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The Radio Neutrino Observatory Greenland (RNO-G)

The RNO-G Collaboration

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The Radio Neutrino Observatory Greenland (RNO-G) is being constructed at Summit Station in Greenland. It seeks to detect the radio emission of neutrinos interacting in the 3 km thick ice. Radio detection of neutrinos is sensitive to neutrinos above 10 PeV and therefore complements existing optical detectors. RNO-G currently consists of 8 out of planned 35 stations, each combining the signals of 24 antennas distributed in shallow trenches and three holes of 100 m depths. This contribution will provide an overview of ongoing activities at RNO-G, with a focus on recent scientific results and plans for future seasons.

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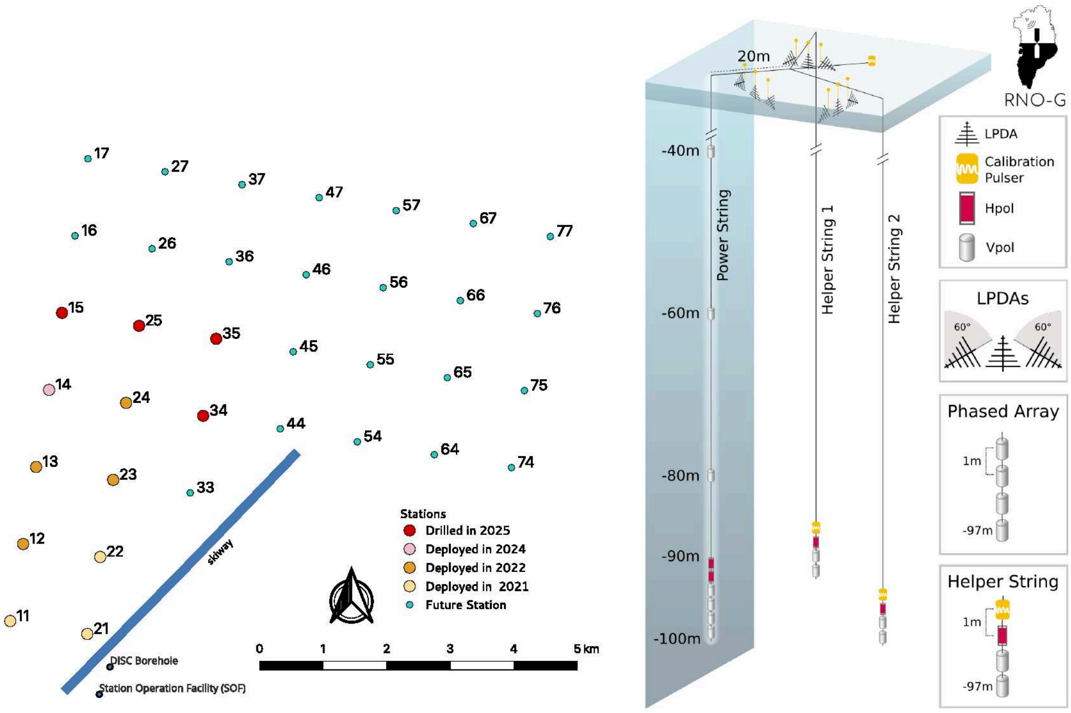

Figure 1: Left: The RNO-G array near Summit Station. Indicated are landmarks such as the Station (SOF) and the skiway where airplanes land, as well as planned and installed station positions. The status reflects the progress as of mid-season 2025. Right: Layout of each individual RNO-G station. 24 antennas (Vpol, Hpol, and LPDA) are installed trenches and in holes down to 100 meters in depth.

1. Introduction

The Radio Neutrino Observatory Greenland (RNO-G) is under construction at the highest point of Greenland, on top of 3 km of homogeneous cold ice [1]. In its first stage, RNO-G is planned to consist of 35 stations, each with 24 antennas distributed in 3 holes of 100 meters in depth (see Figure 1). Currently, 8 of these stations are operational and taking data. In the currently on-going field season four additional stations have been drilled, as of July 13th.

The start of construction of RNO-G in 2021 was heavily affected by the global pandemic, followed by chip shortages, and drastic changes in the global political landscape. The largest challenges at the moment are the efficient drilling of the holes, ideally one hole per day, and supplying each station reliably with power throughout the polar winter to enable year-round operations. The challenges that come with the extremely small power budget of less than 25 W in polar conditions, available for data taking and transfer, essentially dominate the design.

