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The Radio Neutrino Observatory Greenland: Status Update and Prospect for Air Showers

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In the ultra-high-energy (UHE) regime, the low predicted neutrino fluxes are out of reach for currently running neutrino detectors. Larger instrumented volumes are needed to probe these low fluxes. The Radio Neutrino Observatory Greenland (RNO-G) detects in-ice radio waves emitted by neutrino induced particle showers in the Greenlandic ice sheet. Radio waves have a large attenuation length ($\sim$1 km), and therefore RNO-G implements a sparse instrumentation to cover an unprecedented volume. By 2022, seven stations have been deployed, consisting of a deep in-ice component and antennas just below the surface. Apart from measuring UHE neutrinos, RNO-G will be able to detect cosmic-ray air showers with a total effective area of close to $O(100\,\mathrm{km}^2)$ above 0.1 EeV. Detected air showers can be used as a source for in-situ calibration of the detector and provide an important verification measurement due to the possible backgrounds. Prospects for in-ice signal detection of air showers are developing further: Simulations suggest energy dense cores which propagate though the ice and are visible to deep antennas. In addition, catastrophic energy losses from high energy air shower muons penetrating the ice may mimic the interaction of a neutrino. An efficient surface trigger will provide a veto mechanism for both types of events. The collected data of shallow and deep antennas can be used to verify simulations for in-ice development of air showers. This contribution introduces RNO-G, discusses lessons learned from the first year of data taking and outlines possible backgrounds.

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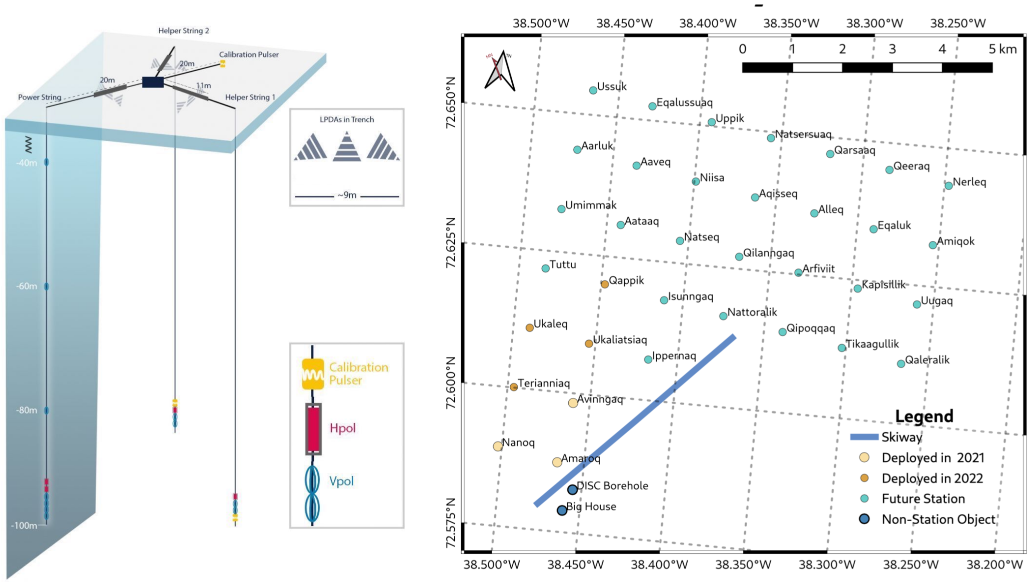

Figure 1: Left: Schematic layout of an RNO-G station with log-periodic dipole antennas (LPDA) at the surface (surface component), complemented by antennas for vertically (Vpol) and horizontally (Hpol) polarized electric field in the boreholes that reach down to 100 meters (deep component). The deep- as well as surface-components contain pulsers used for calibration purposes. Right: The planned array layout of which seven stations have currently been deployed.

