nitrogen above the array, induced by traversing charged shower particles. We analyze the FD observations to reconstruct the longitudinal shower profile and estimate the energy of the primary cosmic-ray particle as the integral of the profile. Due to the rather low duty cycle of the FD, we use the correlation between the FD energy and a shower-size parameter measured by the SD to perform an energy calibration of the SD. For an accurate energy calibration of the Pierre Auger Observatory, it is therefore mandatory to know the exact conversion between a captured signal in the FD telescope camera and the flux of incident photons.

Up to the year 2013, we performed the absolute end-to-end calibration of the FD telescopes with a uniform large-diameter light source, the so-called *drum* [3, 4]. Since this method of calibration is very demanding in person-power and time required to perform measurements, such measurements were discontinued in 2013. Since then we rely on a nightly relative calibration of the telescope cameras.

2. XY-Scanner

We developed a novel tool to absolutely calibrate the fluorescence telescopes of the Pierre Auger Observatory – the *XY-Scanner*. The XY-Scanner employs a portable and absolutely calibrated light source, which we mount onto a motorized rail system. As light sources we use modified general-purpose integrating spheres (Ulbricht spheres), which are equipped with an LED emitting at a

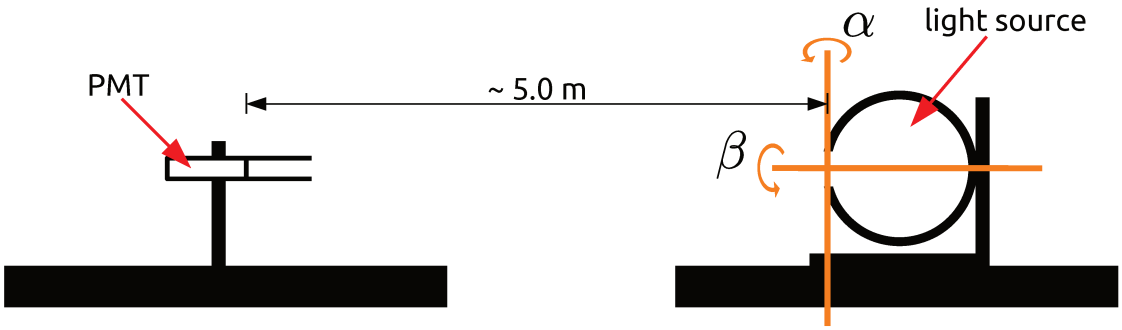

Figure 2: Schematics of the laboratory setup to characterize the angular emission of the light sources.

wavelength of 365 nm. Due to internal reflections within the integrating sphere, its exit port appears as a Lambertian source.

A summary of the XY-Scanner setup and the measuring procedure was presented at the last ICRC in 2021 [5] and a detailed description of the system is given in Ref. [6]. We give here only a very brief description of the system.

The rail system consists of two vertical linear stages, which are permanently installed onto the aperture of each FD telescope. With some delay due to the global pandemic, we completed equipping all 27 telescopes of the observatory with such rail systems in spring 2023. A horizontal axis is only mounted for XY-Scanner measurements and otherwise stored inside the telescope building. For calibration measurements, we drive the light source to ~1700 evenly distributed positions on the scanner. At each position, the light source emits a short light pulse and we capture the total signal collected in the telescope camera. Depending on the distance between light source positions (step size), the total number of positions and thus the total actually illuminated area varies. Since the readout of the entire FD camera takes slightly longer than ~1 s, we made a compromise between the illuminated area and the required measuring time. We decided on a step size of 6 cm, which results in a measuring time of less than ~45 min per telescope, while still ~65% of the telescope aperture is actually illuminated.

We then combine (a) the total signal collected by the telescope for all positions of the light source, (b) corrections we obtain from ray-traced simulations of the light source and telescope, and (c) detailed studies of the light source emission characteristics to estimate an absolute end-to-end calibration constant for each pixel-PMT of the telescope camera. Combining all contributing uncertainties we are able to reach a total uncertainty of less than 4.5% on the absolute calibration estimated from XY-Scanner measurements.

