νSpaceSim: A Comprehensive Neutrino Simulation Package for Space-based & Suborbital Experiments

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We describe a new comprehensive, end-to-end simulation package for the modeling of the extensive air shower (EAS) signals from very-high energy (above a PeV) cosmic neutrinos applicable to sub-orbital and space-based observations. The goal is to provide an efficient and practical cosmic neutrino EAS signal generation modeling package to the community that will provide a standard to gauge the neutrino measurement performance of these experiments and aid in their development. The modeling will be performed in such a way to easily be used to provide the neutrino-induced EAS signals delivered to a specific altitude for a given instrumental field-of-view and orientation. In this paper, we discuss the modeling of tau neutrino interactions inside the Earth, propagating the τ-leptons into the atmosphere, modeling the decays, forming composite EASs, generating the air fluorescence, Cherenkov, and radio signals, and the propagation through the atmosphere. Future work on the modeling of atmospheric transmission and scattering effects will include consideration of the uncertainties and more robust modeling of atmospheric and UHECR backgrounds. Additionally, the framework will allow for the calculation of the sky coverage, the pointing requirements for target-of-opportunity follow up observations of transients, and the inclusion of different neutrino interaction cross-sections to allow for the modeling of non-standard physical processes.

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1. Motivation and Simulation Overview

We are developing a comprehensive, end-to-end simulation package for the measurement of cosmic neutrinos from the optical and radio signals from EASs, leveraging development that supported the ANITA LBD campaigns [1, 2] and that developed to quantify the neutrino sensitivity of the future POEMMA mission [3]. The goal is to provide an efficient and practical simulation that will provide a standard tool to determine the neutrino measurement performance of sub-orbital and space-based experiments. We are starting with the modeling of the τ-lepton EAS generated from tau neutrinos interacting in the Earth, including the modeling of the neutrino interactions, propagating the τ-leptons through the Earth and into the atmosphere, modeling the decays, forming air showers from the decay products, generating the air fluorescence, Cherenkov, and radio signals. After determining their propagation through the atmosphere, and including detector response models for the optical and radio signals, the results will be translated into experimental variables, e.g. photo-electrons for the optical signal and front-end signals for the radio. The results of this modeling effort will allow for the calculation of the sky coverage and the pointing requirements for target-of -opportunity follow-up observations to extremely energetic transient events.

2. Simulation Framework

The initial development is focused on the modeling of tau neutrino interactions in the Earth and the τ-lepton EAS optical and radio signals. The simulation is based on a sampled libraries approach, with separate generation of the libraries, to provide a fast and efficient simulation.

2.1 Library Generation

Tau neutrino → τ-lepton Library: Module development is underway to use two independent neutrino and τ-lepton propagation codes discussed in detail in Refs. [4] and [3]. Neutrino production of τ-leptons and their propagation through a model of the Earth will be available via look-up tables either directly in Python or in gfortran with a Python wrapper. The look-up tables will allow for several sets of neutrino cross section extrapolations at high energy, and several τ-lepton energy loss models that depend on high energy extrapolations of electromagnetic scattering on nuclear targets. Figure 1 shows the average energy of emerging τ-leptons as a function of elevation angle β_{tr} for $E_\nu = 10^{17}$, 10^{18} eV calculated independently, as reported in Refs. [3] and [5].

τ-lepton Decay Library: The characteristics the Cherenkov and radio signals are sensitive to the development of the EAS, formed from the τ-lepton decay products. In order to accommodate the large variety of possible final states, we have generated a library of τ-lepton decay events simulated using PYTHIA 8 [6]. The library contains event information for one million events per decay channel included in PYTHIA 8. Event information consists of the final state decay products and their energies and momenta in the τ-lepton rest frame. Fig. 2 (left) shows the distribution of fractional τ-lepton energy put into the EASs from electrons and the sum of the hadrons per event.The event-by-event generation will sample the decay channels according to their branching ratios and boost the decay products to the laboratory frame, producing kinematic distributions for negative helicity states for the τ-lepton . Note that for $E_\nu \gtrsim 10^6$ GeV (e.g. Ref. [7], the neutrino and anti-neutrino cross sections are virtually identical and thus modeling neutrino interactions with negative helicity τ-leptons adequately describes the generation process.

