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# Simulation and Optimisation for the Radar Echo Telescope for Cosmic Rays

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The SLAC T-576 beam test experiment showed the feasibility of the radar detection technique to probe high-energy particle cascades in dense media. Corresponding particle-level simulations indicate that the radar method has very promising sensitivity to probe the >PeV cosmic neutrino flux. As such, it is crucial to demonstrate the in-situ feasibility of the radar echo method, which is the main goal of the current RET-CR experiment. Although the final goal of the Radar Echo Telescope is to detect cosmic neutrinos, we seek a proof of principle using cosmic-ray air showers penetrating the (high-altitude) Antarctic ice sheet.

When an UHECR particle cascade propagates into a high-elevation ice sheet, it produces a dense in-ice cascade of charged particles which can reflect incoming radio waves. Using a surface cosmic-ray detector, the energy and direction of the UHECR can be reconstructed, and as such this constitutes a nearly ideal in-situ test beam to provide the proof of principle for the radar echo technique. RET-CR will consist of a transmitter array, receiver antennas and a surface scintillator plate array.

Here we present the simulation efforts for RET-CR performed to optimise the surface array layout and triggering system, which affords an estimate of the expected event rate.

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## 1. Introduction

In spite of their status as some of the most important astrophysical messengers, the detection of ultra high energy cosmic rays (UHECR) and neutrinos (UHEN) faces major challenges.

In order to successfully probe the highest energies, an observatory must be able to efficiently instrument large enough areas and volumes to collect sufficient data to draw statistically significant conclusions. Large experiments, such as the Pierre Auger Observatory [1], Telescope Array [2] and IceCube [3] are currently probing the highest energy cosmic rays (up to $10^{20}$ eV) and neutrinos (up to a few PeV). Nevertheless, to probe the cosmic particle flux at even higher energies, larger detection volumes are required. Here we present a new technique designed to instrument large volumes of high density media and provide an approach complementary to those currently employed. The radar echo technique enables the detection of particle cascades initiated within large volumes of high density media [4–7]. We anticipate good sensitivity to neutrino initiated cascades with primary energies exceeding >10 PeV, and therefore offering considerable overlap with existing experiments.

Herein, we focus on the simulation efforts for RET-CR, performed to optimise the surface array layout and triggering system for total event rate. Technical details on the proposed hardware layout will be presented in contribution [8].

## 2. Radar Echo Telescope for Cosmic Rays

Here we summarise the key features of and predictions for RET-CR; full details can be found in [5]. We currently propose to deploy RET-CR at Taylor Dome, Antarctica, a high altitude ice sheet with elevation 2400 m. RET-CR will be a fully autonomous solar-powered system (and therefore only operable during the austral summer), including remote monitoring and control.

### 2.1 RET-CR Surface Detector

The RET-CR surface detector simultaneously serves as a method to trigger the in-ice radar detector, to ensure that the core of a UHECR air showers has entered the detector volume, and to provide an independent reconstruction of the triggering air shower properties. The surface detector consists of a scintillator plate array combined with radio antennas operating in the range of 30-300 MHz. Each 'station' consists of two scintillators, separated by 20 m and one antenna. The working layout of the surface detector, shown in the left panel of Fig. 1, comprises two clusters of three stations each. The scintillators will detect a UHECR traversing the detector volume, after which a trigger signal is sent to both the radio antennas in the surface detector, as well as the in-ice radar detector.

Detailed simulations have been performed to study the response of the surface detector. For our initial deployment the radio antennas have been donated by the CODALEMA/EXTASIS experiment [9], with the scintillators supplied by the KASCADE experiment [10]. To produce air shower simulations with particle and radio data outputs, CORSIKA [11], version 7.7400 (with QGSJETII-04 [12] and URQMD 1.3cr [13, 14]), was used in conjunction with CoREAS [15], version 1.4. For the site-specific configuration of the CoREAS code, a detailed study was conducted with the gdastool [16] to determine typical atmospheric conditions for the proposed deployment location. The response of the scintillators to air shower particles was simulated using Geant4 [17] version 9.6.

