# Advancing ARA: the Next-Generation (ARA-Next) DAQ System

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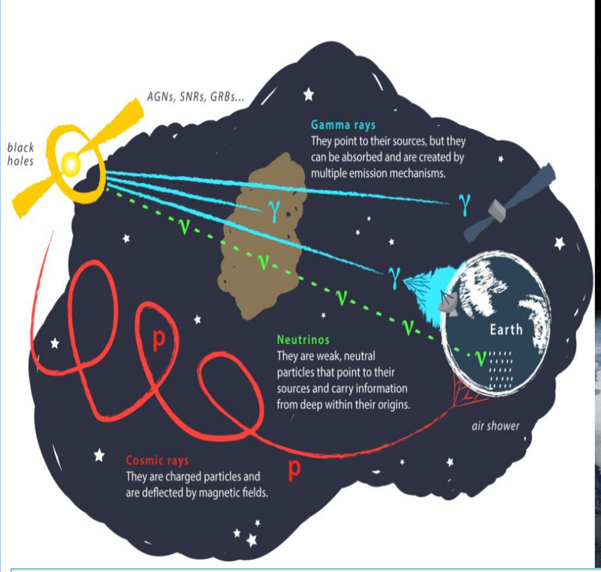
## Overview

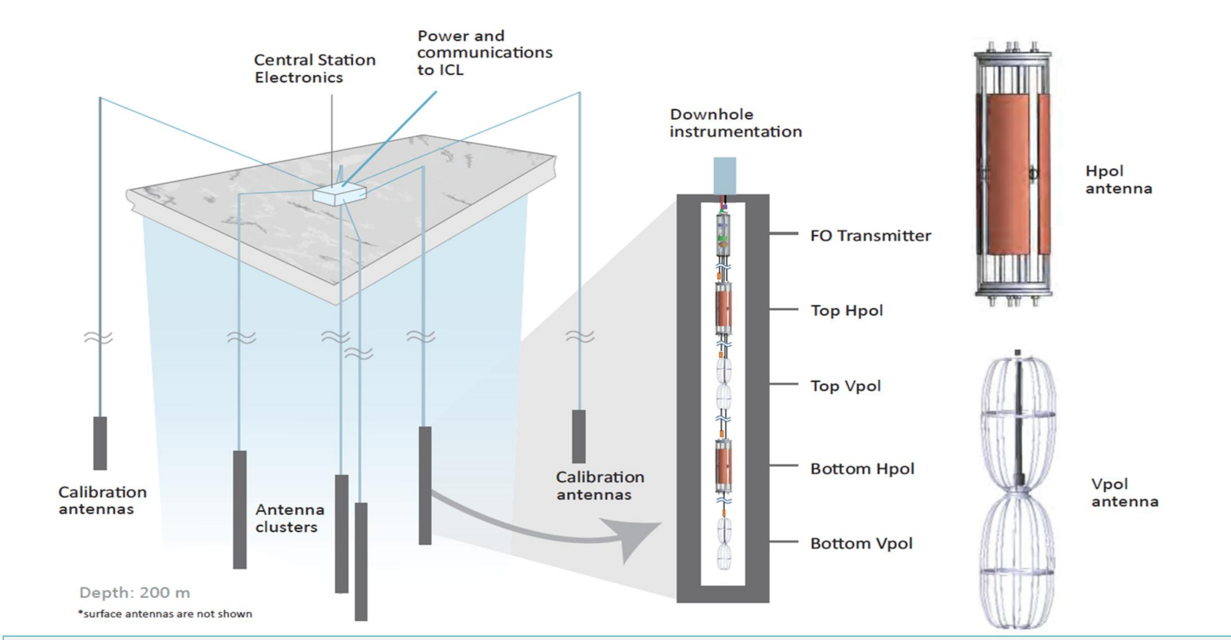
The Askaryan Radio Array (ARA) has been operating at the South Pole for over a decade, searching for ultra-high-energy astrophysical and cosmogenic neutrinos via the Askaryan effect. ARA has consistently served as a testbed for innovative trigger designs and electronics development, with major Data Acquisition (DAQ) improvements pursued over the past several years. A long-term upgrade plan, known as **ARA-Next**, is underway to transition to Radio Frequency System-on-Chip (RFSoC) technology, enabling real-time signal processing and more selective triggers. These involve identification of double pulses from in-ice neutrino interactions, matched templates for cosmic rays, correlations with IceCube events, and filtering of anthropogenic noise using directional reconstruction. In 2024, two of ARA's five stations received upgraded DAQ systems based on improved existing electronics. Full RFSoC-based DAQ is anticipated in the coming seasons. This poster presents recent progress and challenges from the recent deployment seasons and outlines future directions for ARA-Next.

