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Update of the Offline Framework for AugerPrime

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Work on the Offline Framework for the Pierre Auger Observatory was started in 2003 to create a universal framework for event reconstruction and simulation. The development and installation of the AugerPrime upgrade of the Pierre Auger Observatory require an update of the Offline Framework to handle the additional detector components and the upgraded Surface Detector Electronics.
The design of the Offline Framework proved to be sufficiently flexible to accommodate the changes needed to be able to handle the AugerPrime detector. This flexibility has been a goal since the development of the code started. The framework separates data structures from processing modules. The detector components map directly onto data structures. It was straightforward to update or add processing modules to handle the additional information from the new detectors.
We will discuss the general structure of the Offline Framework, explaining the design decisions that provided its flexibility and point out the few of the features of the original design that required deeper changes, which could have been avoided in hindsight. Given the disruptive nature of the AugerPrime upgrade, the developers decided that the update for AugerPrime was the moment to change also the language standard for the implementation and move to the latest version of C++, to break strict backward compatibility eliminating deprecated interfaces, and to modernize the development infrastructure. We will discuss the changes that were made to the structure in general and the modules that were added to the framework to handle the new detector components.

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1. Introduction

The Offline Framework [1] was started about 20 years ago as a project to provide a common framework for the different simulations and analysis activities in the Pierre Auger Collaboration at that time. The framework can handle multiple input and output formats for the main data stream. The data format from the DAQ, the Offline internal format, and the ADST format [2] for end-user analysis all use the I/O component of the ROOT framework [3]. For simulations, the framework can process the output of common air shower Monte Carlo packages, like CORSIKA [4], CONEX [5], Aires [6], CoREAS [7], and ZHAireS [8]. It is also possible to generate input directly for special analyses. Most detector simulations are based on Geant 4 [9–11], complemented by customs simulations for tracking of Cherenkov and fluorescence photons and electronics simulations.

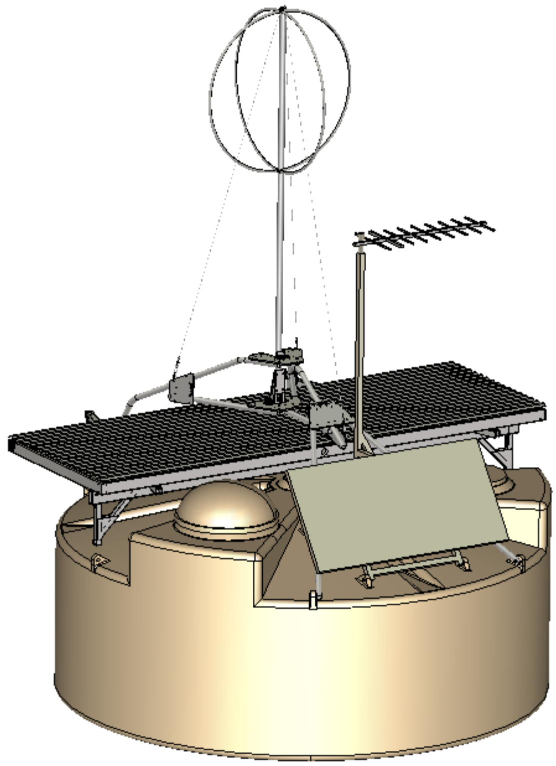

Figure 1: Upgraded Surface Detector station. The visible, new elements are the Salla Antenna for Radio Detection and horizontal enclosure of the scintillator detector (SSD). The small PMT for extending the dynamic range is inside the detector enclosure and therefore not visible. One can also identify the dome for the station electronics, the solar panel and the communications antenna.

At the time when the Offline Framework was designed, the Pierre Auger Observatory consisted of a surface detector overlooked by four groups of six fluorescence detectors [12]. Since then, a low-energy extension in the form of an infill array and additional, high elevation fluorescence telescopes have been added [13]. The installation of the Auger Engineering Radio Array (AERA) [14] required significant additions to the Offline Framework [15], which made both technical and physics studies [16] possible. A large number of the ongoing analyses in the collaboration depend on the Offline Framework, which is regularly executed as part of the centralized Monte Carlo production running on grid resources [17].

The latest challenge for the framework is the adaptation of the Offline Framework to the changes in the Pierre Auger Observatory brought by the AugerPrime [18] upgrade. The changes to integrate are

- The addition of the Scintillator Surface Detector [19],
- The addition of a small PMT to extend the dynamic range of the surface detector stations [20],

- The upgraded electronics of the surface detector [21] with a changed sampling frequency and new FPGA logic for triggering,
- The additional radio detector added to each surface detector station [22].

