PROCEEDINGS OF SCIENCE

The Radar Echo Telescope for Cosmic Rays: Contribution to ICRC 2023

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The Radar Echo Telescope for Cosmic Rays (RET-CR) was deployed in May 2023. RET-CR aims to show the in-nature viability of the radar echo method to probe in-ice particle cascades induced by ultra high energy cosmic rays and neutrinos. The RET-CR surface system detects ultra-high-energy cosmic ray air showers impinging on the ice using conventional methods. The surface detector then triggers the in-ice component of RET-CR, that is subsequently used to search for a radar echo off of the in-ice continuation of an ultra high energy cosmic ray air shower. The two systems independently reconstruct the energy, arrival direction, and impact point of the particle cascade. Here we present RET-CR, its installation in Greenland, and the first operations and results of RET-CR.

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1. Introduction

In the multi-messenger era, ultra high energy neutrinos (UHENs) are one of the most important cosmic messengers. Neutrinos are unique in their ability to point back to their sources, and measurement of their properties provides an essential probe for Beyond the Standard Model physics. However, UHENs are some of the most difficult particles to detect due to their small interaction cross section and strongly decreasing cosmic flux as neutrino energy increases. As such, a successful neutrino observatory must be able to efficiently instrument large volumes of dense material in order to detect enough neutrinos to draw statistically significant conclusions.

In order to overcome the difficulties in detecting neutrinos, many experiments have successfully instrumented large volumes of air, ice, and water [1–5]. Additionally, there are several next generation instruments which aim to build on previous successes to instrument even larger volumes and detect more neutrinos and probe the highest energies [6–9]. A common issue encountered by these experiments is the high cost in both time and money in instrumenting such large volumes. As such, finding new ways to sparsely instrument increasing volumes of material is advantageous. Therefore, here we present the radar echo technique; a novel technique for the detection of UHENs in high density media using a sparse detector array.

1.1 The Radar Echo Technique

The details of this technique are laid out in [10–12]. Here we briefly summarise the key points.

When a UHEN interacts in a dense medium, such as ice, it creates a cascade of secondary particles that ionises the medium upon propagation. The secondary particles and the ionisation electrons create a dense, short-lived plasma. If a transmitter is illuminating the volume in which the UHEN interacts with radio waves the plasma will reflect the incoming radiation. Receivers monitoring the illuminated volume can be used to detect these reflections and determine the properties of the neutrino that initiated the cascade.

The magnitude of the plasma density plays a key role in the radar echo technique, where the received signal scales directly with the instantaneous ionisation density. Details can be found in [13].

The radar echo technique in high density media was successfully demonstrated in the two runs of the T576 experiment at the Stanford Linear Accelerator (SLAC) [14, 15]. However, the next step is to prove that this same technique is also successful in nature and can, therefore, be used to detect cascades induced by the interactions of UHENs.

1.2 Cosmic Rays as an In-Nature Test Beam

As stated above, neutrino interactions are rare and very difficult to detect. As such, neutrinos themselves will not provide a reliable test beam in order to verify that the radar echo technique is as successful in nature as it is in the laboratory. Therefore, it is necessary to find an in-nature test beam with a higher interaction cross section and greater flux than that for neutrinos of an equivalent energy. Cosmic ray air showers can provide this test beam in order to verify the radar echo technique.

As shown in [16], when an ultra high energy cosmic ray (UHECR) air shower with an energy of at least 10^{16} eV impacts a high altitude ice sheet, at least 10% of the primary energy is transferred

