

Modeling Neutrino and Background Signals for the Payload for Ultrahigh Energy Observations (PUEO) Experiment

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Abstract. In the current age of multi-messenger astrophysics, Very High Energy (VHE) cosmic neutrinos ($E > 1$ PeV) represent a unique observation window into the most extreme astrophysical events in the universe. Measurements of the neutrino flux in this high energy regime provide information regarding the distribution and composition of Ultra-High Energy Cosmic Rays (UHECR), details of source acceleration mechanics, and definitive tests of physics beyond the standard model. Observations in multiple different detection channels (e.g. optical, radio, direct particle counting) are being explored to extend the sensitivity to neutrinos above PeV energies.

The Payload for Ultrahigh Energy Observations (PUEO) is a long duration balloon experiment that builds on the successes of the Antarctic Impulsive Transient Antenna (ANITA) experiment to probe the cosmic neutrino flux above EeV energies. PUEO, like ANITA, seeks to measure coherent radio emission in the form of Askaryan emission from in-ice neutrino interactions and both geomagnetic and Askaryan emission from Extensive Air Showers (EAS) produced by the decays of Earth-emergent τ -leptons sourced from τ neutrinos.

To evaluate the sensitivity of PUEO (and other detectors) to a given flux of neutrinos, it is necessary to accurately model i) the propagation of neutrinos through the Earth ii) the emission generated from the neutrino-sourced particle shower iii) the detector performance to a generated signal and iv) relevant backgrounds. Numerous software frameworks exist to model these different mechanisms independently, but often require significant work to use together.

ν SpaceSim is an open source, end-to-end neutrino simulation package that models these described mechanisms for an arbitrary detector geometry in both the optical and radio emission channels. For a given experimental design, ν SpaceSim is designed to model the sensitivity to both the cosmogenic neutrino flux and to astrophysical neutrino transient events. The highly modular design of ν SpaceSim allows for comparison and exploration of different physics models within the same code base.

In this contribution, we detail the state of the ν SpaceSim code as it pertains to modeling the sensitivity of the PUEO experiment, and highlight the mechanisms necessary to perform this calculation. We also describe the near-term improvements to the radio emission calculation in ν SpaceSim and the modeling of the most relevant backgrounds for PUEO: the direct (above-the-limb) cosmic rays, and the indirect (ice-reflected) cosmic ray signals.

1 Introduction

The Payload for Ultrahigh Energy Observations (PUEO) is a long-duration, high-altitude (33 km) balloon experiment that aims to probe the cosmic neutrino flux above EeV energies [1]. During flight, PUEO is expected to observe coherent radio emission (via the geomagnetic and Askaryan production mechanisms) from four different classes of events: i) Direct (above the horizon) cosmic rays ii) Indirect cosmic rays, with emission reflected off the Antarctic ice iii) Upgoing extensive air showers (EAS) produced through the decay of neutrino-sourced τ -leptons iv) In-ice neutrino interactions. A diagram of PUEO's observation strategy and the major event classifications is

shown in Figure 1.

PUEO is built on the heritage of the Antarctic Impulsive Transient Antenna (ANITA) experiment, which has completed 4 long duration flights between 2006 and 2016 [2–4]. During these flights, ANITA collectively observed 64 reflected cosmic rays candidates, 7 direct cosmic ray candidates, and several candidates with non-inverted polarity from below the horizon, consistent with the phenomenology of upgoing EAS. This latter category of anomalous events can be divided into two sub-categories based on the angle with which they were observed: i) steeply upgoing, which both ANITA-I and ANITA-III recorded with elevation angles of -27° and -35° and energies of ~ 0.5 EeV and ii) near-horizon, which were observed four times during the flight of ANITA-IV. While

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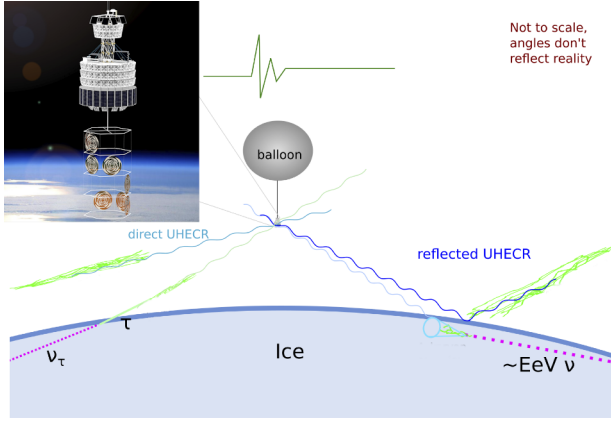


Figure 1. Diagram of PUEO's observation scheme of cosmic rays and neutrinos, modified from original image from Cosmic Deaconu.

each of these measurements is in tension with existing limits set on the diffuse neutrino flux by existing ground based observatories, the steeply upgoing candidates in particular cannot be explained as neutrino-sourced EAS under standard model assumptions of neutrino propagation inside the Earth. An example signal from each type of these candidate events is shown in figure 2, superimposed and offset in time and electric field values for easier comprehension.