1. Introduction

The Radio Neutrino Observatory Greenland (RNO-G), currently under construction at the apex of the Greenlandic ice sheet, near Summit Station, has seven deployed stations, searching for ultra-high-energy (UHE) neutrinos [1]. RNO-G uses the detection of radio pulses emitted by electromagnetic showers created when a neutrino interacts in the ice. Due to the transparency of ice to radio frequencies, sparse arrays of low-density instrumented volumes can be built while monitoring large areas. This would allow for an array with a large enough volume to achieve a sensitivity to the low fluxes of UHE neutrinos. 35 stations (1.25 km spacing) are funded and scheduled for deployment in the coming years (see Figure 1).

The prospect of detecting an UHE neutrino in the coming years is promising. The projected event rates allow either for the first UHE neutrino detection or rule out several astrophysical and cosmogenic neutrino flux models as indicated in Figure 2. RNO-G will moreover serve as an explorer experiment for the proposed radio component of IceCube-Gen2 [2]. No neutrino above 10 PeV has ever been detected, nor the radio emission stemming from a neutrino induced shower. Events are rare and therefore a proper understanding of the backgrounds, human-made as well as natural, is a must for solid identification of the first *radio* neutrino.

Natural background events may stem from cosmic-ray air showers via three mechanisms: a) a high-energy muon from the air shower may penetrate the ice and generate radio pulses by catastrophic energy losses [3], b) developing air showers from vertically arriving cosmic rays can generate energy-dense cores, penetrating the ice [4], and c) the geomagnetic emission of air showers can propagate into the ice [5]. Background rates are uncertain and rare, as is the predicted neutrino

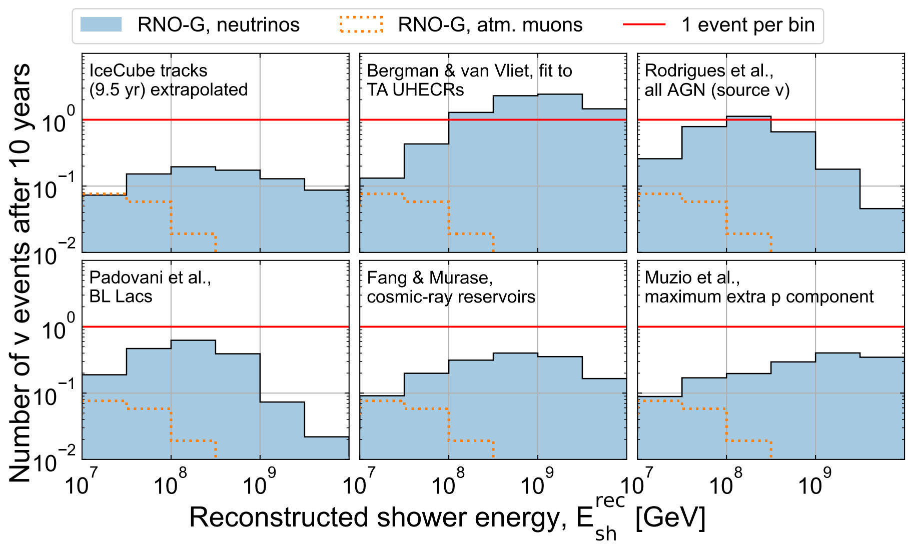

Figure 2: Event rate predictions for 10 year livetime of RNO-G. Shown are predictions of neutrino event numbers (blue) for six different neutrino models and an estimate for atmospheric muons (orange).

rate.

The station design accounts for the detection of different signals. Whereas dipole antennas are located deep in the ice (100 m), broadband antennas (log-period dipole antennas, LPDA) are located near the surface. Three upward-pointing LPDAs function as air-shower detectors, which will then be used to veto the backgrounds coming from above. Furthermore, cosmic ray identification will function as a calibration tool for the detector performance. The *surface component* and *deep component* of the station, naturally come with two independent triggers; the *deep trigger* and the *surface trigger*. The deep trigger is a phased-array trigger that uses the signals of nearby antennas to form beams of constructive signal interference for noise reduction to obtain a very low trigger threshold, and therefore increase the effective volume [6]. The surface trigger is an amplitude trigger applied on the signal registered by a diode. Exact understanding of the diode is needed to calculate the cosmic-ray effective area. This will be discussed in section 3.