3. Angular Emission Characteristics of Light Sources

We developed a laboratory setup to estimate the angular emission characteristics of the calibration light sources. For this setup, the light source is mounted onto a combination of motorized rotation stages, which allows us to rotate the source around two independent axes. The first axis is the vertical, going through the midpoint of the exit port, which rotation is denoted by an angle α. The second rotation is around the optical axis of the light source and is labeled β. A schematic

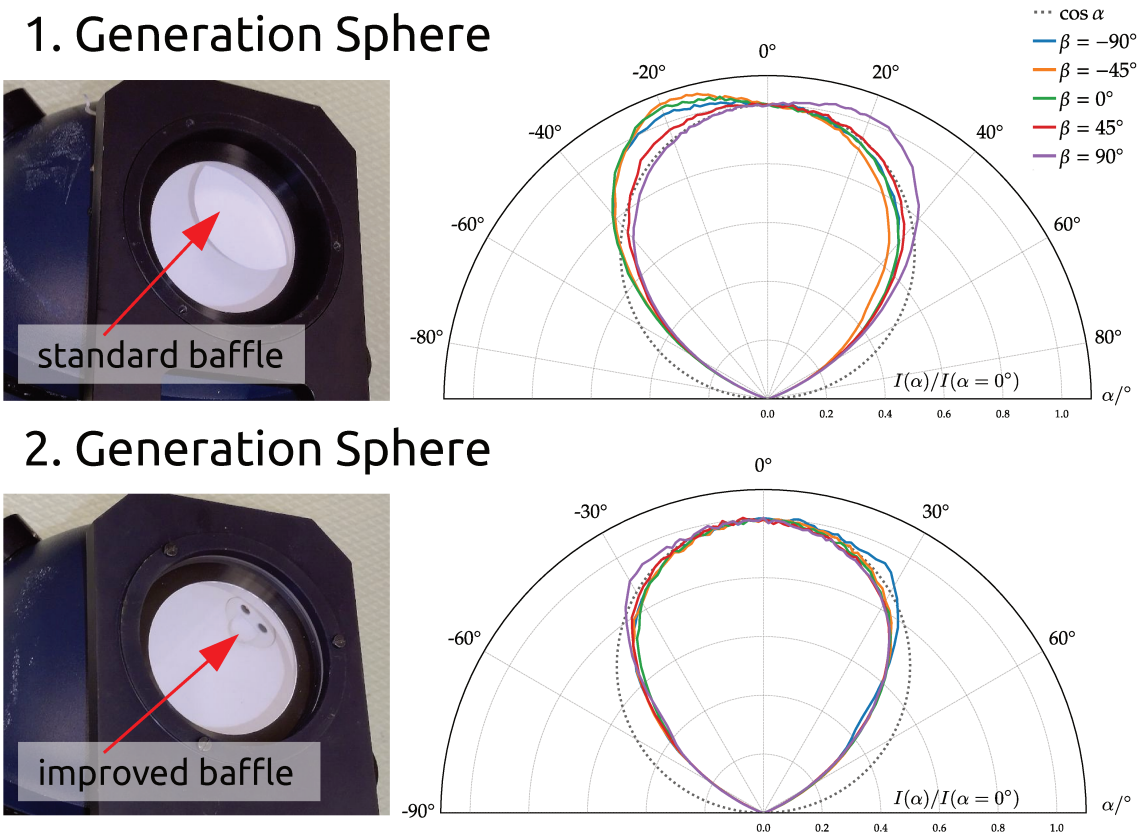

Figure 3: Measurements of the angular emission characteristics of the two generations of integrating-sphere light sources.

drawing of the setup is shown in Fig. 2. Within this figure the rotation axes are indicated by orange lines. At a distance of ~5 m a PMT observes the emission from the light source. We choose this particular distance so that the laboratory PMT covers approximately the same solid angle as a pixel-PMT of the FD telescope camera. This setup allows us to directly measure the angular emission of all light sources by observing the source under different viewing angles (α, β) with one single PMT.

