PROCEEDINGS OF SCIENCE

# The Radar Echo Telescope: Detection of Ultra High Energy Neutrinos and Cosmic Rays Using the Radar Echo Technique

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The SLAC T-576 beam test has shown the radar echo detection method as a feasible technique to probe high-energy-particle-initiated cascades in dense media, such as ice. Furthermore, particle-level simulations show that the radar echo method has a very promising sensitivity to investigate the flux of cosmic neutrinos at energies greater than 1 PeV. Detecting these cosmic neutrinos is the aim of the Radar Echo Telescope for Neutrinos (RET-N). To show the in-nature viability of the radar echo method, we present the Radar Echo Telescope for Cosmic Rays (RET-CR). RET-CR will provide the proof of principle necessary for the construction of RET-N by detecting, using radar, the in-ice continuation of cosmic-ray induced air showers impinging on high altitude ice sheets.

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## 1. Introduction

Neutrinos are one of the most important messengers in modern multimessenger astronomy. Where photons can be absorbed by dust and gas between sources and the Earth, and cosmic rays spend millennia trapped by galactic and extragalactic magnetic fields, neutrinos travel from their sources to detectors on Earth unimpeded. As such, they are able to provide insights into the highest energy processes in our Universe. Unfortunately, that which makes neutrinos such good cosmic messengers also means that they are incredibly difficult to detect. Neutrinos are very weakly interacting and, as such, their interaction cross sections are very low. This, along with their steeply falling flux towards the highest energies, means that extremely large volumes have to be instrumented to detect enough neutrinos to draw conclusions. There are many current experiments that tackle this problem of neutrino detection by instrumenting, in various ways, large volumes of air, water, and ice [1–8]. In this paper we discuss a novel technique for instrumenting ice in order to detect ultra-high energy neutrinos, the radar echo technique, along with a new experiment; the Radar Echo Telescope.

## 2. Radar Echo Technique in High Density Media

The radar echo technique in high density media was first successfully demonstrated at the Stanford Linear Accelerator Center (SLAC) in experiment T576 [9, 10]. Two experimental runs were carried out with the electron beam at SLAC's End Station A. Suggestions of radar echoes were reported after the first run [9], with observations of radar echoes from high energy particle induced cascades reported after the second run [10].

A volume of high density target material is illuminated with radio of a given frequency. When a cascade is initiated in the target material by a high energy particle, the ionisation cloud of the cascade absorbs and re-emits the illuminating radio. The re-emitted echo is then detected by receiver antennas monitoring the same volume. For T576, the cascade was initiated in a high density polyethylene (HDPE) target by a bunch of approximately $10^9$ electrons with energies $O(1-10\text{ GeV})$. This creates a cascade in the HDPE equivalent to that initiated by a 1 EeV neutrino.

With the success of the technique in the laboratory, we can look forward towards its applications in nature for the detection of ultra high energy neutrinos.

## 3. The Radar Echo Telescope for Neutrinos

Our ultimate goal is to use the radar echo technique to detect cascades initiated in ice by ultra high energy neutrinos with the Radar Echo Telescope for Neutrinos (RET-N).

A neutrino interacting in ice will initiate a dense in-ice cascade. If the neutrino interacts in a volume of ice into which transmitting antennas are placed and receiver antennas are monitoring, it will be possible to detect the cascade using the radar echo technique described above. This active method of neutrino detection contrasts with the passive method of Askaryan detection. RET-N will, therefore, provide a complimentary method of detecting ultra high energy neutrinos, with a peak sensitivity between that of the optical Cherenkov and Askaryan detection methods. Additional complimentarity is given by RET-N's lack of restriction to the Cherenkov cone.

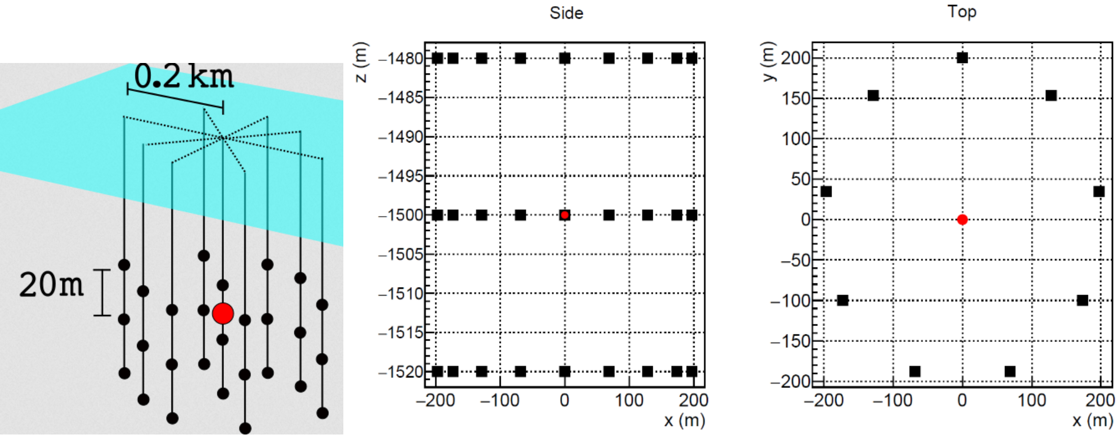

**Figure 1:** Diagrams of the RET-N station layout showing 27 receivers, in black, surrounding a single transmitter, in red. The receivers are arranged in 8 spokes at a distance of 0.2 km from the transmitter and with a vertical separation of 20 m. The station layout is shown in cartoon form, *left*, in a side projection, *middle*, and in an overhead projection, *right*.

