PROCEEDINGS OF SCIENCE

The Radar Echo Telescope for Neutrinos: Contribution to ICRC 2023

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The Radar Echo Telescope for Neutrinos (RET-N) is a next generation experiment to detect cosmic neutrinos with energies in the PeV to EeV energy range by utilizing the radar echo method in polar ice. RET-N will consist of a phased-array radio transmitter and an array of receivers, aiming to detect the ionization trail from an ultra-high-energy neutrino interaction in-ice via active radar sounding. The received signal is a function of the transmitted signal (including any modulation), array geometry, geometry of the reflection, and propagation effects. We present potential triggering methods, the properties of the expected radar signal, and how to use these properties to reconstruct the neutrino arrival direction and energy. These methods are being tested in the pathfinder experiment for RET-N, the Radar Echo Telescope for Cosmic Rays (RET-CR) currently deployed in Greenland.

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1. Introduction

Ultra-high-energy (UHE) neutrinos are a unique probe into the cosmos. As the only observed particles with beyond-standard-model properties, neutrinos represent a means to probe fundamental physics at the highest energies. Neutrinos only interact weakly, leading to a small interaction cross-section, making detection challenging. This does, however, make neutrinos an excellent tool for multi-messenger astronomy as they travel unimpeded over cosmic distances pointing directly back to their source. In addition to the small interaction cross-section, cosmic neutrinos have an observed flux that falls steeply in the UHE regime. To combat these problems in a reasonable time, UHE neutrino detectors are built to observe massive volumes. The IceCube neutrino observatory, a cubic-kilometer array located in the deep ice at the South Pole, detects optical Cherenkov radiation emitted in neutrino interactions [1]. IceCube has been detecting neutrinos with energies up to several PeV for the past decade [2], and has also demonstrated the neutrino as a potential multi-messenger candidate, with the evidence of neutrinos pointing back to the region of Blazar TXS-0506+056 [3]. Recently, the first steady neutrino point sources were found, being the nearest Syfert 2 galaxy to Earth, NGC 1068 [4], and our own galaxy [5]. In order to continue probing the UHE neutrino flux, detection volumes need to increase even beyond the cubic-kilometer size to obtain reasonable sensitivities.

In order to increase statistics, many new detectors are aiming to use radio-based methods to instrument even larger volumes. For an overview of these methods, see [6]. In this proceeding we discuss the status of the Radar Echo Telescope for Neutrinos (RET-N), a next generation experiment to probe the PeV to EeV cosmic neutrino flux. RET-N will be a multi-static radar system located in polar ice. The radar echo method relies on reflection of a transmitted radio wave off the ionization trail produced in a UHE neutrino interaction. As a radio-based experiment, the long attenuation length of radio in polar ice allows for sparse instrumentation with large detection volumes. The reflected signal from the ionization trail is, in part, a function of the transmitted signal. Therefore the radar echo method can be used, with appropriate design, to probe ionization trails down to PeV energy neutrino interactions. The control over the transmitted signal also provides additional handles on reconstruction of the primary neutrino properties.

2. The Radar Echo Method

The radar echo method is a fairly straightforward process that has been in use for over a century. A transmitting antenna illuminates a volume with radio waves, and receiving antennas observe that same volume. If there is an object which reflects radio waves inside this observed volume, part of the transmitted signal is reflected back to be detected by the receiver. Properties of the received signal can then be used to determine the objects physical qualities and motion.

2.1 Ionization trails as a reflector

When an UHE particle interacts in a medium, a relativistic cascade of particles is induced. This cascade develops along the primary particle's incidence direction, losing energy to ionization as it propagates. In ice or rock, this ionization is dense enough to reflect radio waves (50 MHz - 1 GHz). This ionization is relatively short-lived $\mathcal{O}(10\,\text{ns})$ (depending on the material properties and temperature [7]) but dense enough to reflect radio. Therefore, this ionization is the object that we aim to detect using the radar echo method.

