Phased Arrays for Radio Detection of UHE Neutrinos

arXiv:1504.08006

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Waiting for a broadband (100 to 1200 MHz) impulsive (few ns) wavefront to cross the detector

Romero-Wolf et al. 2014
Interferometry

Waiting for a broadband (100 to 1200 MHz) impulsive (few ns) wavefront to cross the detector
Interferometry

Waiting for a broadband (100 to 1200 MHz) impulsive (few ns) wavefront to cross the detector

Romero-Wolf et al. 2014
Interferometry

Trigger threshold is set by rate that data can be acquired. Most triggered events are uncorrelated thermal noise background.

Beam-forming in hardware might achieve a lower (more sensitive) trigger threshold relative to simple coincidence trigger.
Phased Array Concept

16 antenna phased array example
Co-located but distinct “pointing” and “trigger” arrays
Phased Array Concept

16 antenna phased array example
Co-located but distinct “pointing” and “trigger” arrays

Construct an effective high-gain antenna by phasing multiple low-gain antennas

\[ G_{\text{eff}} = 10 \log_{10} (N \times 10^{G/10}) \]
Phased Array Concept

Triggering on **beams** rather than waveforms from **individual antennas**
Phased Array Concept

Compact trigger array results in wide beams
Can attain good zenithal coverage with small number of trigger channels

Beam pattern for one trigger channel 200 MHz (16 antenna example)
Simulations

Consider 10 stations in Greenland as concrete example
For widely spaced stations, acceptance scales linearly with number of stations

Station Configurations
1. 16 antennas unphased (E-field threshold = 0.15 mV m\(^{-1}\), 100 to 800 MHz)
2. 16 antennas phased (lower by factor 4)
3. 400 antennas phased (lower by factor 20)

\[
V\Omega = \frac{4\pi V_{\text{sim}}}{N} \times \sum_i \left( p_{\text{Earth},i} \times p_{\text{detect},i} \times \frac{\rho_i}{\rho_{\text{water}}} \right)
\]

\[
A\Omega = V\Omega/l
\]

See appendix of arXiv:1504.08006 for details
Event Geometry Cartoon

- Radio antenna station
- ~100 m deep firn layer (ray bending)
- Cone of coherent radio emission strongest at angles ~56 deg
  Polarized in radial direction
- ~3 km solid ice (rays travel ~ straight)
- Reflections off bottom
- Incoming neutrino

Greenland Neutrino Observatory
Askaryan Emission

Use simple analytic parametrization of Askaryan emission from Lehtinen et al. 2004
Ray-tracing Library
Distance to Interaction Vertex

Triggered events in three station configurations

$E_\nu = 1 \text{ PeV}$
- 16 Antennas
- 16 Phased Antennas
- 400 Phased Antennas

$E_\nu = 1000 \text{ PeV}$
- 16 Antennas
- 16 Phased Antennas
- 400 Phased Antennas
Observation Angle

Triggered events in three station configurations

![Histogram of triggered events at 1 PeV](image1)

1 PeV

![Histogram of triggered events at 1000 PeV](image2)

1000 PeV
Primary Neutrino Zenith Angle

Triggered events in three station configurations

E_\nu = 1 \text{ PeV}

\begin{align*}
16 \text{ Antennas} & \quad 16 \text{ Phased Antennas} \\
400 \text{ Phased Antennas} &
\end{align*}

\begin{align*}
1 \text{ PeV} & \\
1000 \text{ PeV} &
\end{align*}

E_\nu = 1000 \text{ PeV}

\begin{align*}
16 \text{ Antennas} & \quad 16 \text{ Phased Antennas} \\
400 \text{ Phased Antennas} &
\end{align*}
Volumetric Acceptance

Acceptance for radio arrays at trigger level, IceCube acceptance at analysis level
Model Comparison

![Graph showing model comparison of neutrino energy distribution.](Image)

- **Kotera et al. 2010, Optimistic Cosmogenic**
- **Kotera et al. 2010, Pessimistic Cosmogenic**
- **IceCube 2014, Power Law**
- **IceCube 2014, Power Law w/ Exponential Cutoff at 1 PeV**

**Y-axis:** $E^2 \frac{dN}{dE} \text{ (GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1})$

**X-axis:** Neutrino Energy (PeV)
Model Comparison

![Graph showing model comparison with various configurations and energy levels.](image)

<table>
<thead>
<tr>
<th>Station Configuration</th>
<th>Power Law</th>
<th>Power Law with Cutoff</th>
<th>Optimistic Cosmogenic</th>
<th>Pessimistic Cosmogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-antenna</td>
<td>0.9</td>
<td>0.0</td>
<td>7.7</td>
<td>2.3</td>
</tr>
<tr>
<td>16-antenna, phased</td>
<td>3.8</td>
<td>0.1</td>
<td>19.6</td>
<td>6.0</td>
</tr>
<tr>
<td>400-antenna, phased</td>
<td>18.4</td>
<td>2.2</td>
<td>52.9</td>
<td>15.6</td>
</tr>
</tbody>
</table>
Expected Events

Kotera et al. 2010, Optimistic Cosmogenic

- 10 stations, 16 unphased antennas
- 10 stations, 16-antenna phased arrays
- 10 stations, 400-antenna phased arrays
Expected Events

Kotera et al. 2010, Pessimistic Cosmogenic

- 10 stations, 16 unphased antennas
- 10 stations, 16-antenna phased arrays
- 10 stations, 400-antenna phased arrays
Expected Events

Neutrino Energy (PeV)

Number of Detected Events (3 Years)

IceCube 2014, Power Law

- 10 stations, 16 unphased antennas
- 10 stations, 16-antenna phased arrays
- 10 stations, 400-antenna phased arrays
Expected Events

IceCube 2014, Power Law w/ Exponential Cutoff at 1 PeV

- 10 stations, 16 unphased antennas
- 10 stations, 16-antenna phased arrays
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Key Points and Questions

Key Points

• Trigger and pointing arrays can be de-coupled (less sensitive to wavefront curvature, ice effects, etc.)

• Radio technique could potentially reach the PeV scale if a sufficient number of antennas are phased together

• Increase event rate over all energies with relatively modest hardware modifications (scalability of radio technique, energy calibration with optical Cherenkov techniques)

Open Questions

• Reconstructing events with lower signal-to-noise per antenna?

• When phasing more antennas, how would beams be distributed? More extensive hardware modifications?

See proceedings by Stephanie Wissel for tests of a prototype station in Greenland June 2015
UHE Neutrinos

UHECRs w/ $E > 10^{20}$ eV

$T = 2.7$ K CMB

“Guaranteed” production of UHE neutrinos w/ $E > 10^{18}$ eV + prompt emission at sources