The layout of antennas currently used for simulations of RET-N is given in FIG. 1. A single transmitting antenna, 1.5 km below the ice surface and broadcasting with a power of 100 kW, is surrounded by 27 receivers. The determination of the final station layout is still underway and is dependent on signal propagation and reconstruction studies currently underway [11]. Shown in FIG. 2 is the predicted sensitivity of RET-N for 10 stations of the current design for 10 years of data taking. Here we assume that we can efficiently trigger the data taking at a level of 0 dB with respect to thermal noise for a 50 MHz bandwidth. This efficient triggering is expected due to the specific and unique radar signal properties. It can be seen from FIG. 2 that RET-N will be competitive with current and proposed experiments in exploring the cosmogenic neutrino flux.

## 4. The Radar Echo Telescope for Cosmic Rays

While the ultimate goal is RET-N and the detection of ultra high energy neutrinos, ensuring that the rarely interacting neutrinos are indeed what we see in the detector is crucial. To this end, we need a reliable in nature test beam that can be used to develop the radar echo technique further in nature. The first step in developing RET-N is, therefore, the Radar Echo Telescope for Cosmic Rays (RET-CR) [13]. For RET-CR, cosmic ray air showers impinging on a high altitude ice shelf, causing a continuation of the cascade in ice, will be used as the test beam.

When a cosmic ray air shower impinges on a high-altitude ice sheet (typical polar ice altitudes are 2-3 km), approximately 10% of the primary energy is transferred to a dense in ice cascade. For more details on this process see [14, 15]. This means that a cosmic ray initiated cascade can be observed by two systems, one above and one below the surface of the ice. It is on this principle that RET-CR is designed. The cosmic-ray air shower is detected by a surface array of scintillators and radio antennas which trigger the readout of the radar echo technique in ice detector. In this way the air shower and in ice cascade can be detected and reconstructed independently. This will allow the direct comparison of results obtained by the radar echo technique to those obtained by more

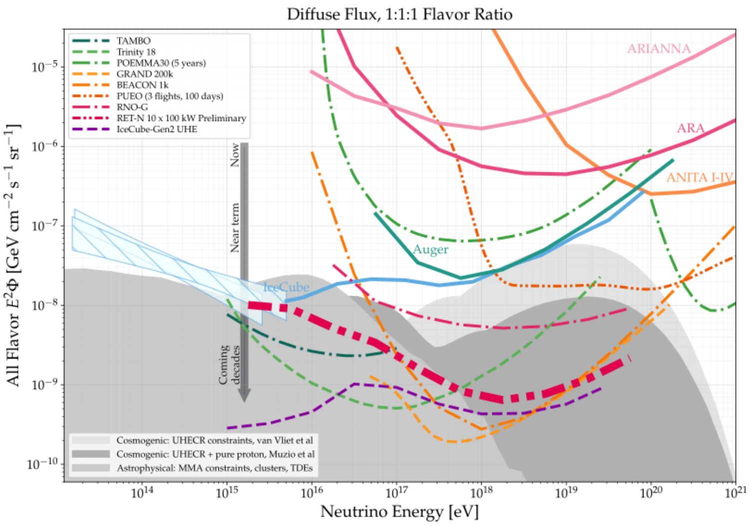

**Figure 2:** The neutrino sensitivity of 10 RET-N stations with the proposed layout operating for 10 years in comparison with other neutrino detection experiments. This sensitivity assumes a trigger at a signal to noise ratio of 0 dB with respect to thermal noise for a 50 MHz bandwidth. Here, the RET-N line is enlarged for clarity. [12]

typical methods of cosmic ray detection. The layout of RET-CR is shown in FIG. 3. This layout has been optimised based on surface detector trigger studies, air shower reconstruction and radio in-ice propagation studies [13, 16].

The surface detector of RET-CR is designed and optimised such that 100% trigger efficiency obtained for cosmic ray air showers with energies of $10^{16.5}$ eV and above. It is these showers that we most expect to see in both the surface and radar systems, and so it is essential to capture as many of these showers as possible. The surface detector is composed of 6 independently triggered stations with two scintillators and one radio antenna each. A station passes a L0 trigger when both scintillators in one station contain an energy deposit of one equivalent muon or greater. A L1 trigger is obtained when at least three stations meet the L0 requirement. Once a L1trigger is obtained, the trigger signal is sent to the radio antenna and the in-ice radar system read out. Furthermore, for reconstruction purposes, the surface radio antennas record a snapshot of the air shower in the 30 to 300 MHz band.