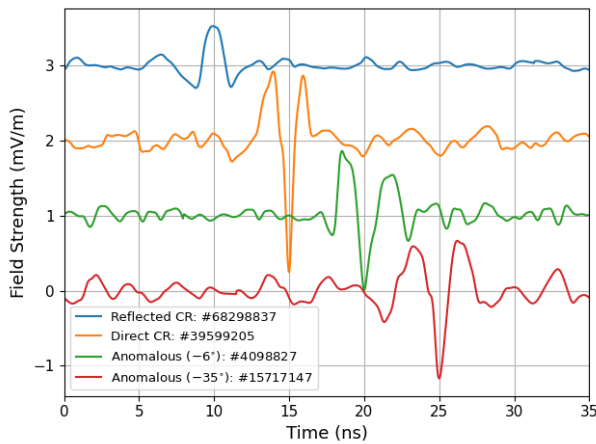


Figure 2. Four candidate H-Pol signals from different event classifications observed during the flights of ANITA, superimposed on the same plot, shifted in time and field strength for clarity. The four event classifications shown are: i) reflected cosmic rays, ii) direct (above-the-horizon) cosmic rays iii) slightly below horizon upgoing EAS iv) steeply upgoing EAS [2–4].

PUEO will further resolve the measurements made by ANITA by lowering energy thresholds to record more event candidates and improving detection strategies to optimize observations and improve event quality of these candidates. During the course of a single 30 d flight, PUEO will either set stringent limits on the diffuse neutrino flux above EeV energies or measure the highest en-

ergy neutrino to date. In this work, we describe the PUEO experiment, its improvements over ANITA, and the most current attempts to model its performance regarding neutrino signals and potential backgrounds.

2 PUEO

2.1 Main Instrument

The main instrument of PUEO consists of 108 dual-polarization quad-ridge horn antennas, improving significantly on ANITA's 48 antenna layout. This is made possible by increasing the low frequency cutoff of the antenna from ANITA's 200 MHz to cover a frequency range of 300 MHz to 1200 MHz. PUEO's antennas are arranged in four 24-antenna rings, with each column representing one "phi-sector", and a 12-antenna drop-down ring, downward-canted at 40° to increase sensitivity to upgoing EAS.

PUEO's biggest improvement over ANITA comes from the inclusion of an interferometric phased array (or beamforming) trigger. By coherently summing signals received in a number of antennas N_{ant} , the effective signal to noise ratio (SNR) for an event increases as $\sqrt{N_{\text{ant}}}$, resulting in lower energy thresholds, better chance of off-axis detection, and improved event quality. A given signal in PUEO's main instrument is expected to be received in 4 phi-sectors, or 16 antennas, resulting in a typical SNR increase of ~ 4 . A plot of PUEO's single-antenna trigger efficiency as a function of SNR is shown in Figure 3, compared to those of ANITA-IV and the Askaryan Radio Array (ARA).

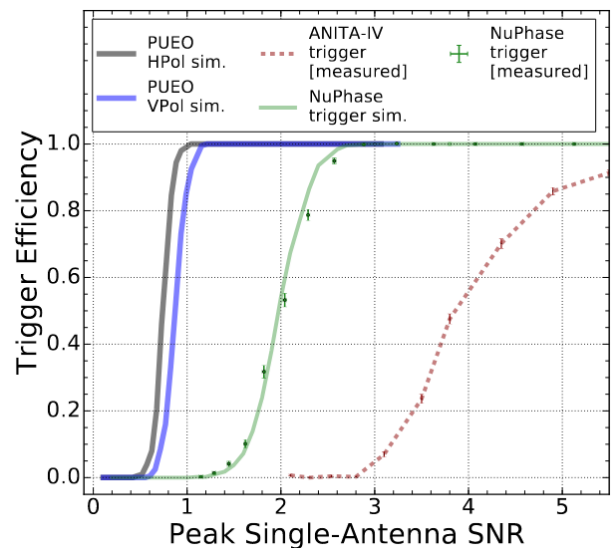


Figure 3. Simulated trigger efficiency of PUEO using a 16-antenna beamforming trigger compared to the trigger efficiency of ANITA-IV and ARA (Askaryan Radio Array) [1]

PUEO will also use a Radio-Frequency System-on Chip (RFSoc) as a combined readout and interferometric trigger system. The RFSoc will allow for improved

filtering of anthropogenic noise via digital notch filtering and will replace the analog filters that were used during the flight of ANITA-IV, thereby improving overall event quality.

