PROCEEDINGS OF SCIENCE

Offline simulation and reconstruction software framework for the JEM-EUSO missions

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The Joint Exploratory Missions for an Extreme Universe Observatory comprises a collection of complementary missions dedicated to pioneering technologies and techniques for a future space-based multi-messenger observatory which will have sufficient sensitivity and exposure to measure properties of extremely rare ultra-high energy (E>50 EeV) cosmic rays and very high energy (E>100 PeV) neutrinos. Here we describe a general-purpose software framework designed to facilitate detailed simulation and reconstruction of events observed by the various missions using both detection of fluorescence and Cherenkov light produced when cosmic ray or neutrino induced extensive air showers traverse Earth's atmosphere. The software builds on a framework developed by the Pierre Auger Collaboration. We describe the techniques used to organize contributions from numerous collaborators, manage an abundance of configuration information, and provide simple access to time-dependent detector and atmospheric information. We also explain how we seamlessly support a multitude of computing platforms, provide fast installation and maintain the broad testing coverage required for stability of the large and heterogeneous code base. We provide a few examples of simulated and reconstructed data gathered by some of the JEM-EUSO missions, including the EUSO-SPB2 instrument.

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1. Introduction

One challenge confronting large, geographically dispersed collaborations is how to effectively manage the development of software for simulation and reconstruction of data in a way that allows contributions from many collaborators to be straightforwardly accommodated and maintained. The Joint Exploratory Missions for Extreme Universe Observatory (JEM-EUSO) Collaboration [1] comprises hundreds of scientists from 10 countries, and thus faces the same challenges as other "big science" collaborations.

The JEM-EUSO [1] missions consist of complementary campaigns in pursuit of a future space-based multi-messenger observatory, such as POEMMA [2], with the ultimate objective of uncovering the origins and composition of Ultra-High-Energy ($E > 20$ EeV) Cosmic Rays (UHECR), and discovery of very high energy ($E > 20$ PeV) neutrinos originating from astrophysical transient sources [3].

Several pathfinder missions have been developed to demonstrate the technologies required to achieve this objective. A first prototype instrument was carried aboard a one-night high-altitude balloon flight in 2014 [4]. This instrument employed Fresnel optics and one photo-detector module (PDM) and was underflown by helicopter-borne light sources to test the technology. In 2017, a long-duration super pressure balloon flight was launched employing the same basic detection technique with the goal of detecting fluorescence light emitted when cosmic ray air showers excite atmospheric nitrogen as they traverse the Earth's atmosphere. Only limited data were gathered due to an apparent balloon flaw [5]. The EUSO-TA instrument, which also comprises 1 PDM and Fresnel optics, is deployed adjacent to a Telescope Array (TA) fluorescence station [6] and can detect both air showers and laser shots. Mini-EUSO, a scaled-down instrument, has been taking data aboard the International Space Station (ISS) since 2019 [7]. A second long-duration super pressure balloon flight, EUSO-SPB2 [8], was launched on May 13 2023. This mission carried two Schmidt telescopes, one pointed downward to detect fluorescence light and one with adjustable pointing in the vicinity of the Earth's limb to detect Cherenkov light from nearly-horizontal showers and to search from up-going showers (below the limb) produced by astrophysical transients, and to study backgrounds. Unfortunately, this balloon was also flawed, and despite good detector performance, limited data were collected.

From the early stages of JEM-EUSO planning, a software package called EUSO Simulation and Analysis Framework (ESAF) [9] was implemented in order to address large-scale simulation and reconstruction challenges of an instrument originally proposed to fly aboard the ISS [10]. At roughly the same time, the Pierre Auger Collaboration [11] was developing software to address similar challenges, with attention to building in the flexibility to accommodate future (unspecified-at-the-time) extensions. The design of the Auger $\overline{\text{Off}}\underline{\text{line}}$ software [12] proved successful in this regard and has been extended for upgrade requirements [13] and adopted in part by the NA61/SHINE Collaboration [14]. It thus seemed natural to adopt portions of the Auger $\overline{\text{Off}}\underline{\text{line}}$ software for the requirements of JEM-EUSO, including the overarching framework and utilities, as well as algorithms related to fluorescence and Cherenkov light emission and propagation that have been vetted with Auger Observatory data.

Here we briefly review the $\overline{\text{Off}}\underline{\text{line}}$ design and describe the extensions that have been developed for the various JEM-EUSO pathfinder missions. Further details are available in [12, 15].

