PROCEEDINGS OF SCIENCE

The Radio Neutrino Observatory in Greenland (RNO-G): Overview and Status

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The Radio Neutrino Observatory in Greenland (RNO-G) is a detector under construction that will be sensitive to Askaryan emission from ultra-high energy neutrinos. Located in Summit Station, Greenland, RNO-G consists of multiple "stations" of 24 antennas each, which include deep antennas buried down to 100 m in the ice and surface antennas to improve our understanding of backgrounds. As RNO-G grows in size, so does its potential to detect the first astrophysical neutrino above 10 PeV. Seven of the planned 35 stations are currently deployed and operational, with more progress expected this summer season. In this talk, I will present our current and future sensitivity, discuss the successes and challenges with installing a neutrino observatory in a remote environment, and give an overview of our ongoing analysis efforts.

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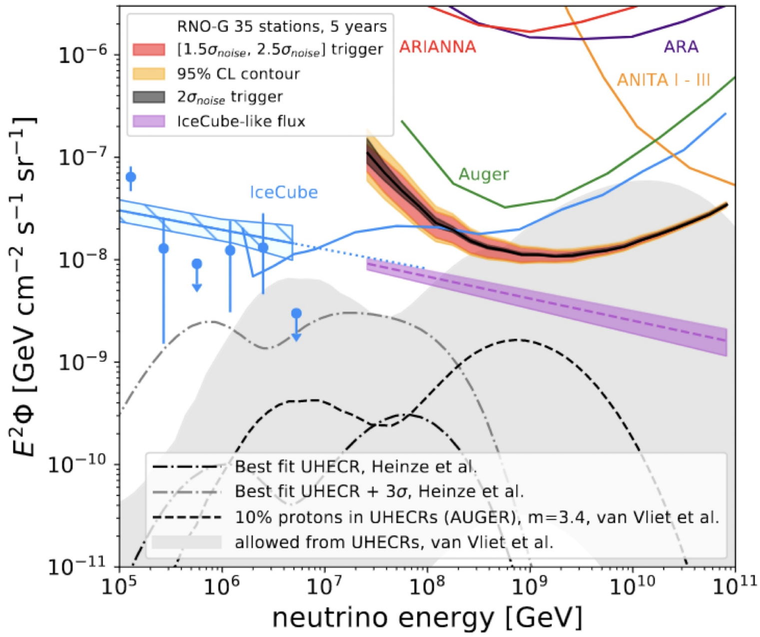

Figure 1: The expected sensitivity of the full RNO-G instrument after 5 years of operating 35 stations, shown for a variety of trigger configurations, from [6]. Also included are limits from other radio experiments, IceCube, and Auger [7–12]. Various potential neutrino fluxes are also shown in grey and black, representing both optimistic and pessimistic flux models that could be confirmed or ruled out by future experiments.

1. Introduction

Neutrinos above 10 PeV are expected to be created in some of the most energetic accelerators in the Universe [1–3], yet no experiment on Earth has yet detected them. These messenger particles carry important information about the physical processes that define astrophysical objects as well as the particle physics that describes the highest known energies [4]. Current neutrino observatories like IceCube are optimized for lower energy neutrinos up to a few PeV [5]; a larger detector is necessary to probe the ultra high energy (> 1 EeV) regime.

To address this, Radio Neutrino Observatory in Greenland (RNO-G) is currently under development at Summit Station, Greenland [6, 13]. Designed to detect the radio emission created when an ultra high energy neutrino interacts with glacial ice [14], RNO-G can monitor many square kilometers of detector area with relatively little instrumentation. When fully built, RNO-G is expected to reach the sensitivity shown in Figure 1. However, there are also unique challenges to building a neutrino detector on this scale in an environment that is dependent on natural ice and susceptible to a variety of backgrounds.

In this contribution, we will describe the current progress in constructing RNO-G, including our design choices, instrument status, and some preliminary calibration data. We will also talk about our timeline for future work and how we hope to transform from a small-scale prototype to a full-scale neutrino observatory in the coming years.

