PROCEEDINGS OF SCIENCE

Portals to Data of the Pierre Auger Observatory

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The Pierre Auger Collaboration has embraced the concept of open access to their data from its foundation. As early as 2007, when the Observatory was almost complete, a portal to 1% of the data from the surface detector was created and updated every year for over ten years. Meant for educational purposes, the portal was the first step towards making data public by the FAIR (Findable, Accessible, Interoperable, and Reusable) principles. A new portal was opened in February 2021, at the end of the first phase of operation. Presented for the first time at the ICRC 2021, it includes not only 10% of the data – raw and processed – from the different instruments of the Observatory, but also a visualisation tool, documentation to make the data user-friendly, and analyses codes that can be readily used and modified. Since 2021, the portal has been updated three times: new data, documentation, and codes have been added. Moreover, the portal has become dual, with one part dedicated to scientists and the other to educational users. Furthermore, a catalog containing details of the 100 highest-energy cosmic rays has been included. At this conference we will discuss these new features, as well as our intentions for the future. We will also share our approach and methods for making data public and understandable to external users, from simplifying the data structure to translating codes from in-house computing architecture into popular available software.

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1. Portals of the Pierre Auger Observatory: a 15 years old story

The interest in, and the commitment to, open science has escalated in the last decades, in all domains of science. This development is not just due to the exponential growth of the Internet and related technologies, but also to the realisation by researchers that open dissemination of data is beneficial to their own research in terms of reproducibility, possible new findings and preservation. Today, every new project involving data production contains a data management plan (DMP) describing the handling of data during and after the project, including sharing and preservation. Although the Pierre Auger Observatory does not have a DMP as it was founded a quarter of a century ago when this concept was not in use, the first constitution of the nascent Collaboration encompassed the commitment to the principle of open-access data. Such commitment was formalised into a first data-release policy as early as 2006, when only 60% of the Observatory was in operation. It stipulated the disclosure of 1% of cosmic-ray data.

The first portal to Auger data was created in 2007: 1% of cosmic-ray data down to 1 EeV, with a latency of 1 year, was made available. The portal was intended for educational purposes, in particular for illustration of cosmic-ray events, which explains its denomination, Public Event Browser: users could easily visualise the data via a ready-to-use event display, by choosing specific events through an intuitive selection menu. The portal was updated and curated for more than 10 years, becoming multilingual over time. Scaler data, i.e., the counting rates of each of the 1600 stations of the surface detector, were added into a “Space Weather" page, where one could display the rate behaviour over a period of time of their choice. The fraction of cosmic-ray data was augmented to 10% in 2016, following the policy change in 2015, which envisaged the release of such data fraction with a latency of two years. The policy reinforced the release of 100% of scaler data and authorised that of 100% of data recorded by the atmospheric monitoring instruments.

The Public-Event-Browser portal served also as stress-test and training for a more articulated release. This took place in 2021, in the form of the new portal, denominated Open Data, which is the subject of this contribution. The reflection and spirit behind the transition from Public Event Browser to Open Data is explained in Section 2, where the methods for tailoring our data to enable open and reproducible research are also described. Section 3 illustrates the evolution of the content of the portal since its first release [1], including the addition of a data set that is an exception to our policy, namely the detailed catalogue of a hundred of our highest energy events [2]. In Section 4 we take stock of our experience with opening our data and we anticipate our plans for the future.

2. The 2021 portal: conception and realisation

The concept behind making data public in the first portal was that of showing our cosmic-ray events rather than having them reused and reanalysed, essentially because of the very small fraction released. The portal included only very basic documentation on the data, and no software to read or analyse them. The policy change that increased the fraction of data was at the origin of a new reflection on the intent and approach in opening our data. 10% of the data accumulated until 2019, when we started to conceive the new portal, roughly corresponded to that used to obtain landmark results such as our early measurement of the energy spectrum of ultra-high energy cosmic rays [3]. We considered that data set as a viable one to be made public for a two-fold purpose, i.e., not only outreach, but also research. For the latter, our intent was that of allowing scientists external to our Collaboration to use our data and reproduce our published results and/or conduct new analyses. To support and facilitate the analysis of external scientists, the approach we adopted was thus that of releasing not only data, but also accompanying software and detailed explanations. It is these ideas that have been our guidelines in the task of opening up our data to reusable research and in the approach to building a framework around our data, rather than just a repository.