2.2 Low Frequency (LF) Instrument

PUEO will include a drop-down array of 8 dual-polarization sinuous antennas below the main array that operate in the frequency range of 50 MHz to 300 MHz (see Figure 1). A separate beamforming trigger will be included for the LF instrument, and has been shown to provide an expected SNR increase of ~ 2.2 via extensive simulation studies. The LF instrument operates independently of the main instrument, and will both help improve event quality and lower energy thresholds by providing an additional trigger.

The primary goal of the LF is to increase PUEO's sensitivity to air showers by measuring events further away from the shower axis, where the generated radio emission is only coherent for lower frequencies. Figure 4 shows the frequency integrated SNR as a function of viewing angle for a sample reflected cosmic ray for the main instrument and LF.

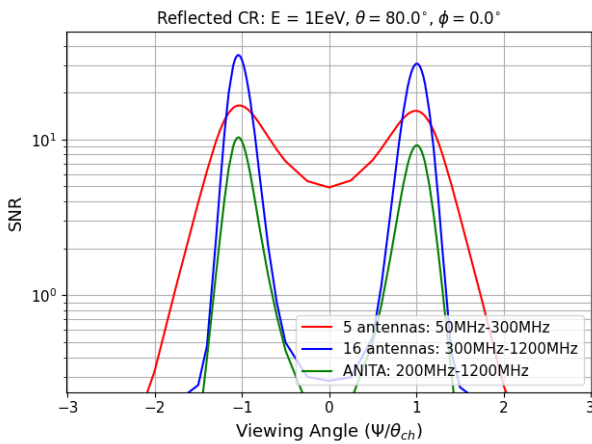


Figure 4. Frequency integrated SNR of a reflected cosmic ray event as a function of viewing angle for the LF instrument compared against PUEO's main instrument. The same curve is also plotted for the ANITA-IV antenna for comparison.

Figure 4 shows, for an example air shower event, that although the peak SNR is lower for the LF than the main instrument (primarily due to increased noise temperatures at lower frequencies), the signal is significantly broader, and has amplified SNR further outside the Cherenkov cone. This behavior ultimately manifests in a higher overall energy threshold, but amplified acceptances at higher energies.

3 Modeling

3.1 PUEOSim

PUEOSim¹ is an end-to-end Monte Carlo simulation package developed to accurately model full time domain signals and backgrounds for PUEO and calculate its neutrino sensitivity under various configurations, observation strategies, and source characteristics, taking into account the complete properties of the instrument. PUEOSim is based on the ANITASim² package, which has been used to calculate ANITA's sensitivity to in-ice neutrino interactions via the Askaryan effect (which is itself modeled by the nicemc³ [5] simulation code). Figure 5 shows PUEO's estimated single event sensitivity to neutrinos via the Askaryan effect, calculated with ANITASim using reasonably scaled thresholds based on the design requirements listed in [1]. The τ -lepton air shower sensitivity was generated using an independent code, and provides additional sensitivity below energies of ~ 1 EeV.

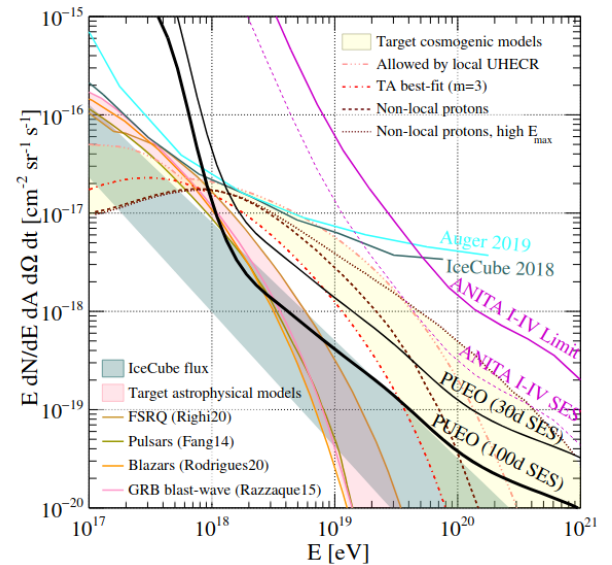


Figure 5. PUEO's single-event sensitivity (SES) to diffuse neutrinos for 30 d and 100 d flights. Also shown are existing limits set by various experiments and some cosmogenic and astrophysical models [1].

