PROCEEDINGS OF SCIENCE

High energy cosmic ray reconstructions with surface stations of RET-CR

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The Radar Echo Telescope for Cosmic Rays (RET-CR) is an experiment to verify the feasibility of the detection of dense particle cascades in ice using radar. A successful detection at RET-CR would provide crucial insights and guide the subsequent development of the Radar Echo Telescope for Neutrinos (RET-N). RET-CR observes the high-energy cosmic ray air shower core that propagates into the high-altitude ice sheet near the Summit Station in Greenland. A dense secondary cascade is produced in ice, and the plasma left behind is theoretically predicted to be detectable via an in-ice radar system. To understand the in-ice cascade using radar, inputs from cosmic ray air shower reconstructions are also necessary, which will be discussed in this article.

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1. Introduction

High-energy astrophysical neutrinos will allow us to explore a new dimension in the field of multi-messenger astronomy [1, 2]. The Radar Echo Telescope for Neutrinos (RET-N) [3] is an upcoming experiment that aims to detect high-energy neutrinos using a radar technique. With the inherent challenges in detecting ultra-high-energy neutrinos, such as their steeply falling flux, it becomes essential to develop a diverse range of methods that cover the entire neutrino energy spectrum. RET-N is predicted to have sensitivity to neutrinos with energies greater than $10^{16.5}$eV [4, 5].

In 2020, the SLAC T576 experiment [6] at the Stanford Linear Accelerator Centre achieved a significant milestone by observing the radar reflections from a particle cascade for the first time. The ionisation density of this particle cascade was equivalent to that of a particle shower induced by a 10^{17} eV neutrino interaction in ice. The success of the SLAC beam test experiment naturally leads to the next step on the road to the ultimate goal of detecting ultra-high-energy neutrinos using radar techniques, namely the Radar Echo Telescope for Cosmic Rays.

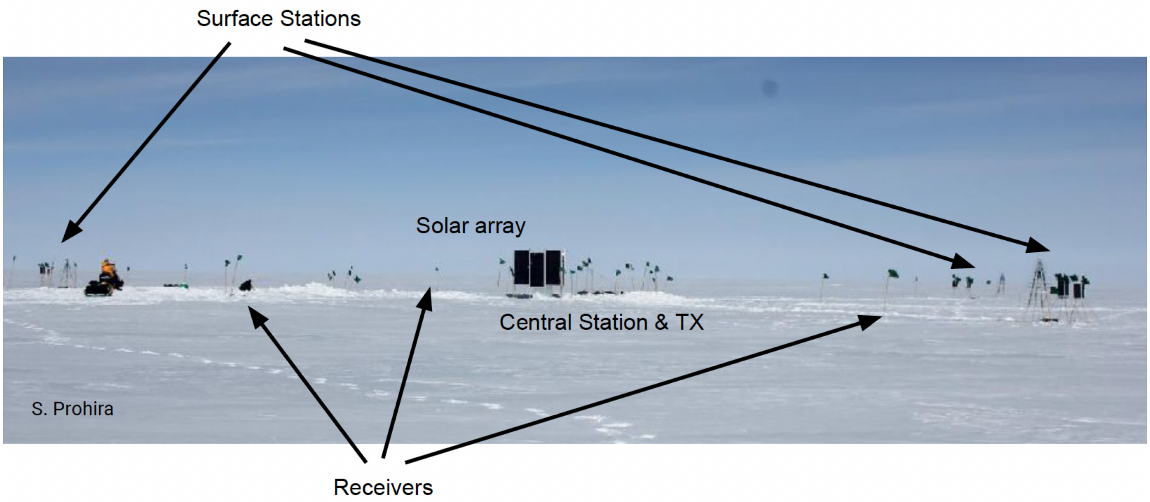
The Radar Echo Telescope for Cosmic Rays (RET-CR) [5] is a prototype experiment designed to explore the radar echo method using a known source in nature, cosmic rays, and to study the capability of observing particle cascades with radar. A high-energy cosmic ray air shower impacting the high-altitude ice sheet (3.2 km from sea level) in Greenland would deposit a significant portion of its energy into the ice sheet close to its shower core [7]. As the air shower core propagates into the ice, it creates a dense in-ice secondary cascade, which could be theoretically observable via radar. A successful detection of this in the ice secondary cascade is the first step forward for the RET collaboration.