## Background




Neutrinos are electrically neutral and extremely light particles that interact only weakly with other matter, enabling them to traverse the universe virtually unimpeded. Unlike high-energy photons, which can be absorbed by radiation fields, or charged cosmic rays, which are scattered by magnetic fields, neutrinos reach detectors on Earth carrying intact information about their origin. This makes them valuable probes of distant and energetic astrophysical sources, including active galactic nuclei, gamma-ray bursts, and supernova remnants.

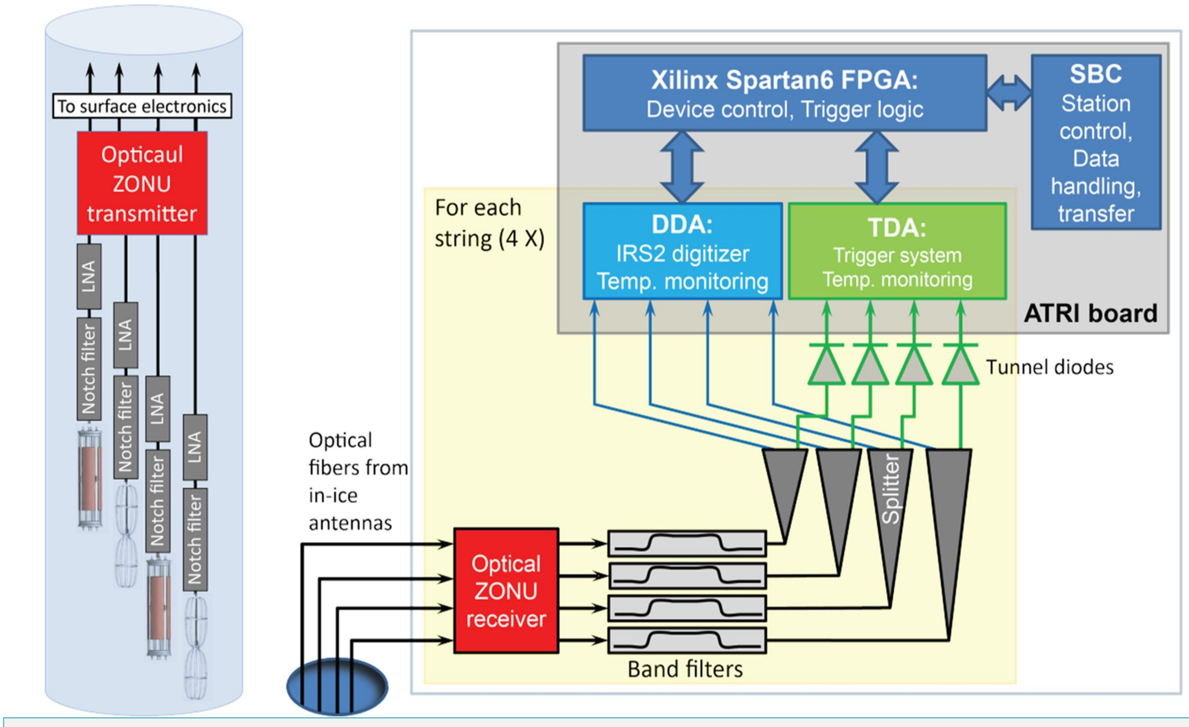