Because of the extent of the changes, it was decided to use the upgrade of the software for some potentially disruptive changes. This includes the deprecation of old interfaces and change of the language standard used for the implementation from C++ version 98/03 to C++ 11/14.

2. Structure

The Offline Framework has a modular structure, made up of several packages for organizing the code. The package dependency is organized to have a strict acyclic dependency to avoid problems building the code. At the lowest level, a set of utilities provides functionality that does not require any knowlege of the Observatory or of Cosmic Ray Physics. The framework layer provides the data structures for the detector description, the event, the sequencing of the execution of analysis modules, and for the overall configuration of the framework. The next layer is the event I/O, which fills the data structures with data, either real or simulated, at the beginning of the event loop, and which also handles the streaming of data back to disk. A small tool layer hosts physical algorithms, which are needed by several physics modules but which do not fit into the bottom utility layer because of dependencies on the framework data structures. The main part of the physics code is split into individual modules, whose execution is sequenced by the RunController.

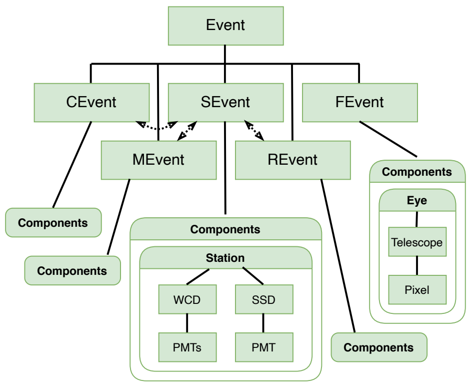

Figure 2: The event data structure. Several sub-detectors refer to the surface detector event, since detectors are co-located and share part of the hardware.

2.1 Data Structures

The Offline Framework provides two core data structures to the modules, the `Event` and the `Detector`. Both data structures follow closely the hardware hierarchy of the Observatory.

The event (fig. 2) provides the accumulated knowlege for a single recorded or simulated event. For data events, this includes calibration information, raw and calibrated data, and the results from the different stages of the event reconstruction. For simulated events,we store additional data from the air shower Monte Carlo, for example CORSIKA [4], and from the detector simulation in the event. This data is needed for comparison between simulation input and reconstructed data.

The detector structure (fig. 3) provides slowly varying information, which will be mostly unchanged for consecutive events. Due to the nature of the detection of extended air showers, the atmosphere is part of the detector and the data from atmospheric monitoring is provided as part of the detector.

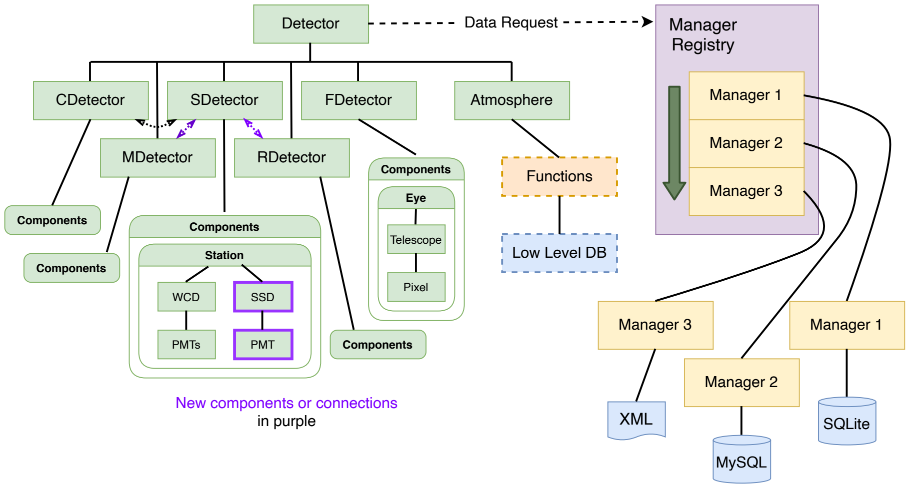

Figure 3: The detector structure parallels the layout of the event structure (fig. 2). Additionally, it provides access to atmospheric data. The actual data access is handled by a chain of managers, which are configured for the existing data sources available.

To allow flexible access to different data sources, the detector structure itself is a facade, provoding the user-visible interfaces to configurable managers. The managers provide access to different data sources, which could be XML [23] files or databases in MySQL [24] or SQLite [25] format.

