PROCEEDINGS OF SCIENCE

Cosmic Ray Detection with RNO-G

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The Radio Neutrino Observatory-Greenland (RNO-G) is an in-ice neutrino detector aiming for the first detection of neutrinos at energies exceeding 10 PeV. Positioned on top of the Greenland ice sheet close to Summit Station, the detector is presently in the construction phase, with 7 out of 35 planned stations already deployed within the ice and operational. Each station is not only equipped with antennas designed to detect neutrino signals but also features three upward-facing log-periodic dipole array antennas (LPDA). These antennas are included to detect signals from cosmic-ray air-showers. Upon completion, the detector will cover an area of $O(50)\text{km}^2$, allowing RNO-G to measure cosmic-ray air-showers and use them for detector calibration, study the phenomenon of the air-shower core hitting the ice, and veto cosmic-ray events for the neutrino search.

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1. Cosmic rays in in-ice neutrino detectors

Cosmic rays play several crucial roles in in-ice radio detectors. First of all, they are an essential calibration and analysis verification source. Air shower pulses are extremely similar to neutrino shower pulses, so if an experiment can show that expected and recovered cosmic ray signatures are in agreement, it is well-positioned for a neutrino search. In addition, cosmic rays also cause very important physics backgrounds for in-ice neutrino arrays. It is expected that incomplete air showers hitting the ice lead to signatures mimicking neutrino signals, e.g. [1]. Fortunately, these signals are expected only from close to the surface, which will likely provide a handle to separate them from neutrino signals in analysis. Furthermore, extremely hard muons stemming from air showers can constitute a background [2]. The muons do not necessarily interact close to the surface, which makes them harder to reject. The rate expectation of these background events is subject to large uncertainties at this point. However in general, the muon rate is expected to be much lower than most predicted neutrino fluxes, unless the neutrino flux at 100 PeV is also found to be extremely low, in which case there could be a significant confusion background.

Earlier in-ice arrays have searched for cosmic ray signals. The ARIANNA experiment has published a cosmic ray flux measurement [3], showing that (within systematics) the expectation matches what has been found using a template based signal search. Furthermore, ARIANNA has been able to show that the detected signals show the right polarization signatures and other event properties [4] as expected from cosmic rays. This is good evidence that a similar search strategy may work for neutrinos, however, the signals were all measured close to the surface, so that one cannot draw conclusions about long-distance in-ice propagation.

ARIANNA shares the same antennas as RNO-G in shallow trenches, albeit with different DAQ electronics and, thus, most importantly a different trigger threshold. Also, cosmic rays were detected with ARIANNA stations both on the Ross ice-shelf, as well as at the South Pole.

The ARA collaboration has not published a dedicated cosmic ray search. However, a number of cosmic ray candidate events were found in PhD theses e.g. [5]. Also, one event passed the cuts in a neutrino search [6]. It is believed to stem from an air shower core interacting in the ice. This is, however, less straight-forward to prove, since ARA does not have antennas close to the surface, which would provide additional evidence for this hypothesis by tagging the air shower.

2. Search for cosmic rays in shallow antennas of RNO-G

RNO-G will be the first experiment that could measure both the direct air shower signals in the shallow antennas, as well as the down-going signal from air shower remnants. However, this ability has only been implemented in firmware in 2024. Before the firmware change, the trigger windowing missed the deep signal, if the shallow antennas triggered a signal and the shallow signal was not buffered for long-enough, if the deep antennas caused a trigger. Therefore, the early analyses of RNO-G will focus on either the shallow or the deep antennas only.

2.1 General strategy

The analysis follows the approach of [3], as refined in [7]. It will use signal templates to identify cosmic rays. A future extension to use methods presented in [8] to improve the low-signal-to-noise