3. Method Validation

The radar echo method has been used for nearly a century in attempts to detect high-energy particle cascades [8]. In 1941, Blackett and Lovell used radar in an attempt to measure cosmic ray showers in the atmosphere [9]. The experiment failed to detect cosmic ray interactions, but was successful in measuring meteors in the upper atmosphere. It was realized that the ionization density of a cosmic ray air shower was too low, the free electron lifetime too short, and the collisional damping too high to measure cosmic rays in air with radar. There has been renewed interest in measuring cosmic rays with radar in the decades since, with the most recent in the 2010's with the Telescope Array Radar (TARA) experiment [10]. TARA, for the same reasons as Blackett and Lovell, failed to detect cosmic rays in the atmosphere [11]. However, around the same time, using the radar echo method to detect neutrino-induced ionization trails in more dense media, such as rock and ice, was proposed [12, 13].

3.1 Test Beam Experiment 576 (T-576)

The first relevant energy test of the radar echo method to measure high-energy particle induced ionization trails occurred with the T-576 experiment at the Stanford Linear Accelerator (SLAC) in 2018 [14, 15]. T-576 consisted of dumping a high-energy beam of electrons into a block of HDPE. The HDPE was probed with a radar system, which detected the radar echo off a high-energy particle induced cascade.

3.2 The Radar Echo Telescope for Cosmic Rays

Following the successful T-576 test, we aim to further test the method in-situ on cosmic ray particle cascades penetrating a high-altitude ice sheet. In May 2023, the Radar Echo Telescope for Cosmic Rays (RET-CR) was deployed at Summit Station, Greenland [16]. RET-CR has a near-surface multi-static radar system consisting of a central phased-array transmitter and three receivers located around the transmitter. The experiment also instruments an array of surface scintillation detectors, which provide the system triggers, and surface radio antennas for reconstructing the cosmic ray shower. This additional test serves to both further verify the method, and give us insight on the expected signal. With the RET-CR scintillator panels, we have an independent well-studied detection mechanism to trigger the array. We aim to use RET-CR data in concert with simulation to design a triggering mechanism for neutrino-induced ionization trails. At the time of these proceedings, RET-CR is taking data in Greenland.

For more on RET-CR, see [16] and [17].

4. The Radar Echo Telescope for Neutrinos

Once RET-CR successfully demonstrates that the radar echo method is suited to detecting cosmic ray induced ionization trails, then we will proceed to develop and deploy RET-N. The data and experience from RET-CR will be crucial for a success as a next-generation UHE neutrino

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detector. As noted above, RET-CR is triggered by scintillator panels, but when we move to RET-N the system must be self-triggering. Studies of triggering methods for RET-N are already underway, and will be optimized using data from RET-CR. Multiple triggers will be tested and actively used for RET-N.

4.1 Preliminary Detector Geometry

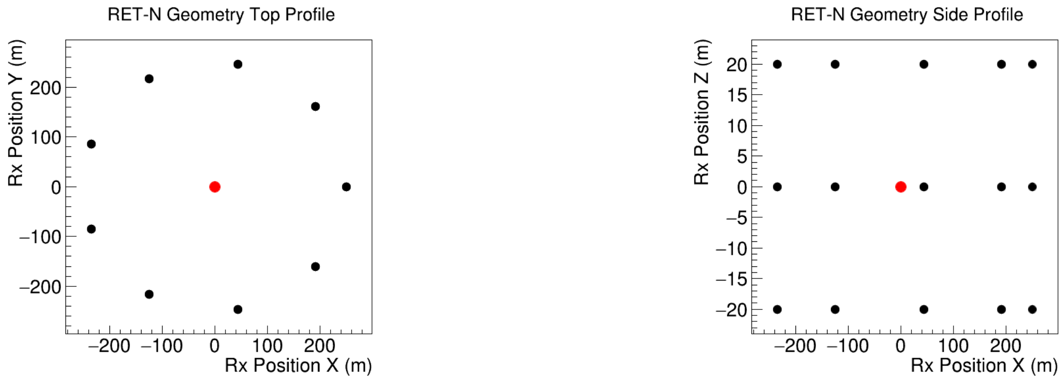
The preliminary design for a single station of RET-N consists of ten strings: a central phased-array transmitter, and nine receiver strings. The exact configuration of the transmitter has not been determined, but will consist of several antennas to allow for higher effective power and beam steering. Each receiver string will have three receiving antennas, spaced vertically by 20m. These nine receiver strings will be placed $O(200\,\mathrm{m})$ away from the central transmitter "spoked" in a full circle as seen from above. This preliminary design is semi-optimized, and further improvements to detector design are being studied.

