# In-Ice Phased Antenna Arrays for Radio-Detection of Energetic Neutrinos

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## Ultra-High Energy Neutrinos

Cosmic rays have been detected up to enormous energies (>100 EeV), yet the sources of the ultra-high-energy cosmic rays (UHECRs) remain unknown. Interactions of the UHECRs with the cosmic microwave background not only attenuate the cosmic ray flux, but are also are expected to produce neutrinos through photonuclear processes, for example the GZK process for protons:

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \underset{(1)}{\rightarrow} p + \pi^{0} \rightarrow p + 2\gamma$$
$$\underset{(2)}{\rightarrow} n + \pi^{+} \rightarrow (p + e^{-} + \bar{\nu_e}) + (\nu_\mu + \bar{\nu_\mu} + e^{+} + \nu_e)$$

These EeV-scale cosmogenic neutrinos can reach Earth unimpeded, providing an excellent probe of the high-energy universe. Successful measurement would also probe the Standard Model at a new scale. Due to the low expected flux, enormous detectors must deployed.

IceCube has also detected a separate population of PeV-scale astrophysical neutrinos, which may extend to higher energies. A large detector with a low-enough energy threshold could probe the cutoff.

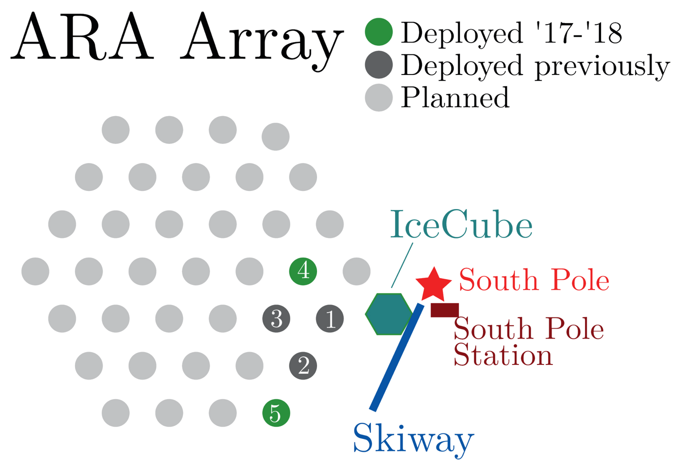
*Active galactic nuclei are a potential source of the UHECRs. (NASA)*

## The Askaryan Radio Array (ARA)

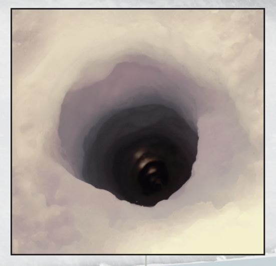
The Askaryan Radio Array (ARA) experiment searches for Askaryan radio emissions from ultra-high-energy neutrinos interacting in the Antarctic ice cap. ARA is located near Amundsen-Scott Station at the geographic South Pole. ARA is made up of independent stations, located approximately 2 km apart. Power and network are provided from IceCube lab. In the 2017-2018 Austral summer, two stations were deployed, bringing the total to five. A total of 37 stations are planned.

Near the surface, the ice gradually transitions from loose snow to deep glacial ice. This changing density (and therefore index of refraction) adversely affects acceptance and reconstruction, so ARA buries antennas 200 m below the surface.

*Left: ARA deployment down a borehole (E. Oberla).*
*Below: Map of planned and existing ARA stations.*