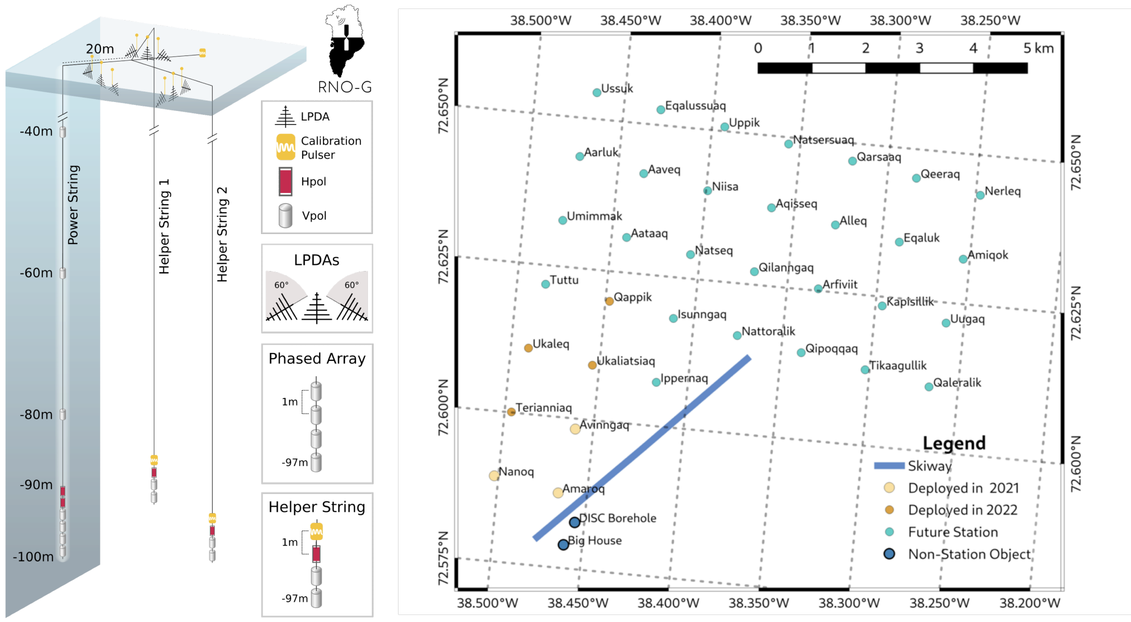

Figure 2: Left: a close up of a single RNO-G station, with the different types of antennas identified. Right: A bird's-eye view of the entire RNO-G instrument, located next to the Big House of Summit Station. Each station is named after an animal in native Greenlandic.

2. The RNO-G Instrument

A view of the planned RNO-G instrument is shown in Figure 2 from above. With 35 planned independent stations, each spaced out from the next by approximately 1.5 km, RNO-G is capable of observing $O(50)$ square kilometers of ice. Each station acts independently and is set up to trigger at a rate of approximately 1 Hz, determined by local limitations on data transfer speeds. It is expected that most neutrino events will only trigger one station, although some fraction of events could be detected by multiple stations.

The view of a single RNO-G station is also shown in Figure 2. Each station consists of three strings of antennas buried to a depth of 100 m. The first string, called the power string, includes the main triggering array of four vertically-polarized antennas, two horizontally-polarized antennas for enhanced reconstruction, and additional vertically-polarized antennas at staggered depths throughout the hole. The two helper strings have antennas at the deepest part of the hole for reconstruction and a local radio pulser for calibration and station monitoring. At the surface, nine LPDA antennas are deployed in various directions to monitor the surface backgrounds, act as a veto, and provide minimal neutrino effective volume.