The preliminary RET-N design is located $O(1500\,\mathrm{m})$ below the surface in a polar ice sheet. This depth serves a few purposes. First, the radio background is suppressed, because radio made in anthropogenic, galactic and triboelectric sources from the surface will be attenuated in deep ice. Second, in deep polar ice the index of refraction (nominally a function of depth) is essentially uniform. Finally, with the transmitter serving as the center point of the array, the detectable volume will be a full sphere not cut off by the ice surface, maximizing the detectable volume.

4.2 Signal Properties and Reconstruction

RET-N is simulated using RadioScatter, an in-house simulation package built around GEANT4 [19]. With this simulation package we can study the unique signal properties of the radar echo method, design the detector to fit specific needs, and determine the sensitivity of the proposed experiment.

One benefit to the radar echo method is that the received signal is a function of the transmitted signal and detector geometry. For example, motion of a particle-induced ionization trail relative to the transmitter and receiver produces a measurable frequency shift (caused by the bi-static Doppler



(a) **(b)**

Figure 1: The preliminary RET-N geometry. Red dot denotes the phased-array transmitter, and black dots are the receiver locations. The Array is 1500m below surface (Z = 0 at -1500m in figure 1b).

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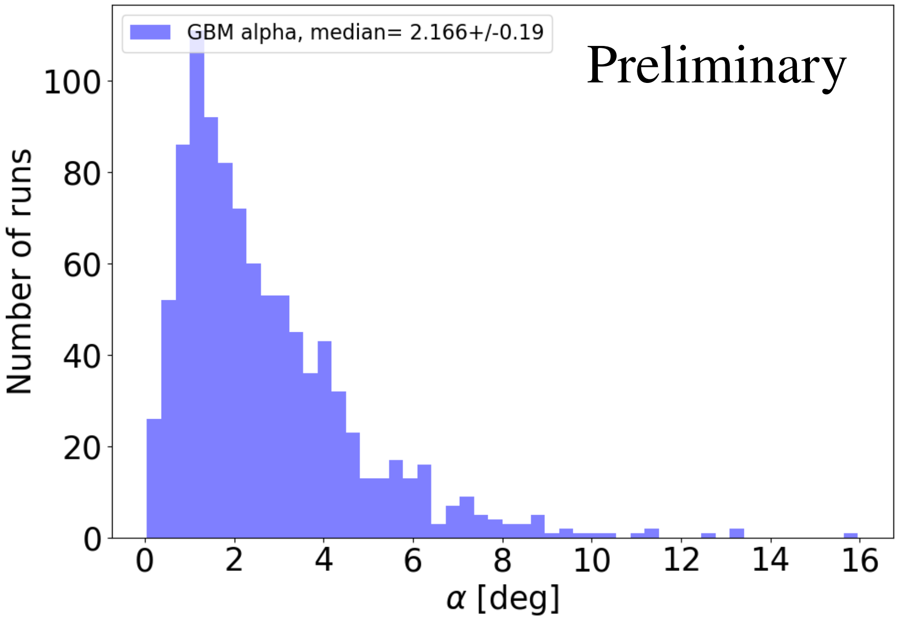

Figure 2: Histogram of direction reconstruction of RadioScatter events performed with a boosted decision tree (BDT) [18]. Here α is the opening angle, an angle between the "true" RadioScatter event incident direction and the BDT best guess.

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effect),

$$f = \frac{1}{\lambda}\frac{d}{dt}(R_1 + R_2),$$

where R_1, R_2 are the transmitter-reflector and reflector-receiver baselines, respectively. This frequency shift, minimized in the bistatic approach, but with values of up to tens of $MHz/\mu s$, can be used to trigger the array to reconstruct direction. Called a "chirp", this frequency shift is a low-background and high signal-to-noise ratio (SNR) signal [20, 21], specific to the geometry of the reflecting system. In a multi-receiver detector one can use the frequency content of each receiver to determine the incident neutrino direction. The array geometry discussed here has 27 co-located receivers to provide varying baselines and viewing angles to an neutrino event.