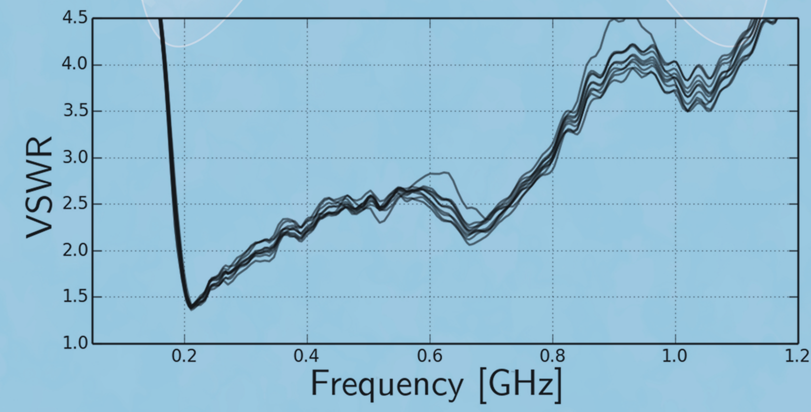




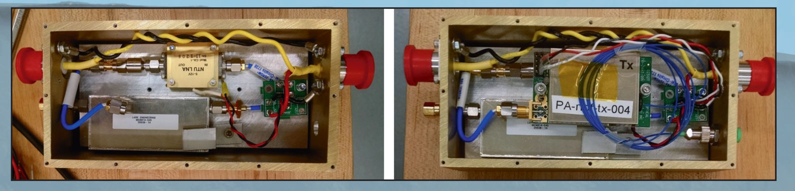
*(E. Oberla images)*

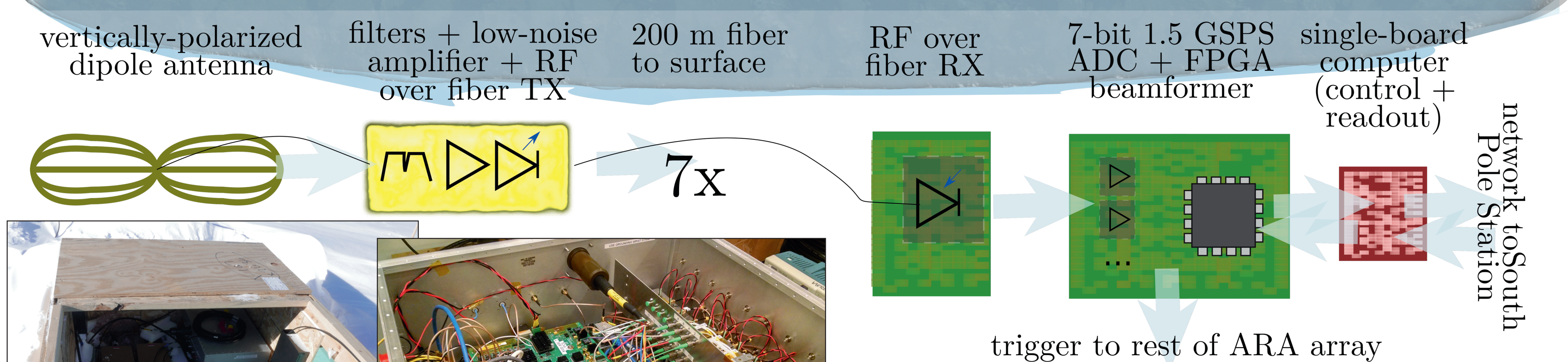
## Askaryan Radio Emission

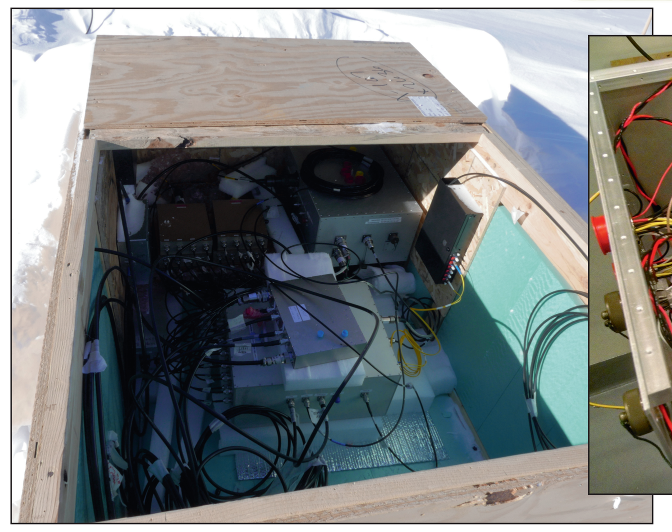
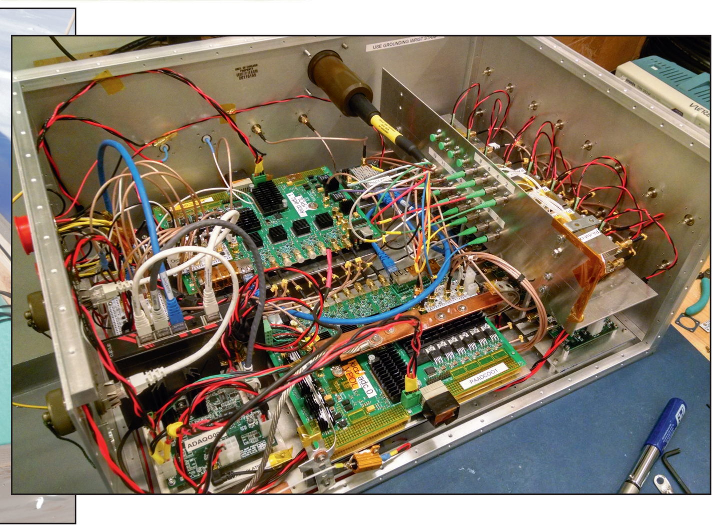
Neutrino-induced electromagnetic cascades in dielectric media such as ice will develop a fast-moving negative charge excess due to annihilation of positrons with atomic electrons. At long wavelengths (larger than the ~10 cm cascade radius), individual charges are not resolved, producing coherent Cerenkov emission that scales as the cascade energy squared. This Askaryan emission provides a