An RNO-G station is designed for a phased array trigger, in which signals from the four deepest antennas on the power string can be added and summed prior to the trigger logic being applied. This allows signals with a lower signal-to-noise (SNR) value to trigger more easily, as the signal can add across multiple channels when a plane wave signal is assumed. The early RNO-G stations have been deployed with a simple power-sum trigger, while development on a phased array trigger is ongoing.

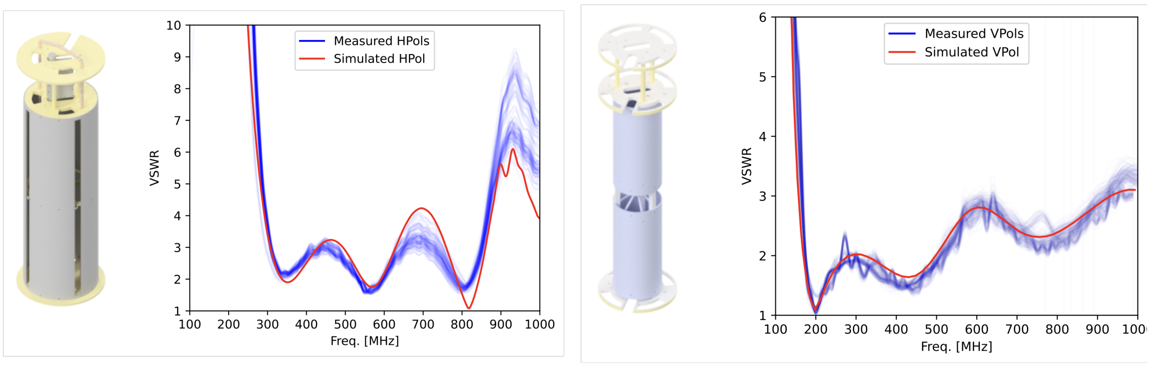

Figure 3: Left: a model of the horizontally polarized antenna and the simulated and measured VSWR as a function of frequency. Right: the same, but for a vertically-polarized antenna.

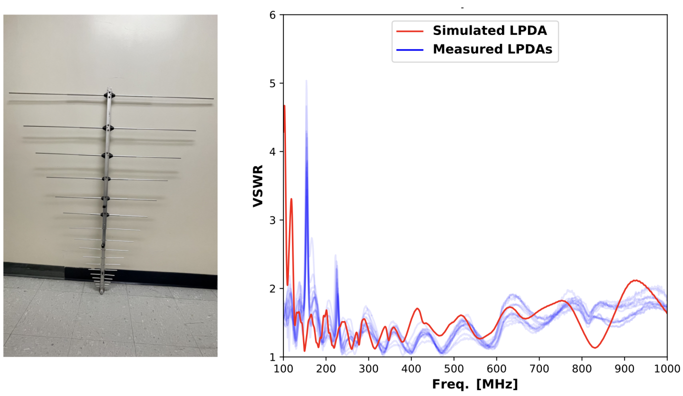

Figure 4: Left: a picture of the LPDA surface antenna. RIght: the VSWR of the LPDA antenna as a function of frequency.

Particular investment has been focused on improving the antenna performance for the downhole antennas. The current measurement and simulation for the vertically- and horizontally-polarized antennas is shown in Figure 3, along with the models of each antenna. Each antenna is designed to have broad sensitivity across the 200-800 MHz band, although the lower bound frequency for the H-pol antenna is closer to 300 MHz. This limitation occurs because the antennas must fit within the 11-inch borehole diameter, significantly limiting the design allowance of the H-pol antenna. The broadband range reflects the expected broadband nature of the Askaryan emission from neutrino signals. The agreement between measurement and simulation in each case is indicative that the simulated antenna response can be used in our detector simulation with reasonable confidence.

3. Installation and Drilling

Installation of the RNO-G instrument began in 2021 and has continued each summer since. As of the beginning of the summer 2024, RNO-G consists of 7 independent stations, and work is ongoing to upgrade these stations and drill holes for additional stations.

