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Study of an Isolated Double-pulse Cosmic Ray Candidate Recorded with the Askaryan Radio Array

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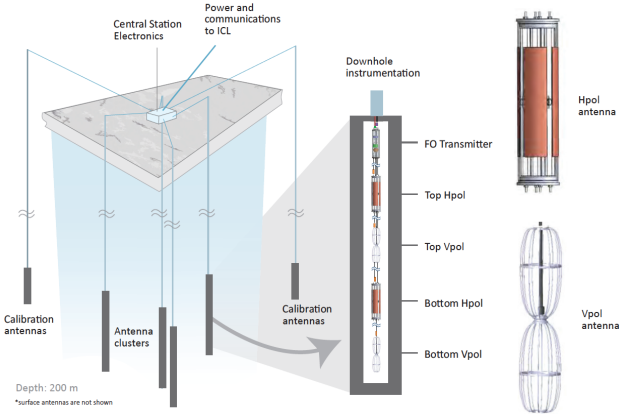
The ARA Detector

- The Askaryan Radio Array(ARA)[1] is a large in-ice radio detector designed to search for ultra-high energy neutrinos (UHE-νs), complementing the study of cosmic rays (CRs)
- 16 antennas with response over 130-850 MHz are buried up to a depth of 200m in South polar ice
- Each station has 4 boreholes (strings), each with 4 antennas
- There are two calibration strings, each holding two antennas.



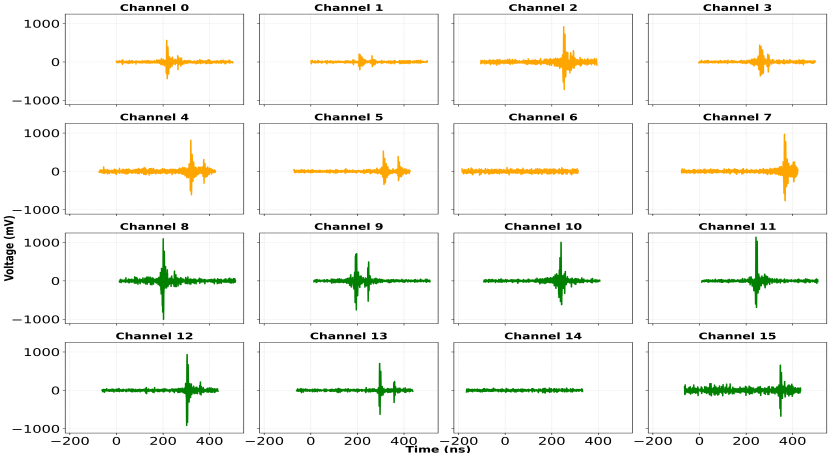
ARA station layout (ARA website)

Event Overview

- A double-pulse event was identified in an 8 station-years neutrino search[2], potentially from a downward propagating CR-induced air shower, with geomagnetic and Askaryan emissions producing the two pulses. Presented publicly at APS conferences[3][4].
- The vertex reconstruction of both signals points towards sources coming from above the station.
  - Azimuths are the same, but elevations differ
- The time difference of the two pulses is inconsistent channel-to-channel) indicates two different sources, rather than a single double-pulsing surface source
- H/V power ratio is higher for the first pulse, consistent with geomagnetic CR origin.

A2 Event 39072, Run5505 Waveforms

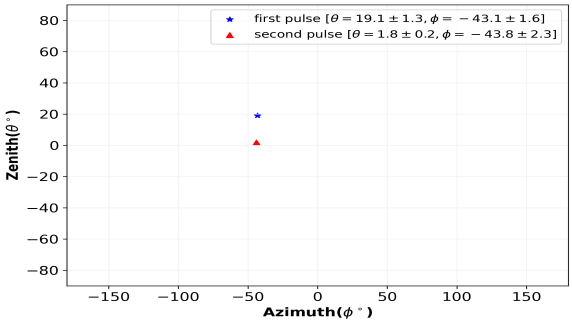
- Top 8 traces (orange) correspond to VPol antenna
- The bottom 8 (green) traces belong to HPol antennas
- The apparent double pulses in several channels, separated by 45 ns - indications of two separate signal generation mechanisms

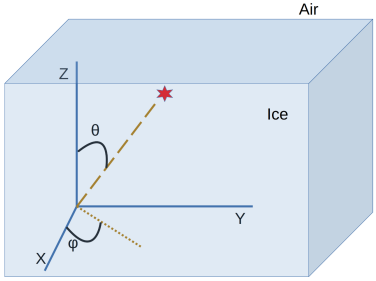


The signal chain phase of the waveforms was removed using AraSim de-dispersing codes

Vertex Reconstruction

- Reconstruction was performed in station-centric coordinates (SC) using AraVertex and Interferometry tools, with results averaged.
- AraVertex determines the incident direction from channel hit times, while Interferometry compares observed delays with propagation time delays from ray tracing in ice.
- All channels except 6 and 14 were used for the first pulse reconstruction.
- The second pulse reconstruction included channels: 0, 1, 3, 4, 5, 7, 9, 12, and 13.





SC coordinate system

HPol:VPol Power in the Two Signals

- Took all the channels and used relation: $A_{pulse} = \sqrt{pk^2 \quad V_{rms}^2}$
- $\frac{P}{P} \frac{A_{Hpol}}{A_{VPol}}$ is expected to be greater for geomagnetic as compared to in-ice askaryan emission

A Simulation-Driven Model

- Parameters:
  - ¶ Impact location of the shower can be estimated using the reconstructed zenith of the Askaryan pulse
  - · The shower zenith can be tuned using the reconstructed zenith of the geomagnetic pulse
  - ¸ Shower Azimuth is related to the reconstructed azimuth as:

$$' _s = 180 \quad _{rec}$$

- Simulated 10 PeV proton showers using FAERIE[5] with A2 geometry, and reconstructed in SC.