natural way to detect very-energetic neutrinos in the radio, where the attenuation length in glacial ice is of order a kilometer.




*Above: VPol antenna in-air VSWR*
*Right: Antenna + Filter/LNA / RFoF unit*
*Below: Inside of the Filter/LNA/RFoF unit*
*(E. Oberla images)*

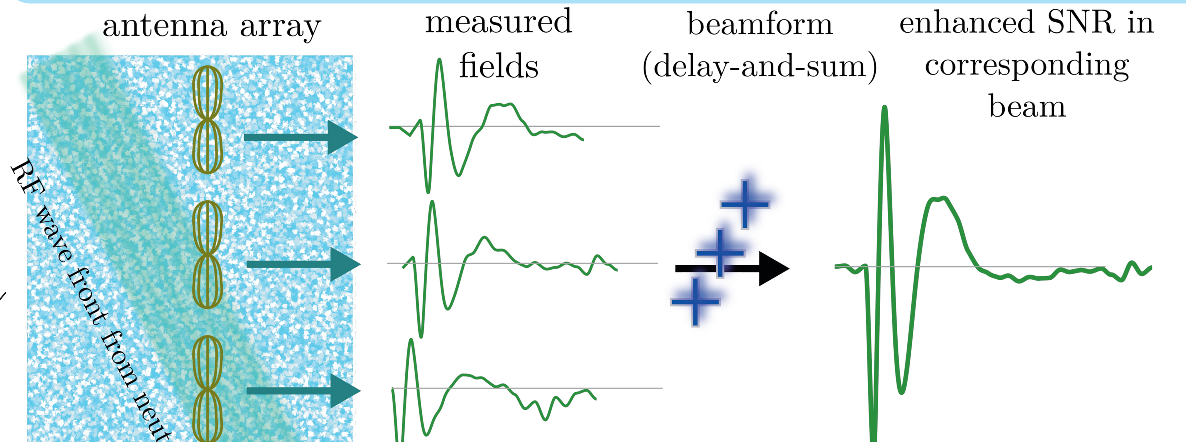




*Above: Signals from the the antennas are filtered, amplified, and sent to the surface via RF over fiber. The signals are digitized and beams are formed on an FPGA. If a beam exceeds a power threshold, a global trigger is formed and the signals are recorded.*
*Left: The station vault and phased-array electronics. (E. Oberla)*