Figure 5 shows the relative drilling speed for each of the holes drilled at the end of the 2023 season. RNO-G uses an electromechanical drill called the BigRAID drill, developed by the British

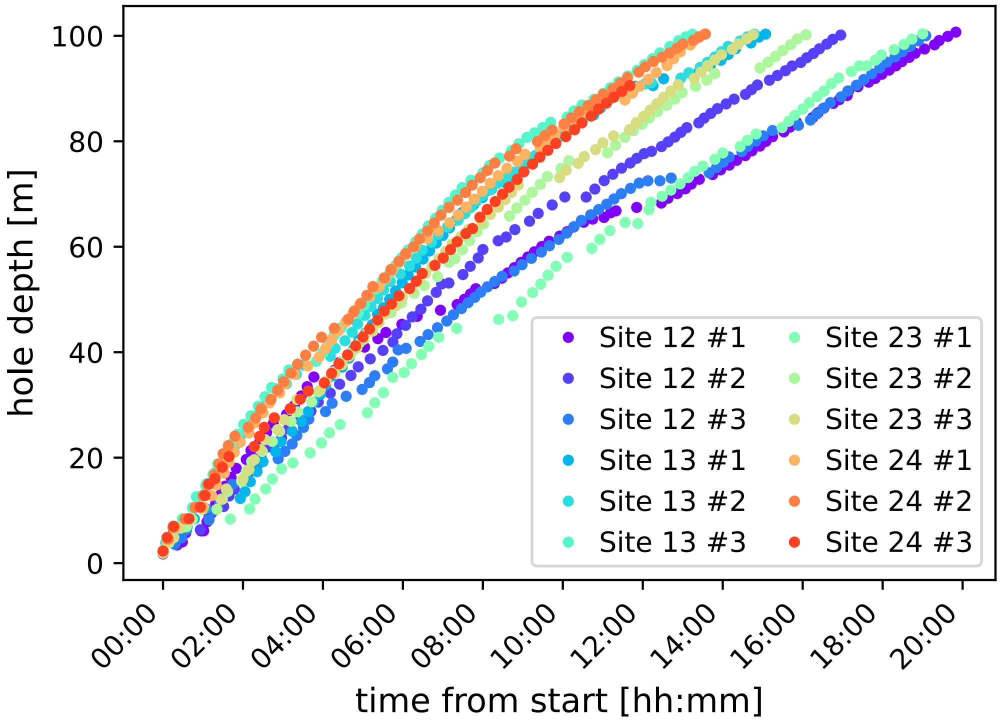

Figure 5: The drilling speed of each hole as a function of hole depth. Over time, the drilling speed has improved, but drilling is still a significant contribution to the overal time of deployment. Each station requires three holes to be drilled to a depth of 100 m.