A Promising Event Topology

- Estimated shower impact location:

$$d_s = (d_c \quad d_{max}) \tan(\ _{rec,\,2ndpulse}) + d_{max} \tan(\ _{rec,\,2ndpulse} + \ _c) \quad 12\,m$$

- Shower zenith:

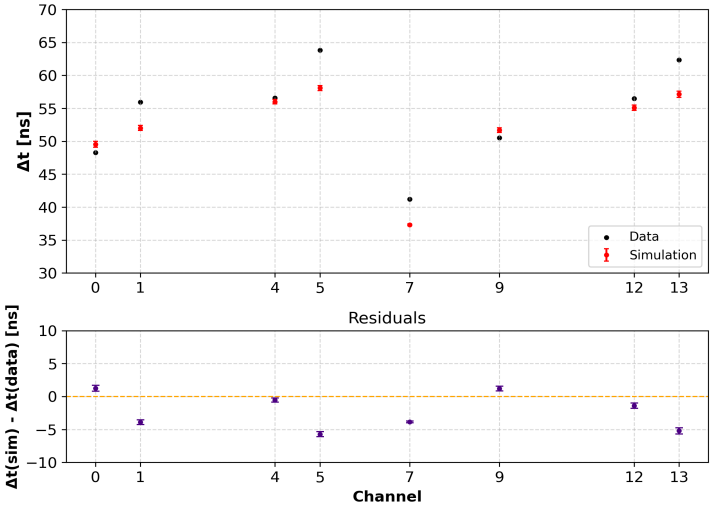
$$_s = \sin^{\ 1}(1{:}78 \sin(19{:}1)) = \ 35{:}62$$

Event topology: Data vs. Simulation

- Data: Event Run 5505 39027
- CR shower:
  $_s$ = 36
- Passed the FAERIE waveforms to the AraVertex and Interferometry to get the vertex reconstruction

Time Delays

- For downward-propagating CR-induced showers, the event topology indicates that geomagnetic emission reaches the detectors before Askaryan emission.
- The time delays, defined as $dt = t_{hit,Askaryan} \quad t_{hit,geomagnetic}$ are analyzed for channels showing clear double-pulses.
- Statistical uncertainty is derived from 10 simulated shower events



Summary

- The analyzed parameters and event topology are consistent with the simulated CR-induced down-propagating shower
- We model expected cosmic ray signals in ARA by integrating the FAERIE framework for cosmic ray shower simulations with the AraSim detector simulation.
- As a part of an independent background estimation analysis, we independently identified this event in a dedicated A2 search (2015–2016) for double-pulse events; only two events passed the selection—this double-pulse candidate and a cal pulser event where two pulsers fired simultaneously.

References

- M.F.H.Seikh, *Askaryan Radio Array: searching for the highest energy neutrinos*, *arXive: hep-ph* (2024) .
- B. A. Clark, *Optimization of a Search for Ultra-High Energy Neutrinos in Four Years of Data of ARA Station 2*, *Ohio State University,* (2019) .
- A. Connolly, *Cosmic Ray Candidates in the Askaryan Radio Array and Implications for Neutrino Detection*, *APS April Meeting* (2020) .
- D. Z. B. Shoukat Ali, *Understanding the ARA02 cosmic ray candidate event*, *APS Global Physics Summit 2025* (2025) .
- D. Simon et al., *Simulation of radio signals from cosmic-ray cascades in air and ice as observed by in-ice Askaryan radio detectors*, *astro-ph.HE* (March, 2024) .

BACK UP: FAERIE Waveforms

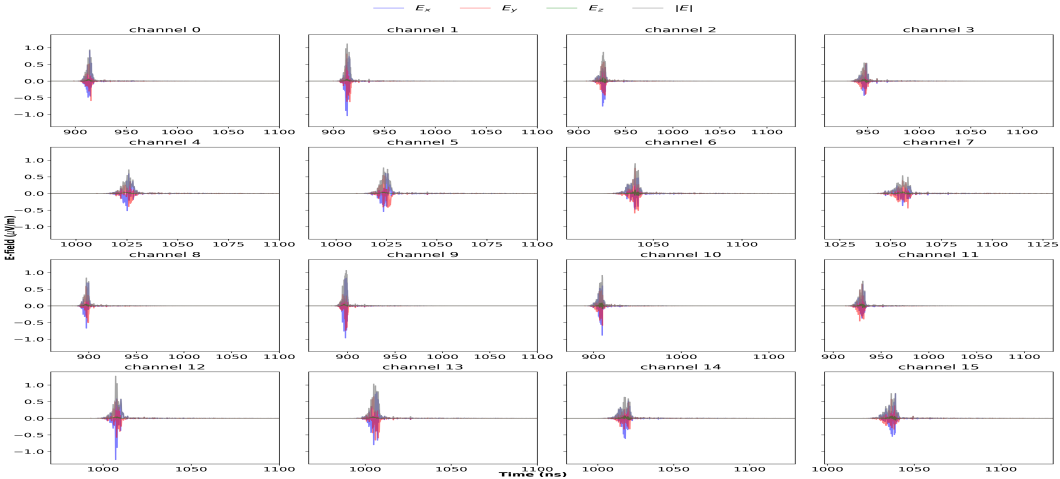


Figure: E-field traces in time domain for geomagnetic emission only