RET-CR consists of five surface stations which trigger and reconstruct the geometry of an incoming air shower. There is also an in-ice radar system set up to detect the in-ice secondary cascade. Each of the five surface stations consists of two scintillator panels and a SKALA radio antenna [8]. We aim to reconstruct the arrival directions, core positions, and energy of an air shower with the surface stations and then compare these quantities with those observed by radar for the in-ice cascade. As a result, the surface stations play a crucial role in validating the radar method and verifying its reconstructions.

Due to challenges related to triggering [9], we were unable to continue using data from the SKALA antennas in our reconstructions. As a result, we now rely exclusively on the scintillator array to determine the arrival direction and energy of the primary particle, and to estimate the core position of the air shower. Understanding the core position is essential, as it provides insights into where the air shower propagates into the ice and helps identify the vertex of the in-ice cascade relevant for radar detection.

2. Surface station layout and cosmic ray arrival directions

RET-CR consist of five surface stations, each with two scintillator panels, as depicted in Figure1. One significant step towards understanding the geometry of a cosmic ray air shower is measuring its arrival direction. The arrival direction information can be derived from the first arrival hit times at the scintillator panels. For our reconstructions, we utilise a first-order approximation



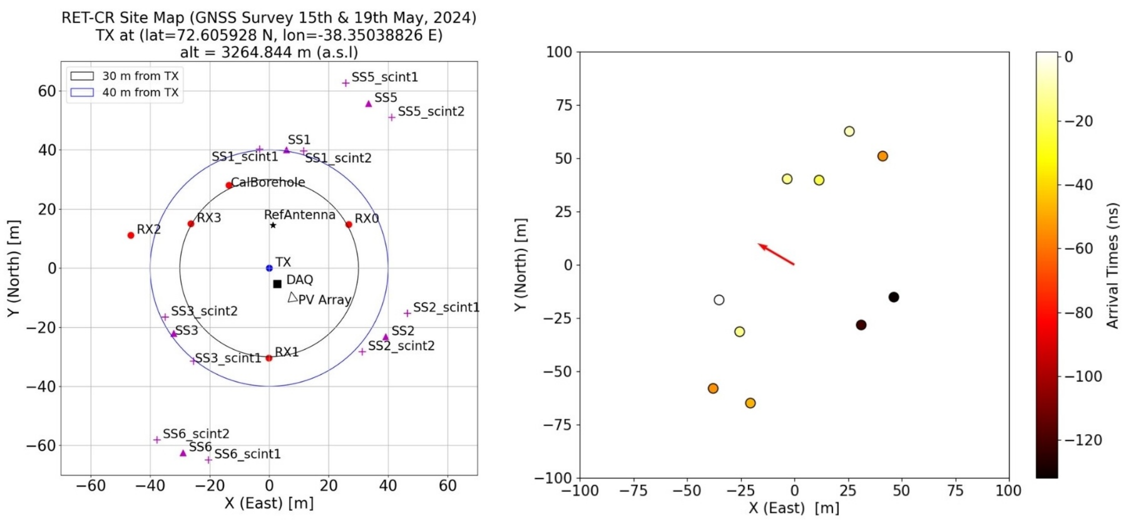


Figure 1: Map of RET-CR layout *(Left)*. The arrival direction calculated for a cosmic ray air shower event at RET-CR, $(\theta, \phi) = (24.8° \pm 2.7°,\ 116.2° \pm 4.2°)$. The red arrow is the azimuth angle ϕ (from north towards east clockwise) projected onto the ground. *(Right)*

for the shower front model with a plane wave. We employ a simple minimisation procedure to fit the shower plane to match the recorded arrival times at the panels, as described below.

$$\delta^2 = \sum_{i=1}^{k} [lx_i + my_i + nz_i + c(t_i - t_0)]^2 \tag{1}$$

In Equation 1, (x_i, y_i, z_i) are the coordinates of the panels in the layout, and t_i is the arrival time at the respective panels. The l, m, n parameters represent the direction vectors of the plane wave, and t_0 is the time at which the plane wave passes through the origin of the RET-CR layout.
The zenith and azimuth angles can be calculated from the direction vectors of the plane wave.

Figure 1 (*Right*) shows the arrival reconstruction for a single event. The stations are coloured based on their arrival times, with zero corresponding to the last panel that was triggered. Figure 2 below is the arrival direction distribution for the 2024 data at RET-CR, when at least three stations are triggered[9]. The RMS residual error is also calculated between the arrival time information from the panels and the plane wave fitting.