EAS Library for Optical Cherenkov: We will use the CONEX [8] simulation package to generate libraries of the Gaisser-Hillas profiles [9] of the EAS as a function of energy and particle
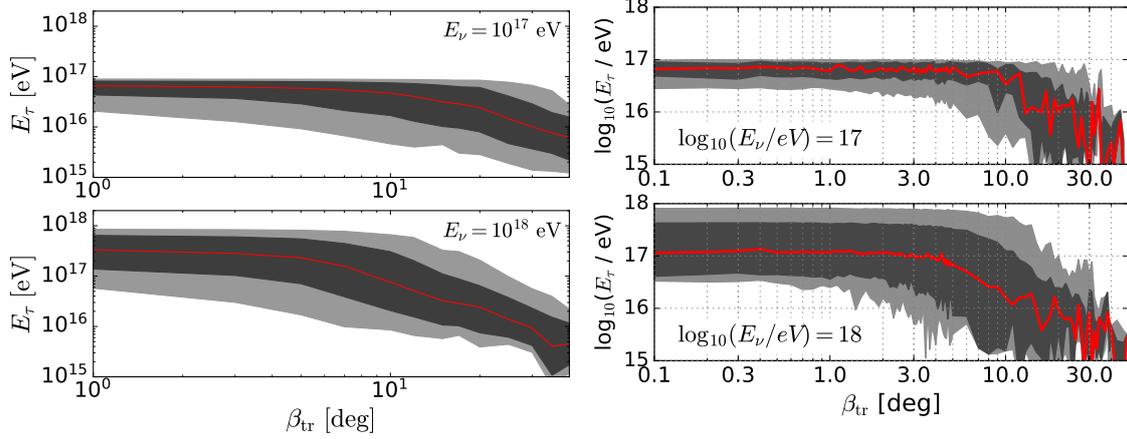
Figure 1: The average energy of the outgoing τ-lepton (red line) and range of energies within 68% and 95% of values, calculated in Ref. [3] (left) and Ref. [4] (right).
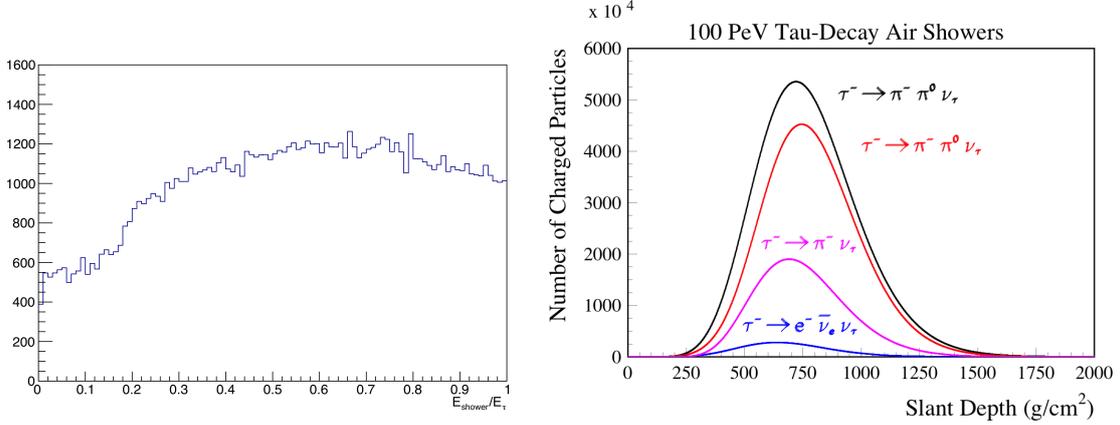

Figure 2: Left: The frequency of events as a function of the fraction of the τ-lepton energy, $E_{\mathrm{Shower}}/E_\tau$ put into the EAS, from the decay products (electrons and hadrons) obtained for polarized τ-lepton decays from Pythia 8. Right: The longitudinal profiles of four different simulated EAS from 100 PeV τ-lepton decays. From top down, the 1st decay has 82% of the initial τ-lepton energy in the hadronic system the 2nd has 62%, the 3rd has f_{π^-}=62%, while the 4th has f_e=3%.

species, the latter needed to form composite EAS from the τ-lepton decay products. Fig. 2 (right) shows several examples of composite EAS formed from τ-lepton decays based on the Pythia results. We plan on using the Cosmos [10] EAS simulation packages to generate the full 3-dim cascade profiles needed for sub-orbital detector modeling.