## Phased Antenna Array Trigger

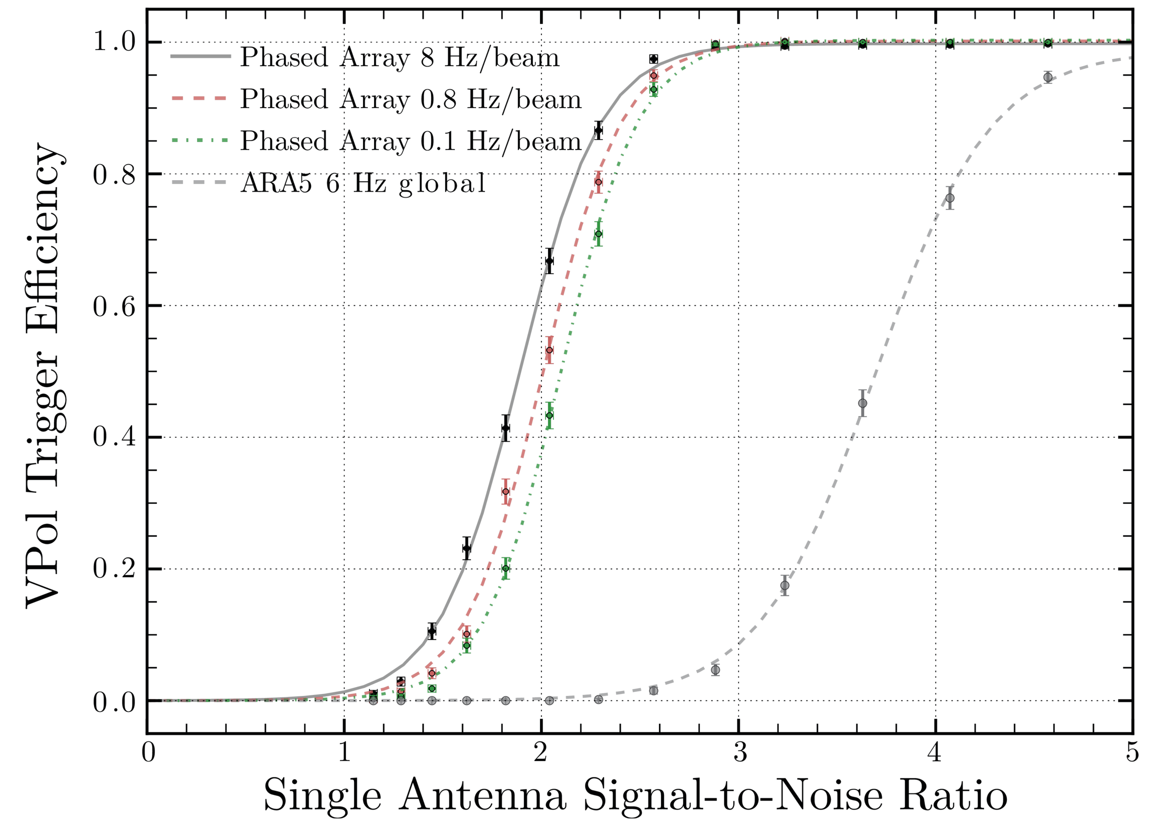



*By summing signals from each antenna with appropriate delays for sets of incoming angles (beams), it is possible to increase the SNR.*

As ARA antennas are deployed in boreholes, high-gain antennas cannot be used. It is however possible to combine signals from multiple antennas in order to effectively increase the gain of an array of dipole antennas. Such a prototype phased antenna array trigger was installed along with the ARA5 station in the 2017-2018 Austral summer.

Signals from each antenna in a string are digitized at 1.5 GSPS. An FPGA then forms "beams," combinations of channels delayed and summed appropriately to correspond to incoming plane-wave directions, in real-time. By triggering on the power envelope of these beams instead of the raw signals, it is possible to trigger at lower signal levels without being overwhelmed by noise triggers. This results in a larger effective volume for each station (or equivalently, a lower threshold for an effective volume).

Thresholds for triggering are dynamically adjusted to achieve the maximum rate possible without incurring deadtime. The rate budget may be allocated to specific directions as desired.




*The trigger efficiency, measured in situ with a calibration pulser, as a function of single-antenna signal-to-noise ratio at various rates with the phased array and for the ARA station's self-trigger without the phased array. (E. Oberla)*

## Acknowledgments

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