Beyond 2015

Simulation study of the Auger upgrade proposals

Auger Upgrade Committee

PIERRE AUGER OBSERVATORY

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1 Introduction

Addressing the physics questions outlined in the BEYOND 2015 proposal will require the upgrade of the surface detector array of the Pierre Auger Observatory. Several proposals for additional or upgraded detectors have been presented at recent Auger meetings, which aim at providing the data needed to increase the sensitivity of the Auger Observatory to the composition of the primary particles and possible changes of particle physics at ultra-high energy.

The BEYOND 2015 Upgrade Committee is providing a framework for testing the capabilities of the different proposals in terms of test installations as well as performance studies based on simulations. This note defines the strategy which has been developed for simulation-based performance evaluation, and gives the presently envisaged sequence of "deliverables" from the proponents to the Upgrade Committe for its evaluation.

The first stage (for the March meeting) focusses on the precision and resolution of the station based quantities. The second stage extends the comparison to benchmark physics quantities such as reconstruction of the number of muons, based on simulations of a common library of UHECR events. Each upgrade proposal will reconstruct the same set of events, provided in several libraries, as detailed below.

In addition to evaluating the respective merits of the different tank upgrade proposals, the simulations to be performed by the proponents include two alternatives regarding a possible SDE upgrade, in order to evaluate the interplay between an SDE upgrade and the net gain in detector performance.

2 Simulation package

The common framework for simulating the detector response of Auger detectors is the $\overline{\text{Off}}\underline{\text{line}}$ software package, which enables us to simulate SD (40 MHz and 120 MHz), FD telescopes, and radio. The $\overline{\text{Off}}\underline{\text{line}}$ package has been extended by the individual groups to include their specific detector extensions, which are by now included in the SDE upgrade branch (v2r8-blacktank-experimental) and is based on a previous $\overline{\text{Off}}\underline{\text{line}}$ release v2r8. Note that this branch diverged from the one used for current analysis about a year ago; both have seen significant changes and improvements, but they are not generally compatible at present. In the future, an optimzed version merging advances from both can be developed for general collaboration use.

The detector simulations are continuously stored directly after production on a server at KIT and can be downloaded at:

```
ssh -p 24 pinch@beyond.fzk.de  or
rsync  -auvz --rsh='ssh -p24' \
pinch@beyond.fzk.de:/home/pinch/data/beyond2015/FILENAMEs .
```

2.1 SD detector simulation

The branch, on which all upgrade simulations are based, is configured to have the following settings for the SD part:

- White top
- Dynamic range of 12 bit
- GPS accuracy of 4 ns
- Ideal array configuration (station altitude 1400 m)
- Detector spacing of 1500 m, i.e. regular grid

2.2 Existing CORSIKA libraries

The following CORSIKA sets have been simulated already:

- Two sets at fixed energies have been simulated: 10^{19} eV and $10^{19.8}$ eV. The first sets are referred to as **(F)**, for fixed energy, in the following. These include:
  - Number of events: 500 @ 10^{19} eV and 200 @ $10^{19.8}$ eV,
  - Interaction models: QGSJet II.04 and EPOS-LHC,
  - Primaries: p, He, N, and Fe,
  - Zenith angles: 21, 38, and 52 deg.
- Additionally two ranges with continuous event energies have been simulated, referred to as **(C)**, for continuous energy:
  - Number of events: 2000 in the energy range $[10^{18.85}\,\text{eV}, 10^{19.1}\,\text{eV}]$ and 500 in the range $[10^{19.6}\,\text{eV}, 10^{19.8}\,\text{eV}]$
  - Interaction models: QGSJet II.04 and EPOS-LHC,
  - Primaries: p, He, N, and Fe,
  - Zenith angle: $0 - 60^{\circ}$, distribution expected for surface array,
  - Spectral slope: -1.

3 Expected station and event based performance

The proponents are asked to provide information to quantify the expected precision, bias and resolution of the detectors on both station and event level. Is is understood that the analysis of simulated showers at the event level depends on the applied analysis methods (multi-variate methods, universality, etc.), that optimal analysis for a given detector takes time to develop, and that improvements will be made in the future. The benchmarks listed below are intended to enable the Upgrade Committee to make apples-to-apples comparision between proposals, to the greatest extent possible, at this moment in time.

The benchmarks specified below are mainly given in terms appropriate to the majority of detectors, which measure the number of muons or a quantity closely related to it, S_{μ}. (In case of ASCII is might be S_{em} with $S_{\mu} = S - S_{\text{em}}$.) Since the LSD detector proposal modifies the SD, those proponents should provide benchmarks capturing the spirit of each item as closely as possible, for the electromagnetic and muonic signals derived with the new detector. All further information on the performance that proponents can provide in addition to these listed, relevant to understanding the merits of their particular proposal, will be helpful to the Upgrade Committee.