EAS & radio generation: The EAS and radio emission simulations are produced in a single simulation using ZHAireS [1]. The approach that will be applied to for space-based observatories closely follow the approach used to estimate the ν_τ air shower sensitivity estimates for ANITA [2].

Air Glow background: The upper atmosphere of the Earth is continuously ionized by solar radiation with short wavelengths, solar energetic particles and by cosmic rays. producing a faint light that is commonly known as an airglow [11, 12]. By viewing from the orbit, the direct component of the airglow light together with the reflected component of the starlight and zodiacal light act as a

diffuse night atmospheric background. The assessment of the absolute intensity of this background is crucial for simulations of the optical signals from EAS induced by UHECR and VHE neutrinos. The main task is to determine the average absolute intensity of the night atmospheric background for spectral bands within the wavelength range 300 - 1000 nm. The input for these tasks will consist of various ground, balloon and space-based measurements in this spectral range.

Radio Backgrounds: The main backgrounds of concern are radio impulsive events of anthropogenic origin. The ANITA mission has shown that these backgrounds can be handled successfully by using clustering and tracking of signals [13] with an expected background rate of order 1 event per flight. The location of backgrounds can be estimated in simulations using population density maps, airline flight routes, and shipping routes.

Cloud Modeling: Cloud top pressure (CTP) data is retrieved from the NASA MERRA-2 database [14] to generate cloud top height (CTH) maps to be used for the simulation. CTH maps are needed to determine the fraction of Cherenkov light that will propagate to the instrument. In its simplest implementation, the model assumes that the clouds are completely opaque, hence the Cherenkov light produced below the CTH in the simulation is not propagated further. An online-based program will provide to the user randomly-generated monthly global CTP maps for use in the simulation. The conversion to CTH will be handled in the module using different atmospheric models. Figure 3 shows a randomly-generated CTH map for the month of September based on data from 2016-2018 using the 1976 atmospheric model.

Figure 3: Randomly-generated CTH map for the month of September using MERRA-2 data from 2016 to 2018.

2.2 Event Generation

The libraries will be sampled by an event-by-event simulation that inputs user's data regarding the geometry, observation altitude, location and time of observation, detector responses, etc. needed to complete the desired neutrino sensitivity calculation.

Geometry & Master Loop: This module encapsulates the entire simulation package, taking input from the user, generating events, and accepting or rejecting the event based on the geometry and the detection thresholds specified by the user. The user selects the detection technique (Cherenkov or radio), supplies the relevant detector characteristics, and specifies the observation region on the surface of the Earth via an XML file. The user may also specify the ν_τ energy or the module will randomly generate the ν_τ energy from a pre-generated neutrino spectrum. The module generates events by sampling the location of the emerging τ-lepton within the observation region and the trajectory of the τ-lepton (β_{tr}). The module then samples the τ-lepton energy from the τ-lepton spectrum libraries and generates a random decay path length for the τ-lepton . The module rejects the τ-lepton if it decays outside of a sufficiently large 3-dim observation cone of the detector; otherwise, it determines the altitude at which the τ-lepton decays and the shower energy and invokes the EAS signal generator and the relevant libraries for modeling environmental
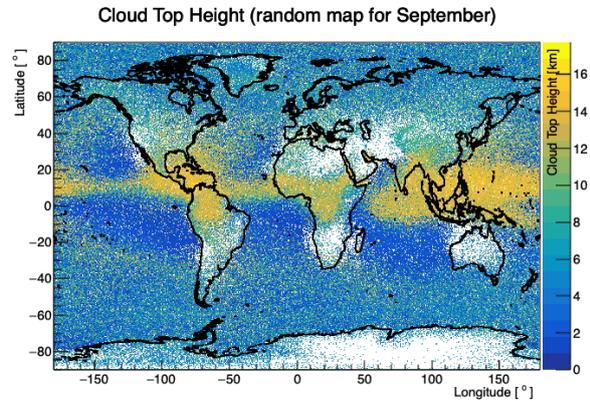
impacts on the signal (*i.e.*, atmospheric optical attenuation and scattering, clouds, ionospheric dispersion). The module then propagates the signal to the detector and accepts or rejects the event if the detector response to the signal (*i.e.*, number of photo-electrons or antenna response) is above the user-specified threshold. After generating the number of events specified by the user, the module calculates the neutrino aperture for the detector. If the user also provides orbital characteristics or other timing information, the module will also calculate the detector's exposure as a function of celestial coordinates. Timing information will also enable simulations of events arising from specific astrophysical source locations in the sky.