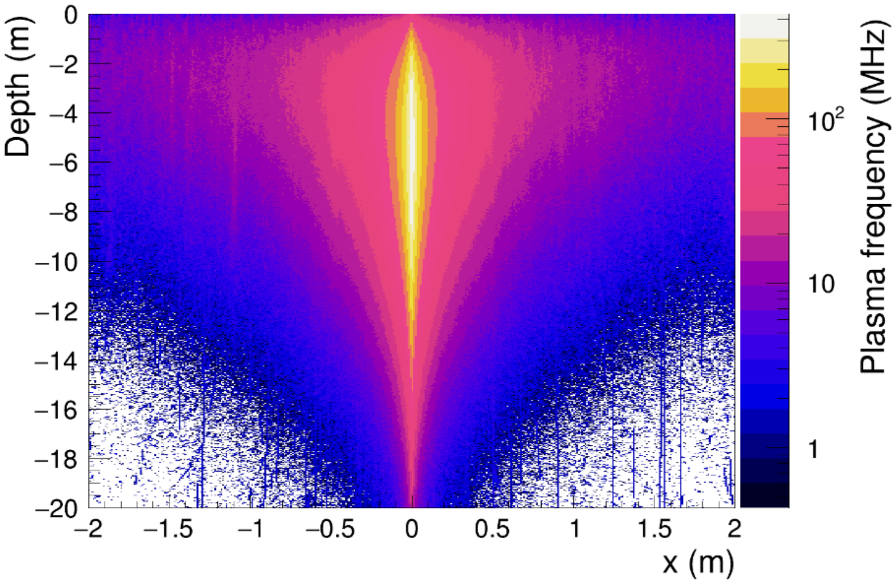


Figure 1: The plasma frequency, in a vertical slice, 1 cm wide, through the centre of the particle cascade induced in the ice by a 10^{17} eV proton primary This shower was simulated using CORSIKA and Geant4. Figure taken from [16].

to the ice within a radius of 1 m around the impact point. This induces a secondary cascade at the surface of the ice, as shown in Figure 1. This in-ice cascade develops in much the same way as the preceding air shower, but is condensed in length from $O(10 \text{ km})$ to $O(10 \text{ m})$. The ionisation particle density is large enough for in-ice cascades, such that, in a volume illuminated by radio waves, the incident radio waves will be reflected and can be detected. As such, the in-ice secondary cascade from a cosmic ray with energy greater than 10^{16} eV is an excellent candidate to test the radar echo technique in nature.

2. The Radar Echo Telescope for Cosmic Rays

The Radar Echo Telescope for Cosmic Rays (RET-CR) [10] combines a surface cosmic ray detector and an in-ice radar echo detector in order to detect and reconstruct the cosmic ray air shower and in-ice continuation using two methods. In this way, RET-CR will test and validate the effectiveness of the radar echo technique for detecting high energy particle cascades.

The deployed RET-CR surface detector comprises three stations, with each station having two scintillator panels, an antenna, a data acquisition system, and its own solar array. The surface detector is designed to provide both the trigger for the in-ice detector, and an independent reconstruction of the incoming cosmic ray. The trigger to both the surface antennas and the in-ice system is provided by the scintillator panels. This will ensure that the cosmic ray that has entered the system has enough energy to produce a radar echo. In order to limit the number of low energy cosmic rays that trigger the system, both scintillators in at least three different stations of the surface detector must coincidentally contain an energy deposit of at least one equivalent muon. A trigger (L1) is then sent to both the surface station antennas and the in-ice receiver antennas to record the cosmic ray signal in the different components of the detector. With the surface detector trigger, we aim to reach 100% efficiency at an energy of approximately $10^{16.5}$ eV. Therefore, the in-ice, radar echo detector should be triggered on any shower entering the detector volume that can produce a radar echo.

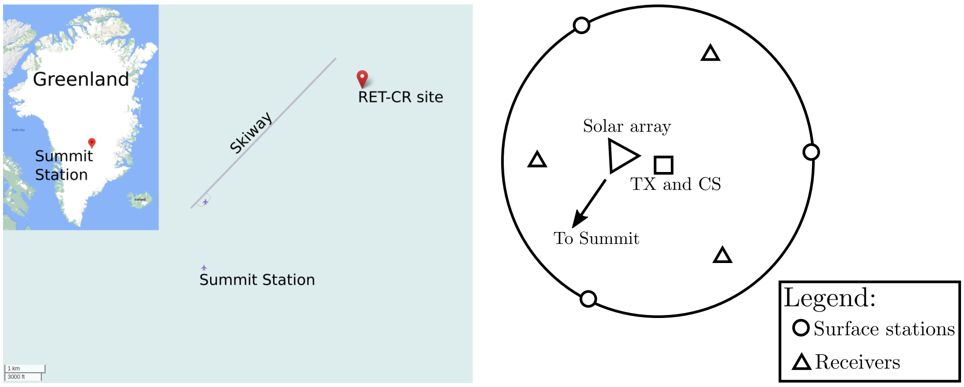
The surface detector antenna is a log-periodic dipole antenna,with a sensitive frequency of 50-350 MHz [17] of the type to be used for the Square Kilometre Array [18]. The surface antennas will primarily be used for reconstructing the incoming cosmic ray in order to obtain a baseline for the energy, Xmax, and core position. Additional information from the scintillators can also be used during the reconstructing process, however, the primary reconstruction will be done using the radio information from the antennas.

