PROCEEDINGS OF SCIENCE

Deployment and status of the Radar Echo Telescope

Dylan Frikken[a,*] **for the RET Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *Department of Physics, Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus OH, USA*

E-mail: frikken.1@buckeyemail.osu.edu

The Radar Echo Telescope for Cosmic Rays (RET-CR), a pathfinder experiment for a future ultrahigh energy neutrino detector, is a recently deployed experiment designed to detect the ionization trail from an in-ice cosmic ray shower via active radar sounding. 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 a cascade with energy densities several orders of magnitude higher than in air. This dense in-ice cascade can then be interrogated with an in-ice radar system. RET-CR consists of a phased-array transmitter and an array of receiving antennas triggered by scintillator panels on the surface with a surface-based radio array to aid in cosmic ray reconstruction. 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 at Summit Station, Greenland, running from May to August 2024.

10th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA2024)
11-14 June 2024
The Kavli Institute for Cosmological Physics, Chicago, IL, USA

*Speaker

PoS(ARENA2024)012

1. The Radar Echo Method

The radar echo method relies on well-known radar technology that has existed for decades. The basic method utilizes a transmitting antenna and a receiving antenna. The transmitter illuminates a region with radio waves, while the receiver monitors that region. If some object that reflects radio enters that volume, the radio from the transmitter can be reflected into the receiver. This signal depends on the Tx-Rx geometry and the properties and motion of the objects. In the case of the Radar Echo Telescope, the reflecting object is an ionization trail resulting from an UHE particle interaction in a dense medium. This work will briefly summarize the concept, but a more detailed explanation can be found in [1–3].

When an UHE particle interacts in a medium, a cascade of relativistic particles is produced. As the cascade develops along the momentum direction of the primary UHE particle, the cascade loses energy to ionization. In dense media, such as ice, this ionization has sufficient density to reflect radio waves. The ionization is dependent on the properties of the media as well as its temperature [4]. In the case of polar ice, the ionization trail is expected to be of sufficient density and lifetime to provide a detectable reflection.

The radar echo method has been verified in a laboratory setting during experiment 576 (T-576) at the SLAC National Accelerator Center [5, 6]. In this experiment, a high-energy beam of electrons was directed into a block of high density polyethelene (HDPE). The HDPE was interrogated with radar, and a radar echo was measured from the ionization trail induced in the wake of the electron beam. The Radar Echo Telescope for Cosmic Rays (RET-CR) is an in-nature validation of the method demonstrated in the laboratory. If successful, the Radar Echo Telescope collaboration intends to design an UHE neutrino detector, the Radar Echo Telescope for Neutrinos (RET-N).

2. The Radar Echo Telescope for Cosmic Rays

RET-CR consists of an in-ice radar system, a surface based array, and central electronics (DAQ).

2.1 The In-Ice Radar System

The in-ice radar system of RET-CR consists of an eight channel phased-array transmitter (Tx) in the center of the array, four co-located receiving channels (Rx), and an unamplified reference channel, shown in Figure 1. The radar system and central electronics are powered by an omnidirectional 3.6kW array of solar panels, and a bank of batteries.

The transmitter array consists of eight independent antennas deployed vertically. Each antenna is connected to an independent 20W power amplifier, and the collection of eight antennas acts as a phased array. This allows the beam to be steered, while also increasing the beamed power in the signal region. The majority of data during the 2024 run was taken with a transmitter frequency of 182MHz, a frequency chosen by balancing physics requirements with local band constraints.

The in-ice radar system utilizes a process called "carrier cancellation", which cancels the transmitter signal from the receiver channels before amplification. This carrier cancellation routine prevents amplifier saturation and damage from the nearby high-power transmitter, allowing the receivers to remain sensitive to the relatively weak radar echo. Carrier cancellation is a two step