## Askaryan Radio Array Experiment



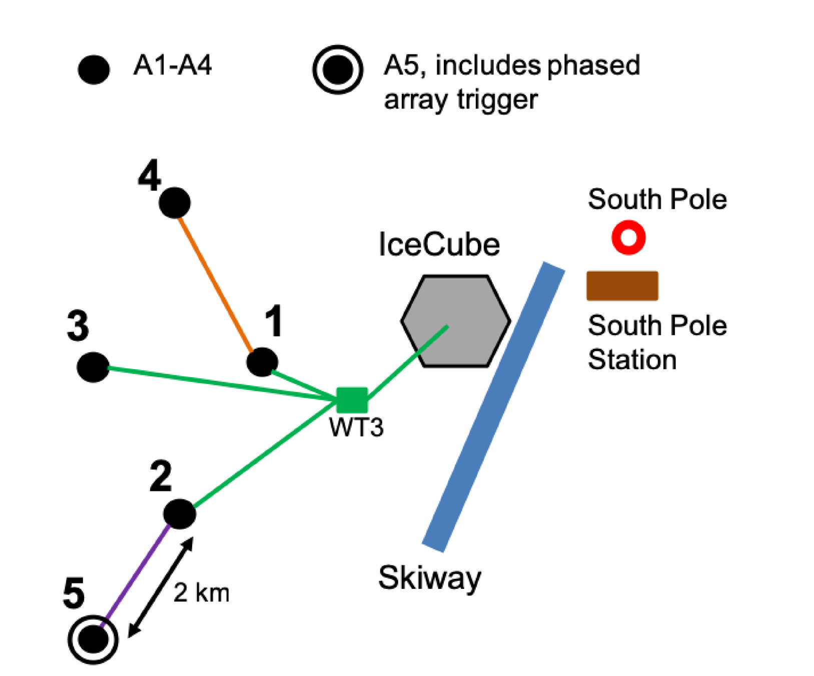

The ARA detects ultra-high energy neutrinos by observing coherent radio-frequency Cherenkov radiation produced via the Askaryan effect from neutrino-induced particle cascades in Antarctic ice.

The ARA consists of five neutrino-detecting stations in the Antarctic ice at the South Pole. Each station has four strings, and each string includes two vertically-polarized (VPol) and two horizontally-polarized (HPol) antennas. Signals from the antennas are sent to the DAQ electronics on the ice surface.