2. Instrument Performance and Schedule

During the construction of RNO-G, the performance is constantly evaluated with respect to reliability and maintainability. While building on the unmissable heritage of RICE, ARA, ARIANNA, and ANITA, RNO-G is the first large-scale effort of the in-ice radio detection technique and therefore has to address some challenges that come with scale. Until installation is complete, the task list for the RNO-G collaboration is clear. Elements of the success metric are: stable performance and easy maintainability, understanding and mitigation of backgrounds, accurate calibration of the instrument, as well as the first search for physics signals. A more detailed report of the technical details of RNO-G can be found in the recent publication illustrating the performance [1] and the dedicated proceedings [2].

RNO-G is currently working on a new generation of DAQ-boards that provides a more hands-off operation and allows for a faster start-up without lengthy calibration for periods in the polar winter, when power from the wind-turbines is available. Therefore, in the currently on-going field-season no additional stations are planned to be instrumented, while drilling continues.

Figure 2 provides an impression of the currently on-going installation effort. For 2025 only maintenance and drilling of new holes is planned. Since the open holes do not close from the sides, a simple cover with a wooden plank will allow us to instrument the holes in a future season. In the past, drilling performance has been the limiting factor of installation speed. The schedule for completion for RNO-G will be evaluated after this year of gathering extensive drilling experience. Most ambitious plans foresee a completion of 35 stations within the next three field-seasons, with additional stations to be added later.

Throughout the past two years of operations, many important improvements have been made, using lessons learned from the eight operational stations.
The main trigger of RNO-G is based on the signals from the four antennas at the bottom of the most densely instrumented string (see Figure 1). While during the first seasons only a coincidence trigger based on a high-low threshold crossing was running, a true phased-array has been implemented already at the end of 2024. This significantly improves the triggering efficiency for neutrinos by more effectively vetoing thermal noise fluctuations. There is a maximum trigger rate, limited by the data-throughput rate between each RNO-G station and the server at the main station. By being able to lower the signal threshold and at the same time not increase the trigger rate, both the neutrino energy threshold is lowered and the effective volume in which a detectable neutrino interaction can take place is enlarged.
Also, the triggering of cosmic rays has undergone an improvement, with the newest stations being both more efficient in triggering direct signals from air showers and also being able to record the causally connected signals in all antennas. The latter had previously been precluded by signal travel times through ice and cables, which meant that the signal in the antennas close to the surface was overwritten in the buffer before the signals from the deep antennas arrived at the DAQ.

3. Early Results

These proceedings give an overview of all recent RNO-G results and analysis efforts. This naturally has to be terse, so the reader is encouraged to follow the provided references.

3.1 Cosmic Rays

The first important milestone for RNO-G will be the validation of the detection of cosmic ray signals. We report at this conference about the results of the first search of the in-air signals of cosmic rays in the antennas installed close to the surface [3], which are in line with results

Figure 2: Impression of the RNO-G installation. Left: View of an installed station. From the outside, only the towers providing power and communications are visible. Middle: Drilling tent at the RNO-G site on June 10th 2025. The mount in front of the tent, stems from ice chips that are expelled from the drilling barrel. Right: View into the drilling barrel, showing one of the mechanical cutter-heads. With the limited infrastructure at Summit Station, the relatively shallow depths, and the large scales of the radio array, a hot-water drill is considered unfeasible.

from pathfinder experiments and dedicated radio air shower experiments. Cosmic rays are detected and identified above the background using their characteristic signal shape. Their consequently reconstructed event parameters, such as energy, arrival direction and signal polarization match expectations. Essential progress had to be made in understanding the system-response towards air shower signals, which helped to refine the testing and calibration procedures ahead of installation.

On-going is also a first search for signals of impacting air shower cores in the ice of Greenland [4]. Air showers that have not fully developed in the atmosphere, contain enough particles to produce signals that mimic neutrino-like signals, as they are dominated by the Askaryan effect. While the in-air signals can build on years of experience with simulations, for in-ice signals the simulations are still being refined, as also reported on at this conference [5]. The fast-changing refractive index of the ice, as well as boundary layers and near-field effects make this a challenge.

