PROCEEDINGS OF SCIENCE

Using NuRadioMC to study the performance of UHE radio neutrino detectors

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NuRadioMC is an open-source, Python-based simulation and reconstruction framework for radio detectors of ultra-high energy neutrinos and cosmic rays. Its modular design makes NuRadioMC suitable for use with a range of past, current and future detectors. In addition, the recent deployment of a complete documentation as well as a pip release make NuRadioMC relatively easy to learn and use. Here, we outline the features currently available and under development in NuRadioMC, with a focus on its usage to simulate and study in-ice radio neutrino detectors.

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1. Introduction

Two key aspects to the design and operation of large-scale physics experiments are the simulation and reconstruction of the expected observations. As with all code development, challenges include ensuring the (continued) accuracy of simulations, enabling new users to learn how to use it, and avoiding the duplication of development efforts. NuRadioMC [1, 2], an open-source, python-based software framework for simulation and reconstruction for radio detectors of ultra-high energy (UHE) neutrinos and cosmic rays, aims to tackle these through

1. an extensive comparison with existing codes, as well as continuous automatic and manual consistency checks;
2. a complete API documentation, annotated examples, and a pip-installable release;
3. a modular design, enabling straightforward adaptation for a wide range of use cases.

Thanks to the above, NuRadioMC has been used in an increasing number of studies and publications. An up-to-date overview of these is provided on the NuRadioMC GitHub page[1]. For all released features, annotated examples, manuals, and a description of the relevant modules can be found as part of the code base or in the online documentation[2].

This article will provide a brief introduction to the features available in NuRadioMC, as well as those currently in development. In section 2, we provide an overview of the simulation capabilities of NuRadioMC, with the reconstruction algorithms outlined in section 3.

2. Simulation

The simulation of UHE radio emission from particle to detector is split up into several stages, each incorporated in an independent module:

1. event generation;
2. radio signal generation;
3. in-ice signal propagation;
4. detector response.

Figure 1 shows a sketch of the simulation process. The modular approach provides the user with the flexibility to use or modify only a specific part of the simulation; one can for example simulate the electric fields of an in-air cosmic ray shower using CoREAS [3], and use these as an input in the detector simulation in NuRadioMC.

An extensive description of the simulation features in NuRadioMC can be found in the original NuRadioMC paper [2]. A brief summary, focussing in particular on the new features introduced since then, is presented in the following sections.

[1] github.com/nu-radio/NuRadioMC
[2] nu-radio.github.io/NuRadioMC/main

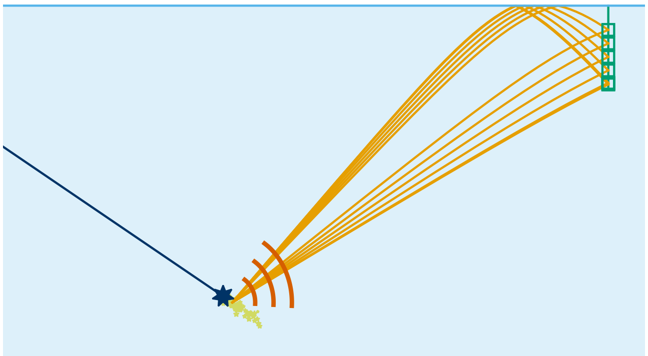

Figure 1: A sketch of the simulation process in NuRadioMC: 1. Generating the UHE particle shower (e.g. neutrino) (blue, yellow); 2. Simulating the Askaryan radio emission from the in-ice shower (red); 3. Propagating the radio signal through the ice (orange); 4. Incorporating the hardware response (antenna, amplifier, ...) of the detector (green).

2.1 Event generation

The first step of the simulation is the generation of the UHE particle showers. For neutrinos, NuRadioMC comes with several flux models, although one can of course also simulate a custom flux by an appropriate convolution of log-uniform energy bins. The relevant quantities generated in this step are the shower position, direction, energy, type (hadronic or electromagnetic) and weight due to attenuation in the earth. It is also possible to take into account secondary interactions from μ and τ by using Proposal [4–6], a Monte-Carlo code that simulates the propagation and stochastic energy losses of charged leptons.

2.2 Radio signal generation

Several models for the in-ice Askaryan radio emission are included in NuRadioMC through the `NuRadioMC.SignalGen.askaryan` module. More details can be found in the NuRadioMC paper [2]. In particular, there are both fast, fully analytic models such as `Alvarez2009` [7], which are suitable for e.g. effective volume studies, as well as the highly accurate semi-analytic `ARZ2020` model [8, 9], which includes a library of shower profiles to account for the LPM effect. This latter model has been verified to agree with microscopic Monte-Carlo simulations to the level of a couple of percent, and is therefore suitable for neutrino identification or reconstruction studies.

2.3 Signal propagation

As the index of refraction in ice is not constant, the radio emission does not travel along straight lines, but along multiple ('direct' and 'refracted'/'reflected') curved trajectories. For the approximation of an exponential index of refraction profile, this can be solved analytically, and NuRadioMC includes a fast, C++-based ray tracer that does this. For more complicated ice models, one has to resort to solving the ray tracing problem numerically, which can be done by installing RadioPropa [10, 11], which is under ongoing development and can already be used from NuRadioMC.

