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NuRadioOpt: Optimization of Radio Detectors of Ultra-High Energy Neutrinos through Deep Learning and Differential Programming

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Detection of neutrinos at ultra-high energies (UHE, $E > 10^{17}$ eV) would open a new window to the most violent phenomena in our universe. Radio detection remains the most promising technique at these energies. However, owing to the expected small flux of UHE neutrinos, the detection rate will be small, with just a handful of events per year, even for large future facilities like the IceCube-Gen2 neutrino observatory at the South Pole.
In this contribution, we will discuss how to substantially enhance the science capabilities of UHE neutrino detectors by increasing the detection rate of neutrinos and improving the quality of each detected event, using recent advances in deep learning and differential programming. First, we will present neural networks replacing the threshold-based trigger foreseen for future detectors that increase the detection rate of UHE neutrinos by up to a factor of two. Second, we will outline and present preliminary results towards an end-to-end optimization of the detector layout using differential programming and deep learning, which will improve the neutrino direction and energy determination. We will quantify the expected improvements for the planned IceCube-Gen2 in-ice radio array: Gen2 will be able to expedite the discovery of UHE neutrino fluxes by up to a factor of five, see sources from deeper in our Universe, increasing the observable volume by up to a factor of three, and measure the neutrino-nucleon cross-section at EeV energies with up to 3x smaller uncertainty.

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1. Introduction

In this contribution, we outline how the capabilities of radio neutrino detectors can be improved substantially using recent advances in deep learning and differential programming. We will focus on the in-ice technique as it is the most efficient and/or mature way to observe neutrinos of all flavors in the energy range between 10^{17} eV and a few times 10^{19} eV [1] and because - with IceCube-Gen2 - a large detector is in advanced planning stages [2–4]. However, the proposed optimizations can be applied directly to other in-ice radio detectors and adapted to other radio-based detection techniques of neutrinos.

An in-ice radio detector for UHE neutrinos is built as an array of compact detector stations. The stations are separated by approx. 1.5 km to see largely independent ice volumes. Radio antennas measure the radio emission created by a neutrino-induced particle shower in the ice via the Askaryan effect. Each detector station operates autonomously, i.e., it self-triggers on potentially interesting events and has enough instrumentation to reconstruct the neutrino properties of interest.

Two key factors will impact the science output: The detection rate of UHE neutrinos and the ability to determine the neutrino's energy and direction. The science output will improve with the number of detected neutrinos and a more precise determination of their energy and direction. Here, we propose improving both key factors through:

Intelligent Trigger: The sensitivity to UHE neutrinos can be increased by replacing the current threshold-based trigger with an intelligent deep-learning-based trigger. We discuss preliminary results that show that the detection rate of UHE neutrinos can be increased substantially by analyzing the data stream in real-time with neural networks.

End-To-End Optimization: The detector's ability to infer the neutrino's direction and energy can be improved by systematically optimizing the detector station layout and simultaneously developing the matching deep-learning-based reconstruction algorithms.

2. Intelligent Deep-Learning-Based Trigger

Radio detector data cannot be stored continuously because of the large data rate of approximately 10 TB/s (for Gen2-radio) and the bandwidth and power limitations of remote detector stations. Instead, the detector is only read out following a trigger condition, and the maximum manageable data rate is approx. one trigger per second per station, depending on the exact choice of communication method. The challenge is to design an algorithm that efficiently triggers neutrino signals while being insensitive to thermal noise fluctuations. All other sources of background are less frequent or restricted to short time periods only. Therefore, only thermal noise fluctuations need to be considered at the trigger stage, which simplifies the problem and allows for most of the testing and verification to be done in a local lab.

The current design of Gen2-radio uses a threshold-based trigger founded on prior experience from the ARIANNA, ARA, and RNO-G projects. The trigger already underwent several improvements (e.g., bandwidth optimizations [5], and interferometric beam forming [6]), but the final trigger condition is still determined by a threshold crossing, either on amplitude or integrated power. The deep component uses an interferometric phased array which exploits the radial symmetry of four dipole antennas with small separation on a vertical string. The shallow component uses a simpler