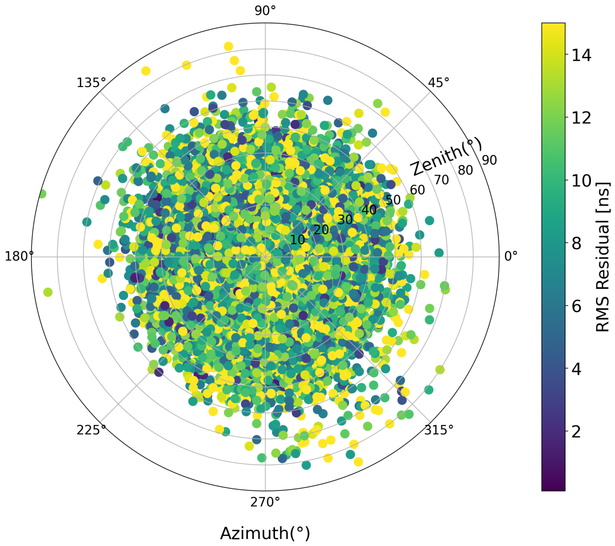


Figure 2: Arrival direction reconstructions from the RET-CR cosmic ray data subset

3. Scintillator calibration for RET-CR

RET-CR has adopted the IceTop [12] scintillators for its surface stations. We have also conducted the calibration for the specific twelve panels used for our layout, and the results align well with the range of values presented in [14][13].

To reconstruct cosmic ray energy, we need to calibrate the scintillators to understand the energy

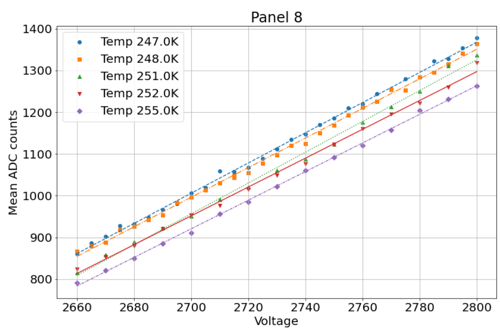


Figure 3: Calibration estimates for panel 8 (as an example) showing the high-gain channel vs voltage bias for a specific threshold, studied at multiple temperatures

deposited by a minimally ionising particle (MIP). The calibration of the panels is studied under varying voltage biases, temperatures, and threshold conditions. We measured muons that traverse the scintillators, which produce a charge deposit in ADC counts, as in Figure 3. We also simulated the IceTop scintillator panel with Geant4 software to determine the energy of a minimally ionising particle (MIP) to understand the charge deposit in MeV.

The total energy deposited in the panel is calculated by correlating the mean energy deposited by

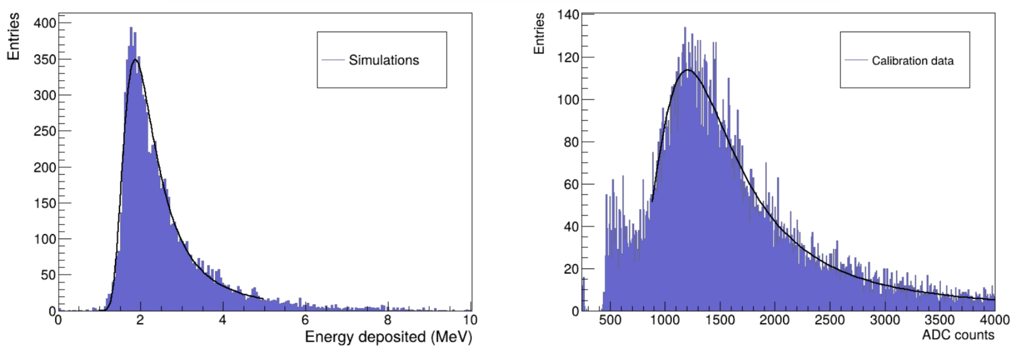


Figure 4: MIP peak from the Geant4 simulations *(Left)* Scintillator calibration data *(Right)*. Both are fitted with a Landau distribution function (black line) .

MIP in the simulations with the peak charge deposits (ADC counts) from the scintillator calibrations. The results from the calibration data and Geant4 simulations are shown in Figure 4.