3.1 Performance of individual stations

The following information should be provided. As applicable to the item, quantitative values should be based on the analysis of individual stations using the reconstructed datasets at fixed energies (F) : 10^{19} eV and $10^{19.8}$ eV and for p, He, N and Fe primaries. The target for these metrics is the March meeting, with items (iii) and (v) having highest priority.

(i) Strategy for calibrating the new detectors. Expected precision of the relative and absolute calibration to be achieved should be provided. Means for validating the calibration should be discussed.

(ii) The time resolution of the signal trace(s) and response time of the detector.

(iii) The resolution and the bias in reconstructing the muonic signal (or electromagnetic signal, as applicable to the upgrade) in individual detector stations. The bias is defined as $\Delta S_{\mu} = (S_{\mu,\text{rec}} - S_{\mu,\text{MC}})/S_{\mu,\text{MC}}$ and the resolution is given by its variance $\sigma(\Delta S_{\mu})$. These quantities should be shown as a function of the distance, r, of the tank to the shower core for each of the different zenith angles of the simulation sets (F).

(iv) Lateral distance range and corresponding typical range of signal amplitudes within which the detectors are expected to perform optimally. At a minimum this should include determination of the saturation distance, $R_{\rm sat}$, defined to be the radius above which the reconstructed signal has less than a 20% departure from linearity in at least 90% of the events, for showers of $10^{19.8}$ eV, for the different angles as given in (F).

(v) For a detector which is planned to trigger independently of the existing water-Cherenkov detectors (WCD), or is a modification of the existing WCD, the trigger probability as function of the lateral distance of the detector should be given. In particular, above what distance and below what typical detector signal does the trigger probability fall below 95% and 50%?

3.2 Event-based observables

The performance of the event reconstruction is of great interest even though such performance measures are only approximate for the time being, because some reconstruction codes are clearly not as mature as others. With that being recognized, the following information should be provided by June. It would be helpful if the different proponents would undertake a first evaluation of items (b), (c), (d) and (e) earlier.

(a) Average lateral distribution of measured signals and any other pertinent quantities, for different energy, zenith angles and composition (F).

(b) The resolution and bias of the reconstructed S_μ (or applicable relevant quantity such as N_μ) of the proposed detector, at an "optimum radius" $r_{\rm opt}$:
$\Delta S_\mu\big|_{r=r_{\rm opt}}$ and $\sigma(\Delta S_\mu\big|_{r=r_{\rm opt}})$.
The optimum radius[1] for a given detection method and detector spacing is the radius giving the smallest variance of ΔS_μ, or alternatively the best separation power for different primary masses. As $r_{\rm opt}$ depends on the shower properties, it should be estimated for the fixed energy library (F). In general, $r_{\rm opt}$ will not be 1000 m; in the event that $r_{\rm opt}$ has not yet been determined for the given upgrade proposal, the resolution and bias can be reported taking $r_{\rm opt}$ =1000 m or other specified distance.

(c) The resolution and bias of the reconstructed muon production depth distribution (MPD), for different energies, zenith angles and primary composition (F). The reference is the MPD one would obtain from the muons for a given detection energy threshold, arriving at ground as predicted by Monte Carlo simulation.

(d) Scatter plots for each library in (F) to illustrate the correlation and separation power of the different composition sensitive parameters that can be derived with the upgraded array (i.e. S_μ, N_μ or $S_{\rm em}$ vs. $S(1000)$, with each shower being one point in the plot).

(e) Merit factor, $f_{\rm I,J}$, for separating primary mass groups, to be derived from simulation sets (F). The primary combinations p-Fe, N-Fe and p-He should be specifically considered. This might be, e.g.,

$$f_{\rm p,Fe} = \frac{|\langle S_\mu^{\rm Fe}\rangle - \langle S_\mu^{\rm p}\rangle|}{\sqrt{\sigma^{2\,\rm Fe}_\mu + \sigma^{2\,\rm p}_\mu}},$$

or a more general multi-variate discrimination method can be used. In addition it will be important to consider also the limited energy resolution by deriving the same merit factors including a realistic energy reconstruction using simulation sets (C).

(f) The event reconstruction efficiency should be evaluated (F,C). Are there event geometries or other conditions that lead to an improved or much poorer than average event reconstruction?

[1]See D. Newton et al., The optimum distance at which to determine the size of a giant air shower, Astropart. Phys. 26 (2007) 414.