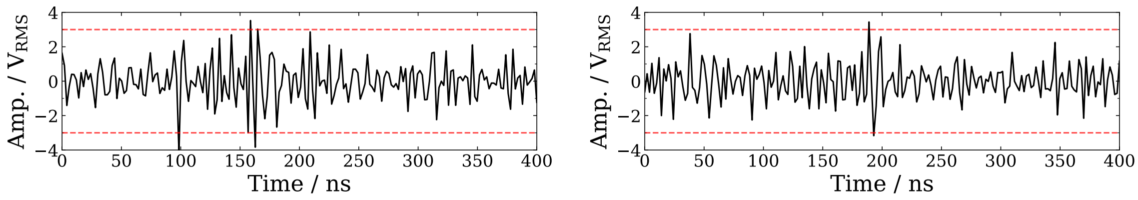

Figure 1: Typical signal pulseform (left) and noise pulseform (right) measured by an LPDA antenna.

time-coincidence trigger from four downward-facing LPDAs as no simple symmetry can be exploited. An example of a typical signal and noise pulseform from an LPDA at a low signal-to-noise ratio is shown in Fig. 1.

In both cases (deep and shallow), the thresholds need to be set high enough so that noise fluctuations trigger the readout at a manageable rate of less than 1 Hz. This limits the sensitivity of Gen2-radio and any radio neutrino detector in general. Our goal is to increase the sensitivity to UHE neutrinos by an intelligent deep-learning-based trigger while keeping the low trigger rate on noise fluctuations of 1 Hz. We expect a large gain because the current trigger algorithms do not consider the shape of the signal pulseform, but offline analyses showed that the pulse form is a powerful discriminator between signal and background [7, 8]. In addition, in the case of the shallow trigger, the time structure in the four antennas is not considered in the trigger algorithm because the shallow antennas have no simple symmetry that can be exploited as in the case of the deep phased array. Therefore, we expect the gain to be larger for the shallow component. An intelligent trigger can be implemented in two ways:

Second stage filter: Potential interesting signals are still triggered by the existing threshold-based triggers but run at a much higher rate (e.g., 10 kHz) by simply reducing the triggering threshold. Then, a neural network is used to reject triggered noise fluctuations, reducing the rate to what the DAQ can handle (approx. 1 Hz) while accepting neutrino signals with high efficiency. Here, the gain in effective volume is still limited by the first-level threshold trigger. This limitation can be overcome by using a neural network directly as the first trigger stage.

Continuous analysis of data stream: A neural network analyzes the antenna outputs continuously and identifies interesting signals. The network is tuned to trigger at a manageable rate of approx. 1 Hz. This trigger scheme has more potential for improvement but requires increased on-station computing resources.

Promising results have already been achieved for a second stage filter by ARIANNA for a shallow detector station [9] and more recently by RNO-G for a deep detector station [10]. In these studies, a convolutional neural network (CNN), small enough to run on existing hardware, is used to reduce the background of thermal noise fluctuations by four orders of magnitude. In the case of the already very efficient phased array, it was found that the neutrino detection rate can be further improved by approx. 50% at 10^{17} eV and 20% at 10^{18} eV neutrino energy with a small CNN [10]. The improvement is larger at lower neutrino energies because more signals are closer to the trigger threshold. Further improvements can be expected with increased FPGA computing resources as foreseen for future DAQ systems that will enable larger, more efficient neural networks.

In this contribution, we make two generic assumptions of possible improvements to show how much can potentially be gained with an improved trigger and to motivate further development of

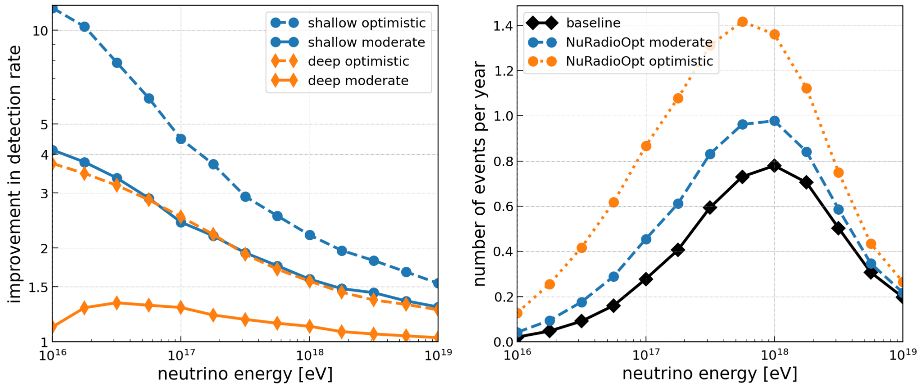

Figure 2: (left) Increase in detection rate due to the intelligent deep-learning-based trigger. (right) Number of neutrinos detectable per year with IceCube-Gen2 with and w/o the intelligent trigger.