2. Status Update

When aiming for the discovery of UHE neutrinos and using a technique that has not yet detected neutrinos, it is essential to have a good understanding of the radio backgrounds. Due to the low threshold trigger technique, neutrino signals need to be collected out of a large number of triggers that are mainly caused by thermal noise fluctuations. The first available data of RNO-G has been exploited to understand impulsive events, noise trigger rates and other radio backgrounds. Calibration data has been taken for a better understanding of the detector response and of the instrumented ice volume. We highlight here the main findings, whereas the next section will focus on the rare natural backgrounds expected from cosmic-ray air showers.

RNO-G stations are powered by renewable energies, using solar panels and wind turbines. Wind turbines serve to provide power during the Arctic winter, when sunlight is not sufficient to

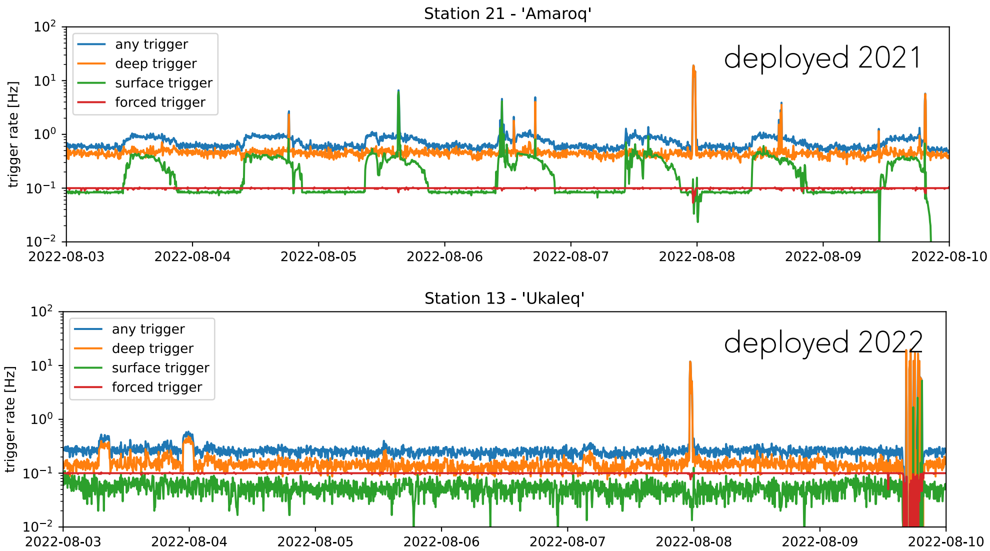

Figure 3: Trigger rates for a week of RNO-G data taking for station 21, installed 2021 (top) and station 13, installed 2022 (bottom). Different triggers are shown; the deep trigger (orange), the surface trigger (green), and the forced triggers taken every 0.1 second (red). The cumulative trigger rate is given in blue. Clearly seen is the reduction in surface triggers for the latest iteration of the hardware (2022) compared to the first deployment season (2021), using a similar threshold.

charge the batteries. Analysis of the first year of data taking has revealed that the solar panels of the station may create a background. Figure 3 top, shows the trigger rate for a week of data taking of the first deployed station in 2021. Clearly visible is an increase of the surface trigger rate during periods of 8 hours of daylight, resulting from radio pulses created by the batteries when charged by solar panels. An efficient iteration of the hardware, by redesigning the power system, resulted in stable and quiet stations, as shown in Figure 3 bottom. Wind turbines were added in the second deployment shift 2022, but are still under active development. It is planned to install a revised wind turbine version in 2023.

Furthermore, it has been found that naturally produced radio pulses occur during periods of high winds exceeding $\sim 10\,\mathrm{m\,s^{-1}}$. Figure 4 left shows the event rate for extremely large amplitude events (uncalibrated ADC counts > 200) which filters out any trigger due to noise fluctuations or self-induced hardware triggers. A clear correlation of the number of triggers with large wind speeds is observed. This has been observed in all other pioneering radio neutrino experiments in polar regions [7]. The current hypothesis for these *wind events* is the triboelectric effect, which describes any process where a force applied at a boundary layer results in displacement of surface charge. Besides potentially saturating the throughput of the system, a handful of wind events may result in pulses that look very similar to neutrino events and are therefore hard to reject. Since the exact wind speed of the 'turn-on' depends highly on the specific hardware and trigger threshold, a good detector understanding is needed to reject these event. Characterizing wind events will be one of the priorities of the first seasons of RNO-G.