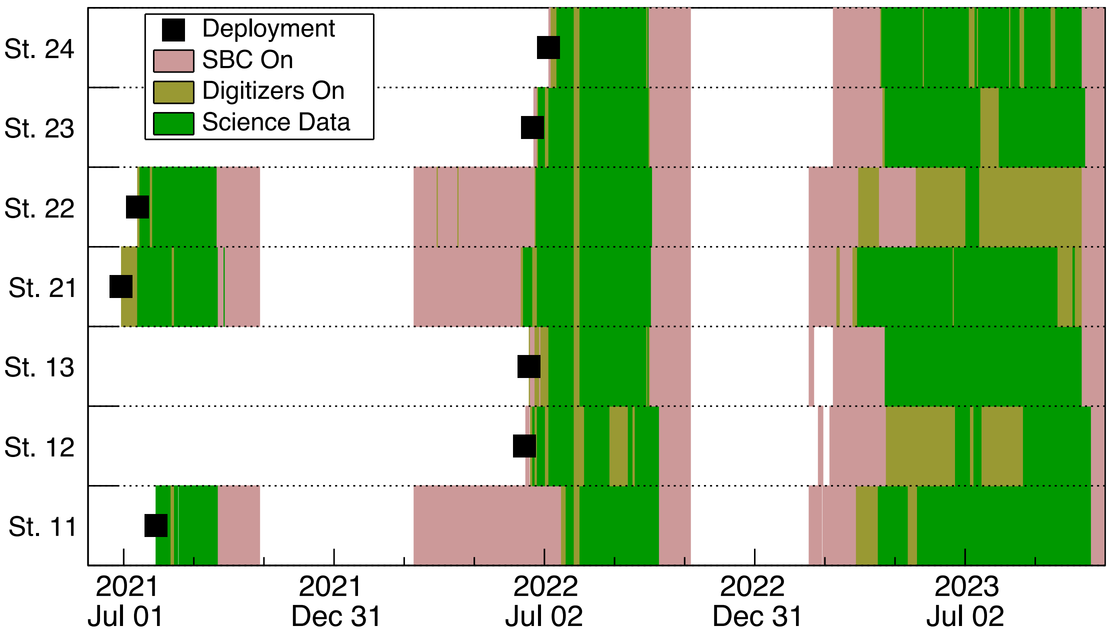

Figure 6: The fraction of each year in which science data was recorded with each of the seven existing stations. Because RNO-G is solar powered, it is only capable of running during the daylight months. Future wind turbines may improve this.

Antarctic Survey team and modeled after the ice core drills. However, unlike the ice core drills, instead of optimizing for preserving the integrity of the ice cores themselves, this drill is optimized for speed. Each hole takes between twelve and 20 hours to drill, and generally the speed has increased as the drill operation is improved. Even still, the drill remains one of the largest uncertainties for deployment timelines; a stuck drill can take days to resolve, and with only one drill, this is enough to delay progress.

Summit Station does not have the infrastructure to support a cabled, powered array, and thus must run on solar power during the summer daylight months. To assist in this, each RNO-G station can run in various modes of power consumption, with the science data mode taking the most power and the "housekeeping only" data taking the least. The uptime of each of the existing seven stations is shown in Figure 6. Each year, the uptime of the stations has increased, as our understanding of our power supply has improved. We are also investigating wind turbines to supplement solar power in the winter months; this is a work in progress, with more prototypes installed in summer 2024.

4. Calibration and Data

With the existing seven stations, some preliminary radio signals have been identified as potential calibration sources. In this section, we will discuss a few of the sources that have been detected