4. An Overview of Core Positions and Energy Reconstructions

For our reconstructions, the energy deposits in the triggered panels are fitted with a Nishimura-Kamata-Greisen (NKG) function in the shower plane; this is a widely adopted method for particle arrays [10]. The information on the arrival direction measured beforehand is utilised to model the shower plane. We use a sequential minimisation to derive the initial estimates of the core positions using the NKG function:

$$\rho(r) = \frac{C}{r_m^2} \cdot \frac{\Gamma(4.5 - s)}{2\pi\,\Gamma(s)\,\Gamma(4.5 - 2s)} \cdot \left(\frac{r}{r_m}\right)^{s-1} \cdot \left(1 + \frac{r}{r_m}\right)^{s-4.5} \tag{2}$$

However, we face challenges associated with higher energy air showers, where energy deposits exceed the saturation limit for our panels, as indicated in Figure 5.

We have explored methods to recover these energy deposits. First, we extrapolate the ADC counts in the saturated panels in a step-by-step manner. Then, using data from the remaining unsaturated panels, we obtain an optimal chi-squared value after fitting the NKG function for each combination of ADC bins for those panels. When a cosmic ray event has many more unsaturated panels than saturated ones, the retrieval of energy deposits is more accurate. Hence, this process is much more easily accomplished when either one or two stations (i.e., a maximum of four panels) reach the threshold, as opposed to events where multiple stations are affected.

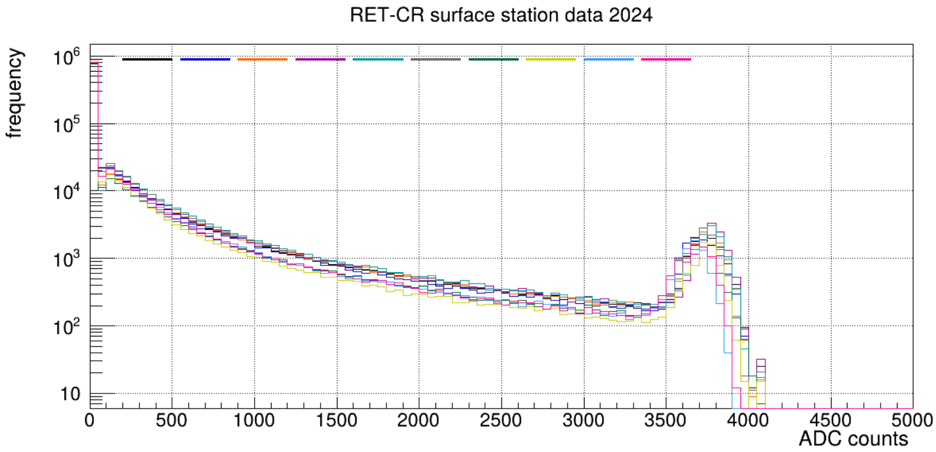


Figure 5: RET-CR surface station data 2024. Different colours are the 10 panels of surface stations, which are showing saturation after around 3200 ADC counts.

In Figure 6, we trace the energy deposits when a whole station (ie, two panels) is saturated, with the above method.

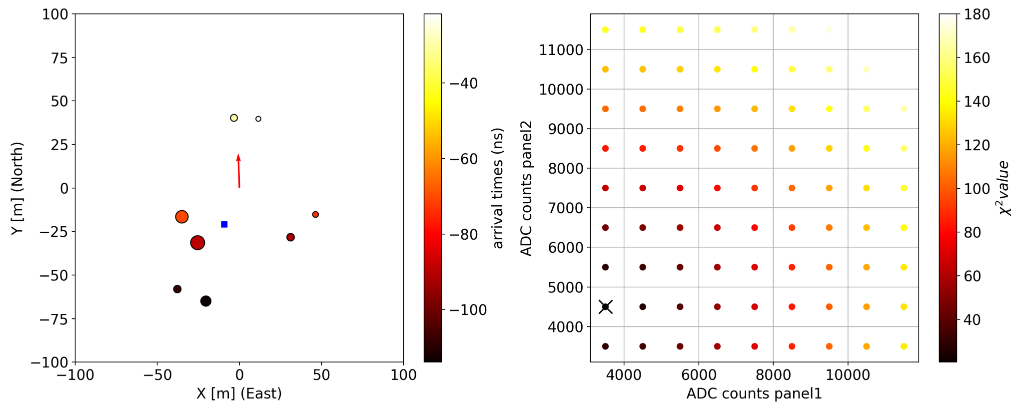


Figure 6: A saturated event with two panels saturated (the blue square corresponds to the reconstructed core position) *(Left)*. A two-dimensional χ^2 fit is depicted, whose minimum (marked with ×) will provide a rough estimate of the actual energy deposit *(Right)*.