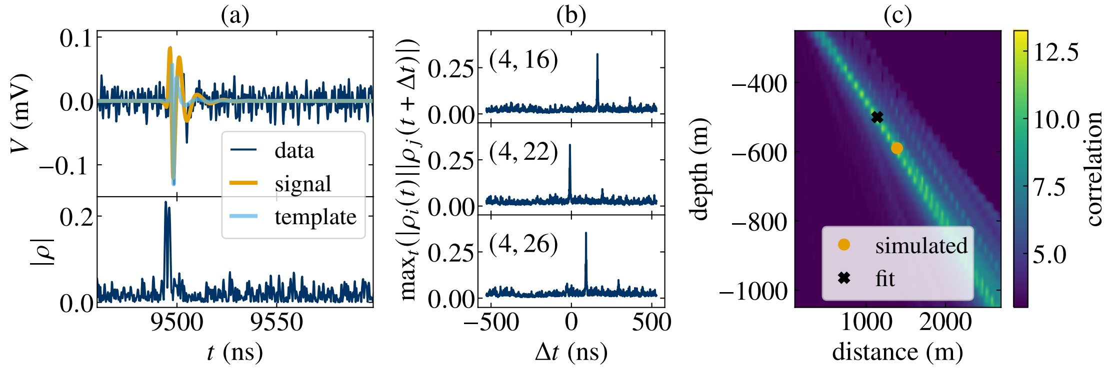

Figure 2: The vertex fitting algorithm in NuRadioReco. (a) The recorded voltage trace is correlated with a signal template for each channel. (b) The correlations $\rho_{i,j}$ for different channels (i, j) are shifted with respect to each other by Δt and then multiplied together. This results in a peak for the 'true' timing difference. (c) The sum of the correlation over all possible channel pairs and ray types is maximized as a function of vertex position.

In addition, polar ice can be a birefringent medium, due to alignment of the ice crystals with the ice flow or gravitational stress. Code to simulate birefringence in NuRadioMC has been developed recently [12], and is expected to be included in the main release version soon.

2.4 Detector response

The final step of the UHE radio shower simulation is the detector hardware response. NuRadioMC provides the flexibility to specify the signal chain either using human-readable files in JSON format, or through a database for a more advanced, time-dependent detector description. An array of different trigger options (high-low threshold, envelope, phased array, etc.) is also available.

In addition to the built-in options in NuRadioMC, one can also easily define a custom hardware (e.g. filter or amplifier) response or trigger by adapting just a couple of lines of code.

3. Reconstruction

The reconstruction capabilities of NuRadioMC are included as part of the NuRadioReco [1] modules. Several standard data processing and reconstruction modules for both neutrinos and cosmic rays are available. In general, the reconstruction of an in-ice radio event has three aspects: first, the interaction vertex (which is, approximately, the source of the radio emission) has to be reconstructed. Using the reconstructed vertex as an input, both the energy and the direction of the radio shower can then be determined. The following sections give a brief summary of the reconstruction algorithms currently available in NuRadioReco.

3.1 Vertex reconstruction

The reconstruction algorithm for the in-ice interaction vertex works through cross-correlation of the voltage traces with a pulse template. The maximum cross-correlation between different channels would then be expected when their relative time shift corresponds to the actual difference in pulse arrival times. The vertex position is obtained by maximizing the total channel-channel correlation. This process is illustrated in Figure 2.

In order to avoid recomputing the ray propagation times for each vertex position in the fit procedure, they can be precomputed once on a (2D, in the case of azimuthal symmetry) grid for each antenna depth. The propagation times are then obtained by interpolation. More details can be found in section 3 of [13].

3.2 Direction reconstruction

Once the interaction vertex position is known, it is possible to determine other properties of the in-ice shower, such as its direction or total energy flux. The direction reconstruction algorithms available in NuRadioMC are based on the forward-folding principle [1]: the total detector response is simulated for a given shower direction and energy. The reconstructed direction is then obtained by minimizing the χ^2 difference with the measured voltage trace. Implementations exist for both shallow ('ARIANNA-like') [14] and deep ('ARA-like') [15] in-ice radio detectors. The latter will be included in NuRadioReco in an upcoming release.

3.3 Energy reconstruction

Although the shower energy can be obtained through the forward-folding approach outlined in subsection 3.2, NuRadioReco additionally contains an energy reconstruction algorithm based on Information Field Theory (IFT). This approach allows for a more model-independent way to obtain the electric field pulse from the antenna measurements from which the neutrino energy is estimated. More details on this algorithm are given in [13].

4. Conclusion

NuRadioMC is a tool under active development, suitable for many detectors in the radio neutrino and cosmic ray world. It implements state-of-the-art physics and also serves as a well-tested reference implementation for the radio community. Its modularity allows for straightforward additions, modifications and comparisons between different approaches. The availability of an extensive documentation and tutorials additionally enable new users to quickly run their first simulation or reconstruction study. Should you consider using NuRadioMC for your experiment, please do not hesitate to reach out to the development team.

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