The radar echo detector also consists of two parts; the phased transmitter and the receiver array. The transmitter is a vertical phased array of 8 transmitting antennas lowered into a hole under the surface of the ice to a depth of 20 m. A phased transmitter provides a high level of control over the direction in which the radio waves are transmitted. The beam can be steered such that there is a limited proportion of the radiation that is transmitted into regions where no reflections from UHECR cascades are expected. Additionally, while the overall power available to the phased array goes as NP_A, the maximum beamed power scales as N^2P_A, where N is the number of antennas and P_A is the power emitted by a single antenna. This results in a much higher emitted power, and hence a high received power, than is possible without a phased array. The antenna design for all of the in-ice antennasis based on that of previous in-ice radio experiments [19]. The design of these antennas is limited by the necessity that they fit into a borehole with a width of 14 cm. However, their design provides a good frequency range for both transmitting and receiving, while being possible to deploy. The receiver array consists of single antenna strings, deployed in four boreholes around the transmitter borehole, at a depth of 20 m.

3. Deployment of RET-CR

The first deployment season for RET-CR took place from May 1st to May 22nd, 2023 at a site 5 km away from Summit Station in Greenland, shown in Figure 2a. The deployment was conducted in two shifts; the first organising the cargo, preparing necessary equipment, and cargo transport to the site, and the second for the construction, deployment, and commissioning of RET-CR. The initial 10 day shift was very successful; however, extreme and unfavourable weather meant that the deployment shift experienced some delays. Therefore, the scale of the deployed RET-CR detector was reduced from that presented in [10]. The number of receiver strings and the number of surface stations were both set to three. This also lead to an alteration of the layout of the strings and stations. Additionally, the final depth of each borehole was 13 m for the transmitter and 10 m for the receivers. A reduction in scale was anticipated prior to the deployment, and simulations were performed with the reduced RET-CR system that showed the sensitivity goal of RET-CR is unaffected by these changes.

The photo-voltaic array, that powers the central station, transmitter, and receivers, was successfully deployed in its full extent. The full phased transmitter with 8 antennas was also successfully deployed in the transmitter borehole. All three surface stations were fully deployed, with scintillators commissioned and calibrated, with their own solar panel arrays for power. Once all of the equipment was linked, remote communication with every part of RET-CR was possible as a WiFi



(a) The RET-CR site is located approximately 5 km North East of Summit Station Adapted from OpenStreetMap and Google Maps.

(b) Surface stations are represented as circles and the in-ice receiver antennas are shown as triangles. The surface stations are laid out on a 40m radius circle from the transmitter (TX), while the in-ice receivers are on a 30m radius circle from the transmitter.

Figure 2: The location and layout of the RET-CR site within Greenland, with respect to Summit Station, and the positions of each component of the detector in relation to the others. The red marker on the left corresponds to the transmitter at the centre of the RET-CR layout.