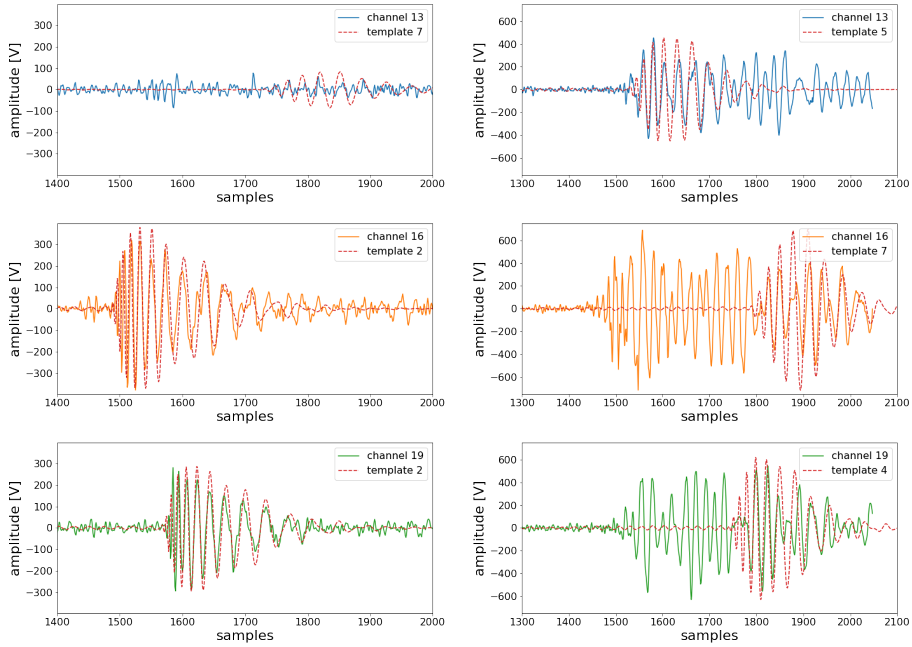

Figure 1: Contrasting a potential cosmic ray candidate (left) with a background event that accidentally shows a good correlation (right). Large signals were picked to illustrate that the waveforms are captured well, but not perfectly and how accidental high correlating waveforms can happen. The situation is obviously much less clear in events with small SNR.

performance is under consideration. The analysis will follow these steps:

- Apply an up vs. down cut on the signal power received in the antennas pointing upward and downward as discussed in [4], to ensure that all signals are from above.
- Apply a time-correlation cluster cut, i.e. remove signals with high template correlation, if they arrive in clusters. This will remove the triboelectric signals as reported in [9]
- Remove waveforms with long-pulse trains as reported in e.g. [10], to ensure that solar flares or other high signals do not spoil the event sample.
- Select final sample based on correlation with signal template.

This analysis chain has been tested on a subset of data and has provided good evidence for this being a working strategy, as discussed in [11]. However, it has been observed that the correlation obatiend from data is not as good as it is expected from Monte Carlo simulations, with a systematic shift of about 0.1 in correlation value across all signal strengths. This is also illustrated in Figure 1. Given that such an offset has not been observed in ARIANNA using the same antennas, it has to be assumed that there is a piece of the RNO-G signal chain that is currently not modeled well. The RNO-G electronics, owing to the 24 channels and long waveforms, are more complex than the 4 channels-system of ARIANNA. Once this systematic shift has been accounted for, the full data-set of RNO-G 7 can be unblinded for analysis.

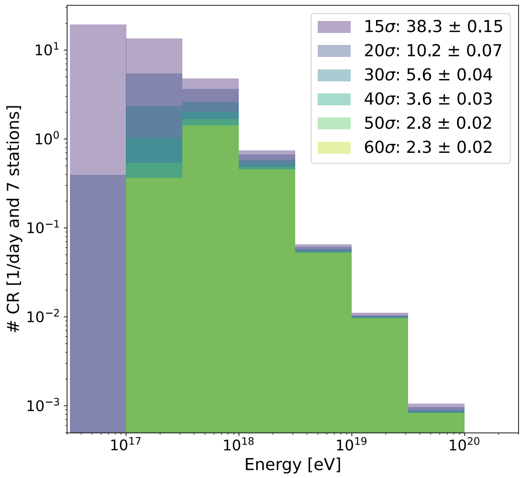

Figure 2: Estimate of the number of cosmic rays detected with the shallow antennas of RNO-G per day and 7 stations as function of energy. Different estimates correspond to different effective trigger thresholds. The definition of σ is the RMS of the integrated waveform over 11 ns, which the relevant time-scale for the diode. See [12] for details.

