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The Radio Neutrino Observatory in Greenland: Status and Perspectives

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High-energy neutrinos propagating over cosmological distances are the ideal messenger particle for astrophysical phenomena, but the neutrino landscape above 10 PeV is currently completely uncharted. At these extreme energies and the frugal flux expected, the dominant experimental strategy is to detect radiofrequency emissions from particle cascades produced by neutrinos interacting in the vast polar ice sheets. The Radio Neutrino Observatory in Greenland (RNO-G) is an array of radio antennas embedded in the ice near Summit Station, currently being deployed. At completion, RNO-G will consist of 35 autonomous antenna stations distributed over $O(50\,\mathrm{km}^2)$, making it the largest and most sensitive in-ice neutrino telescope with unique access to the northern sky. This article describes the design of RNO-G, outlines the calibration and simulation strategies developed, and summarizes first results based on the dataset collected by the first seven operating stations.

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1. Introduction

High-energy neutrinos from the cosmos are powerful messenger particles. Produced in interactions of charged cosmic rays with baryonic matter near astrophysical sources ("astrophysical neutrinos") or the photons of the cosmic microwave background ("cosmogenic neutrinos"), they carry information about the nature and the cosmological history of high-energy cosmic accelerators. The IceCube observatory has firmly established the existence of cosmic neutrinos with energies above hundreds of TeV, also identifying the first point neutrino sources outside our own galaxy.

Many questions remain open, however. The observed IceCube neutrino flux extends up to energies of order 10 PeV, but neutrinos with much higher energies, 100 PeV–1 EeV, are predicted to exist, providing a direct window on the highest-energy astrophysical phenomena. The central experimental challenge in the search for these extreme particles is their extremely small expected flux. Vast detector volumes need to be instrumented to generate sufficient sensitivity to probe this regime.

The Radio Neutrino Observatory in Greenland (RNO-G) [1] is an experiment targeting the regime of trans-10 PeV neutrinos. A large-scale array of radio antennas deployed near the surface of the Greenlandic ice sheet, it searches for the Cherenkov-like radio pulse produced by a neutrino-induced charged particle cascade. Capitalizing on the extreme transparency of glacial ice to electromagnetic radiation in the MHz to GHz band, a single antenna station can instrument a volume of order 1 km^3. At completion, RNO-G will consist of 35 stations and provide world-leading sensitivity to neutrinos in the EeV range.

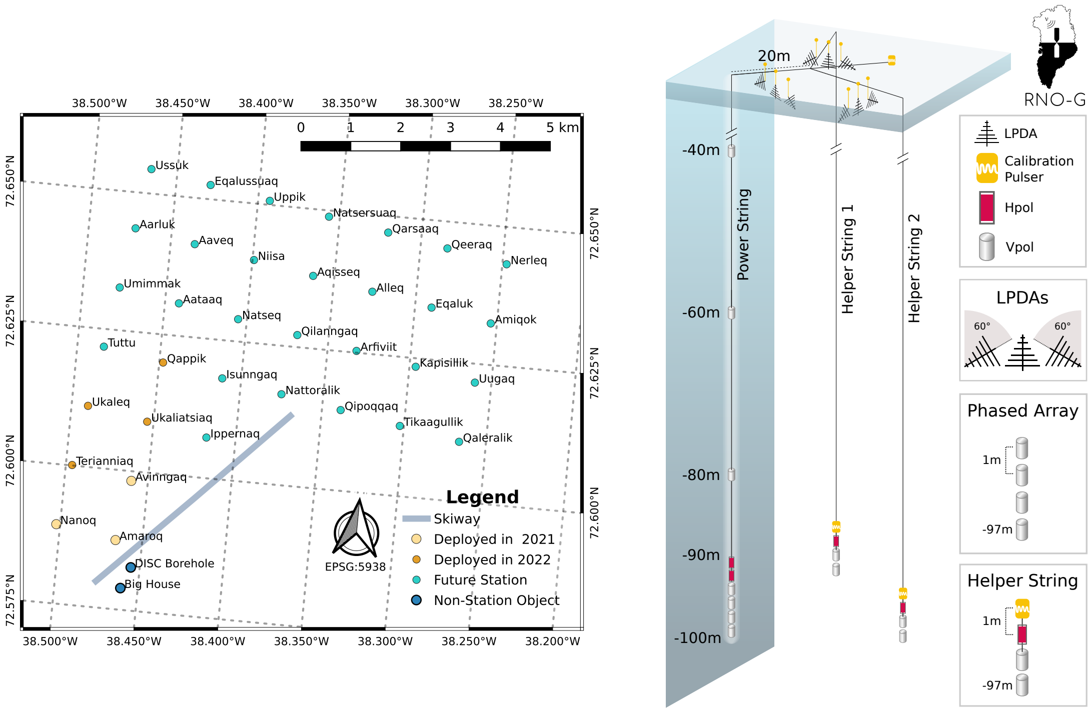
With seven stations already deployed and taking data, this article gives a brief overview of the design of the experiment, the calibration and simulation strategies developed on the way to first (neutrino) physics, and a summary of the present status and first results.