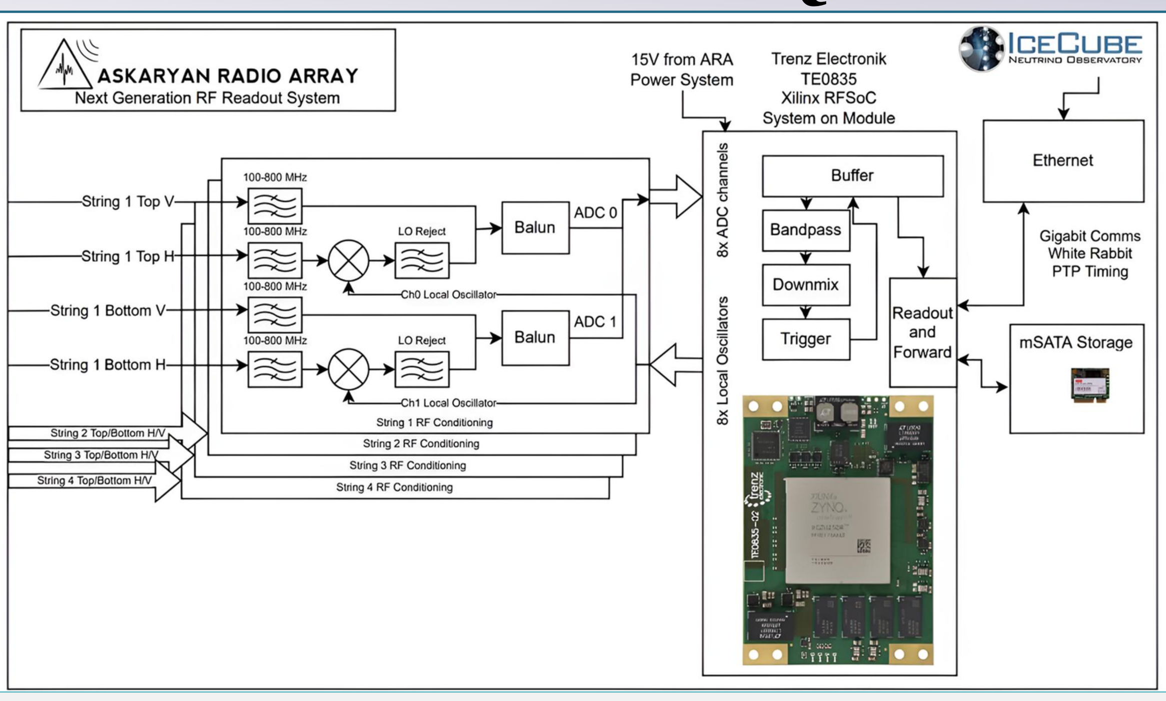
## Data Acquisition in ARA




The ARA Trigger and Readout Interface (ATRI) is constructed on a custom motherboard. Each string entering from the ice carries signals from four channels. These signals are simultaneously routed into the digitizer (DDA) and trigger (TDA) using a splitter. In the FPGA, the trigger logic is implemented with a 3-hit logic on each of the polarization types.




## ARA-Next DAQ




### ARA-Next DAQ based on Radio Frequency System on Chip

- **high-speed ADCs, DACs, and FPGA fabric**
- **extensive customization through programmable logic**
- **real-time processing at multi-GS/s rates**
- **standard development tools (Vivado, Vitis, PYNQ)**
- **power-efficient performance**

## Complex trigger logic for ARA-Next

- ❑ Reject unphysical events(based on hit time) at trigger level
- ❑ Tag or reject/veto anthropogenic events
- ❑ New DAQ will be flexible to record waveforms of variable length
- ❑ ARA can respond to multi-messenger alerts

### ❑Trigger for tagging cosmic-ray events via template matching with known waveforms

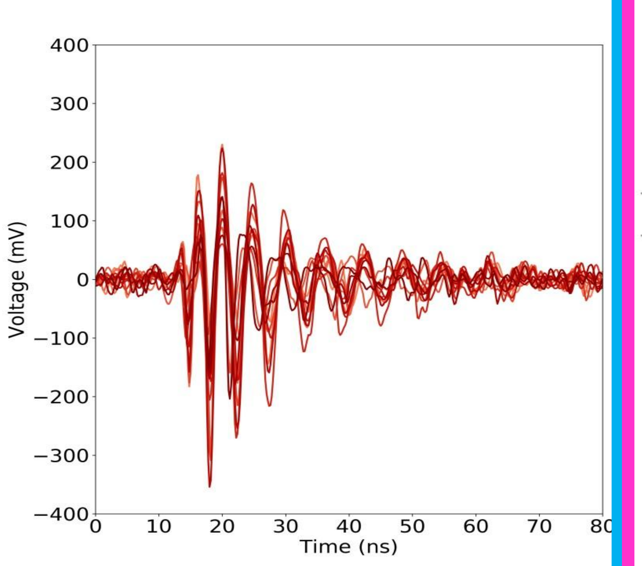



Fig: An example of cosmic ray templates

### ❑Incorporating polarization information into the trigger could enhance its ability to distinguish neutrino signals from the background.