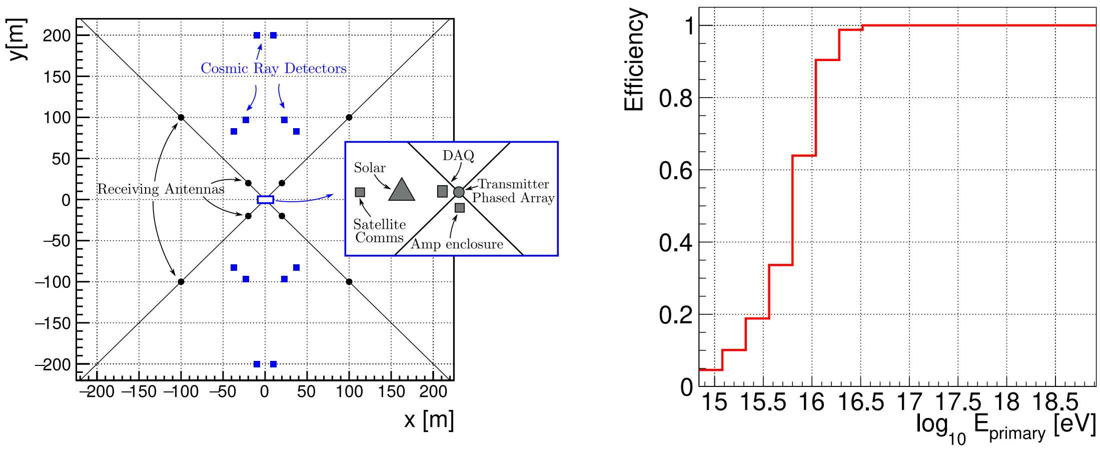


**Figure 1:** *Left*: RET-CR layout for both the surface detector (in blue) and the radar detector (in black). The radar transmitter lies in the centre of the configuration with the two surface detector clusters on either side. Receiver antennas are placed on radial lines from the transmitter, surrounding the surface detector stations. All components indicated in blue will be buried 2-20 m in the ice while the red-coloured components are on the ice surface. *Right*: Trigger efficiency of the RET-CR surface detector as a function of cosmic ray primary energy.

To model the material of the polyvinyl-toluene KASCADE scintillators, a carbon:hydrogen ratio of 9:10 was used [18]. It should be noted that in the final experiment a different type of scintillator is foreseen, similar to the ones currently deployed at the IceTop site [19].

We target a detection efficiency of 100% for UHECR air showers with a primary energy of $10^{17.0}$ eV or greater. At this energy, the air shower should have sufficient energy to produce an observable in-ice continuation of the shower. To accommodate limited telemetry, we aim for a trigger rate of $\approx 10^5$ events per month. The two major aspects of the surface detector considered for optimisation were the station geometry with respect to the radar detector, and the scintillator trigger threshold.

Many different station layouts were simulated; each layout produced a surface detector trigger efficiency curve, as a function of UHECR energy. Those simulations currently indicate an optimized surface detector layout with two symmetrical clusters of stations, with stations located at points (30 m, 90 m), (-30 m, 90 m), and (0 m, 200 m) with respect to the transmitting antenna of the radar detector at (0 m, 0 m), as shown in the left panel of Fig. 1. This layout enabled us to achieve a steep turn-on of surface detector efficiency over one decade of energy, beginning at $10^{15.5}$ eV (Fig. 1, right panel). The trigger threshold was also optimised to control both the rate of triggers within the surface detector, and the minimum detectable surface detector energy. We set the trigger threshold at a minimum energy deposit of 6 MeV per scintillator, corresponding to approximately one minimally ionising particle ('MIP') with this scintillator design. With this threshold, the 'Level 0' trigger rate for one station is approximately 0.1 Hz for a two-fold scintillator multiplicity within one station. A 'Level 1' (L1) trigger requires that all stations in a single cluster satisfy the Level 0 requirements. After a L1 trigger, the surface detector will send a trigger signal to the radar detector.

The L1 efficiency of the RET-CR surface detector was then estimated, calculated as the fraction of UHECRs entering the detector area (approximately 1 event per day at 100 PeV) that trigger the surface detector. The final trigger sensitivity is shown in the right panel of Fig. 1.