Fig. 3 shows the measured angular emission profiles of the two integrating-sphere light sources employed by the XY-Scanner. For the first generation of light sources, we observe a deviation from an ideal Lambertian emitter on the order of ~10%. This deviation is induced by the baffle installed in this integrating sphere, as indicated in the top-left photograph of Fig. 3. A baffle is a structural element included in the integrating spheres to prohibit photons emitted from the LED from directly leaving the sphere without any internal reflections. For the second-generation light sources we replaced the large baffle with a smaller one, resulting in a closer agreement between the measured angular emission profile and an ideal Lambertian source. See the bottom row of Fig. 3.

In addition, we implemented the measured angular emission of the two light sources into the XY-Scanner simulation and compared the results of the simulation with measurements at the FD telescopes. We present the results of this comparison in Fig. 4. Therein the top-left plot shows the ratio between the pixel signals captured during two XY-Scanner measurements performed at

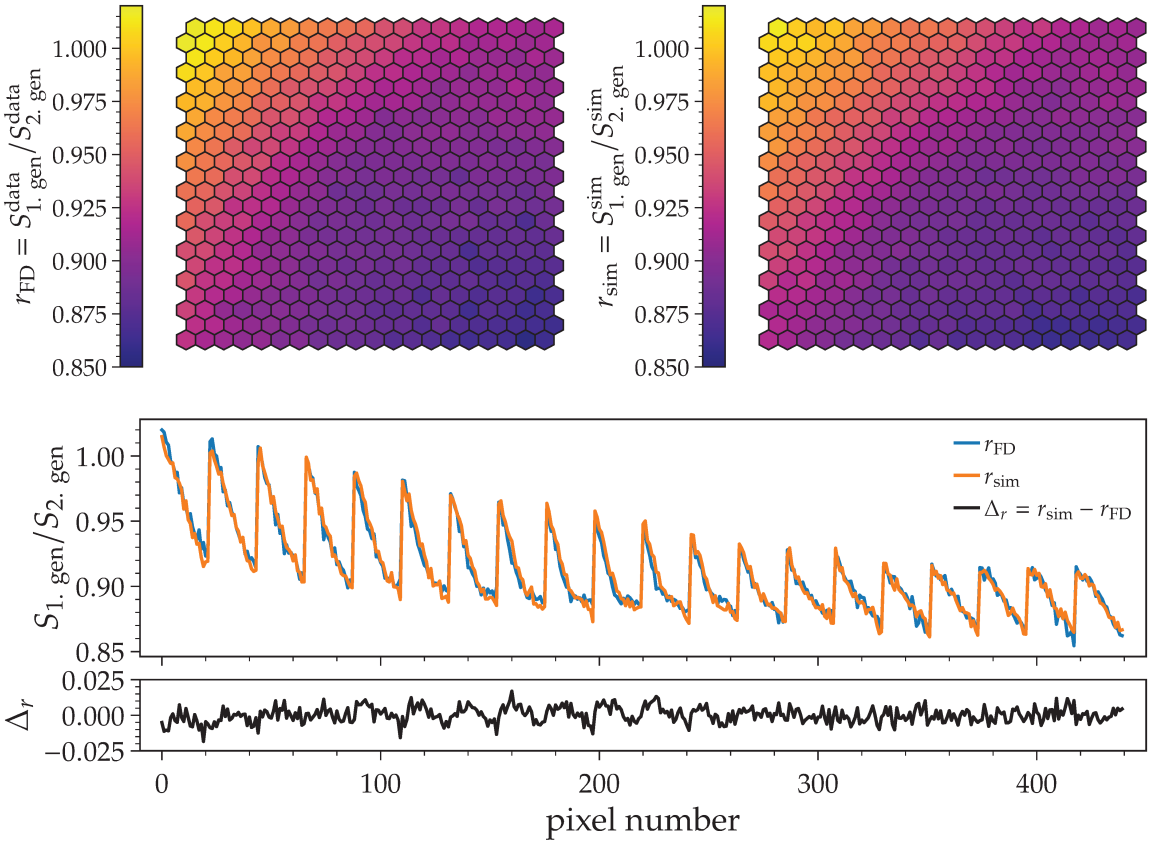

Figure 4: *Top-left:* Ratio of the FD pixel signals for XY-Scanner measurements employing either of the two integrating-sphere light sources. *Top-right:* Similar to the left plot, but the results of simulations are shown. *Bottom:* Shown is the same data as in the top plots, but as a function of the pixel number. Difference Δr between FD measurement and simulation is attached below.

a FD telescope and employing the two different generations of light sources. The top-right plot shows the results of simulating the very same conditions, including the angular source emission as discussed above. In the bottom plots, we show again the ratios from the real FD measurements r_{FD} and simulations r_{sim} as a function of pixel number. Additionally, we show a plot of the difference between measurement and simulation below. We observe a maximal difference of less than 2% while the mean difference is compatible with zero, which we interpret as a validation of our laboratory setup and simulation chain.