2.2 Configuration and Control

At the beginning of a run, the framework processes a hierarchy of XML file, starting from a bootstrap file. The bootstrap file links to all the other XML files needed to configure the detector, set up the module sequence to be executed. The XML hierarchy is also used to provide additional configuration data required by the individual modules. Reading and writing is handled by special modules, which provide a thin interface to the event I/O layer of the framework. The names of the

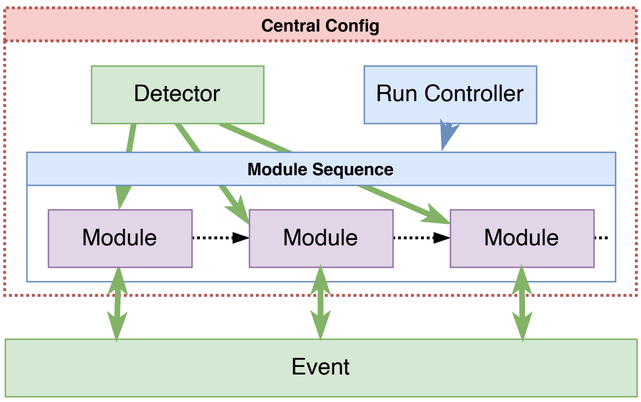

Figure 4: Module configuration, sequencing, and the detector are all configured by the `CentralConfig` component of the framework. The `RunController` determines the sequence in which modules get executed. The modules obtain information from the `Detector` and `Event` structures and return results in the `Event`.

files to be processed and written to are part of the data provided to the modules. The connection between the components is illustrated in fig. 4.

For repeatability and debugging, it is possbile to write the effective XML tree to disk. The resulting file can be used as the bootstrap file for another run of the framework.

2.3 Event I/O

At the beginning of the event loop, the event data structure has to be filled with the data expected by the module sequence. Typically, this is done reading the initial data in one of many formats from file. In exceptional cases, the initial data can also be generated, e.g., to simulate the calibration of a surface detector station using single muons. Besides the raw data from the Observatory and its own, internal format, the Offline Framework is able to process input from CORSIKA 7 [4], CONEX [5], Aires [6], and simulations of radio emission using CoREAS [7] and ZHAireS [8].

The internal root-based data format allows the user to save and restore the full information in the event data structure. It is also possible to save the result of simulations in the raw data format used for data acquisition or in the analysis-oriented ADST [2] format. The later is designed to provide lighter weight tools for the later stages of data analysis.

3. The Upgraded Framework

In the past, enhancements to the Pierre Auger Observatory, like the AERA radio array [14], the AMIGA underground muon detectors [26], or the HEAT telescopes [27] required changes to the Offline Framework. In all those cases, the changes could be implemented without significant changes to the existing data structures by adding new components and adjusting detector parameters.

In comparison, the AugerPrime upgrade [18] introduces changes to the details of the individual surface detector station by adding an additional scintillator [19], a small PMT to the main Water Cherenkov Detector (WCD) [20], and a radio detector [22]. In addition, the station electronics gets replaced [21] to provide a faster digitizer and additional channels to accomodate the new detectors.

3.1 Consequences of changes in the electronics

Handling additional electronics channels was not a significant challenge. The change of the digitizer frequency from the original 40 MHz to 120 MHz turned out to require some unexpected changes. In the detector and electronics simulation, the signal was originally binned in 1 ns for arrival times of photo electrons and signal processing, before getting mapped to the 25 ns binning of the digitizer. At 120 MHz, the bin length is $8.\bar{3}$ ns, with a natural time unit of ≈ 1.042 ns. That way, the mapping is 8 elementary bins in simulation to one bin of the new digitizer. For the old digitizer, 24 elementary bins fit into one digitizer bin. This change in binning makes it possible to use identical code and parameters for the early stages of the simulation of detectores with the old and new electronics. The implementation and debugging, however, required careful review and comprehensive testing to detect all places with implicit or explicit assumptions of binning in multiples of 1 ns.

3.2 Radio detectors

In the original AERA array [14], the stations were placed independently of the existing surface detector stations of the Observatory. In the AugerPrime upgrade, the radio stations are co-located with surface detector stations and share part of the local station electronics and data acquisition. In the raw data, some channels carry information from the surface detector, while others are used for the radio detector. This means that both detectors also share the raw event I/O. In the calibration stage, the data gets split into independent parts of the event, loosely coupled by the station id and position. That way, the structure of a radio detector stations as seen by the higher stages of the analysis remains unchanged from the one developed for AERA and existing algorithms work without significant modifications.