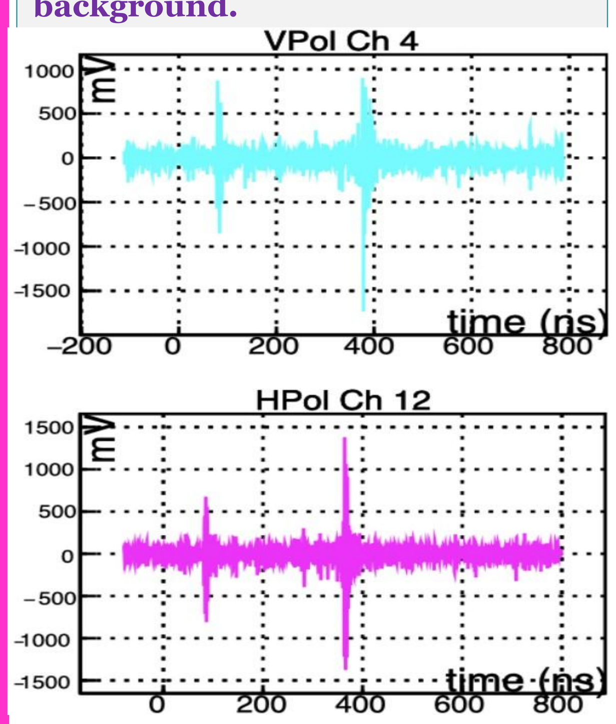



Fig: An example of an event with signals recorded in both Vpol and Hpol

### ❑Trigger for in-air and in-ice radio emission pulses (Cosmic Ray Backgrounds)

ARA has already recorded such an event in 2018

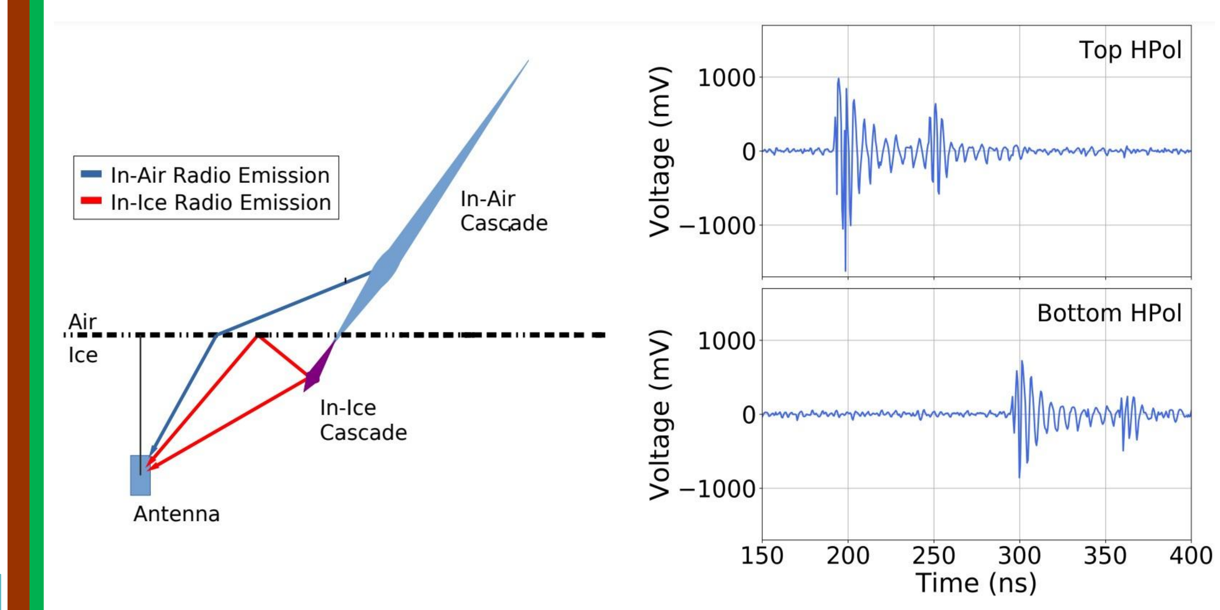



Fig: Cosmic Ray candidate event with in-air and in-ice radio emission

### ❑ New trigger to identify pulses from in-ice neutrino interaction (Targeted Neutrino events)

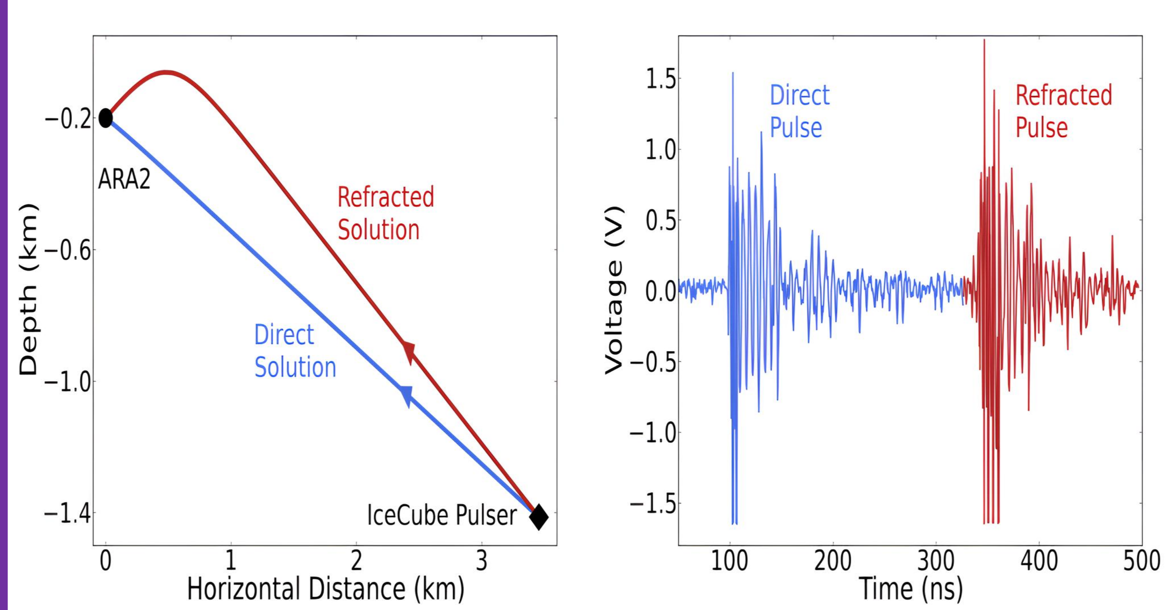



Fig: An example of an event with two pulses recorded on a channel

## 2024-2025 Pole Season

- **ATRI-based DAQ boards with a revised USB FX2 interface were reinstalled at ARA stations A2 and A4 during the 2024–2025 austral summer to resolve communication-related reliability issues.**
- **The upgrade restored control and readout functionality at both stations, which had previously been inoperable due to FX2 controller failures.**
- **While not part of the RFSoC upgrade, the deployment provided operational insights to inform the design of the future ARA-Next system.**

## Ongoing Works and Future Plans

### Simulation Work

- **Developed a Python-based streaming trigger simulation using real and simulated data to validate the current ARA trigger and test new concepts.**
- **Work is underway on enhanced logic based on hit time sequence, time-over-threshold, double pulses, etc, with CNN-based triggers planned.**

### Hardware Development

- **At UNL, early trigger prototyping is being tested on the RFSoC 4x2 board to explore feasibility and resource constraints.**
- **At Ohio State University, Dr. Allison is leading full-scale RFSoC DAQ board development for ARA-Next.**
- **ARA aims to deploy RFSoC-based DAQ at two stations by the end of 2027.**

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