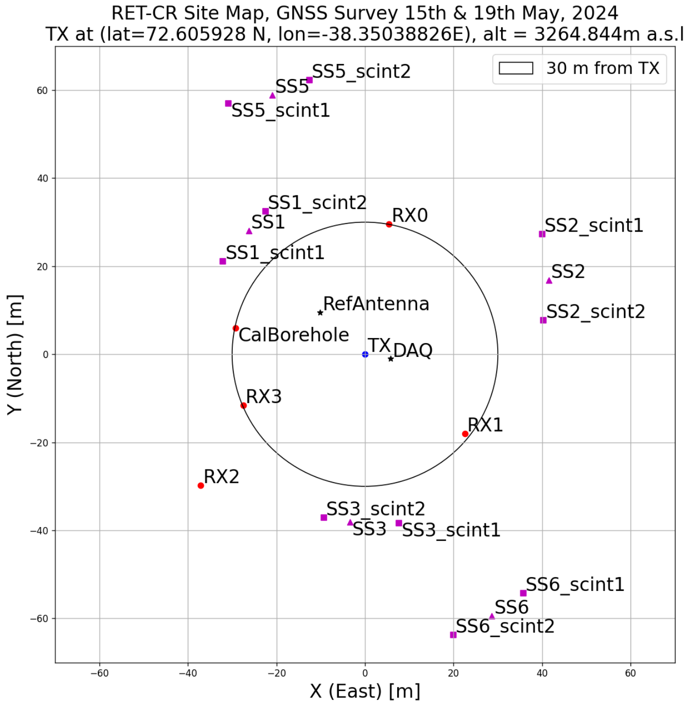

Figure 1: Showing the site map of RET-CR 2024. The site map was created using a GNSS Survey. The array geometry is centered on the transmitter (tx).

process, course and fine. The course step finds the phase that best cancels out the transmitted signal at a modest transmitter power, ensuring that the power can be raised without damage to the amp. Next, the transmitter power is raised, and a fine cancellation phase routine is run to find the best possible phase and amplitude to cancel the transmitted signal. The process is repeated until the system is at maximum running power. The carrier cancellation routine is run regularly to ensure saturation and damage does not occur. The carrier cancellation routine cancels out the global phase of the transmitted signal, both direct and reflected from the many possible reflected paths between transmitter and receiver. This means that changing conditions, such as precipitation or drifting will affect the efficiency of cancellation, requiring the process to be run more frequently.

There are three Rx channels in the system which utilize this carrier cancellation routine, labeled as (Rx0, Rx1, Rx3) in Figure 1. One Rx channel, Rx2, is not carrier cancelled, but has a bank of high-pass filters to eliminate the transmit signal. The unamplified reference antenna is used to monitor the transmitter signal and operation.

2.2 The Surface Array

RET-CR has five independent surface stations used to trigger and aid in the reconstruction of any signals detected by the in-ice radar system. Each surface station consists of two scintillator panels, one above surface cross-polarized log-periodic dipole antenna, and an electronics enclosure. The two scintillator panels are seperated by 20 m and are primarily used to trigger the in-ice radar system. RET-CR has three inner surface stations located 40 m from the transmitter and two outrigger stations located 65 m from the transmitter , as seen in Figure 1. The surface stations are independently powered with solar panels, charge controller and a 12 volt battery.

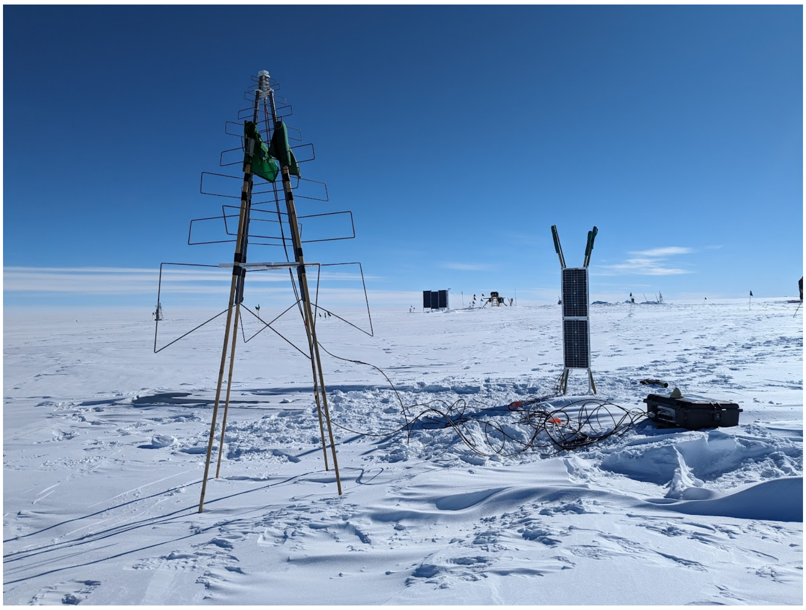

Figure 2: A deployed surface station. A log-periodic dipole antenna can be seen on the left. The right shows the surface station electronics and solar power. The central station solar array can be seen in the background.