The first step towards the realisation of the framework was the choice of the data to be opened for a use outside the Collaboration. The Observatory [4] is in fact a composition of different instruments that output a variety of independent data streams. Those devoted to the detection of extensive air showers include three arrays of water-Cherenkov detectors, 1660 in total, nested within one another, and a graded array of radio antennas, all overlooked by a fluorescence detector consisting of five units and 27 telescopes. The Observatory comprises also several devices to monitor atmospheric parameters [5], such as meteorological stations, lidars and lasers. Not only are there multiple instruments, but also multiple types of data, ranging from primary data, those produced directly from the acquisition, to derived data, such as calibrated and reconstructed data. The primary data typically consists of binary streams containing the waveforms of signals acquired at the occurrence of a trigger. Proprietary computing frameworks, built in C++ environments, are used to reduce the primary data into physical calibrated quantities, such as charge and timing of the signals. The calibrated data are then injected into a reconstruction process that, based on the distribution of the signals and their arrival times, derive the parameters that characterise the shower parameters (direction, energy, mass) and ultimately those of the cosmic ray.

For the sake of simplicity, we resolved to release first only cosmic-ray data from the instruments that had taken data for the longest time, the 1500 m spaced surface array and the telescopes of the original 4-unit fluorescence detector. To minimise the level of detail needed to use the data, we pursued the idea of simplification of primary data by sparing the user the first step of data reduction, i.e., the transformation of binary data into physical calibrated data. All proprietary primary and derived data are produced in the ROOT framework [6]: to make the users independent from external software packages, we converted the calibrated data (pseudo-raw data) for each event into the flexible and interoperable JSON format, with summary files extracted in the standard CSV format, containing the high-level information (such as arrival direction, energy, position at ground...) for each event. To complement this "support and facilitation" approach, we compiled a detailed documentation of the files content and of the meaning of each variable included in the files. The user is further assisted through a detailed explanation of the method of reconstructing cosmic-ray events from pseudo-raw data, as well as via a visualisation tool that is an adaptation of the Event Browser designed for the first portal. The event display allows the user to discover the details of the pseudo-raw data of exemplary events, or of events chosen by the user. It also allows one for hands-on reconstruction of each event.

In fact, users can learn to visualise, and manipulate, the events via a series of analysis examples that complement the users' accompaniment and support them in understanding and using the data. While all analysis frameworks used by the collaboration are written in C++, for public dissemination we adopted Python. Two types of Python Jupyter notebooks are included in the framework, via the Kaggle environment: all of them are mostly designed to require only the core python analysis packages and can be downloaded or run online in the web browser. A set of notebooks serves the user to understand how to read the JSON data, and how to perform simple analyses, such as constructing a histogram, or visualising an event and reconstructing it. Another set, that exploits the summary data, is intended to reproduce landmark results obtained by the Collaboration, published in peer-reviewed journals. These codes recall the spirit of the original analyses, but, for the sake of simplicity, the more advanced methods used in the publications are omitted. Nevertheless, the codes provide an insight about how the original results were obtained, and the more complex methods can be implemented on the public data.

The final brick in the construction of the framework was the interface to the portal so that users could easily access the data, the software, the documentation and any other resources. The experience with our first web portal, PHP-based, served us well: the very intuitive interface, the use of which does not require of the user any knowledge, or expertise of the underlying system or of the location and treatment of the data, seemed well-suited to our purpose. Moreover, the interface, which had shown to be easily adaptable to changes and additions, looked ideal for the dual portal we had in mind, i.e., for researchers and for citizens scientists, and for a regular insertion of more and more data, from different instruments and of different kinds.

Thus our Open Data portal was created in February 2021, providing access to three sections, *Datasets*, *Visualisation* and *Analysis*. The data were released under the (CC BY-SA 4.0) International License. To make them easily and uniquely citable, all datasets have a Digital Object Identifier (DOI) provided by Zenodo (https://zenodo.org) where all of them are uploaded. The portal includes also a user helpdesk (section *Contact*) as an additional support, which allows users to contact us and answers frequently asked questions both on technical and content-related issues.

3. Portal curation and updates

Since its creation in 2021 the portal has been regularly curated and updated. At the same time as the current data-release policy was approved, an Open Data task was created under the responsibility of the Project Management, which implies that the task will last over the lifetime of the Observatory. The task, which includes a core-team in charge of curation and updates, cuts across all of the detector and physics groups. The curation and verification of the released data is done under the supervision of data and instrument experts, the analysis codes are realised and certified by the related physics tasks, and the documentation follows the internal approval path of that of any other publication, via the body of the Publication Committee.