Both the new antennas of PUEO's main instrument and those of the LF instrument are fully modeled in PUEOSim, as are the beamforming triggers for both instruments. As a novel feature to PUEOSim, time domain signals from both ice-reflected cosmic ray and upgoing τ -lepton initiated EAS are being included via tables generated by the ZHAireS air shower simulation code [6]. In the near future, signals from direct above-the-horizon cosmic rays will also be included using a modified form of ZHAireS. In addition, the model of Askaryan emission used in nicemc

¹<https://github.com/PUEOCollaboration/pueoSim>

²<https://github.com/anitaNeutrino/anitaSim>

³<https://github.com/PUEOCollaboration/nicemc>

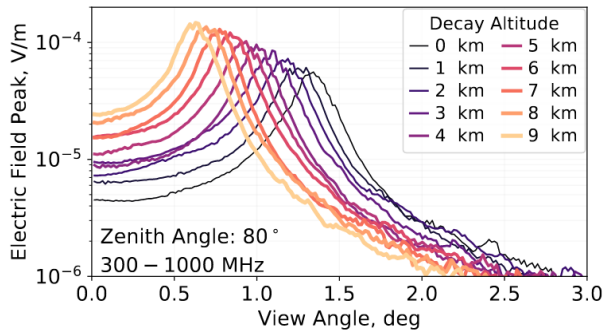


Figure 6. Peak electric field value for τ -lepton induced air showers with an 80° zenith angle and varied decay altitudes generated by ZHAireS for use in the ν SpaceSim framework [8].

has recently been updated, improving PUEO's sensitivity to neutrinos across nearly all energies, outperforming the expected curves shown in Figure 5. A full update of PUEO's science capability using PUEOSim is in progress.

3.2 ν SpaceSim

ν SpaceSim⁴ is an open-source, modular, end-to-end simulation which models the signals produced by upwards moving extensive air showers (EAS) sourced by cosmic neutrinos [7]. ν SpaceSim is designed to evaluate the sensitivity of an experiment with an arbitrary geometry and measuring technique (both optical Cherenkov and radio) to diffuse and transient neutrino fluxes.

ν SpaceSim models radio emission generated by upgoing τ -lepton initiated EAS via lookup tables generated by ZHAireS, taking into account geometric scaling. The radio emission lookup tables are integrated in the frequency domain to yield peak electric field values, which are used during runtime to provide simple thresholding-based acceptance arguments. Peak electric field values for an example upgoing EAS with different starting altitudes are shown in Figure 6 as a function of shower viewing angle, integrated withing the frequency range 300 MHz to 1000 MHz. Using this approach, ν SpaceSim has been able to reproduce the ANITA neutrino sensitivity (via the τ -lepton upgoing EAS observation channel).

To further improve upon sensitivity estimates for PUEO and other proposed neutrino telescopes utilizing the radio technique, ν SpaceSim will be updated in the near future to consider full time domain waveforms of radio signals from EAS sourced by neutrinos and cosmic rays (both direct and ice-reflected). This improvement will allow for implementation of realistic detector properties, signal chains, and trigger mechanisms beyond simple thresholding arguments, resulting in more accurate estimations of neutrino sensitivity and more realistic comparisons between ν SpaceSim and other computation schemes. For the calculation of transient neutrino sen-

sitivity, ν SpaceSim necessarily requires time based positioning of a given instrument, a feature which is currently under development. One potential future development to consider in ν SpaceSim involves the inclusion of Askaryan emission from in-ice neutrino interactions when measuring over large ice sheets in Antarctica or Greenland.

4 Summary

PUEO builds on the framework of the ANITA missions to target the flux of very high energy neutrinos through radio emission produced by in-ice neutrino interactions and upgoing EAS initiated by neutrino-sourced τ -leptons. PUEO significantly improves upon the performance of ANITA by including i) more than double the number of antennas with respect to ANITA ii) an interferometric phased array trigger iii) a dedicated low-frequency instrument iv) a dedicated drop-down antenna ring dedicated to air shower measurements and v) better filtering of man-made noise at the trigger level. Over the course of a single 30 d flight, PUEO will either measure the first neutrino with energy exceeding 1 EeV or set strict limits on the diffuse flux, which helps to constrain models of cosmic ray composition and source evolution.

Comprehensive simulation efforts have been made to model PUEO's sensitivity to diffuse and transient fluxes of cosmic neutrinos. In this work, we have discussed two potential simulation packages that can be used to approach this problem: PUEOSim, the dedicated simulation for PUEO, based on the framework of the successful ANITASim package, and ν SpaceSim, a generalized simulation package for both optical Cherenkov and radio experiments. PUEOSim uses the nicemc simulation package to model Askaryan emission from in-ice neutrino interactions, which forms the dominant observation channel for PUEO, while ν SpaceSim uses the ZHAireS air shower simulation to model the geomagnetic emission from upgoing τ -lepton initiated EAS. Both packages are making progress in including all candidate signal classes shown in Figure 2 and have overlap between one another, providing two robust methodologies for evaluating the impact of signals and backgrounds for the PUEO experiment.

References

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⁴<https://github.com/nuSpaceSim/nuSpaceSim>