4. Absolute Calibration of Light Sources

For the absolute calibration of the light sources we setup and are operating two calibration benches, which are installed at two different institutes. The setups are located at the Bergische Universität Wuppertal (BUW) and the Karlsruhe Institute of Technology (KIT). Since both setups rely on a similar working principle, we focus the following discussion on the setup at KIT.

In Fig. 5 a photograph of this absolute light-source calibration setup is shown. The setup is entirely installed within a light-tight enclosure. To measure the emitted photon flux from the source

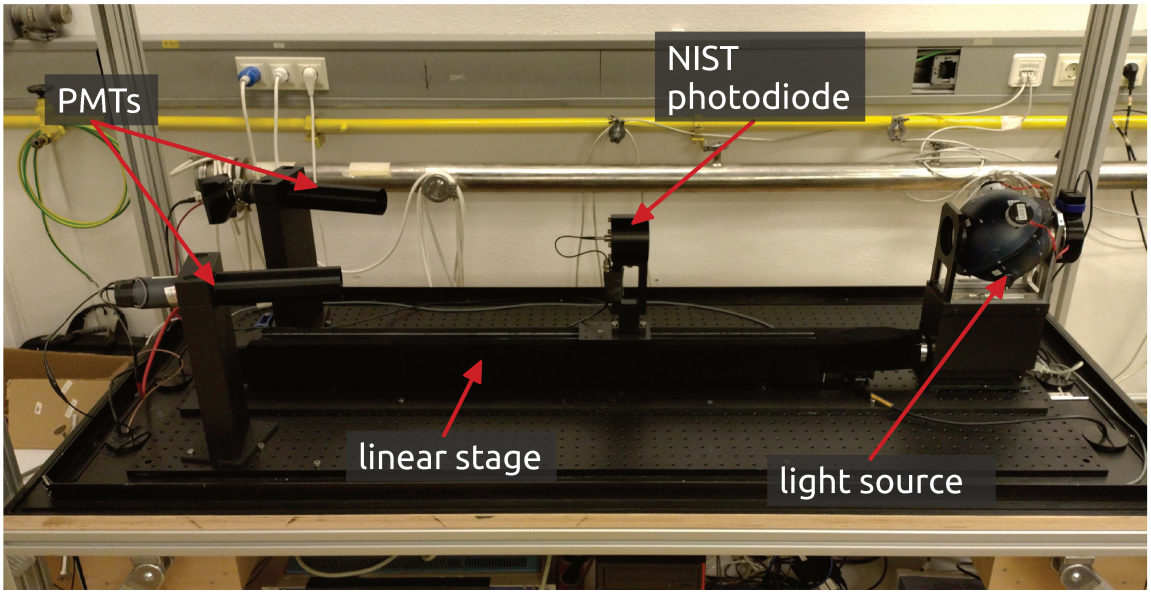

Figure 5: Photograph of one of the setups to absolutely calibrate the light sources of the XY-Scanner. All important components are labeled.

we employ a NIST absolutely-calibrated photodiode. We installed the photodiode on a motorized linear stage, which allows us to change the distance between the source and detector without breaking the light-tightness of the setup. The employed photodiode is designed to be operated with a constant illumination, however for the calibration of the FD telescopes we need to operate the light source in a pulsed mode. Furthermore, we are limited to a maximal flashing frequency of ~1 Hz due to the time needed to read out the 440 pixel-PMTs of a telescope camera. We overcame this issue by increasing the flashing frequency for the source calibration and thus nearly constantly illuminating the photodiode. By including two PMTs into the setup, which can resolve each individual light pulse from the source, we are able to correct frequency-depended intensity variations of the light source.

