PROCEEDINGS OF SCIENCE

The Radar Echo Telescope for Cosmic Rays: Contribution to ICRC 2025

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The Radar Echo Telescope for Cosmic Rays (RET-CR), a pathfinder experiment for a future ultra-high-energy neutrino detector, is an experiment designed to detect the ionization trail from a cosmic-ray-induced particle cascade penetrating a high-altitude ice sheet. In high-elevation ice sheets, a high-energy cosmic ray (E > 10 PeV) at a small zenith angle deposits more than 10 percent of its primary energy into the ice sheet, resulting in energy densities several orders of magnitude higher than the in air component. This dense in-ice cascade can then be interrogated with an in-ice radar system. This technique, called the radar echo method, relies on reflection of a transmitted radio wave off the ionization trail produced in a UHE particle interaction. RET-CR consists of a phased-array transmitter and an array of receiving antennas located in the ice, triggered by scintillator panels on the surface. RET-CR is a pathfinder experiment, which aims to test the radar echo method for the Radar Echo Telescope for Neutrinos (RET-N). RET-CR was deployed near Summit Station, Greenland, running from May to August 2024. We discuss the ongoing cosmic-ray analysis of the 2024 campaign, and initial results will be presented.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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1. Introduction

Ultra-high-energy (UHE) neutrinos (> 10 PeV) are a unique probe into the cosmos. As the only observed particles whose properties are not fully captured by the Standard Model, neutrinos present 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 [1, 2]. In addition to the small interaction cross-section, cosmic neutrinos have an observed flux that falls steeply with energy in the UHE regime.

In order to combat this steeply falling flux, UHE neutrino detectors need to instrument massive volumes, $O(10\,\text{km}^3)$, of some dense material [3]. Ice is commonly chosen as the material as it is naturally occurring in the polar regions. Radio techniques to probe the UHE neutrino interactions in ice are well suited for this due to a factor of ten difference in the attenuation lengths between light and radio in polar ice $\lambda_{\text{optical}} = O(100\,\text{m}) \mid \lambda_{\text{radio}} = O(1\,\text{km})$ [4–6]. This attenuation length difference means that a UHE neutrino detector based on the radio technique can be sparsely instrumented, scalable, and cost-effective at higher energies, in which optical detectors, efficient detectors at and below the $O(10\,\text{PeV})$ scale, run low on statistics.

2. The Radar Echo Method

Radar has been in use for over a century. A transmitting antenna (Tx) illuminates a volume with radio waves, and receiving antennas (Rx) 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 physical qualities and motion of the objects. When a UHE particle interacts with a dense medium, such as polar ice, a cascade of secondary particles is created. This cascade then ionizes the medium as it develops, leaving behind a short-lived, but dense plasma. The signal from a radio transmitter interrogating this medium will then reflect off the dense plasma, which can be detected with co-located receiving antennas. For more details on this method, see [7–9].

The radar echo method has been verified in a laboratory setting at the SLAC National Accelerator Center during experiment 576 (T-576) [10, 11]. T-576 consisted of dumping a high-energy beam of electrons into a block of high-density polyethylene (HDPE). This HDPE was then interrogated with a radar system. A radar echo was measured from the ionization trail which was induced by the beam of electrons.

After the experimental validation of the radar echo method of detecting high-energy particle interactions in T-576, the RET collaboration aims to validate the method using cosmic rays as an in-nature test beam in polar ice.

3. The Radar Echo Telescope for Cosmic Rays (RET-CR)

RET-CR is a pathfinder experiment designed to test the radar echo method in nature using cosmic rays as a test beam. In high-elevation ice sheets, a high-energy cosmic ray (E > 10 PeV) at shallow zenith angle deposits more than 10 percent of its primary energy into the ice sheet producing energy densities several orders of magnitude higher than in air [12]. RET-CR was deployed in the summer of 2023 [13] and the summer of 2024. The 2024 run discussed here will be designated RET-CR-24.

The general design of RET-CR consists of two main sub-systems, the in-ice radar system, and the surface detectors.

3.1 The in-ice radar system

The in-ice radar system consists of a centrally-located eight antenna phased-array transmitter (Tx) and an array of co-located receiving antennas (Rx). The in-ice antennas were deployed in the ice in boreholes, drilled with a modified Kovacs Mark V Ice Coring System [14]. The antennas were designed to be modular, easily deployable, and provide a good response in the VHF range for both transmitting and receiving while still fitting into the borehole. The eight transmitting antennas are deployed vertically with spacing $O(0.5\,\text{m})$, and with the center of the phased array located ~(10 m) below the ice surface.