The scintillator triggers are sent to the central DAQ which monitors for coincidence. The radar trigger logic requires a multi-station coincident scintillator panel response. Nominally, the logic is satisfied with 4 station coincidence, requiring at least one outrigger station coincidence to form.

The surface-based antennas are cross-polarization log-periodic dipole antennas which are used in the Square Kilometre Array [7]. The surface antenna array is used to aid in reconstruction of the detected cosmic ray air showers including energy, core position, and xmax. These reconstructed cosmic ray properties will be used in analysis of the in-ice radar events.

2.3 Improvements from 2023 Campaign

There were several improvements made on the 2023 campaign to prevent overheating, improve uptime and data quality, and to perform in-situ ice property measurements. The primary improvement was to the thermal management system. The central DAQ enclosure holds the transmitter amplifiers, which produce considerable heat at full power. The 2023 campaign of RET-CR was cut short when the DAQ, which had been buried in a vault under the snow surface, overheated. A thermal management system including a large external heat sink and deployment above the surface ensured a complete data taking run in 2024 free of overheating.

Improvements to the surface stations included deployment of two additional outrigger stations, a new scintillator timing system, new electronics, and software improvements. The two outrigger stations increase the energy threshold of the experiment as well as improve the reconstruction footprint. The new electronics and improved software were designed to improve the uptime from the 2023 campaign.

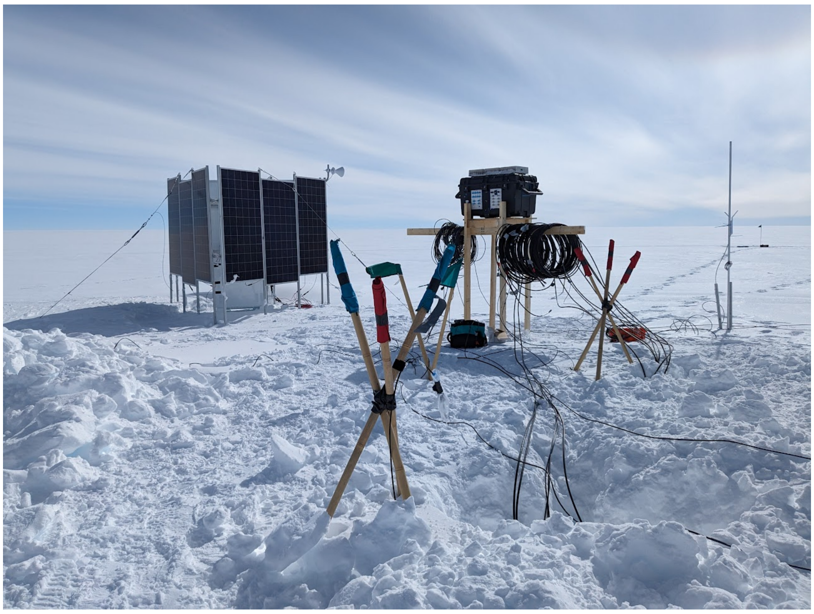

Figure 3: Showing the DAQ crate on an elevated platform. In the background, the central solar array can be seen which powers the radar system and DAQ.

3. Deployment of RET-CR

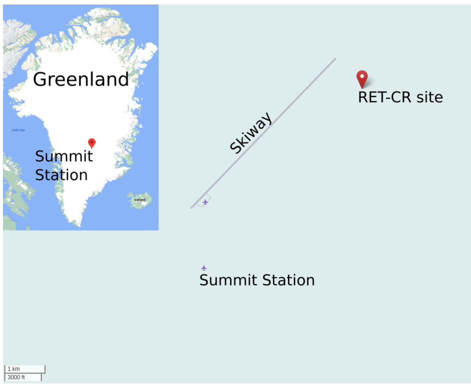

Figure 4: The RET-CR site is located approximately 5 km North East of Summit Station Adapted from OpenStreetMap and Google Maps.

RET-CR 2024 was deployed in May 2024 at a site roughly five km from Summit Station, Greenland. This site was also used for the 2023 RET-CR campaign, which was winterized in August 2023. The main solar array was left for the winter, which had drifted in and needed to be removed and redeployed. Two additional holes were drilled, one for in-situ ice property measurements, and the other for a longer-baseline in-ice Rx channel. The system was powered on with initial commissioning and calibration occurring by early June, 2024. The system was in operation into August of 2024, when it was decommissioned and removed.

4. Performance of RET-CR

The RET-CR 2024 campaign took place between early June and mid-August, with a commissioning phase beginning in mid-May.

