Askaryan Radio Array – status and considerations for a future array

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For the ARA collaboration

ARENA
Catania, June 2018
Askaryan Radio Array

- 12 institutions, ~50 authors
  - North America: California Polytechnic State University, University of Wisconsin–Madison, Kansas University, Ohio State University, University of Delaware, University of Maryland, University of Chicago, University of Nebraska-Lincoln
  - Europe: University College-London
  - Asia: Weizman Institute, National Taiwan University, Chiba University
South Pole glacial ice: cold and RF transparent

- Thickness: 2800m
- Temperature: -55°C at top, -40°C at 1500m
- Attenuation length at 300MHz: ~1.5km at depths < 1500m.
- Low noise
Ground penetrating radar (350MHz) image of Antarctic ice sheet

Figure: WAIS GPR map at 150MHz ~4km deep, 25km wide

Ref: WAIS 2006 CReSIS Radar Data

Summary
Detection of ultrahigh-energy neutrinos in ARA
In-ice:
- Notch filter at 450 MHz (anthropogenic noise)
- Low noise amplifiers
- Optical Zonu RF (analog) over fiber

1 detector string: 4 antennas

X 4
Askaryan Radio Array: 2017/18 upgrade

1. Major maintenance on stations 1, 2 and 3.
2. Repaired power system
   (now just passive cables to IceCube lab)
3. Deployed 2 new stations (40m baseline up from 20m)

Testbed: 2010/11
ARA 1: 2011/12
ARA 2-3: 2012/13
ARA 4-5: 2017/18
Geometry Optimization

Passing Rate = \( \frac{\text{reconstructed events (nchan} \geq 4) }{\text{Total Simulated Events}} \)

Selection ~ “analysis level”

\( n\text{chan} \geq 4 \)

Energy \( 10^{18} \text{ eV} \)

<table>
<thead>
<tr>
<th>Size</th>
<th>Passing Rate</th>
<th>Azimuthal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 m</td>
<td>( 8.14 \times 10^{-4} )</td>
<td>0.14°</td>
</tr>
<tr>
<td>40 m</td>
<td>( 1.082 \times 10^{-3} )</td>
<td>0.10°</td>
</tr>
</tbody>
</table>

- Passing Rate and angular resolution increases as we increase the baseline size
• Hot-water drilling. Water pumped out and leaves dry hole
• Hole diameter ~15cm
• Design depth 200m (8 hr)
IceCube infrastructure
   helpful as a lab to host the ARA DAQ
   and facilitate ARA operations
   (similar data flow mechanisms)

ARA station: 10 TB /station*year

Two IceCube winter-overs
Calibration

There is no physics background like in water/ice Cherenkov neutrino detectors:
No muons, no atmospheric neutrinos!
Only thermal noise and man made backgrounds.

→ ARA uses various radio pulsers:

• Local pulser antennas, embedded with detector
• Deep pulser (1500m) deployed with IceCube
• Pulser on IceCube lab building
• Portable pulsers from the surface
The ARA calibration with the TA-ELS (ARAcalTA)

Performed in January, 2015 at TA site, Utah

Purpose: Better understanding of the radio emissions and the detector calibration

We measured
- Polarization
- Angular distribution
- Coherence

→ talk by Keiichi Mase, Chiba University
Pulser on rooftop of the IceCube Lab.

Distance: 4 km
Serendipity: Solar flare Feb 15th, 2011

- ARA Testbed: We found 300 events pointing nicely at the Sun - thousands with cuts loosened
- Nicely reconstruct to the Sun

- Not impulsive
- Not CW
Serendipity: Solar flare Feb 15\textsuperscript{th}, 2011

- ARA observation of radio emission from solar flares that is reconstructable event-by-event

In communication with solar radio folks - one says compared to Culgoora spectrum, “Your spectrogram is better” at frequencies where we are sensitive
Depth and effective volume at South Pole.

Ray traces from 200m
Depth and effective volume at South Pole.

Simulated events triggering ARA station at 200m

$10^{16}$ eV Triggered Vertex Position

<table>
<thead>
<tr>
<th>eventNumberDistribution</th>
<th>Entries</th>
<th>Mean x</th>
<th>Mean y</th>
<th>RMS x</th>
<th>RMS y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>324</td>
<td>0.7661</td>
<td>-0.3323</td>
<td>0.5193</td>
<td>0.2839</td>
</tr>
</tbody>
</table>
Simulated events triggering ARA station at 200m

10^{17}eV Triggered Vertex Position

depth and effective volume at South Pole.
Simulated events triggering ARA station at 200m

Depth and effective volume at South Pole.
Depth and effective volume at South Pole.