The other portion of the in-ice radar system are the three receiving antennas. The receiving antennas are located around a 30m circle of the transmit antenna. Each receiving string consists of one antenna located ~(10 m) below the surface. In 2024, a fourth receiving antenna was added, however it has a different setup which will be detailed later in this work. Figure 1 shows the RET-CR detector layout as deployed in 2024. These receiving antenna channels each have a "front-end" consisting of a $O(60\,\text{dB})$ low-noise amplifier and 100-300 Mhz bandpass filtering.

The in-ice radar array is controlled and readout by the central station DAQ. This DAQ is built around a xilinx RFSoC which has eight analog-to-digital converters (ADC) and eight digital-to-analog converters (DAC). The transmitted signal is created on the DAQ and split into four DAC channels. Each of these four signals are routed into a pair of 20 W power amplifiers which power the transmitting antennas. The 8 channels of the phased-array antennas are split into stacked pairs. This separation of signal into pairs allows the phased-array transmitter to be steered via pairwise phasing.

The close proximity of the Rx to the high power Tx could cause permanent damage and/or loss of data quality without removal of the transmitted signal. The central station DAQ has 8 DAC channels, four of which are used for the phased-array transmitter. The remaining four DACs are used to operate the Carrier Cancellation (CC) routine. This routine creates an amplitude scaled and time-delayed copy of the transmit signal, which is then routed to the front-ends of the inner 3 Rx channels (Rx0, Rx1, and Rx3 in Figure 1). The outrigger Rx channel (Rx2), added for the RET-CR-24 campaign was not included in the CC routine because of a malfunctioning DAC channel. An additional, unamplified reference channel was used as a passive transmitter monitor. The signal created in the CC routine is fed into the Rx signal chain before amplification, ensuring the front-end amplifiers do not saturate. The CC routine is a two step process.

In the first pass of the CC routine, the transmit power is lowered to a level which does not saturate the Rx front-ends. The resulting Rx signals are then used to determine the approximate phase and amplitude required for cancellation. Then, the transmit power is increased to full power, with the first-guess CC signal increased to best match the amplitude in the Rx(s). The second pass

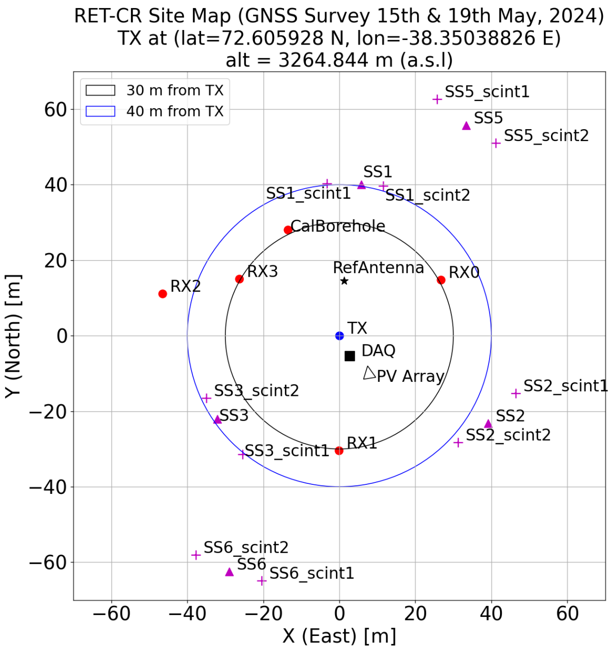

Figure 1: Diagram of the RET-CR detector geometry as deployed in 2024. The locations in this map were measured during the 2024 deployment via GPS.

of the CC routine is then ran, fine tuning the amplitude and phase-difference required to cancel the Tx signal in the Rx signal chain.

3.2 The surface system

The surface system consists of two components, a charged particle detection system incorporating scintillator panels, and a surface radio system.

The first component of the surface system is an array of scintillator panels, which provide the primary triggering mechanism for RET-CR. The scintillator panels are arranged in pairs of two, one pair of panels per surface station. The triggering mechanism for RET-CR is a three level process (L0, L1, L2). An individual scintillator panel registering at least one minimum ionizing particle is considered an L0 trigger. In order to ensure the system is not overwhelmed by low-energy cosmic rays, the next level of trigger requires causal coincidence between both panels in a surface station to produce a station-level trigger. When two L0 triggers are received in a station within this coincident window, an L1 trigger is raised. The full system is triggered when a set number of stations (L1) trigger within a causal coincidence window, this is called an L2 trigger and produces a full readout of the in-ice radar array and the surface radio array. Each scintillator panel underwent a calibration routine to normalize energy response and trigger rate. After this calibration routine, each panel was set to run at $\mathcal{O}(300)$ Hz, aiming for a full system trigger rate of several events per minute.