The portal content has been updated twice, at the end of 2021 and of 2022, with the interface being adapted to the new features. Although the fraction of public data remained at 10%, we included additional data from the surface detector and we added scaler and atmospheric data. All data were accompanied by new documentation and codes, and their visualisation was extended and improved with a 3D event display. Moreover, as planned since the portal conception, we integrated a dedicated outreach section. A sub-portal to the catalog of the 100 highest energy events was also included. The new features in the original tabs *Datasets*, *Visualisation* and *Analysis*, as well as the content of the new *Outreach* and *Catalog* tabs are described in this section.

Datasets. The dataset was augmented in a second release at the end of 2021, when we made 100% of scaler and meteorological data public, while at the end of 2022 we extended the cosmic-ray dataset of the surface detector to include horizontal showers and the highest energy events.

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The *scaler data* consist of more than 10^{15} signal counts detected from March 2005 to December 2020. They are recorded via the so-called "scaler mode", that counts, in each of the 1600 detectors, the number of times that the amplitude of the signal satisfies threshold conditions corresponding to an energy deposit of between 15 and 100 MeV. These energy depositions arise from the remnants of showers produced by primary cosmic-rays with energies from 10 GeV to a few TeV. The typical rate per detector is $\approx$ 2 kHz. The scaler single-mode does not allow one to reconstruct the energy and the direction of the shower. However, it allows one to study the temporal behaviour of the number of counts, which is modulated by terrestrial and extraterrestrial phenomena [7]. The scaler data are provided in CSV files as the 15-minutes counting rate averaged over the detectors that pass quality selections, based on the number and status of the photomultipliers in operation and on the counting rate. As this is altered by the varying atmospheric pressure, the rate is then corrected by means of a linear fit of the pressure dependency.

The *meteorological data* come from five stations located at the center of the array and at each of the four fluorescence sites. They are equipped with temperature, pressure, humidity, and wind speed sensors recording data every 5 min or 10 min. The five primary flows of data are reduced and pre-processed before being used in the reconstruction of showers, because their longitudinal and lateral development is modified by local changes in the atmosphere. The changes in the shower shape in turn affect the response of the surface detector, most notably in terms of the reconstructed value of the energy estimator [8]. Moreover, changes in the properties of the atmosphere have a significant effect on the rate of nitrogen fluorescence emission, as well as on light transmission, and hence on the reconstruction of events seen with the fluorescence detectors. The portal contains two types of data in CSV format: besides the primary data, derived data are available, including, in particular, the air density, calculated from the combination of pressure, temperature and humidity.

The *cosmic-ray data* from the surface detector released in 2021 included only the so-called vertical events, i.e., those with zenith angle $\theta < 60^\circ$. In 2022, we extended the zenith angle range to 80° to include the “inclined" events, that have been used to obtain a variety of our results, by adding 30% more statistics to the surface detector data and extending the exposure to about 80% of the sky. The reconstruction of inclined events [9] differs from that of vertical ones because of the loss of the near-cylindrical symmetry of the shower particles, which are mostly muons that are deflected strongly in the Earth’s magnetic field. To ensure adequate sampling of the shower, we adopted the same selection criterion as for the vertical events, i.e., the detector with the highest signal must be surrounded by a hexagon of six stations that are operational. Also, to guarantee that the detection efficiency is greater than 97%, the energy threshold is set to 4×10^{18} eV. Such selection criteria results in the release of about 3500 inclined events.

Analysis and visualisation. To accompany the release of the new data, physics analysis codes have been either updated or newly created. One of the original codes using high-level data from the surface detectors served to reproduce, within the limited statistics, the construction of the energy spectrum. This has been updated to include the inclined events: the spectrum is now estimated with inclined events too, and compared to that obtained with the vertical ones. As for the meteorological data, a new code has been added, that shows how the energy assignment of each surface detector event is corrected to account for air pressure, temperature and humidity.

The update of the portal at the end of 2021 was also an opportunity to include a *3D viewer* of the cosmic-ray events, developed in Unity, a very popular game development language for mobile