For a better understanding of the ice-target radioglaciological measurements of the ice sheet were performed in parallel to the deployment of the first RNO-G stations in 2021. One of the first

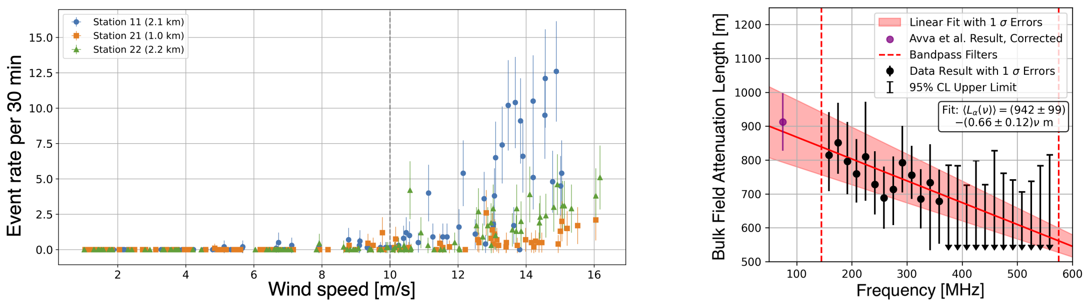

Figure 4: Left: Average RNO-G trigger rate for events containing high amplitude signals as a function of average wind speed. Data are shown for the three stations deployed and commissioned in the summer of 2021. The distance to the main building of Summit Station is indicated in the legend. Figure is taken from [7]. Right: Measurement of the depth-averaged electric field attenuation as a function of frequency at Summit Station, within the system bandpass (shown as red dashed lines). Figure taken from [8].

analyses was a measurement of the attenuation length. An attenuation length linearly dependent on frequency is observed, as shown in Figure 4 right, with an averaged length of 926 m (300 MHz). The expected neutrino event rate depends crucially on the ice properties, since a long attenuation length results in a larger ice volume for which radio signals are detectable at the stations.

3. Cosmic Ray and Muon Background

The similar radiation mechanism of cosmic-ray air showers and in-ice showers make air showers a valuable verification source for the detector performance and in-situ calibration. Since the cosmic ray spectrum is well-known and the radio emission mechanism of air showers well understood, the absolute amplitude scale of the signals received can be calibrated.

In the evolution of cosmic-ray air showers, (prompt) muons that are created in the early stage of the shower can reach ground level. As muons radiate in the ice, they can induce an electromagnetic cascade which creates radio emission via the Askaryan effect. For muons with an energy >10 PeV this can lead to signals strong enough to be observed by an RNO-G station. To a radio detector, such an interaction would in principle look identical to the signal created by a neutrino-induced particle shower [3]. The muon flux above PeV strongly depends on the assumed cosmic ray composition and the hadronic interaction model used, yielding an expected muon event rate in the same order of magnitude as the neutrino event rate (see Figure 2). On the analysis level, the combination of vertex position and arrival direction may allow the removal of a fraction of the atmospheric muon background, given a good reconstruction of both parameters and at the cost of a reduced neutrino sensitivity [3]. For RNO-G only a few muons are expected, where statistical methods will not be sufficient. Therefore a muon identification is needed on an event-by-event basis. Another way to flag muon events is by tagging the parent air shower. Since muons stem from air showers, measuring an air shower signal in proximity to an in-ice trigger provides a veto on a neutrino detection. Therefore, an efficient air shower detection will lend higher confidence in identifying neutrinos and prevent the false positive neutrino detection caused by muons and other air shower related backgrounds.