the trigger algorithms and suitable hardware. Our moderate assumption is that all signals above three times the RMS noise can be identified, which has already been achieved for the deep detector component with the second-stage filtering approach shown in [10]. Our optimistic assumption is that all signals above two times the RMS noise can be identified, which would require continuous processing of the data stream. We calculated the detection rate by performing a detailed NuRadioMC simulation, as done for other Gen2-radio studies including a full simulation of the current trigger system [3, 4, 11–13]. The result is shown in Fig. 2 left. For the deep trigger, the performance of the moderate assumption is close to the current capabilities of the phased array trigger system, which shows that the estimated improvement is indeed moderate. For the shallow component, the improvement is larger because of its larger potential for improvement (see discussion above) and reaches up to a factor of 4.5 increase in event rate at 10^{17} eV.

The Gen2 radio array will be a combination of deep and shallow components. The current reference design has 164 deep and 361 shallow components [4]. To estimate the overall impact, we calculated the expected event rate for a reference neutrino flux (measurement of the astrophysical neutrino flux by IceCube extrapolated to higher energies [14] plus a model for the GZK neutrino flux [15]). The result is shown in Fig. 2 right. With only moderate improvements in the trigger, the number of events will increase by 34%, from 4.7 to 6.3 events per year. With optimistic assumptions, the number of events will more than double to 9.8 events per year. The increased number of neutrinos will significantly increase the science output (see impact section below). It is important to point out that this is achieved at negligible additional cost, which needs to be compared to the standard way of increasing the sensitivity of building a larger detector where the cost scales linearly with sensitivity. However, the additional neutrinos that will be measured through the intelligent trigger will have a lower event quality which will complicate the reconstruction of the neutrino properties. Therefore, this development happens simultaneously with the end-to-end detector optimization discussed next.

3. End-to-end Optimization

The current design of in-ice radio detector stations is based on prior experience but has not been thoroughly optimized for their primary objective of measuring each neutrino's energy and

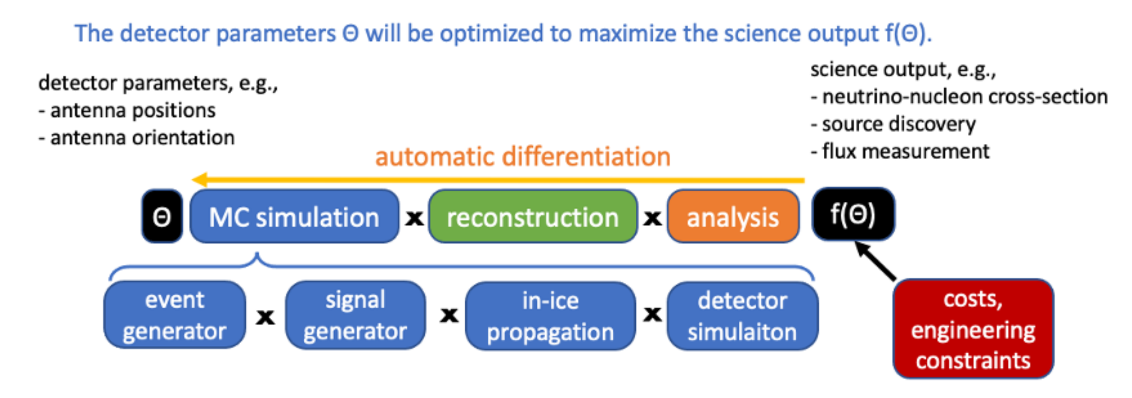

Figure 3: Illustration of end-to-end detector optimization pipeline.

direction. This is because precise and flexible enough MC tools have only become available recently with NuRadioMC [16] and subsequently reconstruction algorithms have been developed that allow quantifying energy and direction resolution (e.g. [17–20]). But still, current MC tools are too time-consuming, and reconstruction algorithms must be re-tuned to match a modified station layout which is time-consuming, rendering a systematic optimization impossible.