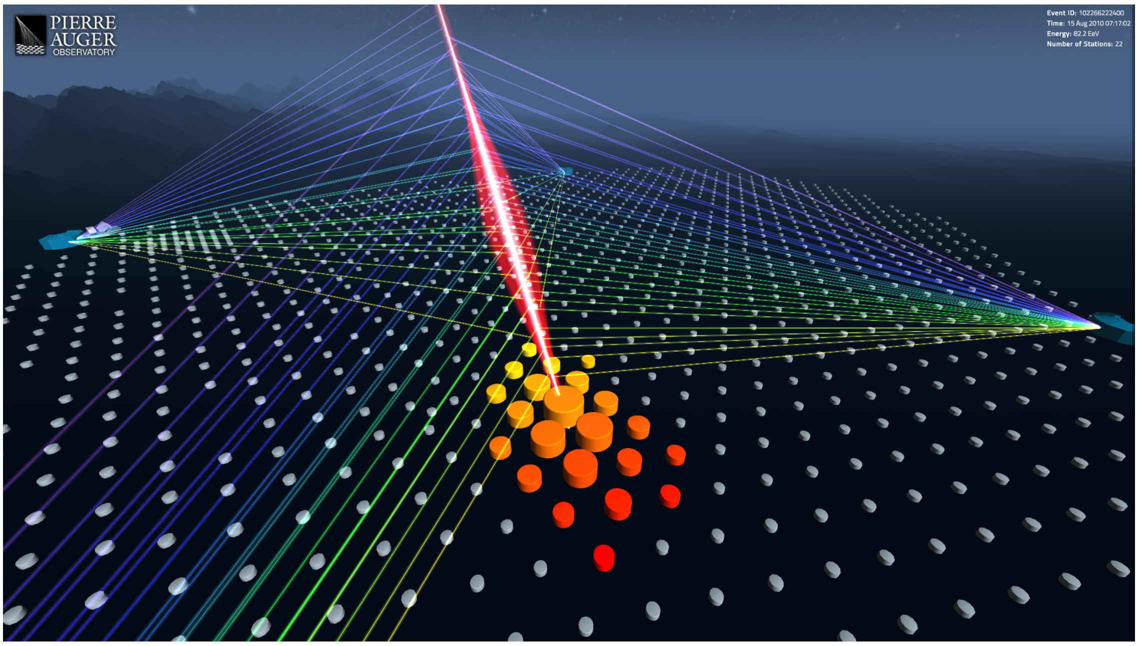

Figure 1: The 3D display of the footprint at ground of a shower detected by 22 detectors of the surface array and by four units of the fluorescence detector. The arrival direction is 54° and the energy is 82 EeV.

devices. For each selected event, the viewer shows a 3D animation from the arrival of the cosmic ray to the detection of the created extensive shower with the instruments of the observatory. The final frame of the animation of a so-called hybrid event, detected simultaneously with the surface and fluorescence detectors, is displayed in Figure 1. As with the original 2D viewer, for each event the user can view the reconstruction and the resulting cosmic-ray parameters; in addition a sky map showing the celestial position of the event is also viewable.

Outreach. In the realisation of the outreach section of the portal, we kept the same spirit as for the research part, namely that of support and facilitation of the user, bearing in mind that in this case the user may not be a scientist. The multilingual outreach section is a portal itself to a "mini-framework" built around the data, simplified ones in this case. The same types of data that are available for research are so too in the outreach framework: cosmic rays, scalers and meteorological data, all provided in summary CSV files. In the exploration of the data, users are assisted with simplified documentation on cosmic rays, on methods used to detect them, on the Observatory, on the data and on how from them one can reconstruct the properties of cosmic rays. A few videos further help the user in understanding the phenomenon of extensive air showers, as well as the functioning of our instruments. Rather than with an *Analysis* menu, the users are guided to the use of our data via an *Explore data* tab, where easy-to-use Python notebooks help them to explore and manipulate the different types of data. A notebook that shows the shower development completes the suite of outreach codes: the output is shown in Figure 2.

Catalog. As Phase I of operation of the Observatory ended on 31 December 2021, we published a catalog of a hundred highest energy events [2]. Inspired by similar enterprises from the previous

