First results from two deep Askaryan Radio Array stations

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Neutrinos from the GZK mechanism

UHE process

GZK effect:
Cosmic ray interaction with CMB
\[ \Rightarrow \text{Resonant at } \sim 10^{19.5} \text{eV} \]
\[ \Rightarrow \text{Cosmic rays don’t reach us} \]
\[ \Rightarrow \text{Neutrinos are produced} \]

Neutrinos carry exclusive information about UHECRs:
• Composition
• Source distribution
• Energy spectrum

Strong evidence for GZK-neutrinos
But: Expect <1 \( \nu \)/ km\(^3\)/ yr

The measured Cosmic ray flux
UHE Neutrino detection via the Askaryan effect

The Askaryan effect:
An excess negative charge (~20%) built up in neutrino induced cascades through:
- Compton scattering
- Other ionizing effects
→ Moving current, emits electromagnetic radiation
→ Coherent for radio wavelength

The advantages of radio waves:
- visible within ~1 km in ice
→ Observe big detector volume with few sensors
→ Very cost efficient
→ Effect has been verified in beam tests: arXiv:hep-ex/0611008
South Pole:

- Ice thickness: 3 km, area: $O(1000\text{km}^2)$
- Radio-quiet zone
- Cold ice $\rightarrow$ good for attenuation length
- Available science infrastructure
The Askaryan Radio Array (ARA)

One station:
- **Measurement system:**
  - 4 holes, 20 m spacing
  - Deployed at depth of 180 m
  - 16 antennas, 150 MHz – 850 MHz (8 horizontally polarized., 8 vertically pol.)

- **Calibration system:** 4 pulsing antennas
  Each station is an autonomous detector!

- 37 antenna stations planned (7-8M$)
- spaced by 2 km
  → Maximizing effective volume by avoiding overlap
- 180m Depth to avoid ray bending effects

- Prototype station: Testbed, first results: arXiv:1404.5285
- 3 deep stations deployed and operating at the current date
- 2 additional stations funded for 17/18 deployment
The detector Hardware and DAQ

Sampling at 3.2 GS/s 10µs analog buffer

1 station operates at 100 W power consumption
What if ... we found a neutrino

For incoming angle and Energy we need:
- Angular reconstruction
- Distance reconstruction
- Amplitude
- Polarization

Incoming $\nu$ $E$ polarization

Antenna cluster

surface

ice

Interaction vertex

Acknowledgment

$\theta = 56^\circ$

$E$ polarization
Calibration needed

Digitizer chip: IRS2
For waveform timing, amplitude
Achieved 100 ps timing precision

Signal chain:
Frequency response, directional
gain, signal to noise ratio

Station geometry on cm level

Current status good enough for...
Angular reconstruction - Yes
Polarization – Sort of
Distance reconstruction - No
Energy reco - No
ARA construction: Drilling
ARA Construction: Deployment and commissioning

Deployment

Commissioning
The detector performance

A calibration signal on ARA03

Accumulated ~224 days of live time in 10 months
31 of 32 channels performing well
Look like neutrino events, but …

- Only neutrinos can penetrate the ice deeply and produce a point-like radio source
- → reconstruct the vertex location
- → reject all background by angular cuts: Calibration pulsers, human activity, etc…

2013 Data analysis: The challenge

What we roughly see within 10 months in 2 stations:
- Trigger at ~5Hz → 300 000 000 events
- Neutrinos (Ahlers2010) 0.2
- Thermal noise 299.998 M
- Impulsive radio background 2000

We need to exclude all thermal noise (10TB of data)

Simple filter: Check consistency of antenna hits with plane wave
Reconstruction performance

1.3 km deep pulsers deployed on IceCube strings

Calibration source: distance 4km
Results

No event in signal region!
Systematic errors

Dominant errors are:

• Interaction cross section uncertainties: never measured at these energies

• Signal amplitude:
  Calibration of the signal chain still relatively coarse
  ➔ This can be improved significantly
No neutrino candidate found (arXiv:1507.08991), at expectation of 0.1 neutrinos from Ahlers2010 estimation after applying cuts.

ARA37 best neutrino sensitivity at $10^{18}$eV

Need new ideas for the PeV range!
A look at the events which we have found

We can follow airplanes:
- Observed object is moving at a speed of 400 km/h at a height of roughly 500 m

We can see radio events and reconstruct them properly!
Where did this come from?

**Crude investigation:**
Event occurred in August 2013 → “NO” South Pole activity
Zenith reconstruction: 45 degree → suggests event generation at ice-air boundary
Go further from here within ARA

Let’s assume we are better in analyzing than in triggering!

Phased radio array trigger:
(see A. G. Vieregg et. al., arXiv:1504.08006)
• Use N antennas, combine signals with different phase shift
• Can theoretically gain factor $\sqrt{N}$ in signal-to-noise ratio for triggering

Phased radio array trigger:
• Technically challenging!
• Working towards deployment with ARA stations in 2017/18
Summary & Conclusions

- Good science case for radio neutrino detection
- Initial ARA stations are deployed, calibrated and produce useful data
- First analysis performed → neutrino limit
- Working on trigger improvement
- 2 more ARA stations will be deployed in 2017/18: Improves shown sensitivity by factor 2.5

ARA is an operating detector and when enlarged ready for a GZK neutrino detection
BACKUP
The askaryan effect

- Predicted in 1962, 1965 by G. Askaryan
- Verified at SLAC beam in sand (2001), salt (2005), ice (2007)
- Electron beam emulates the EM cascade

Motivation for detector geometry

**Ray bending:**
Changing index of refraction in top 200 m of the ice
→ Makes reconstruction difficult
→ Produces shadowed areas

2 km station spacing maximizes detector acceptance at $10^{18}$eV
Thermal noise filtering

Time sequence algorithm:
1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave
   → quality parameter
   \[ QP \approx (\text{similarity to plane wave–front}) \times (\text{hit count}) \]

For 16 antennas per station

Keeps 92% of neutrinos between 1E18eV and 1E19eV at 99.9% noise rejection!
Vertex reconstruction

The algorithm

1. Determine time difference $\Delta t$ by cross-correlation

2. Select good antenna pairs, based on correlation amplitude

3. Set up and solve system of linear equations

Signal arrival time from positions:

$$c^2(t_v - t_i)^2 = (x_v - x_i)^2 + (y_v - y_i)^2 + (z_v - z_i)^2$$

Use difference between antennas & reorder → linear equation for vertex coordinates

$$x_v \cdot 2x_{ij} + y_v \cdot 2y_{ij} + z_v \cdot 2z_{ij} - t_{v,ref} \cdot 2c^2 dt_{ij} = r_i^2 - r_j^2 - c^2(dt_{i,ref}^2 - dt_{j,ref}^2)$$

This can be represented by:

$$A\vec{v} = \vec{b}$$

Solve with matrix decomposition tools

4. Apply quality criteria

Main quality criterion is residual:

$$\text{res} = \left| \frac{\vec{b}}{|\vec{b}|} - \frac{A \cdot \vec{v}}{|A \cdot \vec{v}|} \right|^2 \cdot \frac{1}{N_{ch}}$$

Tells us how well reconstructed position fits time differences