2.2 Event rate predictions

The event rate expectation for cosmic rays with RNO-G 7 has been estimated in [12], as shown in Figure 2. As for all cosmic ray experiments, the event rate is dominated by those events close to the trigger threshold. In the current RNO-G DAQ board (Radiant V2) a diode trigger [13] is used for the signals in the shallow LPDAs, also requiring a 2 out of 2 coincidence in the upward facings antennas. The same type of diode has previously been used for the ARA experiment [14].

Extensive laboratory measurements have shown that the trigger threshold of the diode is both pulse shape dependent and varies from diode to diode. Furthermore, the v2 Radiant had too little amplification on the trigger path, which meant that the diode had to be operated on the edge of its performance parameters. Both issues lead to relatively large uncertainties for the currently realized trigger threshold, which makes an estimate of the expected cosmic ray rates challenging. In-field studies are on-going to further constrain this expectation, which currently is somewhere between 20σ and 40σ as shown in Figure 2. This is both a rather high and ill-defined threshold, which is undesirable moving forward.

2.3 Hardware implications

These results, together with improved reliability testing for the LAB4D chips and SD card readers, and a modified power system required to be able to remove batteries after installation, have led to the plan to update the existing stations with Radiant V3 boards in 2024. The Radiant V3 has been measured in the lab to improve in trigger threshold of at least a factor of 5.

Furthermore, the firmware of these Radiant V3 boards will be updated to accommodate a buffered trigger that will allow the simultaneous recording of cosmic ray signals in the deep and in the shallow antennas, triggered by a signal in the shallow antennas.

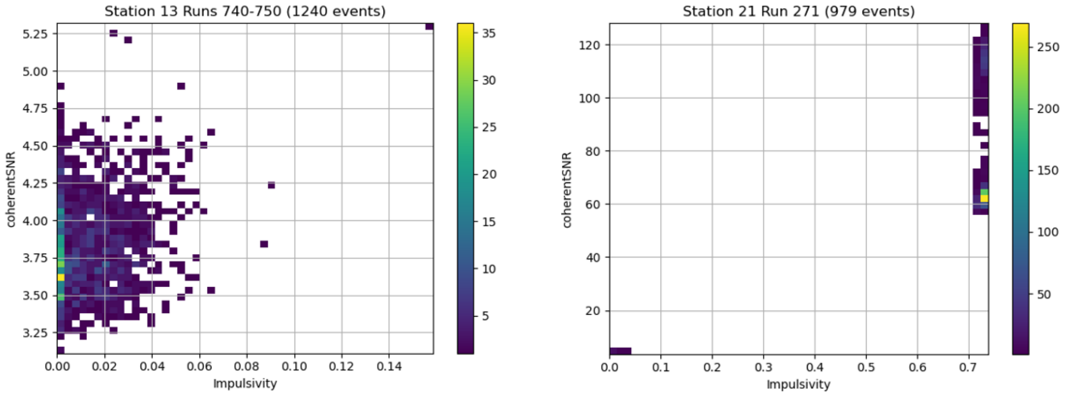

Figure 3: Contrasting two parameters that will be used for the deep cosmic ray search on pure thermal noise (left) and the signals from a bermtop pulser (right). Please note both the different distributions (signal vs. no signal) and the different ranges on the axes, which indicates the power of this parameter.

3. Search strategy for cosmic rays in deep antennas of RNO-G

In parallel to the search for cosmic ray signals in the shallow antennas, a search for signals in the deep antennas is on-going. As elaborated above, it cannot yet use the unique feature of a coincidence between the upward facing LPDAs and the deep antennas, due to the trigger timing offset, which has meanwhile been fixed (see [15]).

The search for deep-only signals will build on experience with ARA and ANITA, as well as conceptual studies using Monte Carlo simulations. It will target both in-air signals refracted into the ice and those stemming from incomplete showers. The search will combine many signal parameters, for illustration two of them are shown in Figure 3.

4. Outlook

The RNO-G collaboration expects a cosmic ray search to be a first proof-of-principle measurement for RNO-G, highlighting the instrument capabilities and providing an estimate for potentially necessary adjustment to the idealized effective areas that have previously been published. With deployment on-going until at least 2027, smaller sub-data sets will be analyzed to show the performance of the system.

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