Here, we propose to develop an optimization pipeline of the detector station layout and a simultaneous development of the matching reconstruction algorithms. Taking into account the interplay between station design and reconstruction algorithm is important. More advanced reconstruction techniques based on deep neural networks might prefer a different station design than simpler traditional techniques. The anticipated improvement in reconstruction performance is likely to arise from a combination of an optimized detector layout and more sophisticated reconstruction algorithms. In analogous experiments, such as IceCube, it has been observed that deep-learning techniques contributed significantly to the enhancement of reconstruction performance which, e.g., led to the recent discovery of neutrino emission from the Galactic plane [21].

The end-to-end optimization can be achieved through differential programming. The basic approach is to construct a differentiable objective function that is dependent on the detector layout, including the parameters we aim to optimize, such as the position of an antenna. Subsequently, the gradient with respect to the antenna depth (or any other detector parameter) can be computed, allowing for the improvement of the station layout using gradient-based optimization techniques. For an in-depth review of end-to-end optimization with differential programming from the MODE collaboration (for Machine-learning Optimized Design of Experiments) that we are part of, we refer the reader to [22].

A schematic representation of the optimization pipeline is shown in Fig. 3. The objective function can be subdivided into several modular steps, which simplifies the problem. The recent progress in quantifying the three main science objectives (characterization of the diffuse UHE neutrino flux, point-source discoveries, and neutrino-nucleon cross-section measurement) [11–13] based on the detector's effective volume and reconstruction resolution can directly be used as the objective function while also factoring in cost and engineering constraints. The high-level analysis is not time-critical and can be rendered differentiable using automatic differentiation tools such as JAX.

The reconstruction algorithm is a deep neural network that is differentiable and fast to execute by construction. The network can be pre-trained on a variety of geometries by using Graph Neural Networks which will allow the network to perform well on new geometries without expensive re-training. The Monte Carlo (MC) simulation can be accelerated and rendered differentiable simultaneously by substituting time-intensive components with surrogate models based on deep neural networks (DNN). Promising results have been achieved where the two most time-critical simulation steps, of generating the radio emission from in-ice particle cascades and propagating the radio signal through the ice, were replaced with surrogate models [23].

The improvements that an end-to-end optimization and deep-learning event reconstruction will yield are difficult to predict without actually performing the optimization. Nevertheless, to get an impression of the impact of possible improvements, we make a moderate and optimistic assumption. Our moderate assumption is that the average reconstruction performance remains at its current level (an average 5° angular resolution and factor-of-two energy resolution) but includes the additionally detected neutrinos due to the trigger improvements. This would already be an achievement because the trigger improvements only add events at smaller signal-to-noise ratios. The optimistic assumption is to improve the angular resolution to 3° and the energy resolution to 30%. This has already been achieved for sub-types of neutrino interactions (and moderate quality cuts in the case of the deep detector components) [19, 20, 24, 25] and is thus not unrealistic.

4. Impact

Now, we quantify the impact of the expected improvements in trigger rate and reconstruction performance on the three main science objectives of UHE ($>10^{17}$ eV) neutrino detection: The characterization of the ultra-high-energy neutrino flux [11], the discovery of individual sources [12], and the measurement of the neutrino-nucleon cross-section at UHE energies that are beyond the reach of particle accelerators [13].

Impact on neutrino-nucleon cross-section measurement [11]: The increased event rate, as well as the better reconstruction resolutions, improve the cross-section measurement significantly (see Fig. 4 left). The expected resolution depends on the realized UHE neutrino flux. Here, we study two representative flux models: The measured astrophysical neutrino flux by IceCube (measured between 10 TeV and a few PeV) extrapolated to higher energies (IceCube ν_μ) [14], and a model of neutrino production from AGNs (Rodrigues et al.) [26]. The latter neutrino flux peaks between 10^{17} eV and 10^{18} eV and is representative of various source and GZK flux models that peak at these high energies (see [13] for a detailed overview). For these two fluxes the analysis of [11] was repeated. For the IceCube ν_μ flux, the measurement uncertainty reduces by a factor of three from $\log_{10} \sigma/\sigma_{\mathrm{std}} = -0.09^{+0.72}_{-0.36}$ to $-0.01^{+0.21}_{-0.19}$. For the Rodrigues et al. flux, the uncertainty halves from $-0.01^{+0.22}_{-0.18}$ to $-0.01^{+0.11}_{-0.08}$.