2. Array and Station Design

RNO-G is situated close to Summit Station, Greenland. Figure 1a shows an overview of the array layout, with individual stations interspersed by approximately 1.25 km on a rectangular grid to maximize the effective instrumented volume. The layout of an individual RNO-G station is shown in Figure 1b. Antennas sensitive to both horizontal and vertical field polarizations are deployed in boreholes at up to 100 m deep. They are complemented by high-gain directional antennas at the surface (both upward- and downward-facing), resulting in a total of 24 antenna channels per station.

This "hybrid" design gives RNO-G the unique capability to detect both in-ice and in-air radio sources, critical to understand the role of e.g. cosmic-ray air showers as important backgrounds to the primary neutrino signature.

Readout, Analog Signal Path, and Powering The signals from all antenna channels are digitized at 3.2 GS/sec utilizing the *LAB4D* switched-capacitor array 12-bit analog-to-digital converter [3]. To bring up the thermal noise floor to a level suitable for digitization, the radiofrequency (RF) signal path provides a forward gain of approximately 60 dB. For downhole channels, a low-noise amplifier is situated in immediate proximity to each antenna, with a secondary amplification stage located in the digitizer enclosure at the surface. An optical-fiber link is used to carry the RF signal from



(a) **(b)**

Figure 1: (a) Layout of the RNO-G array and its placement relative to Summit Station. Deployed antenna stations are shown in orange and yellow, while planned future stations are displayed in cyan. (b) Layout of an RNO-G station, comprised of in-borehole antennas measuring horizontal ("Hpol") and vertical ("Vpol") field polarizations as well as a surface component using log-periodic dipole antennas (LPDAs).

the in-borehole antennas to the surface. Owing to the shorter distances that need to be bridged, the surface channels instead utilize coaxial (copper) cables and are equipped with a single amplification stage providing the required forward gain. The design of the analog RF signal chain is described in more detail in Ref. [2].

Each RNO-G station is autonomously and renewably powered, with a battery-buffered solar system providing the bulk of the required energy during the summer months. The use of wind turbines is being explored as a complementary power source, also promising to extend the detector operation further into the shoulder seasons. During winter, where insufficient power is available, the readout system is shut down, with only minimal status and health monitoring remaining active.

Trigger Strategy RNO-G employs a radio-only trigger, where a readout of all channels in a given station is requested if coincident signal activity is registered in either a number of surface channels or the set of four lowermost downhole antennas. The deployed RNO-G hardware further allows to operate these densely-spaced downhole antennas as a phased array, effectively synthesizing a number of high-gain antenna beams and lowering the trigger threshold. The trigger thresholds are dynamically adjusted to remain within the available rate budget set by data transfer bandwidth constraints. Additional low-rate diagnostic trigger streams are used to monitor ambient noise levels

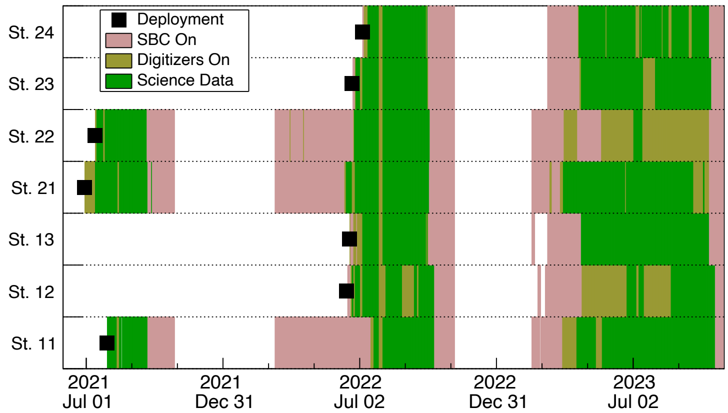


Figure 2: Data-taking history of the seven deployed RNO-G stations, indicating deployment (black squares) and periods with the on-station single-board computer (SBC) turned-on (rose), digitizers turned-on (dark yellow), and science data being taken (green).

and station performance.

3. Detector Calibration and Simulation

To be able to fully exploit the recorded dataset, the per-channel forward gain and relative time delays across antenna channels are calibrated using a number of different techniques, based on measurements taken in the laboratory as well as in the field. This includes the extensive characterization of all signal path components in the laboratory ahead of deployment, the measurement using radioglaciological methods of the dielectric properties of the ice in which the detector is embedded [5, 6], and the automated in-situ calibration of the digitizers to ensure a stable voltage scale. Further information on the employed calibration and measurement techniques may be found in Ref. [4] and references therein.

The simulation pipeline developed for RNO-G covers all relevant processes, from the generation of the radio emission at the location of the shower, its propagation through the inhomogeneous ice, and the response of the detector as informed by the calibration measurements described above. It uses the general-purpose NuRadioMC simulation framework [7], extended by custom and detector-specific components.

4. Current Status and First Results

Figure 2 summarizes the data-taking history of the seven operational RNO-G stations, deployed during the 2021 and 2022 summer field campaigns. Data taking is possible when enough solar power is available, typically from late April to early October.