2. Framework overview

The overall Auger Offline framework has been largely retained for EUSO-Offline , and is outlined here both for completeness and to illustrate some of the ways the flexibility of the software facilitates simulation and reconstruction for a variety of pathfinder instruments. More details can be found in [12, 15].

The framework comprises physics algorithms contained in *Modules*; a *RunController* which commands module execution; a read/write *Event Data Model* (EDM) from which modules read information and to which they write their results; a *Detector Description* (DD) which provides an interface to look up detector properties and conditions data; and a *CentralConfig* which points the modules and framework components to the configuration data they require, and which tracks provenance in order to support repeatability. The general scheme is illustrated in Fig. 1.

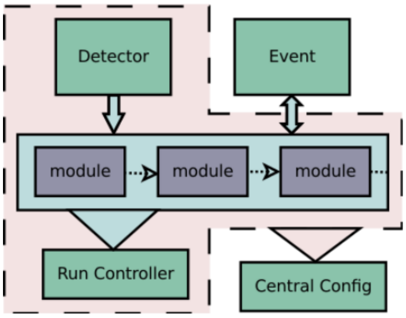


Figure 1: General organization of the Offline framework. See the text for details.

Simulation and reconstruction applications can generally be organized as a sequential pipeline of algorithms, with each encapsulated in a *module* which is registered with the *RunController*. The common module interface enables simple swapping out of algorithms in order to compare different approaches to a given problem, or to build up different applications. For instance, one can choose a module to generate a simulated signal from different sources, such as simulated air showers, laser shots, or other light sources, without having to recompile any code. Steering the execution of the modules is performed using a simple XML file which is read by the *RunController*.

The EDM itself is configurable (using XML) so that it can reflect the data structures of different JEM-EUSO missions. It is also equipped with a mechanism allowing modules to check the EDM constituents in order to determine if they can apply their algorithms to the event, or if some other action is required.

Data related to the instrument and time-dependent conditions data are accessible via the DD interface. The DD relays requests for information to a configurable back-end, known as the *Manager*, which can retrieve the requested data from different sources, such as databases or XML files. In this way, the DD interface code remains relatively simple, while the back-end handles the “dirty work” of finding and reading data in different formats. The Atmosphere and Earth are a part of the DD. A plug-in mechanism in the atmosphere description supports various interchangeable *models* for computing fluorescence and Cherenkov yields as well as Rayleigh and Mie scattering and Ozone absorption. Models can use either parametrizations written in XML files or measurements stored in databases. The Earth provides access to albedo estimates of different terrain, which can be used to simulate Cherenkov light reflected from the Earth surface into an orbiting telescope.

The Offline framework provides an XML and XML Schema-based configuration system with sufficient flexibility to accommodate the different JEM-EUSO instruments. This system is also employed to organize parameters used in individual physics modules. A *Central Config* (CC) object directs modules and framework components to the data they require. The CC also records all configuration data used during a run and stores it in an XML file which can be read back in order to reproduce a given run.

3. DevOps

A significant effort has been devoted to writing thorough tests, which are run automatically with the help of the Continuous Integration / Continuous Deployment (CI/CD) system provided by GitLab. This is particularly crucial for a project like EUSO-Offline, which is designed to support several past, ongoing, and future missions; new instrument designs have to be accommodated without breaking the old ones. We test the low-level code with a battery of unit tests built with the help of CppUnit (for older tests) and GoogleTest (for newer ones). Regression tests are performed on full simulation and reconstruction applications using a set of in-house tools for serializing results to check against references. A set of Python tools has been developed to find and run regression tests and example applications in parallel (using Dask) on the CI/CD for quick turnaround. We also exploit linting and static analysis tools provided by the Clang project.