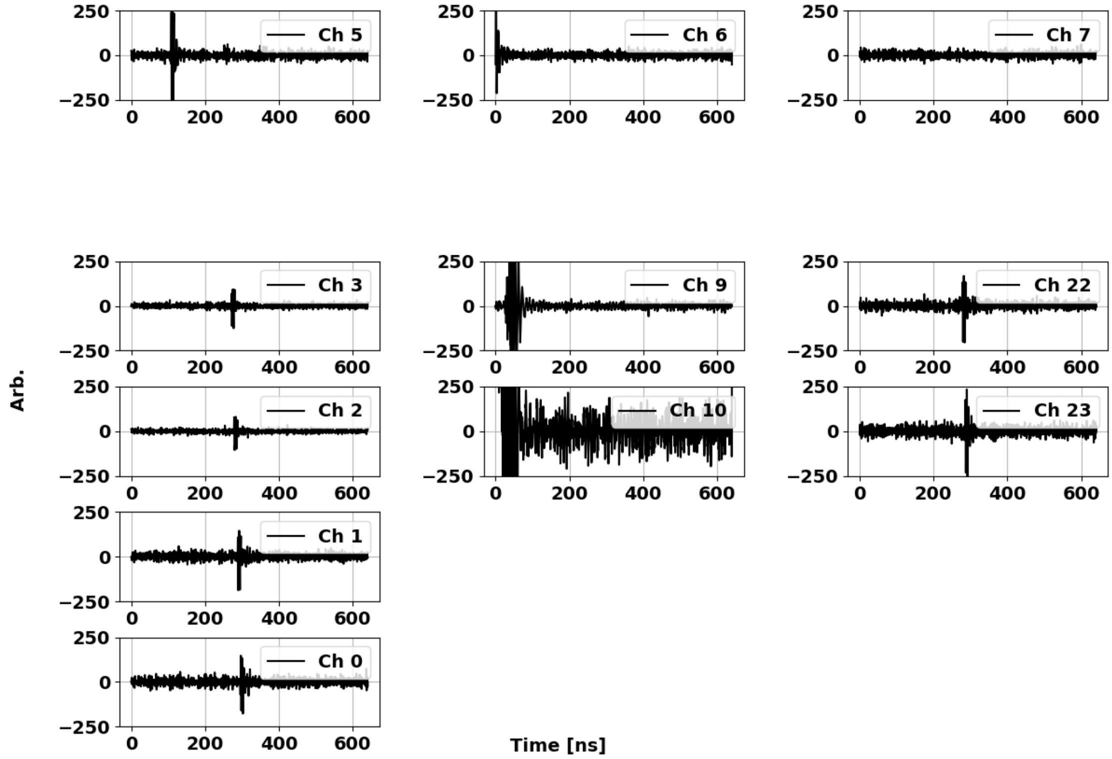

Figure 7: The local calibration pulser on Station 12 as it was dropped into its final location at a depth of approximately 95 m. The pulser is a vertically-polarized signal, so it is visible on the vertically-polarized antennas.

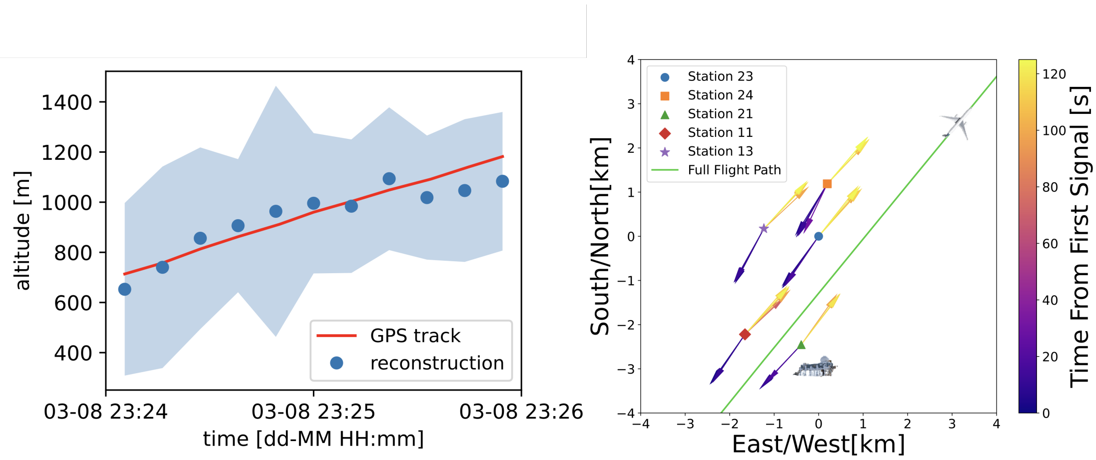

Figure 8: Left: the reconstruction of the local Radiosonde weather balloon, compared to the true reconstruction from the GPS file. Right: a set of reconstructed airplane events seen by five of the seven RNO-G stations.

by RNO-G stations up until this point, and briefly discuss the current strategy for calibrating the instrument.

In Figure 7, we see an example of a local calibration pulser as seen by the vertically-polarized antennas deployed in the holes. This signal in particular was taken while the local calibration pulser was being dropped into the hole; the calibration pulser itself is located just above channel 9 and channel 10, which explains the near-field behavior of those waveforms. Because data was taken over the course of the pulser drop, this dataset could be especially powerful in understanding the position of the antennas as well as the local ice model. This analysis is ongoing.