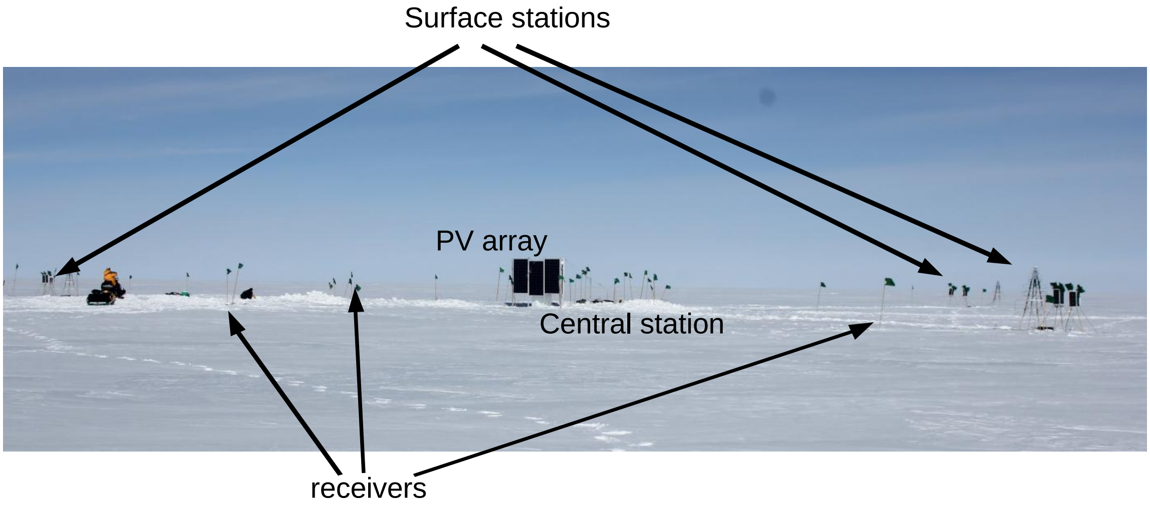


Figure 3: Photograph of the RET-CR site showing all components of the detector that are visible on the surface of the ice. The receiver strings are in the ice below the flags, while the transmitter is in a borehole next to the central station.

link to the site was set up. This enabled us to further commission and calibrate the instrument remotely, as well as change run parameters and control the data flow remotely.

The final deployed layout of RET-CR is shown in Figure 2b with a photograph of the array shown in Figure 3.

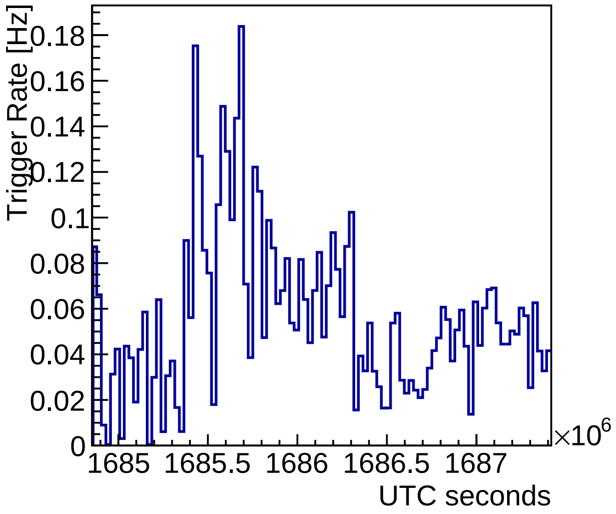


Figure 4: Rate at which the in-ice RET-CR radar detector was triggered by the surface system throughout the data taking run in May and June.

4. The Performance of RET-CR

After its deployment, RET-CR took data from May 21st to June 22nd, with a second run planned for July to August. The rate at which the in-ice radar detector was triggered by the scintillators is shown in Figure 4. Fluctuations in the trigger rate on large timescales can be attributed to running the surface detector with various numbers of stations forming the radar trigger. The highest trigger rates occur with only a single surface station providing the L1, while lower trigger rates can be attributed to periods with two or three surface stations coincidentally forming the L1 trigger.

To prevent the in-ice receiver antennas from being saturated by the transmitter radio signal, the system relies on a carrier cancellation algorithm. A time-delayed and scaled copy of the transmitted signal is injected directly into the receiver channels after the antenna, but before the amplifiers, via a cable. The carrier cancellation is a two-stage process. The first stage includes running the transmitter at fractional power output, and cancelling the direct signal in the receivers. The transmitter is then increased to maximum output, and the second-stage cancellation is run. This is to avoid saturating the receiver amplifiers at any point, to avoid potential damage.

In order to remain effective, the second stage carrier cancellation is run for every receiver antenna once an hour. The effectiveness of the carrier cancellation is affected by the environment and the conditions. For example, snow accumulation causes a change in the power received directly from the transmitter. In periods of high precipitation, the carrier cancellation has to be run more frequently in order to maintain efficient transmitter removal.

Figure 5 shows the effect of the second phase carrier cancellation on the frequency spectrum in one receiver antenna. The significant spike in power received at the transmitter frequency can be clearly seen in the trace labelled "CC OFF" and is greatly reduced in "CC ON". This shows a reduction in power of approximately 50 dBm/Hz for the second-stage cancellation routine, effectively eliminating the carrier in real time. Putative reflections from cosmic ray cascades will