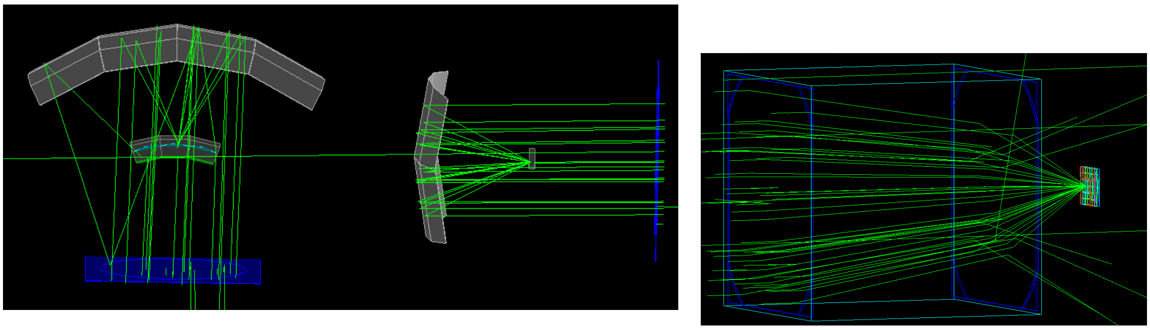
EUSO-Offline is built using CMake to write the build tool (either GNU Make or ninja). External dependencies include ROOT, Xerces, Geant4, boost, mysql, pytorch-c as well as a number of Python packages. We use Anaconda (a.k.a. conda) together with Libmamba to solve all of the dependencies and install the Python packages as well as pre-compiled binaries for the C/C++ dependencies. Installation via an industry standard like conda/mamba is robust and portable and can be performed in a few minutes rather than the many hours typically required to compile large packages like ROOT and Geant4 from source.

4. Simulation and Reconstruction in EUSO-Offline

One of the benefits of inheriting portions of the Auger Offline code is that it provides a set of well-tested modules for simulating light generation and propagation for both air showers and laser shots, various models for computing fluorescence yield, including the latest experimental data, as well as models for computing Rayleigh and Mie scattering and absorption using either parametric models or time-dependent measurements stored in a database. For the JEM-EUSO missions, it was necessary to extend the code in a number of ways, itemized below.

- The effects of Ozone absorption have been included as a *model* accessible via the Atmosphere interface.
- The Earth interface has been added to the DD to provide access to albedo estimates of different sorts of terrain which can be used for simulation of Cherenkov light reflected from the earth's surface into an orbiting telescope.

- A reader for the EASCherSim [16] Monte Carlo generator has been written. This generator supports the simulation of Cherenkov light emitted at very small angles with respect to the shower axis.
- A very configurable Geant4-based telescope simulation module has been written, which can model any of the JEM-EUSO instrument designs by simply specifying the desired XML configuration.
- Custom Fresnel optics simulation (written originally for ESAF) has been incorporated into the Geant4 simulation of the telescopes.
- Background simulation modules (both night-glow and spot-like) have been prepared and can model background light observed by the Fluorescence telescopes in either tilt or nadir pointing modes.
- Simulation of the trigger logic for the different instruments has been prepared.
- A convolutional neural network was developed and trained on simulated data to perform fast in-flight classification of events in order to prioritize event downlinking [17].



(a) EUSO-SPB2 instrument. The green lines represent photons. Mirrors and cameras are shown in grey, and the blue region represents the entrance pupil. The fluorescence telescope is on the right and the Cherenkov telescope is on the left.

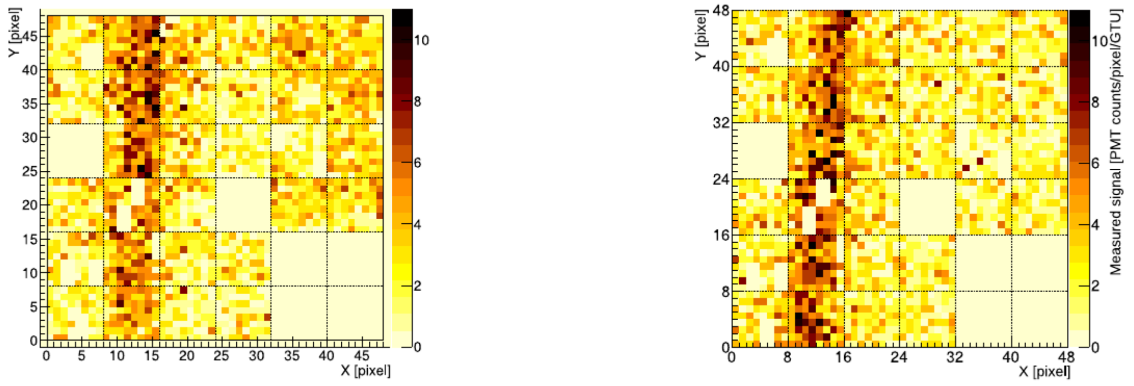
(b) EUSO-TA instrument, comprising 2 Fresnel lenses and 1 PDM.

Figure 2: Geant4 simulations of SPB2 and EUSO-TA telescopes.