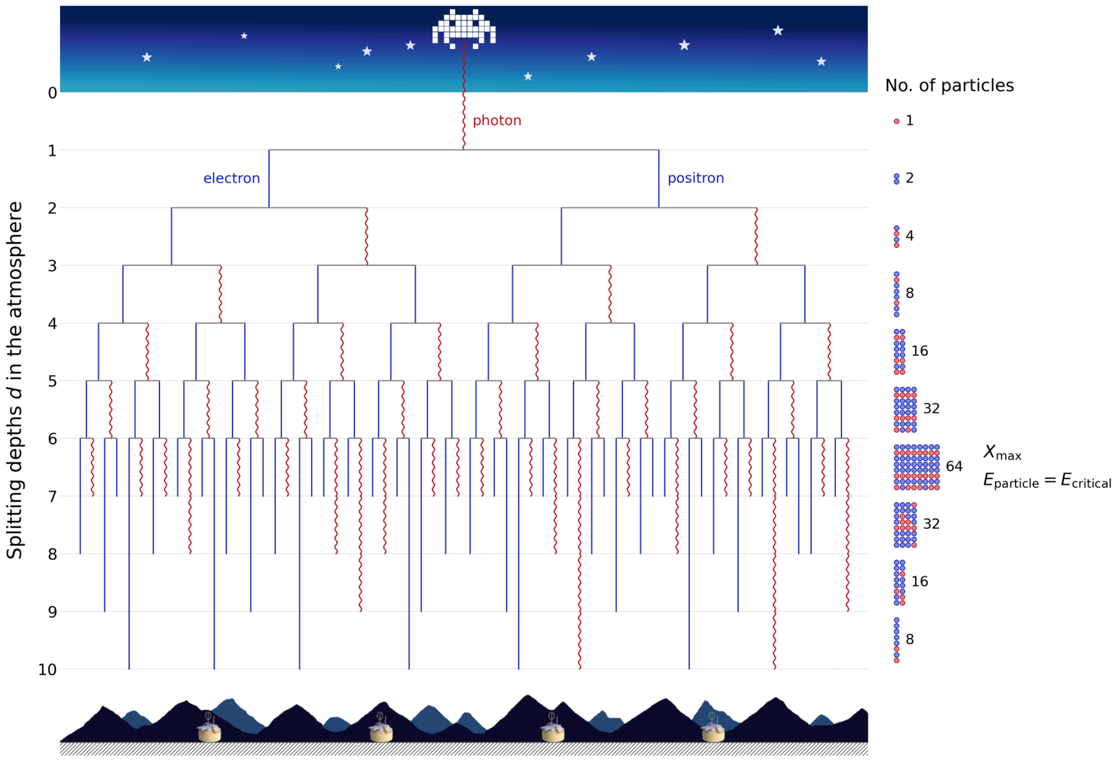

Figure 2: Outreach section: output of the animation code illustrating the development of a photon shower based on the Heitler model.

generation (Volcano Ranch, Haverah Park, SUGAR and Yakutsk [10]), the catalog was made public to make our rarest cosmic-ray events available to the scrutiny of the community. It contains the 100 most energetic events ($78 < E < 166$ EeV) recorded using the surface detector: they are part of the data set used in our latest analysis of the arrival directions of events above 32 EeV [11]. It also comprises nine hybrid events used in the energy calibration the surface detector events. The catalog is accessible in the tab *Catalog* of the portal. All events can be visualised with the portal event displays, both 2D and 3D: the event in Figure 1 is one of the 109. For these events, additional features can be viewed: not only the footprint at ground can be displayed, but also that on the shower plane, and besides the lateral distribution of the shower particles, the user can also see the time delays of the signals with respect to a plane shower front.

4. Open Data: stocktaking and outlook

Auger data are not reproducible, not only because the exact replication of the Observatory would be unfeasible but especially because the sources and the beam of the cosmic rays that generated our data cannot be controlled. Our data are thus unique, and it is because of this uniqueness that in the conception and realisation of the portal we have been more concerned about the reproduction of our analyses over a specific dataset rather than about that of data.

Our experience has taught us that the realisation of open data is not simply a by-product of an instrument, it is a challenging project in itself: the first release was a complex and time-consuming project requiring the involvement of a large number of collaborators, because the knowledge of data and analyses in a project as large as our Observatory is by definition distributed and collective. The conception of how to open our data was challenging not only due to technicalities, but also because we knew that we needed to provide as much useful information to external users as possible, without knowing exactly what would be useful, as we are not external users. The extensive use of our open data, that we monitor via Zenodo and Matomo (https://matomo.org), has compensated us for the effort, mostly on the educational side and, to a much lesser extent, on the research one. As for dissemination and education, the data have been used by teams of students and summer students, both in Masterclasses and other training courses, besides having been exploited in outreach events such as the International Cosmic Day (see, e.g., [12]).

Though so far the use of our data for research has been limited to a handful of publications, we expect a larger interest once the fraction has been augmented to 30%, as stipulated in the newly updated policy of 2023. The release of this fraction of the data of the two oldest instruments, the 1500 m spaced surface array and the telescopes of the 4-unit fluorescence detector, will take place in 2024, to mark the 20th anniversary of the start of their operation. Before then, we will include, at the end of 2023, 10% of data from the 750 m spaced surface array and the telescopes of the 5th fluorescence detector, that will extend the energy range of released data down to 10^{17}eV.

Opening our data is a continuing task. The 2023 policy stipulates the disclosure of 30% of cosmic-ray data taken by all instruments operating during Phase I. The release of these data will be progressively done over the coming years, while new detectors (scintillators [13], underground muon detectors [14], and new radio antennas [15]) will join the old ones to produce Phase 2 data, on which the Collaboration will undoubtedly maintain its commitment to openness.

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