We calibrated both integrating-sphere light sources in both absolute-calibration setups and obtained compatible results. Depending on the setup we reach an uncertainty of the estimated photon flux emitted from the sources between ~2.8% and ~3.5%. We are currently working on upgrading our calibration setups, which will probably reduce the uncertainties on the source calibration measurements even further.

5. Comparison with Night-Sky-Brightness Method

Out of the 27 FD telescopes of the Pierre Auger Observatory, three telescopes take on a special role. These three High Elevation Auger Telescopes (HEAT) can be tilted and thus their field of view covers higher elevation angles than the standard telescopes. HEAT is located close (~150 m) to the FD site of Coihueco in the North-West of the observatory. The location of HEAT is drawn on the map in the left part of Fig. 1. We can use a combination of the HEAT and the standard FD telescopes at Coihueco to observe a larger fraction of the longitudinal profiles of deposited energy

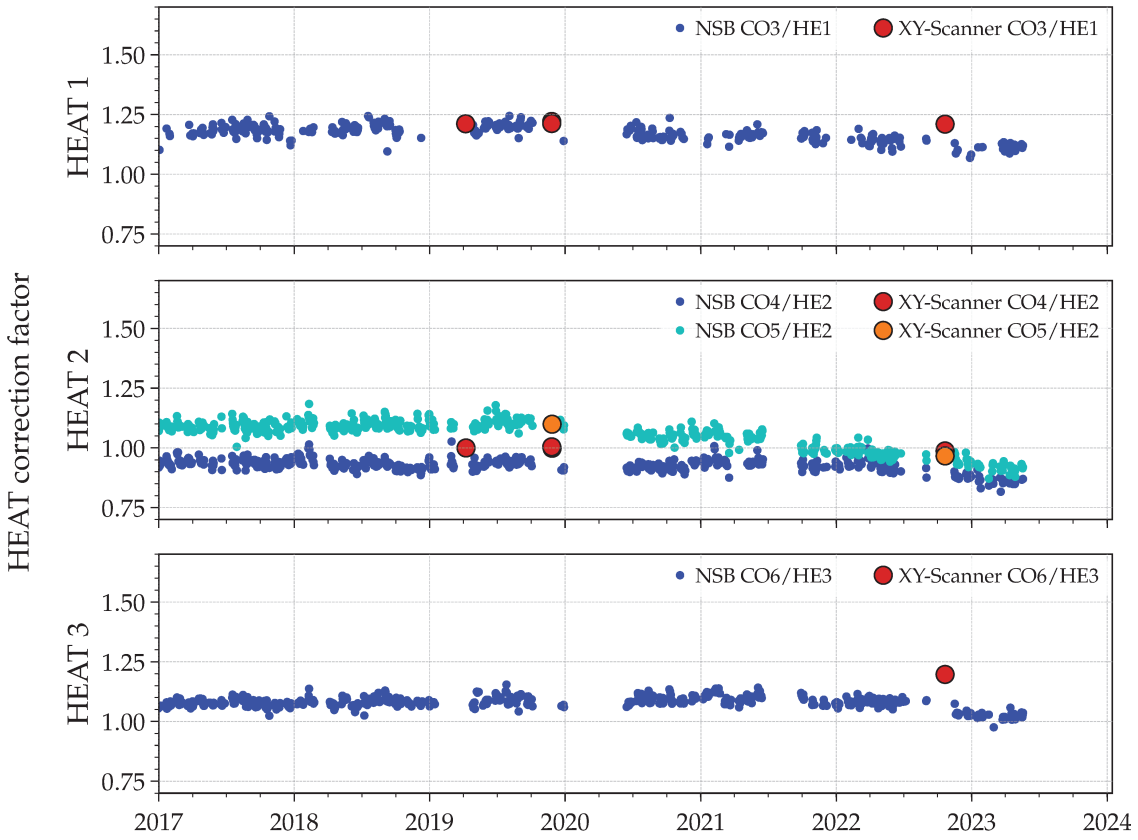

Figure 6: Inter-calibration between the three telescopes of HEAT and the corresponding Coihueco telescopes. Blue and cyan data points represent the NSB method. Results from XY-Scanner measurements are plotted in red and orange.

by air showers. Therefore, the inter-calibration between the telescopes of HEAT and Coihueco is of special interest.