The second component of the surface system is the surface radio array, which consists of one log-periodic dipole antenna per surface station. These antennas are to be used in the Square Kilometre Array (SKA) [15]. The SKA-style antennas have frequency sensitivity in the 50-350

Mhz range, and their primary purpose in RET-CR is to aid in reconstruction of the cosmic ray arrival direction and energy.

The surface radio system readout and control electronics used in RET-CR were provided by the CODALEMA collaboration, which operated a cosmic ray radio detector footprint at Nancay Radio Observatory Decametric Array in France starting in 2004 [16]. The CODALEMA system was housed with and powered by the surface station electronics, described below. The CODALEMA radio data was meant to be read out anytime an L2 trigger was raised, but owing to a bug in the firmware, these data were mis-timed with the rest of the RET-CR data for the 2024 run, and was therefore not used in the cosmic ray analysis.

The RET-CR surface system is an array of five independent surface stations, comprised of an electronics enclosure, two scintillator panels, and a surface radio antenna. Each of these surface stations houses the surface station electronics, a raspberryPi, a solar charge controller, the CODALEMA electronics, and a 12V battery. Each surface station is independently powered via an omnidirectional array of eight 20 W solar panels. The surface stations are connected to the central station via two cat-7 cables, one providing a network link to a switch in the central station, and the other is a custom-made triggering cable. This triggering cable contains the outgoing scintillator triggers, and the incoming full system (L2) trigger. In RET-CR-24, the central station formed the L1 trigger. The incoming L2 is sent to the CODALEMA DAQ to trigger a surface radio array readout. The enclosure was watertight to ensure protection from the harsh polar elements.

4. Initial Performance of RET-CR-24

RET-CR was redeployed to the same site approximately 5 km North-East of Summit Station, Greenland in mid-May 2024 and ran until mid-August 2024. The full campaign recorded $O(10^5)$ cosmic ray triggered events.

Improved trigger logic for the RET-CR-24 campaign resulted in increased system uptime and a flattening of the trigger rate, indicated by the vertical line in Figure 2. The original trigger logic required N number of stations to trigger in a coincident window, where N was set by hand. The upgraded trigger logic changed this condition to require one less than the total number of stations currently powered up, or alive ($N_{alive} - 1$). The central DAQ monitored output from the surface stations to determine if the station was powered on and triggering nominally. If a station went down for any reason, which happened at night as the sun dipped lower in the sky, the trigger logic automatically adjusted the N_{alive} parameter. The minus one condition for the trigger was added to reduce the effect of individual station dead time on the full system trigger rate. Additionally, the individual surface stations automatically power cycled to remedy issues in the data recording or communication to the scintillator panels. This power cycling process took a few seconds between power off and data taking resumed on power up. Before the upgraded trigger logic, the entire array would be unable to trigger during one of these power cycles. This trigger logic change is the start of the nominal data taking run for RET-CR-24, with the preceding data considered the commissioning phase. Figure 2 shows the RET-CR-24 triggered events as a function of run days, partway through the run. The vertical red line denotes the implementation of this new trigger logic. We see both an increase and a stabilization of trigger rate for the system as a result of this change.

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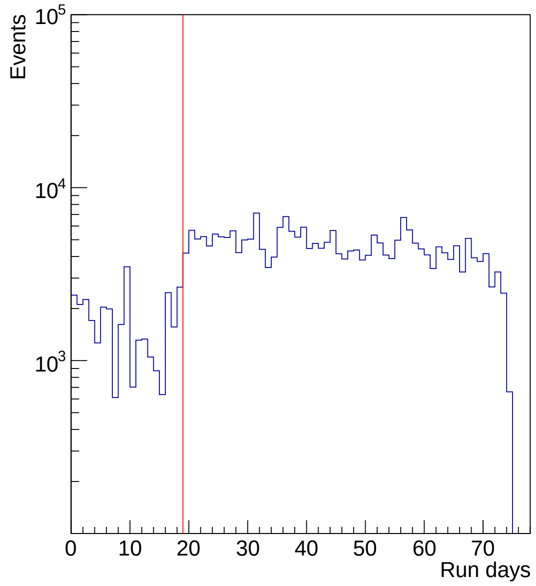

Figure 2: Plot of the RET-CR-24 triggered events as a function of run days. The vertical red line denotes the $N_{alive} - 1$trigger logic change implementation.