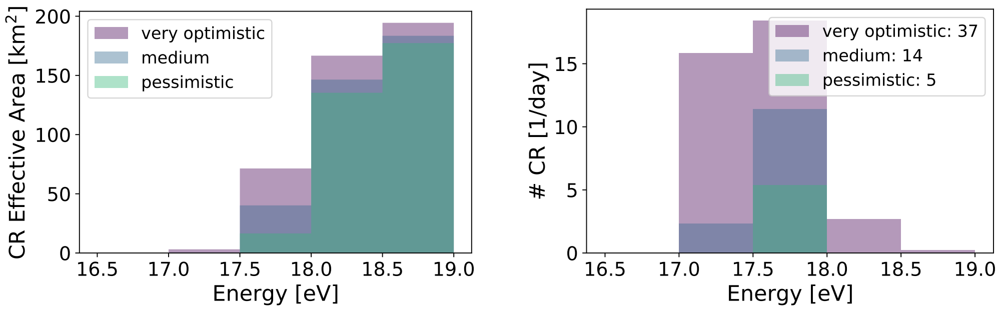

Figure 5: Left: Cosmic ray effective area of the planned 35 station array for different trigger thresholds (color code) with respect to cosmic ray shower energy. Right: Expected cosmic ray events per cosmic ray shower energy.

A cosmic ray search is currently in progress. To calculate the number of expected cosmic ray detections, a good understanding of the surface trigger is necessary. The signal amplitude of an air shower, as observed in the antennas, scales linearly with its energy. Hence the effective area at low energies is strongly determined by the trigger performance. The surface trigger is realized by a self trigger, using a Schottky diode which forms an envelope of the measured trace in time domain. On this, a simple threshold trigger with a two out of three upward-facing LPDA coincidence is applied. To increase the signal-to-noise ratio an optimized bandpass filter of 80 MHz to 180 MHz is implemented in the trigger path [9].

The effective area of the RNO-G array is calculated using ~400 air shower simulations produced with CORSIKA 7.6400 [10], assuming protons as primary particle and with QGSJetII.04 [11] and UrQMD [12] as hadronic interaction models. The radio emission is generated by the CoREAS plug-in [13]. For the time being, the trigger diode is modeled using a Hilbert envelope, which is only a simplified representation. Since the behavior of the diode regarding different pulse shapes, noise fluctuations and low amplitudes is still being studied, three scenarios with varying trigger signal thresholds are simulated (see Figure 5). The very optimistic case includes an effective area of 3 km^2 per array in the cosmic-ray shower energy range of 1×10^{17} eV to 3.16×10^{17} eV. Due to the steep falling spectrum for higher energy cosmic rays, this has a huge influence on the total number of expected cosmic rays, which is increased by ~15 events per day to a total of 37 events per day for the full array including the complete energy spectrum. In the pessimistic case, measurable air showers are only expected in the range of 3.16×10^{17} eV to 1×10^{18} eV, where the cosmic-ray flux is much lower. At higher energies the detection of cosmic rays is limited due to low flux and a sparse array of limited size. Inclined air showers illuminate larger areas but since the air-shower energy is distributed over a larger area, the electric field registered by one antenna is fainter, which makes inclined air-showers only visible with a low trigger-threshold (here the very optimistic case). In the medium scenario, RNO-G expects 14 cosmic rays per day in a 35 station array, but even in the pessimistic case RNO-G expects to measure 5 air showers per day and array. Due to the strong dependence on the trigger threshold, the predictions for the full 35-station array currently have large uncertainties. An optimization and a better calibration of the trigger is planned to first better understand and consequently increase the number of detected cosmic rays.

4. Conclusion

The first seven of 35 stations of the Radio Neutrino Observatory in Greenland are running and taking data. The initial data has been analyzed for a proper understanding of backgrounds. A number of self-induced backgrounds were successfully identified and mitigated. In addition, a number of studies have been performed to understand the ice-target. Studies for rare expected natural backgrounds stemming from cosmic ray air showers are ongoing, emphasizing the importance of the dedicated surface trigger to detect air showers to allow for a solid neutrino identification. A cosmic ray search is in progress and surface trigger improvements are ongoing.

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