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The offline software package for analysis of radio emission from air showers at the Pierre Auger Observatory

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ABSTRACT

In anticipation of the Auger Engineering Radio Array (AERA) to be built at the Pierre Auger Observatory, radio functionality has been built into the Offline analysis framework. For the purpose of radio-hybrid analysis and to facilitate a standardized treatment of simulation as well as experimental data it is important that the analysis software for all types of detectors is bundled in one software package. The design philosophy of the Offline package is discussed with particular attention to the recently included radio functionality. In order to illustrate the full potential and flexibility of the software, two example pipelines for analysis of simulations as well as measured data are outlined and discussed.

1. Introduction

In addition to the existing surface particle detectors and fluorescence telescopes, the Pierre Auger Collaboration is deploying the Auger Engineering Radio Array (AERA). This is a new detector consisting of 161 antennas, covering an area of 20 km^2, which measures radio emission from air showers [1]. To reconstruct the events, and to study and compare the theoretical emission models with the measurements, radio functionality has been built into the existing Offline analysis and reconstruction framework of the Pierre Auger Observatory.

One of the strengths of the Pierre Auger Observatory is that the combination of fluorescence detectors and surface detectors allows for a combined analysis and cross calibration. For the purpose of radio-hybrid analysis, the new radio functionality should also be integrated with the existing software. Apart from this important aspect a combined software package is preferable above separate packages since it facilitates standardized definitions, methods and communication as well as a higher degree of cooperation between different groups within the collaboration.

2. Philosophy of offline

Offline is a very modularly designed piece of software with a simple and transparent interface that can be configured using `xml`-files [2]. The complete analysis pipeline is configured with a single `xml`-file that encapsulates the desired module-sequence. Additional `xml`-files are available for the configuration of every separate module. The design structure ensures that the modules do not communicate directly with each other but share information through the underlying data

Table 1
Reconstruction pipeline.

EventFileReaderOG	Reads measured data
RdEventPreSelector	Preselects events for analysis
RdChannelADCToVoltage-Converter	Converts ADC-values to voltages (Fig. 1a)
RdChannelPedestalRemover	Removes the pedestal (DC-offset) RdChannelResponseIncorporator
Incorporates the backward response of the analogue components (Fig. 1b)	
RdChannelRFISuppressor	Suppresses narrow band noise
RdChannelUpsampler	Upsamples the data
RdChannelBandpassFilter	Applies a user-configurable bandpass filter
LOOP	
RdAntennaChannelToStation-Converter	Reconstructs the *E*-field using the antenna response patterns and the arrival direction RdStationSignalReconstructor
Reconstructs the pulse properties	
RdDirectionConvergence-Checker	Checks whether the direction reconstruction has converged and then breaks the loop
RdPlaneFit	Performs a directional (planar) fit
END LOOP	
RdStationWindowSetter	Clips the Station time series to a 500 ns window
RdStationTimeSeriesWindower	Applies a (Hann) windowing function
RecDataWriter	Writes the data to disk (Fig. 1c)

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structures. Removing, rearranging, reusing and/or adding new modules is therefore an easy and transparent procedure. Essentially, the encapsulating `xml`-file is a small algorithm that executes the appropriate modules as functions on the underlying data structures.

An important design choice of the radio-Offline functionality is that a clear separation between raw measured data and physical quantities is made. The raw data acquired by the detectors are treated on the channel level where low level detector effects such as the influence of cables and filters are taken into account. On the station level, however, the physical electric field (*E*-field) and the geometry of the shower can be reconstructed or simulated.

Offline can be configured for different types of experimental as well as simulation data. The appropriate `xml`-files for the radio detector contain configurable antenna patterns and detector behaviors, while a separate module incorporates the read-in of many different data-files. At this moment measured data from two prototype systems for AERA near the Auger Balloon Launching Station, and data from AERA itself can be read in and analyzed by