While a large fraction of the dataset collected to-date is still blinded, RNO-G has observed a number of natural and anthropogenic radio sources. Once identified and understood, these will transition from backgrounds into valuable calibration signals that provide valuable insight into the functioning and performance of the array. Only a short summary of these results is given here due to space constraints, with more information available in the provided references.

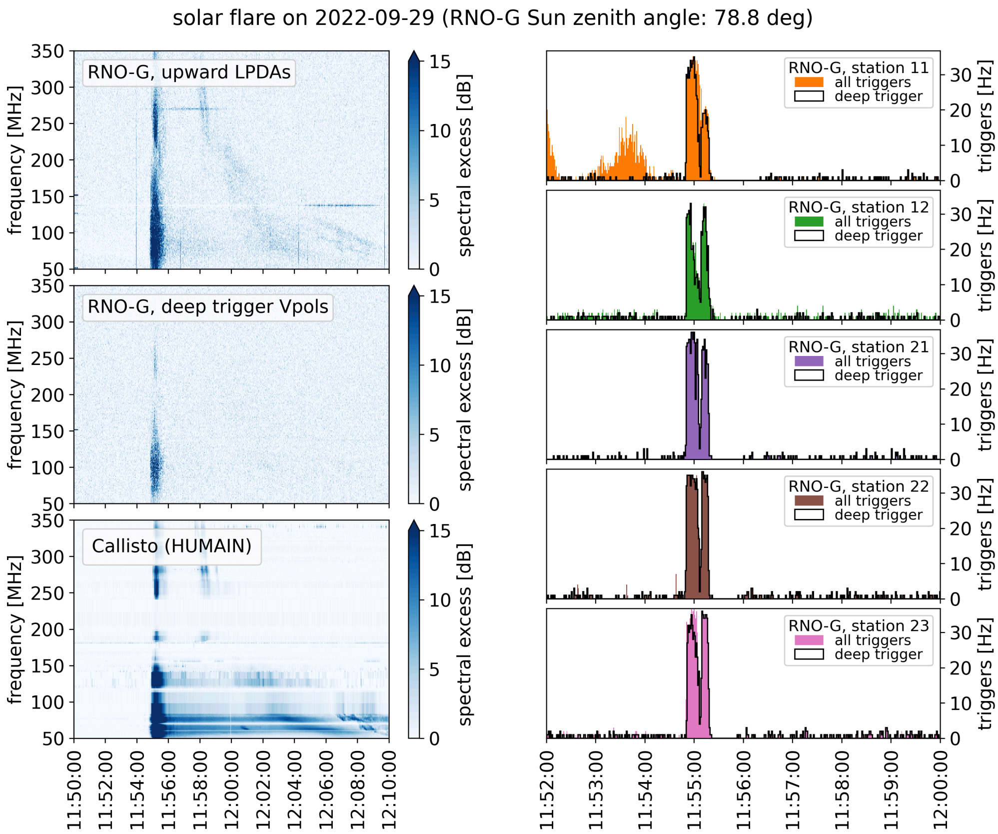


Figure 3: Solar flare of Sept. 29, 2022 as observed in five RNO-G stations. Left: Spectrograms as observed in the upward-facing LPDAs (top) and deep trigger antennas (center), compared to Callisto / HUMAIN [9] (bottom). Right: Deep trigger and total trigger rates as a function of time during the flare for the five participating antenna stations.

Anthropogenic and Natural Radio Sources Despite its remote location in the remote arctic, anthropogenic sources of radio emission are important backgrounds. These include both quasi-continuous narrow-band emissions from communication satellites or handheld radio devices, but also impulsive signals from radar altimeters in commercial airplanes overflying the array at large altitudes.

Natural background radio sources identified in RNO-G data include the galactic center as well as emissions produced by wind-induced triboelectric discharges at or near station components [8].

Solar Flares RNO-G has conclusively observed the radio signature of the flaring sun during its current active phase of the 25th solar cycle [10]. Figure 3 shows a solar flare as observed by the RNO-G array, powerful enough to saturate the trigger rates of five stations. These signals show fast transients on time scales of $O(10\,\text{ns})$, which allow to test event reconstruction algorithms and have established degree-level precision in the reconstruction of the signal arrival direction.

Cosmic-Ray Air Showers Several candidate events for cosmic-ray induced air showers have been identified [11], with work currently ongoing to extend the analysis to the full dataset collected to date. Owing to its hybrid design including near-surface and deep antennas, RNO-G is capable to observe also the in-ice radio emission caused by air shower cores impacting the high-altitude polar plateau near Summit Station, which will be targeted by future analyses.

5. Conclusions and Outlook

The deployment of the RNO-G array is currently ongoing, with seven stations already operational. These are currently being calibrated and readied for first physics-level analysis work, but already allow a variety of natural and anthropogenic backgrounds to be observed and studied. The detector will be built out to the full 35-station array over the course of the next few years, positioning RNO-G to take the role as the leading experiment observing the high-energy neutrino sky.

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