We make use of the continuous estimation of the Night Sky Brightness (NSB) by the HEAT and Coihueco telescopes to monitor their inter-calibration [7]. Due to historic reasons, we adjust the calibration of HEAT to the corresponding Coihueco telescopes. The estimated HEAT correction factors are stored in a database and requested for event reconstruction.

In the following, we present a comparison between the HEAT-Coihueco inter-calibrations obtained from analyzing the NSB and the measurements performed with the XY-Scanner. Note that the XY-Scanner measurements and the NSB observations are independent methods.

We estimate the total signal captured during a complete XY-Scanner measurement as the sum of the calibrated pixel signals for all positions of the light source on the scanning grid. Since the telescopes are designed and constructed in an almost identical way, we can directly calculate the inter-calibration factors between telescopes as the ratio between the signals captured by the corresponding telescopes.

Fig. 6 shows the HEAT correction factors estimated by the NSB method [7] as blue and cyan markers, together with the XY-Scanner measurements depicted as red and orange markers. The

three panels of Fig. 6 show the inter-calibration for the three telescopes of HEAT.

The inter-calibration factors obtained from the XY-Scanner measurements are of the same order as the HEAT correction factors obtained from the NSB observations. Therefore, we give an independent validation of the HEAT correction factors obtained via the NSB analysis.

6. Conclusion and Outlook

In this proceeding, we briefly introduced the XY-Scanner, which is a novel and versatile tool for the absolute end-to-end calibration of the fluorescence telescopes operated by the Pierre Auger Observatory. The setup and the measuring procedure were already presented at the last ICRC in 2021 and are summarized in Refs. [5, 6]. We finished the installation of XY-Scanner systems on all 27 FD telescopes of the observatory in early 2023.

We focused this proceeding on the measurements we performed in the laboratory to accurately study the light-source characteristics. We designed and built two setups to (a) measure the angular emission profiles and (b) estimate the absolute calibration of the employed light sources. For the second case, we installed two independent calibration setups at different institutes, which provide us with necessary redundancy and cross checks.

By including the measured angular emission characteristics of the different light sources into our ray-traced simulations, we observe an excellent agreement between the simulated and the actual (at an FD telescope performed) XY-Scanner measurements.

Furthermore, we used the measurements performed with the XY-Scanner at the FD telescopes to give an independent validation of the inter-calibration between telescopes obtained from analyzing the night-sky-background observations.

We plan to provide a novel absolute end-to-end calibration of all FD telescopes of the Pierre Auger Observatory in the foreseeable future. On a longer time scale, we aim to perform the XY-Scanner calibration campaigns on a yearly basis.

References

[1] A. Aab et al. [Pierre Auger], Nucl. Instrum. Meth. A **798** (2015) 172–213, [1502.01323].
[2] J. Abraham et al. [Pierre Auger], Nucl. Instrum. Meth. A **620** (2010) 227-251, [0907.4282].
[3] J.T. Brack et al., Astropart. Phys. **20** (2004) 653.
[4] J.T. Brack et al., JINST **8** (2013) P05014, [1305.1329].
[5] C. M. Schäfer et al. [Pierre Auger], PoS **(ICRC2021)** 220.
[6] C. M. Schäfer, PhD Thesis (2023), Karlsruhe Institute of Technology (KIT).
[7] A. Segreto et al. [Pierre Auger], these proceedings, PoS **(ICRC2023)** 276.