In Figure 8, we see two additional examples of calibration sources, this time outside of the local RNO-G environment. On the left is the reconstruction of the Radiosonde weather balloon, which is launched locally from Summit Station twice daily and emits its data back to the station at a frequency of 405 MHz. This continuous wave signal is visible for flight paths that cross over the RNO-G stations and appears at a single frequency in the middle of our band. By making some assumptions about the location of the RNO-G antennas and the ice model, the approximate location of the balloon can be compared to the true location from the GPS file. While this method currently carries forward some significant error bars, this could be used as an important check of calibration success in the future as the unknowns shrink.

On the right hand side of Figure 8, events from each of five stations are reconstructed that correspond to an airplane flying across the array. Using a local ADS-B receiver, the true location of the plane at a given time can be compared to the locations reconstructed from each of the RNO-G stations that had a visible line of sight to the airplane. More analysis is underway to determine how frequent these airplane events are, and currently it is unclear what mechanism on the airplane is causing radio emission in the 200-800 MHz band.

Future calibration of an RNO-G station could potentially include signals from each of these sources. We are particularly interested in calibrating the position of the antennas relative to their surveyed positions, as well as the index of refraction of the local ice as a function of depth.

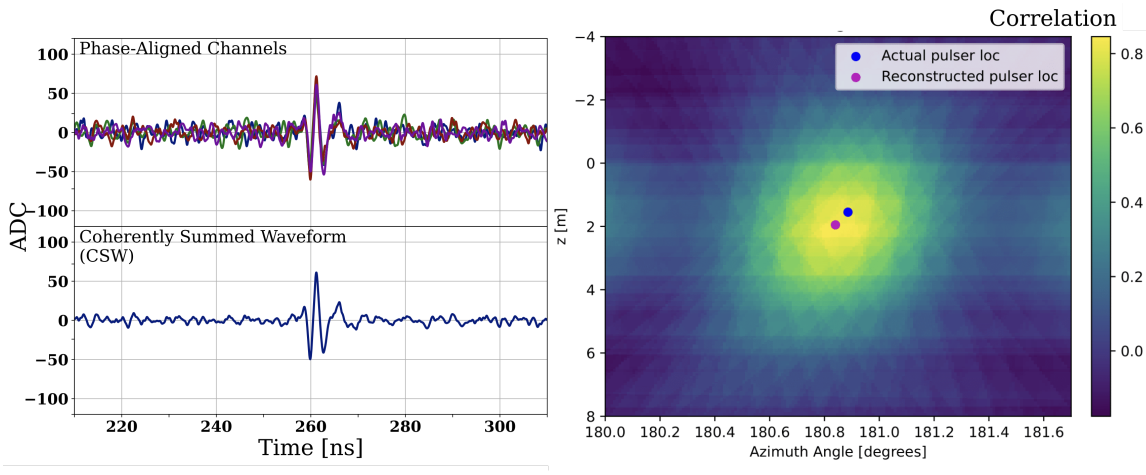

Figure 9: Left: example calibration pulses as seen by the phased array channels (top) and after being coherently summed (bottom). Right: The superposition of multiple correlation maps for multiple calibration events, with the averaged best location compared to the true location for that calibration pulser.

Unfortunately, these two measurements are dependent on each other, making it very difficult to independently verify either one. Our current strategy is an iterative fit that includes the local calibration pulser data and the initial survey positions as truth. An example of the result of this iterative process is shown in Figure 9. By adding additional calibration sources, this fit will likely continue to improve. This calibration effort is a work in progress and still underway.

5. Conclusion

RNO-G is making good progress towards its goal of 35 independent stations operating at Summit Station, Greenland. Currently, seven stations are operational, and more are planned for future summers. The early data is promising, and while there is more work to be done to improve the deployment process, the instrument is currently being calibrated and readied to be used in some preliminary analysis efforts.

6. Acknowledgments

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