Simulated events triggering ARA station at 200m

$10^{19}$eV Triggered Vertex Position

**eventNumberDistribution**
- Entries: 17448
- Mean x: 2.912
- Mean y: -1.202
- RMS x: 1.32
- RMS y: 0.5058

Location of deep pulser in IceCube with respect to ARA3
Deep pulser event reconstruction
**Vertex reconstruction - direction**

- Data set: $10^{18}$ eV neutrino vertices randomly scattered around an ARA station, up to 5km

<table>
<thead>
<tr>
<th>True Vertex Distance: 2581m</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
</tr>
<tr>
<td>Zenith</td>
</tr>
<tr>
<td>Azimuth</td>
</tr>
</tbody>
</table>

- Mean: -0.13
- RMS: 1.30

- Mean: -0.0059
- RMS: 0.31

Gaus. Fit
μ: 0.0049
σ: 0.35

Gaus. Fit
μ: -0.0044
σ: 0.29
Pulser at 1500m depth as observed with ARA stations.

Double pulses observed as expected (in hindsight): Will allow precise reconstruction of vertex distance, thus energy.

Deep Pulser data

- Double pulse – 1st & 2nd ray
- Birefringence
- Polarization mixing
Vertex Reconstruction – Deep Pulser

• Can reconstruct deep pulser position in 4 Km distance within 10%
• Reasonably well understanding of the south pole ice

nominal distance: 4040m

Courtesy M.Y. Lu
ARA preliminary: Electric field $L_{\text{atten}}$ from Jan. 20, 2018 deep pulser measurements: $L_{\text{atten}}$ (upper 1.4 km)$\sim$2.68$\pm$0.4 km (stat error only).

From fit to maximum Hpol voltage as $f(\text{distance(Tx,Rx)})$ for different ARA stations.
SpiceCore:
4 inch borehole to 1700m.
First measurements:

Courtesy IceCube and NSF
SpiceCore hole at Pole will offer unique opportunity to investigate propagation of radio waves in ice.
Vertex reconstruction and Double Pulses

- Vertex Reconstruction is a challenge
- Time resolution of ~100ps on a 20m baseline: sees no curvature beyond ~500m
- Double pulse events provide unique access to distance reconstruction

**Graph:**

- **Target Depth (receiver) = 200 m**
- **Source at a radial distance of 1.5 Km**

**Legend:**

- ARA01
- ARA02
- ARA03
- ARA04
- ARA05
- ARA06

**Axes:**

- **X-axis:** Source Depth (m)
- **Y-axis:** Direct Ray Time – Reflected Ray Time (ns)
- **Z-axis:** Target Depth (receiver) = 200 m

**Legend Colors:**

- Red: ARA01
- Blue: ARA02
- Green: ARA03
- Yellow: ARA04
- Pink: ARA05
- Light Grey: ARA06
Event reconstruction must take into account propagation effects.

- In homogeneous ice radio waves would propagate isotropically.
- Iso-chrones would be spherical.
- The following 3 slides illustrate how the curvature of a wavefront gets deformed as it propagates through ice with changing index of refraction
In-Ice Wavefront Curvature

Need to treat the propagation delays in event reconstruction.

Close to shadow boundary wavefront gets distorted from initially spherical propagation.

This is understood and built in reconstruction.

By tracing the wavefronts in the ice for a given a source position, we see that as we approach the shadow boundary the first (direct) ray wavefront flattens to a plane wave, and then even curves backwards.
Sensitivity vs energy

Published limit based on 8 months of data (arxiv:1507.08991)

Projected sensitivity curves:
Signal chain calibration as in arxiv: 1507.08991

Phased Array will lower threshold - Integrated simulation in progress.

Ahlers & Halzen (2012)  
Eg: IceCube 2016, $E^{-2.1}$:   
2 events in 5 years

5 stations (5 yr), trigger level
100 stations (10 yr), trigger level

Projected sensitivity curves:
Signal chain calibration as in arxiv: 1507.08991

Trigger level.
Science drivers

1.) Neutrino astronomy:
   Aim to probe diffuse flux seen by IceCube up to 10 PeV.
   Spectrum is hard above 200 TeV, in both channels: $\nu_\mu$ Northern sky and contained vertex events mostly southern sky.
   No indication of cut-off. IceCube data runs out of statistics at 10 PeV.
   Neutrinos from accelerators may well dominate GZK flux.