3.2 Solar Flares

An unexpected early result was the detection of solar flares by RNO-G as published in [6] and reported on in [7] at this conference. While it was known that solar flares are visible in radio neutrino detectors (as reported by ARA and ARIANNA), the current solar maximum has increased the number of occurrences of flares and outbursts. To be clear, RNO-G simply detects the radio emission of the sun caused by plasma effects and particle acceleration therein, and not from neutrinos. RNO-G records these radio signals with unprecedented timing resolution, showing nanosecond-scale substructures. This fine-grained observation is not possible with current dedicated solar radio observatories that record in the frequency domain and RNO-G thus provides novel data for modeling solar processes. For RNO-G, the radio bright Sun is an interesting above

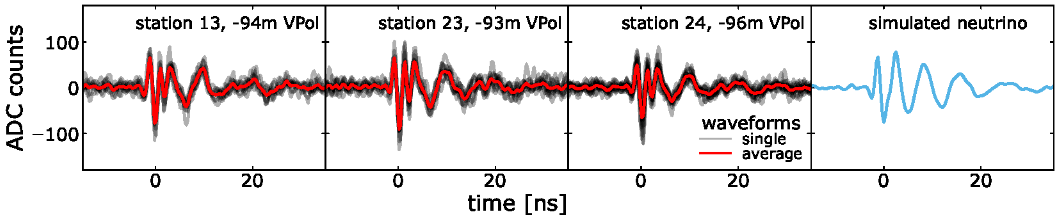

Figure 3: Signals emitted by airplanes as detected with three stations of RNO-G (left three panels), compared to the expectation of a neutrino signal (right panel). Shown are both single waveforms (black), as well as an average waveform of all detected signals from this flight (red). While very similar by eye, the events can be distinguished using e.g. template correlation. More details on the airplane analysis can be found in [10].

ground calibration source, which allows us to test global station rotation and positions-shifts of the antennas.

3.3 Calibration results

Calibration is a major focus during the early commissioning of RNO-G. An almost *classic* calibration signal used by many radio air shower experiments is the diffuse synchrotron emission of the Galaxy. RNO-G clearly sees this signal in the upward-facing antennas [8] and work is on-going to use this as calibration signal. Previous work of air shower experiments has shown that this is the most accurate procedure for antennas with a good view of the Galactic plane.
In addition to the Galactic signal, the known temperature of the ice and the environment contribute to signal power observed with RNO-G and thereby can serve as the absolute scale of the observed thermal noise [9]. Via this route, differences between signal chains (as measured in the lab) and the in-situ performance can be corrected for to obtain fully calibrated measured electric fields. An absolute calibration is essential to retrieve a highly accurate energy estimate for measured neutrinos and air showers.

Another interesting calibration source is provided by airplanes passing overhead in Greenland. In [10], we show that signals are picked up from both commercial trans-continental and local flights. A subset of these signals are highly impulsive and may mimic neutrino signals as shown in Figure 3. However, given that airplanes publicly transmit their presence via ADS-B, the signals can be tagged and removed from neutrino searches. More importantly, the signals can be used as a far-field source to calibrate antenna positions and ice properties. Preliminary work using solar flares and airplanes indicates that a calibration to better than 1 degree is easily obtainable, which is much smaller than the expected angular resolution of radio neutrino detectors [11]. However, it should be noted that such in-situ calibrations always rely on understanding both the locations of the antennas, and the underlying ice properties.

3.4 Glaciology

The ice at Summit is an integral part of the RNO-G detector, which means that significant effort is put into understanding its properties. The most important parameters, are the frequency-dependent index of refraction and attenuation length as function of depth. The most recently

published results provide the world's most accurate index of refraction of the bulk ice [12] and a procedure to monitor the borehole closure using the RNO-G antennas [13].
Every field season, additional measurements are conducted to refine our understanding of the ice. Results from just a few month ago are reported in [14]. Also field-tests of new hardware to monitor the impact of wind [15], like acoustic sensors and electric-field meters are on-going.
Similarly to IceCube, the stability of the ice means that calibration measurements obtained at a later point in time, can always to be used to refine neutrino searches and reconstruction. However, given the absence of detected neutrino signals at this point, searches have to be robust against unknown ice parameters and in that sense conservative. So a better understanding of the ice will already now improve neutrino searches.

3.5 Calibration strategy

As outlined above, the calibration of RNO-G will require a simultaneous evaluation of ice properties and instrument parameters, as they are intimately coupled. The plan is to collect all suitable calibration signals and run a combined calibration, which will be reported on in a forthcoming publication. An absolute calibration of the signal strength will directly influence the systematic uncertainty of the energy scale obtainable. A relative amplitude calibration between antennas will lead to an improved trigger threshold for neutrino signals, as the signals will have the appropriate weighting. The positioning of the antennas, will directly translate into a pointing accuracy of the instrument for both reconstructing neutrinos and vetoing background signals. Calibrating the ice properties will help with vetoing backgrounds and refining the neutrino simulations.