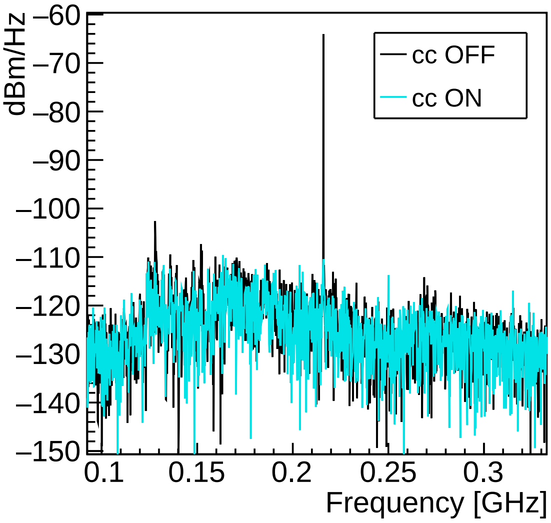


Figure 5: The effect of the second stage carrier cancellation on the frequency spectrum seen in one receiver antenna. Both results are obtained when an initial, coarse carrier cancellation has already been performed to prevent the saturation of the receiver amplifiers.

not be cancelled, as these limited duration signals will be out of phase with both the transmitted signal and the carrier cancellation. This phase difference results in a detectable signal.

At the time of submission (mid July, 2023) RET-CR is offline for maintenance, after having taken 5 weeks of data. A second data run is planned for the remainder of the summer season at Summit Station before retro in late August 2023.

5. Conclusion

The Radar Echo Telescope for Cosmic Rays has been deployed at Summit Station, Greenland and is currently collecting data while continuing to undergo testing and calibration phases. Within the full RET-CR data set, we aim to successfully find the expected radar echo signal and show the in-nature feasibility of the radar echo detection method for the in-ice continuation of the cosmic ray air shower. The results from RET-CR will then go on to inform the further development of the Radar Echo Telescope for Neutrinos. We aim to improve both our simulations for RET-N with the results from RET-CR, as well as develop self triggering routines, based on specific signal properties, for the final neutrino detector.

References

[1] M. Aartsen et al., *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *JINST* **12** (2017) 03012.

[2] J.A. Aguilar et al., *The Next-Generation Radio Neutrino Observatory – Multi-Messenger Neutrino Astrophysics at Extreme Energies*, 2019. arxiv:1907.12526.

[3] P. Allison et al., *Design and initial performance of the Askaryan Radio Array prototype EeV neutrino detector at the South Pole*, *Astropart. Phys.* **35** (2012) 457.

[4] S.R. Klein, *A Radio Detector Array for Cosmic Neutrinos on the Ross Ice Shelf*, *IEEE Trans Nucl Sci* **60** (2013) 637.

[5] P. Gorham et al., *The Antarctic Impulsive Transient Antenna ultra-high energy neutrino detector: Design, performance, and sensitivity for the 2006–2007 balloon flight*, *Astropart. Phys.* **32** (2009) 10.

[6] M.G. Aartsen et al., *IceCube-Gen2: the window to the extreme Universe*, *J. Phys. G: Nucl. Part. Phys.* **48** (2021) 060501.

[7] J. Álvarez-Muñiz et al., *The Giant Radio Array for Neutrino Detection (GRAND): Science and design*, *SCI CHINA PHYS MECH* **63** (2019) .

[8] A.V. Olinto et al., *POEMMA: Probe Of Extreme Multi-Messenger Astrophysics*, in *Proceedings of 35th International Cosmic Ray Conference — PoS(ICRC2017)542*, vol. 301, 2017.

[9] Q. Abarr et al., *The Payload for Ultrahigh Energy Observations (PUEO): a white paper*, *JINST* **16** (2021) P08035.

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

[11] S. Prohira and D. Besson, *Particle-level model for radar based detection of high-energy neutrino cascades*, 2018.

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

[13] E. Huesca Santiago et al., *A macroscopic model of radar detection for the Radar Echo Telescope*, in *9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities — PoS(ARENA2022)017*, vol. 424, 2022.

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

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

[16] S. De Kockere, K.D. de Vries, N. van Eijndhoven and U.A. Latif, *Simulation of in-ice cosmic ray air shower induced particle cascades*, *Phys. Rev. D* **106** (2022) .

[17] E. de Lera Acedo, N. Razavi-Ghods, N. Troop, N. Drought and A.J. Faulkner, *SKALA, a log-periodic array antenna for the SKA-low instrument: design, simulations, tests and system considerations*, *Exp. Astron.* **39** (2015) 567.

[18] 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.

[19] P. Allison et al., *Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole*, *Astropart. Phys.* **35** (2012) 457.

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