### 2.2 Air-Ice Transition

To determine the final trigger rate for the in-ice radar system, we first have to consider the in-ice propagation of the cosmic-ray air shower [20]. This is done by connecting the CORSIKA in-air simulations to Geant4 for the in-ice propagation. To this end, a separate set of CORSIKA simulations was created using CORSIKA, version 7.7100 (with QGSJETII-04 and GHEISHA 2002d [21]). Propagating all showers used for the surface detector study into the ice is computationally prohibitive. We first simulated a set of showers with zenith angles of 0, 15, and 30 degrees for each half decade in energy between $10^{16.0}$ eV and $10^{18.0}$ eV with ground elevation of 2400 m. Thinning is used for showers with a primary energy above $10^{16.5}$ eV, retaining the overall energy of the cascade but changing the distribution of the low energy particles in the final footprint which is subsequently used as the input to Geant4 version 10.5. To produce the in-ice propagation of the particle cascade, an ice volume was created in Geant4 following the density profile measured at Taylor Dome: $\rho(z) = 0.460 + 0.468 \cdot (1 - e^{-0.02z})$, with $\rho$ the density in g/cm$^3$ and $z$ the depth in m. By tracking the ionisation energy loss in each step of the simulation, we obtain the free charge density profile in the ice, which is subsequently used as input for the RadioScatter code to determine the radar reflection off the in-ice core.

In Fig. 2, we show the result of this procedure for a $10^{17.0}$ eV primary cosmic-ray shower with a zenith angle of 0 degrees. Shown is the particle number density of the in-ice core. We observe that the core is O(10 m) long and has a radius of several centimeters. The obtained densities are sufficient to effectively scatter a radio wave, as outlined in the following section.

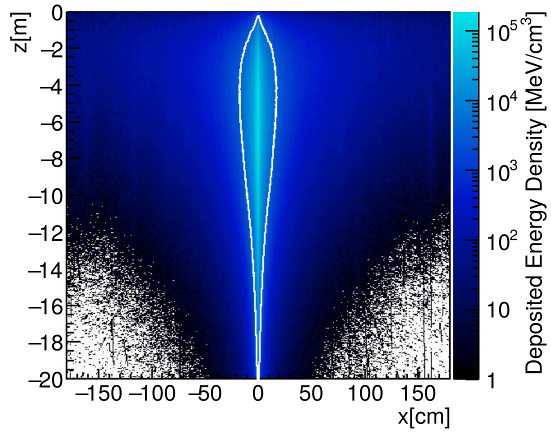


**Figure 2:** A one centimetre slice of the in-ice energy density profile along the axis of the cascade for a proton primary with an energy of $10^{17.0}$ eV. The white line outlines the region from which we expect the strongest reflections in the radar detector.

### 2.3 RET-CR Radar Detector

The RET-CR radio-frequency transmitter, shown in blue at the centre of the left of Fig. 1, comprises a vertically-aligned phased array of 8 vertically polarised antennas buried 2-20 m below the ice surface. The phased array will have good directionality and will lower the required single amplifier gain to each element, distributing the heating losses over 8 antennas and providing redundancy. We anticipate biconical antennas small enough to fit into a borehole but broadband enough to allow for a range of transmit frequencies. Therefore, we will be able to perform a frequency hop or frequency shift around a central carrier of approximately 100 MHz with a bandwidth of 20-100 MHz. The reflected signal has a peak frequency dependent on the cascade dimensions and density; simulations are currently being run to determine the frequency and modulation strategy anticipated for the final deployment.

The receive array, eight antennas shown in blue on left of Fig. 1, also comprise a vertically-aligned phased arrays, similar to the transmitter, and buried 2-20 m below the ice surface. Data acquisition from these receivers will be initiated by an L1 trigger from the surface detector, as outlined above. The receivers will be illuminated by the transmitter; therefore, it is essential to filter the transmitter frequency via carrier cancellation, so that amplifier saturation does not occur. Adaptive filtration will be employed, with the filters updated at intervals throughout the day as environmental changes may have a measurable effect on the radio reflection on timescales O(day) [22].