3.6 Neutrino searches

The on-going RNO-G work in dominated by commissioning activities that ensure that the detector is operational as planned and that unexpected backgrounds from e.g. satellites or atmospheric phenomena do not pose a threat. In parallel to these activities, the first search for neutrino signals is being prepared [16]. Since RNO-G would be the first in-ice radio neutrino experiment to measure a neutrino, several different routes are being followed to obtain a robust search for early signals [17]. Once these analyses have reached maturity, the published effective volumes will also be updated. Most recently published effective volumes [1] are based on trigger design sensitivities and do not contain any analysis efficiency, like it is also the case for other experiments targeting these high energies. Also, given the on-going updates of the hardware, the collaboration thought it prudent to not update effective volumes every year, but provide them once a significantly better understanding is available, based on a neutrino search and a consolidated field-performance.

4. RNO-G in context of the landscape of neutrino telescopes

While IceCube has only set limits on the neutrino flux above 10 PeV, KM3NeT has excited the community with the first reported flux measurements. To give the community an updated perspective on the RNO-G effective volumes, Figure 4 presents a preliminary estimate of the time a fully deployed array would require to detect a single neutrino, based on this flux.

As compared to previously published effective volumes, a number of key updates have been made for this figure and towards updated sensitivities. RNO-G uses NuRadioMC [20] for its

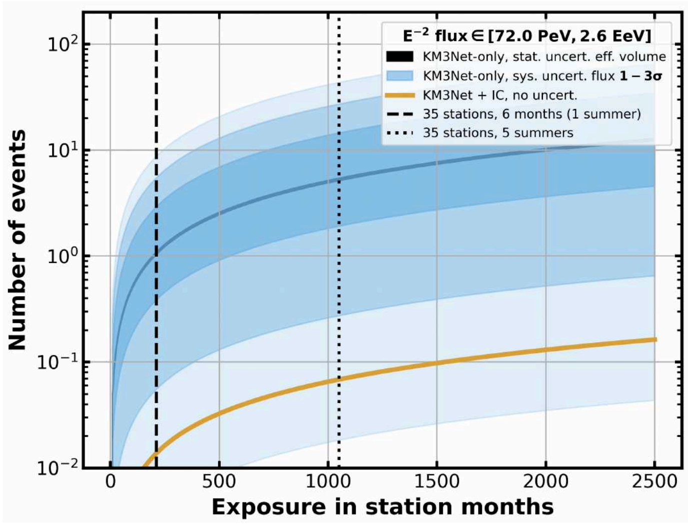

Figure 4: Number of detected events expected based on the currently realized trigger efficiencies and the neutrino flux as reported in [18] as function of operational station months. The blue areas indicate the flux uncertainties as reported by KM3NeT, systematic uncertainties for RNO-G are not included. Also shown is the exposure needed for the neutrino flux derived from a combination of IceCube and KM3NeT (orange line) as reported in [19]. For clarity the uncertainties have been omitted here. The dashed lines indicate one half year (summer operation) of the full RNO-G array and 5 summers with the whole array to provide an indication. As RNO-G is modular, *N* months with *M* stations is roughly equivalent to *M* months with *N* stations.

sensitivity simulations. The code has been improved to use an updated energy dependent inelasticity model [21], which includes a new parameterization for the cross section and an energy dependent fraction of neutral- and charged-current interactions. Furthermore, the attenuation model has been updated to our own most sophisticated measurement of the ice in Greenland, taking into account also the chemical composition of the ice, rather than the temperature only [22]. In addition, the triggering simulation has been updated to match the demonstrated field-performance of the array.

It should be noted that the effective volumes leading to these predictions are mostly affected by the trigger efficiency, which is still subject to development and is foreseen to improve further with the new DAQ. In summary, however, the ball-park estimate is robust that one summer season of RNO-G 35 should detect one event at the nominal KM3NeT-flux value.

While the Pierre Auger Observatory has recently underlined that the *ANITA anomalous events* are in contradiction with their neutrino limits [23], it will be interesting to see what the first RNO-G analysis will yield. If the ANITA signals are due to some unexpected behavior of the ice, for instance, RNO-G may be sensitive to this signal channel from a very different geometry than ANITA and its successor PUEO [24]. Thus, it will be an important cross-check.

The design and operation of RNO-G, also continuously informs the progress towards IceCube-Gen2 [25]. The baseline design of the radio array of IceCube-Gen2 [26] is based heavily on RNO-G. Also, the corresponding logistics and experiences in operating a large-scale array are valuable lessons for the project and influence the design going forward. A close exchange between the two projects is on-going.

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PoS(ICRC2025)1129

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