The Pierre Auger Collaboration

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Cabana-Freire[79], L. Caccianiga[59,49], I. Caracas[38], R. Caruso[58,47], A. Castellina[54,52], F. Catalani[18], G. Cataldi[48], L. Cazon[79], M. Cerda[10], A. Cermenati[45,46], J.A. Chinellato[21], J. Chudoba[32], L. Chytka[33], R.W. Clay[13], A.C. Cobos Cerutti[6], R. Colalillo[60,50], A. Coleman[90], M.R. Coluccia[48], R. Conceição[72], A. Condorelli[37], G. Consolati[49,55], M. Conte[56,48], F. Convenga[41], D. Correia dos Santos[28], P.J. Costa[72], C.E. Covault[84], M. Cristinziani[44], C.S. Cruz Sanchez[3], S. Dasso[4,2], K. Daumiller[41], B.R. Dawson[13], R.M. de Almeida[28], J. de Jesús[7,41], S.J. de Jong[80,81], J.R.T. de Mello Neto[26,27], I. De Mitri[45,46], J. de Oliveira[17], D. de Oliveira Franco[21], F. de Palma[56,48], V. de Souza[19], E. De Vito[56,48], A. Del Popolo[58,47], O. Deligny[34], N. Denner[32], L. Deval[41,7], A. di Matteo[52], M. Dobre[73], C. Dobrigkeit[21], J.C. D'Olivo[68], L.M. Domingues Mendes[72], J.C. dos Anjos, R.C. dos Anjos[25], J. Ebr[32], F. Ellwanger[41], M. Emam[80,81], R. Engel[39,41], I. Epicoco[56,48], M. Erdmann[42], A. Etchegoyen[7,12], C. Evoli[45,46], H. Falcke[80,82,81], J. Farmer[89], G. Farrar[88], A.C. Fauth[21], N. Fazzini[e], F. Feldbusch[40], F. Fenu[41,d], A. Fernandes[72], B. Fick[87], J.M. Figueira[7], A. Filipčič[77,76], T. Fitoussi[41], B. Flaggs[90], T. Fodran[80], T. Fujii[89,f], A. Fuster[7,12], C. Galea[80], C. Galelli[59,49], B. García[6], C. Gaudu[38], H. Gemmeke[40], F. Gesualdi[7,41], A. Gherghel-Lascu[73], P.L. Ghia[34], U. Giaccari[48], M. Giammarchi[49], J. Glombitza[42,g], F. Gobbi[10], F. Gollan[7], G. Golup[1], M. Gómez Berisso[1], P.F. Gómez Vitale[11], J.P. Gongora[11], J.M. González[1], N. González[7], I. Goos[1], D. Góra[70], A. Gorgi[54,52], M. Gottowik[79], T.D. Grubb[13], F. Guarino[60,50], G.P. Guedes[22], E. Guido[44], S. Hahn[39], P. Hamal[32], M.R. Hampel[7], P. Hansen[3], D. Harari[1], V.M. Harvey[13], A. Haungs[41], T. Hebbeker[42], C. Hojvat[e], J.R. Hörandel[80,81], P. Horvath[33], M. Hrabovský[33], T. Huege[41,15], A. Insolia[58,47], P.G. Isar[74], P. Janecek[32], J.A. Johnsen[85], J. Jurysek[32], A. Kääpä[38], K.H. Kampert[38], B. Keilhauer[41], A. Khakurdikar[80], V.V. Kizakke Covilakam[7,41], H.O. Klages[41], M. Kleifges[40], F. Knapp[39], N. Kunka[40], B.L. Lago[16], N. Langner[42], M.A. Leigui de Oliveira[24], Y Lema-Capeans[79], V. Lenok[39], A. Letessier-Selvon[35], I. Lhenry-Yvon[34], D. Lo Presti[58,47], L. Lopes[72], L. Lu[91], Q. Luce[39], J.P. Lundquist[76], A. Machado Payeras[21], M. Majercakova[32], D. Mandat[32], B.C. Manning[13], P. Mantsch[e], S. Marafico[34], F.M. Mariani[59,49], A.G. Mariazzi[3], I.C. Mariş[14], G. Marsella[61,47], D. Martello[56,48], S. Martinelli[41,7], O. Martínez Bravo[64], M.A. Martins[79], M. Mastrodicasa[57,46], H.J. Mathes[41], J. Matthews[a], G. Matthiae[62,51], E. Mayotte[85,38], S. Mayotte[85], P.O. Mazur[e], G. Medina-Tanco[68], J. Meinert[38], D. Melo[7], A. Menshikov[40], C. Merx[41], S. Michal[33], M.I. Micheletti[5], L. Miramonti[59,49], S. Mollerach[1], F. Montanet[36], L. Morejon[38], C. Morello[54,52], A.L. Müller[32], K. Mulrey[80,81], R. Mussa[52], M. Muzio[88], W.M. Namasaka[38], S. Negi[32], L. Nellen[68], K. Nguyen[87], G. Nicora[9], M. Niculescu-Oglinzanu[73], M. Niechciol[44], D. Nitz[87], D. Nosek[31], V. Novotny[31], L. Nožka[33], A Nucita[56,48], L.A. Núñez[30], C. Oliveira[19], M. Palatka[32], J. Pallotta[9], S. Panja[32], G. Parente[79], T. Paulsen[38], J. Pawlowsky[38], M. Pech[32], J. Pękala[70], R. Pelayo[65], L.A.S. Pereira[23], E.E. Pereira Martins[39,7], J. Perez Armand[20], C. Pérez Bertolli[7,41], L. Perrone[56,48], S. Petrera[45,46], C. Petrucci[57,46], T. Pierog[41], M. Pimenta[72], M. Platino[7], B. Pont[80], M. Pothast[81,80], M. Pourmohammad Shahvar[61,47], P. Privitera[89], M. Prouza[32], A. Puyleart[87], S. Querchfeld[38], J. Rautenberg[38], D. Ravignani[7], M. Reininghaus[39], J. Ridky[32], F. Riehn[79], M. Risse[44], V. Rizi[57,46], W. Rodrigues de Carvalho[80], E. Rodriguez[7,41], J. Rodriguez Rojo[11], M.J. Roncoroni[7], S. Rossoni[43], M. Roth[41], E. Roulet[1], A.C. Rovero[4], P. Ruehl[44], A. Saftoiu[73], M. Saharan[80], F. Salamida[57,46], H. Salazar[64], G. Salina[51], J.D. Sanabria Gomez[30], F. Sánchez[7], E.M. Santos[20], E. Santos[32],