Direction reconstruction methods are still under development, but an initial machine-learning approach has been performed. Utilizing several expected observables obtained from the RadioScatter simulation package, the machine-learning approach demonstrates reconstruction of the neutrino arrival direction to $O(2^\circ)$. The algorithm used in this approach was trained on simulated RadioScatter events using a simplified geometry. A more detailed approach using the full detector geometry is in development to further test and improve the direction reconstruction of the proposed array.

4.3 Sensitivity

A full sensitivity study of the RET-N array as described here has been performed. Simulated neutrino events were thrown randomly (weighted by polar angle to include Earth opacity to UHE neutrinos) over a volume surrounding the array. This was performed for the fully realized RET-

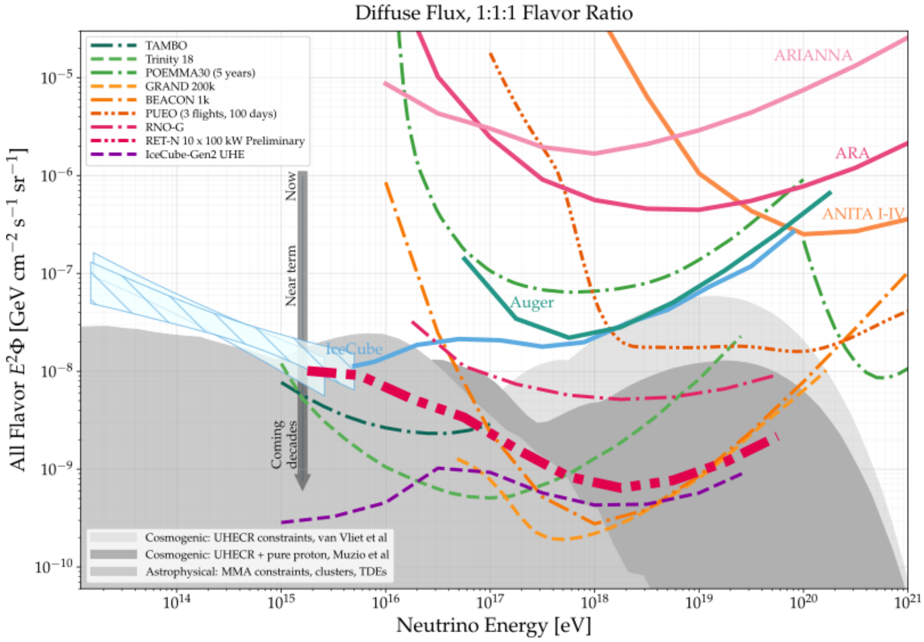

Figure 3: The simulated RET-N sensitivity for ten stations (detailed above) operating for ten years. Plot adapted from [6] with RET-N sensitivity highlighted for clarity.

N (270 receiving antennas over 10 stations) over a ten year period. The preliminary sensitivity curve for RET-N in Figure 3 shows that RET-N can probe leading theoretical models of UHE neutrino flux, shown in gray. RET has comparable sensitivity in this region to other UHE neutrino experiments, with a smaller total number of receivers. This study—in concert with ongoing method validation with RET-CR—suggests that RET will be another valuable instrument in the era of multi-observable, multi-messenger astronomy.

5. Conclusion and Outlook

In these proceedings we detailed the Radar Echo Telescope for Neutrinos (RET-N). With the radar echo method already validated in T-576, we are testing the method further in-situ with RET-CR. We will use these experiments, along with simulation, to design a detector in deep polar ice. The design will be guided by reconstructability of the primary UHE neutrino properties. A sensitivity study for a premliminary detector geometry demonstrates the capability of the radar echo method as a detection mechanism for UHE neutrinos. The ultimate aim of RET is to be a relatively low-cost, scalable UHE neutrino detector.