The radio receiver response to reflections from the in-ice air shower continuation is simulated using RadioScatter [6], a particle-level C++ code, for a specified geometry of transmitters and receivers. The free charge density profile output from Geant4 is used as the input to RadioScatter. In the simulations of radio reflections from the in-ice cascade, there is a clear 'chirping' frequency shift behaviour characteristic of the RET-CR geometry. Generating showers in Geant4 and CORSIKA is computationally expensive, and so cannot be done for every shower in the surface detector simulation set. Therefore, at each air shower position from the surface detector simulation set, two Geant4 cascades are simulated at the closest half decade in energy above and below the shower energy. The zenith angle of the Geant4 cascade is selected from 0, 15, and 30 degrees according to the proximity to the true zenith angle from the surface detector simulation. In the radar detector simulation, the distance between the shower core position and transmitter cannot exceed 150 m. Beyond this, the radio signal will be out of view of the transmitter due to ice properties. The ice properties may have exploitable features that are not taken into account at this point, particularly with regard to ray tracing. This is currently under detailed investigation and will be included in future work.

By combining the separate efficiencies of the surface and radar detectors with calculations of the effective detector area and cosmic ray flux, we compute an expected event rate for RET-CR in this configuration. This result is shown in Fig. 3 as a function of energy for different signal-to-noise (SNR) levels. The SNR is taken relative to a thermal noise voltage, over our bandpass, of 8 $\mu$V. The mean of the 0 dB curve on the left side of Fig. 3 corresponds to a rate of approximately 1 event per day detected by the radar detector. Shown on the right of Fig. 3 is the event rate over one austral summer. Extrapolating, we expect approximately 50 events above $10^{17.0}$ eV per season at the 0 dB SNR level.



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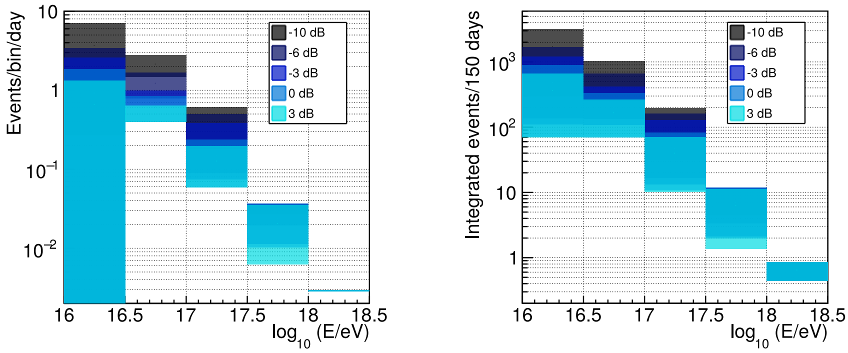


**Figure 3:** *Left*: RET-CR event rate per day as a function of energy. *Right*: RET-CR events rates per austral summer (approximately 150 days). Colours in both plots correspond to the signal-to-noise ratio relative to the thermal noise of 8 $\mu$V.

## 3. Prototype

In preparation for RET-CR, the first prototype of the surface detector has been constructed at the Vrije Universiteit Brussel, together with the Cross-Calibration Array [23, 24]. Consisting of three stations deployed on the roofs of the university buildings, this provides us with an opportunity to develop the electronics of the stations and characterise experimental backgrounds. Additionally, using the data collected we will be able to make a first attempt at reconstructing the incoming air shower with such a sparse array. The noisy environment of central Brussels will provide challenges in order to extract signal from noise; however, this provides us with more opportunities to improve our techniques.

### 3.1 Future prospects and aims

RET-CR provides a new avenue into cosmic ray detection that is complementary to existing approaches. SLAC experiment T-576 provided the first indication that the radar echo method is a viable technique for detecting particle cascades initiated in high density media, such as ice. Therefore, RET-CR will provide the first in-nature detection of UHECR initiated particle cascades in a high elevation ice sheet. However, we also view RET-CR is a stepping stone to a larger goal. By using RET-CR as a test bed for the technique, reconstruction studies, and investigations into self triggering the radar set-up using the reflected signal properties, we aim to develop the experimental groundwork needed to enable the detection of neutrino-initiated particle cascades in ice, RET-N. For the radar echo technique, we expect our sensitivity to peak for primary neutrinos with energy 10-100 PeV [5]. More details on RET-N can be found in [25, 26].

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