τ-lepton Yield Sampling: This module samples τ-lepton energies from pre-generated τ-lepton spectrum libraries. These libraries are implements as cumulative distribution functions of the τ-lepton yield as a function of τ-lepton energy for a given ν_τ energy and β_{tr}. This module accepts the ν_τ energy and β_{tr} from the Geometry & Master Loop Module and randomly generates the τ-lepton energy from the appropriate cumulative distribution function supplied by the τ-lepton spectrum library. The module also determines the τ-lepton exit probability from the ν_τ energy and β_{tr} and passes it back to the Geometry & Master Loop Module for calculating the neutrino aperture and/or exposure skymap.

τ-lepton decay: This module supports event-by-event EAS and signal generation by sampling the τ-lepton decay channels from the τ-lepton library according to their branching ratios and boosting the decay products to the laboratory frame. The resulting kinematic distributions will be for negative helicity states for the τ-lepton .

EAS Sampling (Optical Cherenkov): Once the τ-lepton decay products are sampled, the composite EAS is formed by appropriately sampling the EAS library based on the specific particle species and energy.

EAS Optical Cherenkov signal generator: This module will simulate the optical signal from an air shower in a 1+2 dimensional model the Cherenkov photons produced in the composite EAS. It uses the notion of shower universality[15] to determine the angular distributions of electrons within the shower and then integrates around the electron directions by the Cherenkov cone to get photon angular distribution[16]. The result will be stored as a lookup table for angle, atmospheric density and shower development stage. The Cherenkov angle and energy threshold altitude dependence will be taken from the atmospheric model discussed next.

Atmosphere Optical Attenuation and Scattering: The baseline atmospheric model will use the 1976 Standard US atmosphere to define the pressure and temperature variation of the atmosphere as a function of altitude. This is needed to define the altitude variations of the air index of refraction, for the optical Cherenkov generation, air fluorescence yield [17] while using the wavelength dependence [18, 19] and measured total fluorescence yields. Ignoring clouds, EAS signals in the UV to optical range have three scattering/attenuating components: Rayleigh scattering, Mie (aerosol) scattering, and ozone absorption. The first is straightforward to calculate as it is dependent on the slant depth between point of generation on the EAS and an observation point. An initial aerosol attenuation model by [20] will eventually be expanded to include other aerosol distributions and include the effects of Mie scattering. A ozone attenuation model [21] using Total Ozone Mapping Spectrometer (TOMS) measurements [22] will initially be used. Note that the optical atmospheric attenuation/scattering models could eventually employ data from the MERRA-2 database [14].

Cloud Modeling: Using the cloud library, the location of an event's trajectory will be used to

sample the cloud height distribution. The portion of the EAS optical Cherenkov signal generated below the cloud height will be discarded to model cloud masking effects.

EAS & radio Sampling: Following the approach of [2], EAS and radio emission will be sampled from a parameterized library of events.

Ionosphere dispersion: The treatment of ionospheric dispersion will follow the approach of [23]. Maps of ionospheric density are provided daily and these can be used to sample ionospheric dispersion of radio signals dependent to geographic location, time of day, and season.