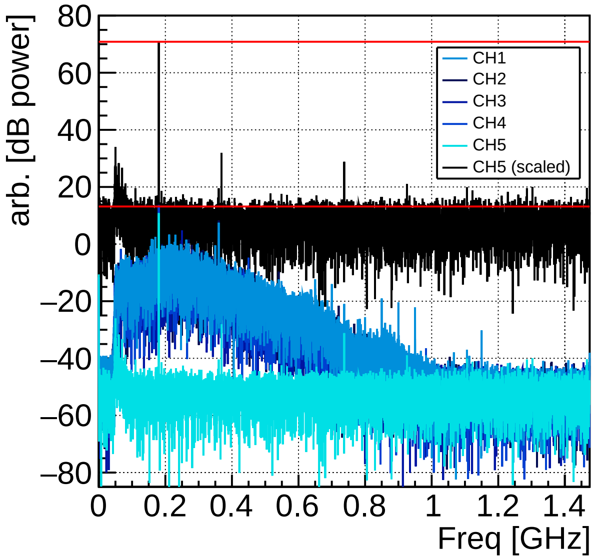

Figure 5: Plot demonstrating the carrier cancellation effectiveness of the in-ice radar system. Channels 1,2,3 and 4 are the receiver channels, and channel 5 is the unamplified reference antenna. Red lines demonstrate the levels between carrier cancelled signal and the uncancelled level.

The performance of the carrier cancellation routine is demonstrated in Figure 5. The unamplified reference antenna (CH5 in figure) was scaled by the nominal amplification used in the other channels (CH5 Scaled in figure). With this scaling, we took reference levels, shown by red lines in Figure 5, between the carrier-cancelled level at the transmission frequency and the expected uncancelled level. This demonstrates a $O(60dBm/Hz)$ reduction in received power.

The ten individual scintillator panels in the surface array ran at $O(300Hz)$ for the campaign. This produced an event rate of roughly one cosmic ray triggered event every 5-10 seconds, with a total of roughly 10^5 triggered events in total. The analysis of these data are currently ongoing at the time of these proceedings.

5. Conclusion and Outlook

In these proceedings, we detailed the Radar Echo Telescope for Cosmic Rays (RET-CR) 2024 campaign at Summit Station, Greenland. RET-CR 2024 was improved in several ways using the data from the 2023 campaign. With the full 2024 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 is to be a relatively low-cost, scalable UHE neutrino detector.

References

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

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

[3] 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.

[4] 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].

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

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

[7] P.E. Dewdney, P.J. Hall, R.T. Schilizzi and T.J.L.W. Lazio, *The Square Kilometre Array*, *Proceedings of the IEEE* **97** (2009) 1482.

Full Author List: RET Collaboration (June 28, 2024)

P. Allison[1], J.J. Beatty[1], D.Z. Besson[2], A. Connolly[1], A. Cummings[3,4,5], C. Deaconu[6], S. de Kockere[7], K.D. de Vries[7], D. Frikken[1], C. Hast[8], E. Huesca Santiago[7], C.-Y. Kuo[9], A. Kyriacou[2], U.A. Latif[7], J. Loonen[7], I. Loudon[10], V. Lukic[7], C. McLennan[2], K. Mulrey[10], J. Nam[9], K. Nivedita[10], A. Nozdrina[2], S. Prohira[2], J.P. Ralston[2], M.F.H. Seikh[2], R.S. Stanley[7], J. Stoffels[7], S. Toscano[11], D. Van den Broeck[7], N. van Eijndhoven [7], S. Wissel[4],

[1] Dept. of Physics, Center for Cosmology and AstroParticle Physics, The Ohio State University, Columbus, OH 43210
[2] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045
[3] Center for Multi-Messenger Astrophysics, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802
[4] Dept. of Physics, Pennsylvania State University, University Park, PA 16802
[5] Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802
[6] Dept. of Physics, Enrico Fermi Institue, Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637
[7] Vrije Universiteit Brussel, HEP@VUB, IIHE, Brussels, Belgium
[8] SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
[9] Dept. of Physics, Grad. Inst. of Astrophys., Leung Center for Cosmology and Particle Astrophysics, National Taiwan University, Taipei, Taiwan
[10] Department of Astrophysics/IMAPP, Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
[11] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

6. Acknowledgements

We would like to acknowledge the following groups.

The CODALEMA collabortation, for providing the surface radio DAQs used in RET-CR.
The IceCube collaboration for providing the scintillator panels used for triggering RET-CR.
The Summit Station staff for providing cargo logistics, warmth, food and much more.

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.