F. Sarazin[85], R. Sarmento[72], R. Sato[11], P. Savina[91], C.M. Schäfer[41], V. Scherini[56,48], H. Schieler[41], M. Schimassek[34], M. Schimp[38], F. Schlüter[41], D. Schmidt[39], O. Scholten[15,i], H. Schoorlemmer[80,81], P. Schovánek[32], F.G. Schröder[90,41], J. Schulte[42], T. Schulz[41], S.J. Sciutto[3], M. Scornavacche[7,41], A. Segreto[53,47], S. Sehgal[38], S.U. Shivashankara[76], G. Sigl[43], G. Silli[7], O. Sima[73,b], F. Simon[40], R. Smau[73], R. Šmída[89], P. Sommers[k], J.F. Soriano[86], R. Squartini[10], M. Stadelmaier[32], D. Stanca[73], S. Stanič[76], J. Stasielak[70], P. Stassi[36], S. Strähnz[39], M. Straub[42], M. Suárez-Durán[14], T. Suomijärvi[37], A.D. Supanitsky[7], Z. Svozilikova[32], Z. Szadkowski[71], A. Tapia[29], C. Taricco[63,52], C. Timmermans[81,80], O. Tkachenko[41], P. Tobiska[32], C.J. Todero Peixoto[18], B. Tomé[72], Z. Torrès[36], A. Travaini[10], P. Travnicek[32], C. Trimarelli[57,46], M. Tueros[3], M. Unger[41], L. Vaclavek[33], M. Vacula[33], J.F. Valdés Galicia[68], L. Valore[60,50], E. Varela[64], A. Vásquez-Ramírez[30], D. Veberič[41], C. Ventura[27], I.D. Vergara Quispe[3], V. Verzi[51], J. Vicha[32], J. Vink[83], J. Vlastimil[32], S. Vorobiov[76], C. Watanabe[26], A.A. Watson[c], A. Weindl[41], L. Wiencke[85], H. Wilczyński[70], D. Wittkowski[38], B. Wundheiler[7], B. Yue[38], A. Yushkov[32], O. Zapparrata[14], E. Zas[79], D. Zavrtanik[76,77], M. Zavrtanik[77,76]

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