Optical Detector Modeling: This module, written in Python, allows the user to simulate a detector response based on configurable detector properties e.g. optical and quantum efficiency. The configuration is done via XML cards and does not require any modification of the code. A photon distribution on the aperture is passed to the module as input. the output of the module will be photon profiles and photo electron profiles as well as the signal in the camera In a next step it will be possible to add background to the signal, allowing the user to test trigger algorithms and efficiency. The output will be in the HDF5 format.

Radio Detector Modeling: A radio detector model will be provided similar to what was applied in [23]. The key elements to be included are a banded and threshold coincidence trigger that has real-time ionospheric de-dispersion capabilities.

Sky exposure: Given the instrument's orbital and field of view parameters, the sky exposure to tau neutrino induced showers can be calculated for different τ-lepton emergence angles (see [24]). Without rotating the pointing direction of the instrument about its axis, the (RA,Dec) coverage is limited to the reach of the orbit inclination. By default, the sky coverage will be calculated assuming that the instrument points in the wake direction of the orbit. The sky coverage calculation will take into account the relative positions of the Sun and the Moon and will also include the loss of detection efficiency due to cloud coverage. The calculation implies that the user provides the start date/time and length of observation.

The output of the simulation will provide the simulation event statistics to provide a determination of the effective neutrino geometry factor and duty cycle dependent neutrino sensitivity while also providing details of the accepted events, source location, τ-lepton trajectory, $_\nu$ and E_τ, τ-lepton decay mode and altitude, etc. to support more detailed analysis.

2.3 Future Development

Once the initial τ-lepton simulation is complete, the EAS from muons from τ-lepton decay will be modeled, which will also support the simulation of upward EASs from muon neutrino interactions in the Earth. This modeling will be then be adapted for simulating the detectable signals from UHECR and UHE neutrino EAS in the atmospheric target. This will allow for the investigation of the potential backgrounds associated with the UHECR EAS signals just over the Earth's limb and the reflection off of clouds and the ground of the downward UHECR air shower signals. The framework will also allow for the inclusion of different neutrino interaction cross-sections to allow for the modeling of non-standard physics, e.g. non-SM neutrino cross-sections.

3. Simulation Software Framework

The software framework for the simulation is specifically designed to enable the types of workflows users have come to expect from a modern analysis environment. The package will maximize performance, usability, and portability to fully support iteration and experimentation.

Modular Structure: The simulation will consist of a high level framework written in Python, wrapping and managing the interface between each of the core components. Each component will be implemented using a high-performance compiled language such as Fortran, C or C++. These components will operate as independent modules, developed on a single responsibility principle to reduce internal complexity. Each module will produce intermediate data products for consumption by other modules in the simulation.

For example, the τ-lepton decay module once called via Python will sample channels from the input τ-lepton library and generate an output data product characterizing a set of kinematic distributions. This output can then be easily sampled by the Master Loop in the simulation.

Orchestrating the composition of module chains will be the responsibility of the high level Python wrapper. Modules can be composed in different ways to perform different analyses. This approach allows each component to be optimized independently, and employed more flexibly, while the high level wrapping framework manages the complexity of interfacing with these many components, exposing a simple and intuitive interface for users.

Ultimate data products will be stored in the robust and efficient HDF5 file format[25]. Intermediate data products will optionally be written to disk in this format to facilitate a flexible workflow.

User Interfaces: Users will be able to interact with the simulation framework through two primary mechanisms: direct execution with an input configuration file, and interactively in a Python programming environment through our simulation Application Programming Interface (API). The main executable will accept an XML configuration file as input. This file will be user editable and control the available simulation option parameters exposed to the users. Such an approach will enable users to customize select parameters of analysis while following a known good thread of execution.

For more advanced users the many components of the simulation package will be made accessible via a Python3 importable library and API. This software package will manage interaction with the core components to provide a flexible, interpreted programming environment to experiment with novel simulation schemes. The Python wrapper will expose the simulation components as individual modules callable from within the Python interpreter in an easy to use library package distributed through pip and conda[26].