2.) Cosmogenic neutrinos/GZK:
   sensitivity to some parameter space at GZK energies – $10^{18}$ eV – see events for some parameter space of proton poor CR ray flux.
Lowering trigger threshold with Phased Array

→ Talk by Eric Oberla (Univ. of Chicago)

Signal to noise at antenna:
ARA trigger: \(~3.5 – 4\)
Phased array: < 2

~170 m
~20 m
~1 m

![Graph showing VPol Trigger Efficiency vs. Single Antenna Signal-to-Noise Ratio]

- reconstruction array
- trigger array
Design considerations

• Depth: event rate increases with depth. Depth dependence more significant at high energies.
• Higher probability of double pulse observation at shallow depth for neutrinos. (direct and reflected rays have smaller launch angular difference at shallower depth.)
  – Double pulse improves event reconstruction dramatically.
    Monotonous relationship between distance and time difference for a given receiving angle.
    Sweet spot between 10 and 50 m also for efficiency of seeing a double pulse from neutrinos.
  – Readout requirement for double pulses
• Drilling must be efficient and moderately light weight in logistics impact.
  – Hotwater drilling does not meet that. Multiple options exist.
  – Balance effort of drilling with gain in effective volume and possibly resolution
• Close to surface, shallow ice, allows more easily the use of higher gain antennas. ARIANNA stations works also at Pole.
• Hybrid approach being investigated by both groups.
A few comments on ice

- Good understanding radio propagation in south pole ice.
- Double pulse detection to offer hugely improved reconstruction for fraction of events (vertex, energy).
- Time to prepare for a large array at Pole.
Why South Pole?

• South Pole ice is very good and thick
• South Pole station and IceCube: infrastructure benefits, operational support, data handling, winter-overs
• Groups are working on a joint plan for future array.

Long term:
• IceCube-Gen2: synergy, possible integration future Gen2 facility surface installations
• Extend to both Poles to cover entire sky – bi-polar
Big picture strategy

• Plan for a large array at the South Pole
• Develop detailed design building on experience obtained by ARA, ARIANNA, and the earlier efforts feeding into those.
• Continue R&D to optimize sensitivity at the low energy end threshold (phased array)
Comment on possible IceCube-Gen2 connection

- IceCube Gen2 is seen by many as the ideal future facility with a radio component.
- Strong science case to make radio in integrated of Gen2.
  - Gen 2 optical extension: 10 TeV to 100 PeV
  - Gen radio: 10 PeV to 100 EeV
Gen2 observation of diffuse flux with and without a radio subdetector

Can distinguish spectral features above 10 PeV only with radio array.

Fig. Courtesy Tianlu Yuan (UW)
IceCube Gen2 schedule - how can radio fit in?

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | ... | 2032

- IceCube Upgrade mid-scale
- Deployment

- R&D Design & Approval
- Production Deployment

- Polar radio (Gen2) schedule

- Radio array, phase 1?
- Radio, extended, part of Gen2?
Concluding remarks

- 5 station ARA array at Pole is taking data and has science potential.
- Lots of progress in understanding of ice, namely the dimension of double pulse feature for vertex and energy.
- Phased array addition important step to lowering threshold.
- Current array presents and ideal laboratory for continued R&D.
- Time has come for a coordinated plan for a larger radio array at the Pole. Design being investigated.

See talks by:
- Simon Archambault
- Keiichi Mase
- Eric Oberla
- John Kelley
Askaryan Radio Array: collaboration

Allison, P., 2 Archambault, S., 3 Bard, R., 4 Beatty, J. J., 2 Beheler-Amass, M., 5 Besson, D. Z., 1 Beydler, M., 5 Chen, C.-C., 6 Chen, C.-H., 6 Chen, P., 6 Clark, B., 2 Clough, A., 7 Connolly, A., 2 Davies, J., 8 Deaconu, C., 9 DuVernois, M. A., 5 Fender, C., 2 Friedman, E., 4 Hanson, J., 2 Hanson, K., 5 Haugen, J., 5 Hoffman, K. D., 4 Hong, E., 2 Hsu, S.-Y., 6 Hu, L., 6 Huang, J.-J., 6 Huang, M.-H., 6 Ishihara, A., 3 Karle, A., 5 Kelley, J. L., 5 Khandelwal, R., 5 Kim, M., 3 Kravchenko, I., 7 Kruse, J., 7 Kurusu, K., 3 Landsman, H., 10 Latif, U. A., 1 Laundrie, A., 5 Li, C.-J., 6 Liu, T. C., 6 Lu, M.-Y., 5 Mase, K., 3 Meures, T., 5 Nam, J., 6 Nichols, R. J., 8 Nir, G., 10 Oberla, E., 9 O’Murchadha, A., 5 Pan, Y., 11 Ratzlaff, K., 1 Roth, J., 11 Sandstrom, P., 5 Seckel, D., 11 Shiao, Y.-S., 6 Shultz, A., 7 Song, M., 4 Touart, J., 4 Vieregg, A. G., 9 Wang, M.-Z., 6 Wang, S.-H., 6 Wissel, S. A., 12 Yoshida, S., 3 Young, R., 1

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