The energy of the cosmic ray(CR) primary is estimated to first order through cosmic ray air shower simulation studies, combined with an understanding of the detector response. We simulated cosmic ray proton primaries across various energies and zenith directions and measured the radial distribution of energy deposits intrinsic to the RET-CR surface detectors. Subsequently, this radial profile is fitted using the NKG function, as in Equation 1, similar to the case for core reconstructions. The results for the amplitude parameter ($\frac{C}{2\pi r^2}$) in the equation were obtained and interpolated, as shown in Figure 7 *(Left)*, the values for lower energies were extrapolated similarly. The energy of the primary CR is quantified by comparing the amplitude parameter from the RET-CR data with that from the simulations. In Figure 7 *(Right)*, we have the energy distribution of the events from the 10% burn sample of the data in the cosmic ray analysis [16]. Figure 8 shows the shower core distributions with primary energy estimates.

In these proceedings, we explore the cosmic ray reconstructions for RET-CR surface stations,

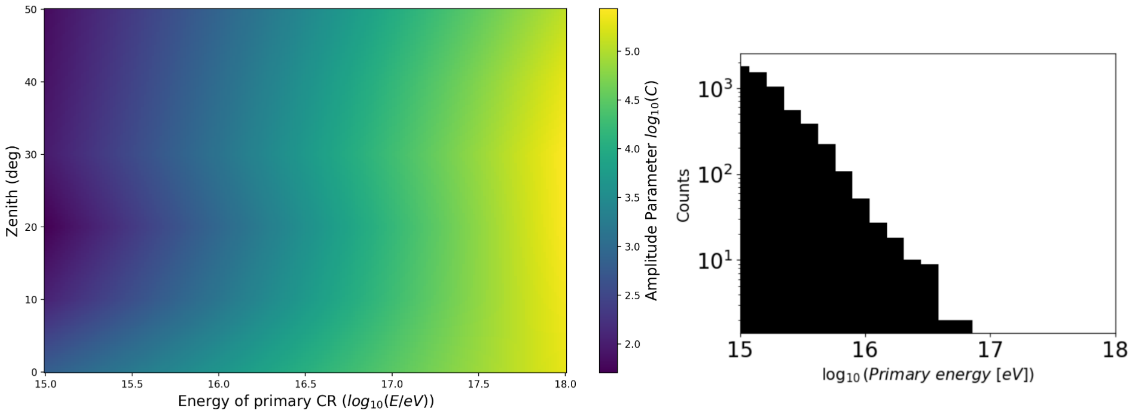


Figure 7: Interpolated amplitude parameters from NKG fits of simulations *(Left)*. Energy reconstructions for the RET-CR data subset, when at least 3 stations are triggered *(Right)*.

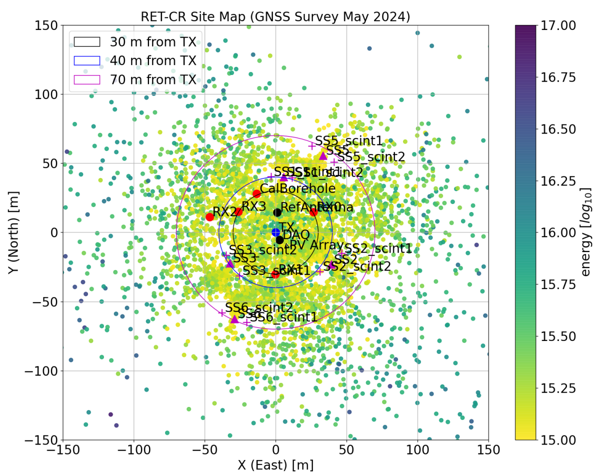


Figure 8: Shower core reconstructions from a data subset of RET-CR, overlaid on RET-CR Map. The colour bar shows the energy reconstructed for the event. Events are selected when at least 3 stations are triggered.

which provide relevant inputs for the in-ice radar system. Further studies on the uncertainty measurements and the effects of snow accumulation on the panels are ongoing.

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