Portability and Containerization: The package will run natively on the Linux and MacOS operating systems with minimal reliance on 3$^{\text{rd}}$ party dependencies. Super user permissions will not be required to install or run the package. The team will also generate Docker containers to encapsulate the tools and allow support for other operating systems[27]. The availability of a containerized distribution via Docker allows the simulation to be run on every major operating system and even in environments where the security restrictions or software version limitations would prevent the installation of new executable tools.

Docker containers are similar to virtual machines in that they enable a guest Linux OS with pre-installed software and environmental specifications to be executed on any host OS while neither affecting nor being affected by the host OS's software or environment. Using these containers allows the simulation to run on a user's machine and never interfere with the user's system settings or environment.

Simulation Distribution: An initial release of the simulation package is planned for early in 2021. The νSpaceSimPackage will be hosted on the NASA/GSFC HEASARC site [28].

4. Summary

The goal of the νSpaceSim development is to provide an efficient and robust end-to-end simulation package for the detection of neutrino-induced EASs for space-based and sub-orbital observations. While we are developers of this simulation, we also are users that will use this to support our own research efforts. Thus, the framework is designed to easily include modeling improvements as the need arises.

References

[1] J. Alvarez-Muñiz, W. R. Carvalho, and E. Zas, Astropart Phys **35**, 325 (2012), `1107.1189`.

[2] A. Romero-Wolf et al., Phys. Rev. **D99**, 063011 (2019).

[3] M. H. Reno, J. F. Krizmanic, and T. M. Venters (2019), `arXiv:1902.11287`.

[4] J. Alvarez-Muñiz et al., Phys. Rev. **D97**, 023021 (2018), [erratum: Phys. Rev.D99,no.6,069902(2019)], `1707.00334`.

[5] A. Romero-Wolf et al., in *Proc of the 35*th*ICRC*(*Busan*)(2017), *PoS*(*ICRC*2017)935.

[6] T. SjÃűstrand et al., Comput. Phys. Commun. **191**, 159 (2015), `1410.3012`.

[7] M. M. Block, L. Durand, and P. Ha, Phys. Rev. **D89**, 094027 (2014), `1404.4530`.

[8] T. Pierog et al., Nuclear Physics B Proceedings Supplements (????).

[9] T. K. Gaisser and A. M. Hillas, in *Proc of the 15*th*ICRC*(*Plovdiv*)(1977), *vol*. 8, *p*.353.

[10] S. Roh et al., Astroparticle Physics **44**, 1 (2013), `1301.5060`.

[11] R. R. Meier, Space Science Reviews **58**, 1 (1991).

[12] C. Leinert et al., Astron. Astrophys. Suppl. Ser. **127**, 1 (1998).

[13] P. W. Gorham et al., Physical Review Letters **103**, 051103 (2009), `0812.2715`.

[14] *MERRA-2: Modern-Era Retrospective analysis for Research and Applications, Version 2*, https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/.

[15] S. Lafebre et al., Astropart. Phys. **31**, 243 (2009).

[16] D. Bergman, in *Proc of the 33*rd *ICRC (Rio de Janeiro)* (2013), 00983.

[17] F. Kakimoto et al., Nuclear Instruments and Methods in Physics Research A **372**, 527 (1996).

[18] A. N. Bunner, Tech. Rep. 62, Cornell-Sydney Univ. Astron. Center Rept. (1966).

[19] G. Davidson and R. O'Neil, The Journal of Chemical Physics **41**, 3964 (1964).

[20] L. Elterman, Tech. Rep. AFCRL-68-0153 (1968).

[21] J. F. Krizmanic, in *Proc of the 26*th *ICRC (Salt Lake City)* (1999), vol. 2, pp. 388–391.

[22] R. D. McPeters et al., Tech. Rep. NASA-RP-1384, NASA (1996).

[23] A. Romero-Wolf et al. (2013), `arXiv:1302.1263`.

[24] C. Guépin et al., JCAP **2019**, 021 (2019).

[25] The HDF Group (1997-2019), http://www.hdfgroup.org/HDF5/.

[26] Anaconda Software Distribution. Computer software (Nov. 2016), https://anaconda.com.

[27] D. Merkel, Linux J. **2014** (2014), ISSN 1075-3583.

[28] https://heasarc.gsfc.nasa.gov/.