Figure 3 shows the in-ice Rx channels with the Tx at full power and the CC routine running. A direct comparison of the power in the Rx with and without CC is not possible, as full Tx power with no CC would saturate the front end amplifiers and cause damage. To estimate the effectiveness, we scale the unamplified reference antenna by the in-ice Rx front-end amplification of 60 dB. The lower red horizontal line in Figure 3 corresponds to the power for the in-ice Rx (CH1), while the upper horizontal redline denotes the amplitude-scaled reference antenna power (CH5). The difference between these red lines, $O(60)$ dB, is the reduction in power provided by the CC in this event. The carrier cancellation runs periodically, but any reflection from a cosmic ray would not be canceled, as it would be out of phase with both the direct transmitted signal, and the carrier cancellation signal.

Figure 4 shows a forced trigger event following the CC routine. The carrier canceled channels 1, 3, and 4 have a similar amplitude to channel 2, in which the carrier is filtered. Also shown is the unamplified reference channel in teal.

The full RET-CR-24 dataset is broken down into sub-sets naturally by trigger condition and Tx power status. We then analyze each sub-set separately to best search for the radar echo signal among the various backgrounds. For example, the set of cosmic ray triggered events with the transmitter off provides a useful set of radio frequency backgrounds from cosmic ray events in which no radar echo could be present.

In addition to these data sub-sets, we utilize a ten-percent burn sample for each subset to train analysis variables and define cuts for the full dataset. Information from the surface system, including time of arrival and charge depositions in the panels, is used to search for the radar echo. Other properties of the radar echo, derived from simulations, are used as well.

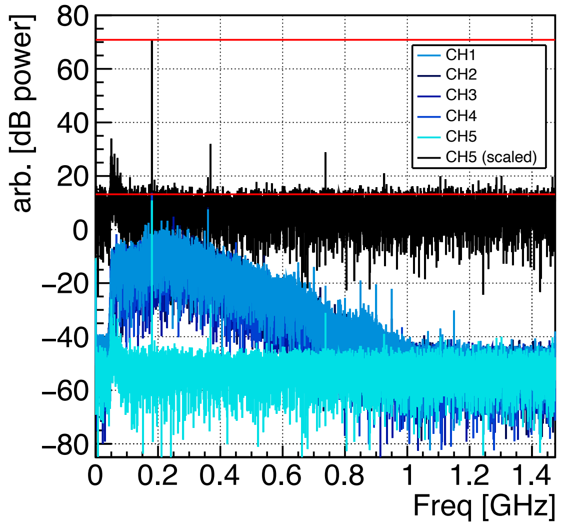

Figure 3: Plot of the Carrier Cancellation routine (CC) for the in-ice Rx channels. Details in the text. The transmitter frequency is 180 MHz.

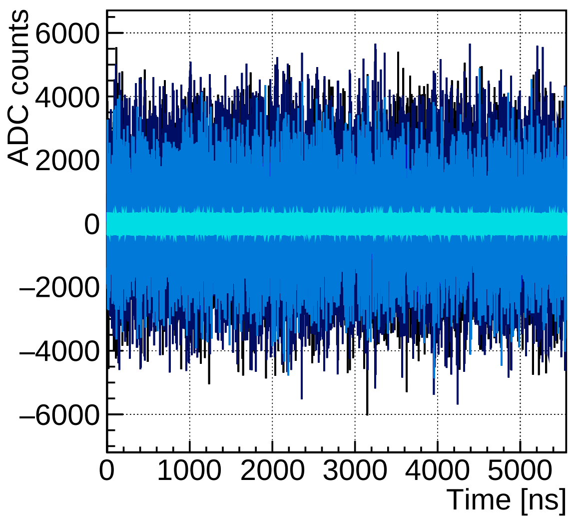

Figure 4: Plot of a forced trigger event in the in-ice Rx following the CC routine.

5. Conclusion and Outlook

In these proceedings, we detailed the Radar Echo Telescope for Cosmic Rays (RET-CR) 2024 campaign at Summit Station, Greenland. With the RET-CR-24 dataset we aim to demonstrate the detection of the in-ice continuation of a cosmic ray air shower using the radar echo method. Results and further analyses of this dataset will then guide the development of the Radar Echo Telescope for Neutrinos (RET-N). The overall goal of RET-N is to be a relatively low-cost, scalable UHE neutrino detector.

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6. Acknowledgements

We thank the CODALEMA collaboration and the IceCube collaboration for providing components of our surface system, and the staff of Summit Station for facilitating our work. We recognize support from The National Science Foundation under Grants No. 2012980, No. 2012989, No. 2306424, and No. 2019597 and the Office of Polar Programs, the Flemish Foundation for Scientific Research FWO-G085820N, the European Research Council under the European Unions Horizon 2020 research and innovation program (Grant Agreement No. 805486), the Belgian Funds for Scientific Research (FRS-FNRS), IOP, and the John D. and Catherine T. MacArthur Foundation.