3.3 Additional, small PMT

The addition of the small PMT [20] broke the assumption that a WCD station has exactly three, identical PMTs. Implementing the change in the data structures was not complicated. However, the simulations and calibration procedures required changes.

In simulations we apply the quantum efficiency (QE) of the PMT at the time of the emission of the photon to avoid tracking photons that will never produce a photo electron. The QE depends both on the model of the PMT and the frequency of the Cherenkov photon. To avoid loosing all the speedup gained by suppressing photons at production time, a hybrid scheme was developed, where the larger QE was applied at the source and then re-applied according to the real QE of the PMT hit.

The calibration of the large PMTs and of the scintillator detector of a surface detector station relies on the detection of the signal generated by individual muons. This method breaks down for the small PMT, which cannot detect individual muons. Instead, calibration is done using small air showers detected by both the small and large PMTs. The corresponding data gets transported out of band. The calibration information has to be merged with the event stream later for event reconstruction.

3.4 General code overhaul

With the migration to C++11/14, the code had to get changed in two stages: First, all outdated constructs or code that was not standard compliant but accepted by the compilers had to be fixed. From then on, the code is migrated to use new constructs from C++11. Important changes include the consistent use of `nullptr` instead of `NULL` or 0 and a strong preference for the use of `auto`-declarations of iterators in `for`-loops. Proper use of initializers is required everywhere and the use of in-class initialization of all members is preferred.

Many classes in the event also act as containers. For example, the surface detector contains the stations participating in the event. The access to the begin and end iterators, provided by `StationsBegin` and `StationsEnd`, is extended by providing a `StationsRange` member function, which can be used in a range-based for-loop:

```
for (auto& station : sEvent.StationsRange()) {
  ...
}
```

This notation is more compact and easier to read than the old style for-loop.

4. Conclusions and Outlook

The $\overline{\text{Off}}\underline{\text{line}}$ Framework has proven to be remarkably flexible and robust, given that it was designed before many of the best practices for C++ projects got accepted in our communities. Also, the use of language elements like templates was generally considered to be too involved for scientific code. This, in turn, provided us with a framework with a clean, feature-complete, and orthogonal interface design. The complexity of implementation details is invisible to the user writing physics code. As a result, the interaction of the user code with the framework tends to be simple and fairly straight-forward. An experienced user can guess the functionality of many parts of the code without knowing the details of the parts of the framework used.

Having a comprehensive testing infrastructure, using unit tests and automatic physics validation played an important role in the maintainability of the framework. Most modern platforms for code hosting, either in-house or cloud based, like GitHub [28], GitLab [29], or Gitea [30] provide automated testing frameworks either integrated or as third-party integrations. External testing frameworks like Jenkins [31], which is currently used for automated testing of the $\overline{\text{Off}}\underline{\text{line}}$ Framework, can deal with a variety of hosting systems. In our experience, testing is essential for successful development and long-term maintenance of any complex code.

In all projects, it is a challenge to strike a balance between using external libraries for established functionality and re-implementing well-known algorithms. Having too many external dependencies complicates the installation of the project, while re-implementation or incorporation of established codes complicated the long-term maintenance, especially in the case of external codes still under development. In 2009, the Pierre Auger collaboration developed and adopted the Ape tool [32] as a platform-independent installation tool for the $\overline{\text{Off}}\underline{\text{line}}$ Framework and dependencies. Since then, Conan [33] established itself as a package manager for C++ projects.

Serializing data remains one of the problematic areas for scientific computing. The ROOT framework [3] provides one possible solution for data structures, but at the cost of importing a lot of other functionality the user might not want. For new projects, it is worthwhile to scan for reasonably recent evaluations of alternatives like the one presented in [34]. In most cases, streaming requieres some code to interface the data structures of the framework with the chosen library. It is also important to consider how to handle schema evolution, since data fields will get added or removed over the lifetime of a project.

In many cases, end-users will also look for a light-weight alternative to the full framework, especially if the installation is resource consuming and only a small subset of the functionality is actually needed for the final analysis. In such cases, users might look either for the ROOT framework [3] or for Jupyter notebooks [35] running Python [36]. Using such tools requires access to the data, which often means the development and maintenance of a tool to extract the required data subset and to write it in the desired format.

Finally, we would like to point out the obvious stating that even with a careful, initial design, there will always be a moment when the developer face the unexpected. This can be a design assumption that turns out to be overly restrictive or it could be old code or interfaces that should be removed, even if this affects some user code. Adhering to the recommendations made above will help to reduce the pain when this happens and ease the transition.

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