References

[1] M. Aartsen, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens et al., *The IceCube neutrino observatory: instrumentation and online systems*, *Journal of Instrumentation* **12** (2017) P03012.

[2] M.G. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J.A. Aguilar et al., *First observation of PeV-energy neutrinos with IceCube*, *Physical Review Letters* **111** (2013) .

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[3] M. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Neutrino emission from the direction of the blazar TXS 0506056 prior to the IceCube-170922a alert*, *Science* **361** (2018) 147.

[4] and R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, *Science* **378** (2022) 538.

[5] I. Collaboration*†, R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Observation of high-energy neutrinos from the galactic plane*, *Science* **380** (2023) 1338 [`https://www.science.org/doi/pdf/10.1126/science.adc9818`].

[6] M. Ackermann, M. Bustamante, L. Lu, N. Otte, M.H. Reno, S. Wissel et al., *High-energy and ultra-high-energy neutrinos: A snowmass white paper*, *Journal of High Energy Astrophysics* **36** (2022) 55.

[7] M.P. De Haas, M. Kunst, J.M. Warman and J.B. Verberne, *Nanosecond time-resolved conductivity studies of pulse-ionized ice. 1. the mobility and trapping of conduction-band electrons in water and deuterium oxide ice*, *The Journal of Physical Chemistry* **87** (1983) 4089 [`https://doi.org/10.1021/j100244a019`].

[8] The Radar Echo Telescope collaboration, "https://www.radarechotelescope.org."

[9] P. Blackett and A. Lovell, *Radio echoes and Cosmic Ray Showers*, *Proc. R. Soc. London, Ser. A* **177** (1941) 183–186.

[10] R. Abbasi, M.A.B. Othman, C. Allen, L. Beard, J. Belz, D. Besson et al., *Telescope array radar (TARA) observatory for ultra-high energy cosmic rays*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **767** (2014) 322.

[11] R. Abbasi, M. Abe, M.A.B. Othman, T. Abu-Zayyad, M. Allen, R. Anderson et al., *First upper limits on the radar cross section of cosmic-ray induced extensive air showers*, *Astroparticle Physics* **87** (2017) 1.

[12] M. Chiba, T. Kamijo, F. Yabuki, O. Yasuda, H. Akiyama, Y. Chikashige et al., *Radar for detection of ultra-high-energy neutrinos reacting in a rock salt dome*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **662** (2012) S222.

[13] K.D. de Vries, K. Hanson and T. Meures, *On the feasibility of RADAR detection of high-energy neutrino-induced showers in ice*, *Astroparticle Physics* **60** (2015) 25.

[14] S. Prohira et al., *Suggestion of coherent radio reflections from an electron-beam induced particle cascade*, *Physical Review D* **100** (2019) .

[15] S. Prohira et al., *Observation of Radar Echoes from High-Energy Particle Cascades*, *Phys. Rev. Lett.* **124** (2020) .

[16] S. Prohira et al., *The Radar Echo Telescope for Cosmic Rays: Pathfinder experiment for a next-generation neutrino observatory*, *Phys. Rev. D* **104** (2021) .

[17] R. Stanley et al., *The Radar Echo Telescope for Cosmic Rays: Contribution to ICRC 2023*, *PoS* **ICRC2023 474** (2023) .

[18] V. Lukic et al., *From signal properties toward reconstruction for the Radar Echo Telescope for neutrinos*, *PoS* **ARENA2022** (2022) .

PoS(ICRC2023)1135

[19] S. Prohira and D. Besson, *Particle-level model for radar based detection of high-energy neutrino cascades*, `1710.02883`.

[20] S. Kunwar, R. Abbasi, C. Allen, J. Belz, D. Besson, M. Byrne et al., *Design, construction and operation of a low-power, autonomous radio-frequency data-acquisition station for the TARA experiment*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **797** (2015) 110.

[21] S. Prohira, D. Besson, S. Kunwar, K. Ratzlaff and R. Young, *Implementation of a custom time-domain firmware trigger for RADAR-based cosmic ray detection*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **890** (2018) 126.

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