We now broadly outline how various modules are assembled to perform simulation and reconstruction of data. Simulations begin with a module that reads output from a cosmic ray air shower generator or a simulation of a laser shot. A common interface, described in [12], connects the Offline to all the generator readers. A subsequent module positions the shower relative to the telescope. Cuts are applied based on the telescope's Field of View (FoV) in order to increase simulation speed. Subsequent modules compute the fluorescence and Cherenkov emission and propagation, including Rayleigh and Mie scattering and Ozone absorption based on models accessible via the Atmosphere interface, which follow parameterizations and data from [18]. The subsequent Geant4-based Simulator performs ray-tracing of the photons through the telescope optical system, as illustrated in Fig. 2 for the cases of EUSO-SPB2 and EUSO-TA.

A sequence of downstream modules simulates the camera efficiency, electronics response, and digitization based on laboratory measurements. Further modules simulate the backgrounds (described above) and the trigger logic. At this stage, the fully simulated shower can be written to file or passed directly to the sequence of reconstruction modules. Figure 3 shows a shower recorded by EUSO-TA next to a shower simulated using the parameters taken from the TA measurement.

Like simulation, reconstruction is performed by a Module sequence, which ultimately produces an estimate of the primary cosmic ray's energy, arrival direction, and composition. Backgrounds first are removed from the data pixel-by-pixel with a threshold cut based on the mean and standard deviation of the pixel trace. Subsequent modules further clean the track using constraints on pixel isolation from tracks and clusters in both space and time. An example of this track cleaning for the EUSO-SPB2 fluorescence telescope is shown in Fig. 4.



(a) Data

(b) Simulation

Figure 3: A UHECR track with an energy of 10^{18} eV and an impact point 2.6 km from the detector, according to TA reconstruction. The zenith angle of the shower was 8° and its azimuth was 82°. Panel (a) shows the track as recorded in EUSO-TA while panel (b) shows the Offline simulation of a shower with the parameters from TA. Figure from [6].

The shower-detector plane is computed from the pointing and signal size of pixels in the track. Using the shower-detector plane, the elevation angle of each pixel is determined, and a fit to the time-elevation distribution is used to extract the shower's arrival direction (see eg. [19]). A final module uses a fit to a Gaisser Hillas function to estimate the shower energy and atmospheric depth where the shower maximum occurs ($X_{\max}$).

5. Summary

Adapting the Auger Offline framework to the JEM-EUSO program has been a relatively straightforward process owing to the modular design, the flexibility provided by the configuration system, and the collection of well-vetted modules to assist in simulations. We have extended the system, predominantly with new modules specific to the JEM-EUSO mission characteristics, while modernizing the code base with newer tools for testing, building and deployment, and adoption of modern C++ standards.

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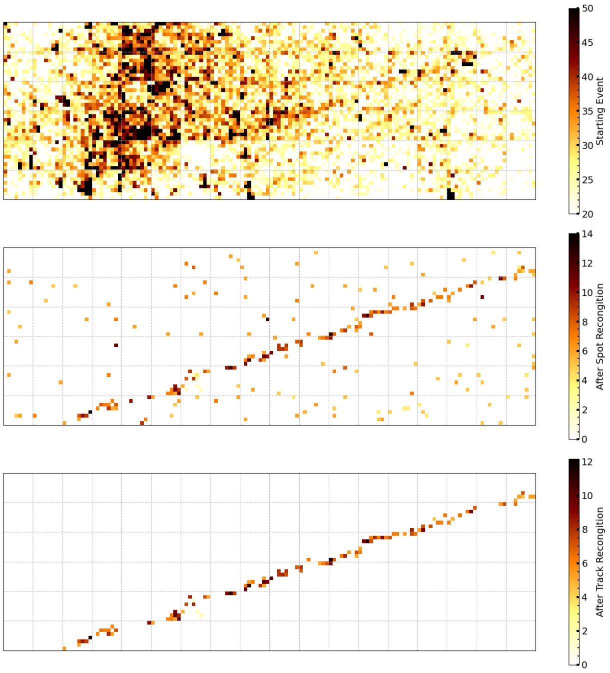

Figure 4: Laser track recorded on the EUSO-SPB2 fluorescence detector focal surface during the field campaign in the summer of 2022 at the TA site. Integrated counts over 128 time frames (top), pixels remaining after spot identification (middle), and pixels remaining after track identification (bottom).

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