Combining the efficiencies of both the surface and in-ice detectors, we obtain an expected event rate shown in FIG. 4. By being able to find the signal at a level of 0 dB with respect to the thermal noise, we expect one event per day at $10^{16.0}$ - $10^{16.5}$ eV. Additionally we expect one event per year at $10^{18.0}$ - $10^{18.5}$ eV. It is possible that, with appropriate methods of digging into the background, we can increase the event rate by a factor of 10.

## 5. RET Status & Outlook

Significant progress has been made towards both RET-N and RET-CR. Studies are underway into signal properties, reconstruction techniques, and final layouts of all the detectors [11, 14, 17, 18]. For RET-CR, a test set up was constructed at the Vrije Universiteit Brussel in December 2020, and

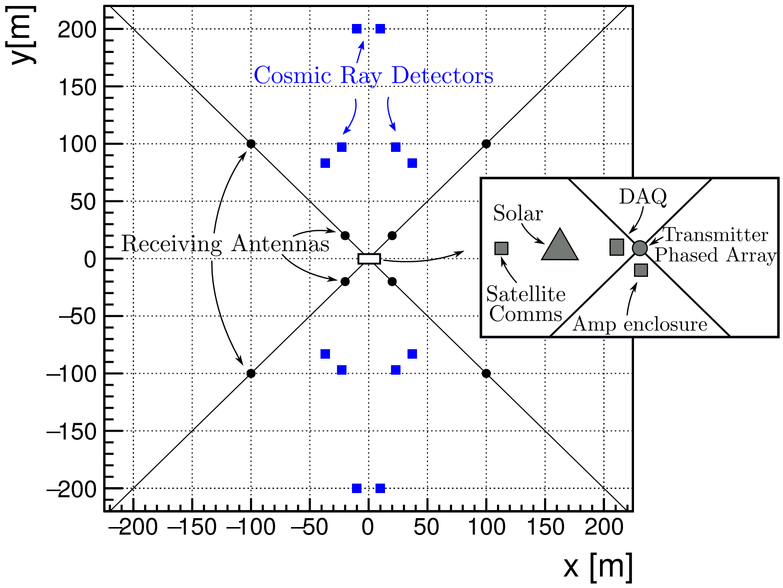

**Figure 3:** The layout of RET-CR with the surface stations shown in blue and the radar echo technique detector in black. The surface stations are concentrated in two quadrants of the set up, either side of the central transmitter. [13]

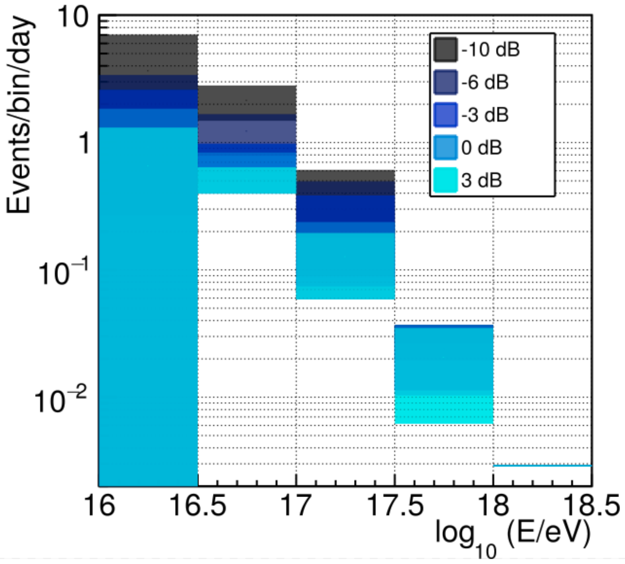

**Figure 4:** Event rates per day as a function of energy for RET-CR, taking into account the efficiencies of both the surface and in-ice systems. The colours represent different signal-to-noise ratios with respect to the thermal noise for a bandwidth of 100MHz. [13]

construction of an end-to-end RET-CR set up is expected locally in January 2023. The final RET-CR design was finalised in April 2022 and several operational tests have been performed or are in progress. A test bench for the surface detector scintillators was set up in May 2022 and an initial cold test on the surface detector radio antennas was conducted in April 2022. The deployment of RET-CR is expected in a polar region in 2023-2025.

## 6. Conclusion

In this proceeding we have presented the Radar Echo Telescope (RET), with its two variations; the Radar Echo Telescope for Neutrinos (RET-N) and the Radar Echo Telescope for Cosmic Rays (RET-CR). The first phase of the project, RET-CR, is in an advance state of construction and expected to be deployed in a polar region within the next five years. The successful detection of in-ice air showers cores by RET-CR will provide essential information for the continuation of the project and the construction of RET-N, informing the final design and providing an essential test bed for the triggering and reconstruction algorithms. To this end, we expect RET-N to be deployed and detecting cosmogenic neutrinos within the decade.

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