Impact on flux characterization [13]: The increased event rate through the intelligent trigger will expedite flux discovery substantially. The analysis of [13] was repeated for the NuRadioOpt improvements. In Fig. 4 right we show the increase in discovery time for an extrapolation of the IceCube measurement using the HESE sample which predicts a low flux at UHE energies [27]. For low fluxes, the improvements are most important and we see that the discovery time decreases from 31 years to 16 years (8 years) for the moderate (optimistic) scenario, hence, the anticipated

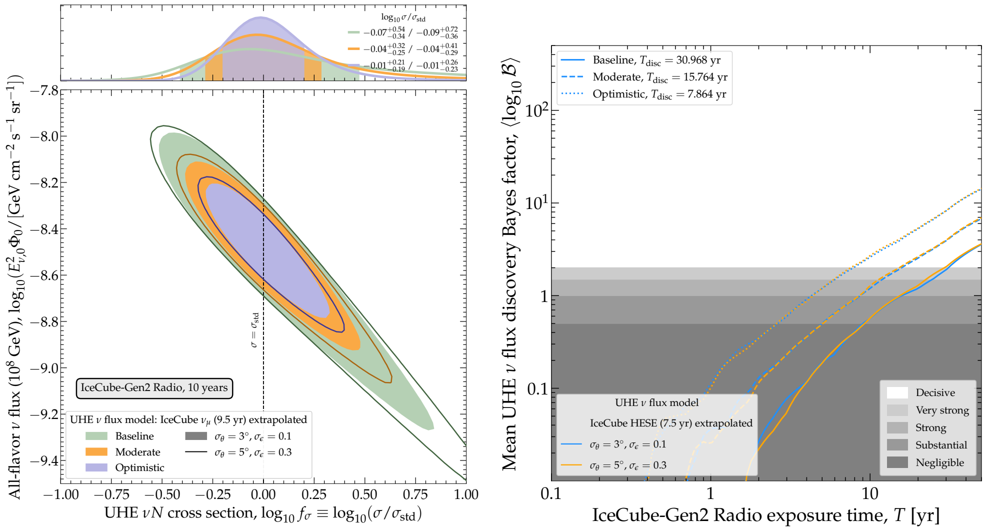

Figure 4: (left) Capability of Gen2-radio to jointly measure the UHE νN DIS cross section and the diffuse neutrino flux normalization. The different colors show the results for the baseline event rate and the event rate after moderate and optimistic improvements in the trigger. The lines vs. areas show the impact of the baseline vs. the improved reconstruction capabilities. Here, the result is shown for the IceCube ν_μ reference flux model. Based on [11]. (right) Discovery potential of the extrapolation of the IceCube HESE measurement of the neutrino fluxas a function of exposure time. The increased event rate due to the intelligent trigger (solid vs. dashed and dotted curves) expedited flux discovery substantially, whereas the improvement in angular and energy resolution (green vs. blue curves) has little impact on the flux discovery. Based on [13].

improvements will enable discovery during the runtime of Gen2. The relative increase in discovery time varies for different flux predictions and ranges between a factor of two and a factor of five for the optimistic scenario.

Impact on point source discoveries [12]: The improved angular resolution and larger event rate will allow the observation of sources two times fainter than those observable with the baseline capabilities of Gen2-radio. Another important performance measure is the volume within the universe in which point sources can be discovered. The sensitivity depends on the position of the source in the sky and is largest above and around the local horizon, i.e., in the declination band from approx. 50° to 100°. For a persistent source with a luminosity of L=10^{43} erg/cm^2/s the detection horizon increases from 44 Mpc to 63 Mpc and thus increasing the observable universe by a factor of 3. The relative improvement is similar for other regions of the sky.

5. Summary and Outlook

The intelligent trigger system, together with an end-to-end optimization pipeline, will substantially increase the capabilities of future observatories for UHE neutrinos. It builds upon previous work on developing the state-of-the-art simulation code NuRadioMC [16], detector optimizations [5, 6, 9] and the development of reconstruction algorithms, especially using deep learning [18, 20]. Overall, the detector improvements are equivalent to building a more than three times larger detector at essentially no additional costs. Because the construction of IceCube-Gen2 is already close to the limit of the logistical resources at the South Pole and extends over seven years [4], it can not be scaled up by a factor of three, even if funding were available. Hence, the improvements outlined here are a unique opportunity to advance UHE neutrino science in the foreseeable future.

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