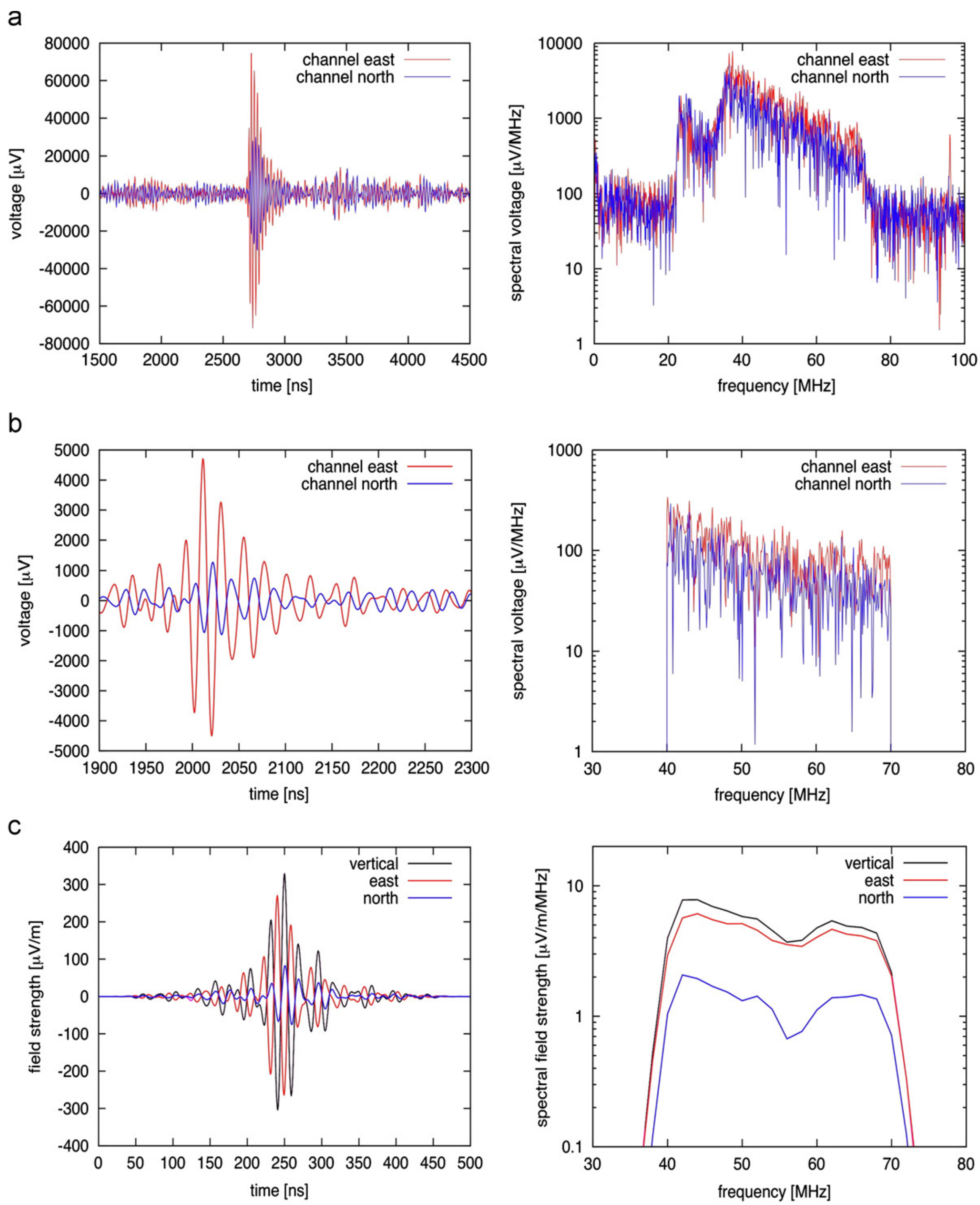

Fig. 1. Reconstruction of an event. On the left the signal is shown in the time domain and on the right one can see the corresponding spectra in the frequency domain. (a) The voltages that were measured at the analogue to digital converter. (b) After the RdChannelResponseIncorporator, one can see the expected voltages at the footpoint of the antenna. The response of the analogue components has been taken out and consequently the pulse has shifted to earlier times mainly due to cable delays. (c) The result at the end of the pipeline. Although the initial data was only 2-dimensional, the 3-dimensional *E*-field has been reconstructed using the arrival direction. It is also worth observing that the pulse has become more symmetrical because all phase shifts due to the detector response have been removed.