Radiowave Detection of Neutrinos

Cosmogenic Neutrinos via GZK-effect

\[ p\gamma_{\text{CMB}} \rightarrow \Delta \rightarrow N\pi; \ \pi \rightarrow \mu \bar{\nu}_\mu; \ \mu \rightarrow e \bar{\nu}_e \nu_\mu \]

Also \[ \gamma\gamma_{\text{CMB}} \rightarrow e^+ e^- \Rightarrow \text{protons and photons have limited range.} \]
Small $\sigma_{\nu} \Rightarrow$ use huge target (Antarctic ice sheet)
Experimental Efforts Current/Planned

- ARA (South Pole, Antarctica)
- ARIANNA (Moore’s Bay and South Pole, Antarctica)
- ANITA/PUEO (NASA balloon, Antarctica)
  - HiCal (NASA balloon, Antarctica; ANITA-calibrator [MEPhI/KU])
- RNO-G (Greenland); first deployment summer 2020→2021
- RET-CR / RET-N (Taylor Dome, Antarctica) - RADAR technique!
- BEACON: Scan down from mountaintop for upcoming radio
- TAROGE-M: Scanning down from Antarctic mountaintop down for upcoming radio signals
  - $\nu_\tau + X \rightarrow \tau + X$; $\tau \rightarrow$ EM shower $\Rightarrow$ radio emissions
- AERA/GRAND-200K in-air radio-emissions from Earth-skimming $\nu$

Time Limitations $\Rightarrow$ focus on ice-target experiments (idea originated with Markov & Zheleznykh; INR, Moscow, 1986)
Askaryan Radio Array: in-ice $\nu$ detector

In-ice Radio Detection Technique

Neutrino interaction point

ARA station detail

Trigger processor
To DAQ/power hub

50–80 m
10–50 m
200 m

DAQ housing
Vpol antenna
Hpol antenna
Lower antenna pair
Antenna cluster

Forward view
E-field polarization

Side view
E-field polarization
ARIANNA concept
ANITA: synoptic strategy sensitive to $\nu$ and Extensive Air Showers (EAS) from UHECR

Scan Antarctic ice (low-noise environment)
Signal Type (Neutrino VS. EAS)

- Askaryan radiation
- Geomagnetic radiation
- Cherenkov cone ~45-50°

- Ice
- Air
- Reflected CR
- Earth-Skimming neutrino
- Cherenkov cone ~45-50°
- Geomagnetic radiation
UHECR and $\nu$ have opposite signal polarity!

(due to inversion after surface reflection of UHECR)
The ANITA Instrument
## ANITAs

<table>
<thead>
<tr>
<th></th>
<th>ANITA-Lite</th>
<th>ANITA-I</th>
<th>ANITA-II</th>
<th>ANITA-III</th>
<th>ANITA-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>18</td>
<td>35</td>
<td>30</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>Antenas</td>
<td>2</td>
<td>32</td>
<td>40</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Notes</td>
<td>Piggy-back on TIGER</td>
<td>Multi-band, Pol-independent trigger</td>
<td>Multi-band, VPol trigger</td>
<td>Full-band HPol + VPol trigger</td>
<td>Full-band, Lin-Pol trigger</td>
</tr>
<tr>
<td>Status</td>
<td>Analyzed</td>
<td>Analyzed</td>
<td>Analyzed</td>
<td>Recently analyzed</td>
<td>Analysis Ongoing</td>
</tr>
</tbody>
</table>
A3 Mystery Evt (15717147 vs. 68298837)

ANITA-III UHECR Air Showers

A. 15717147, -35°

- field strength, mV/m
- anomalous upward air shower
- time, ns

B. 27142546, -5.5°

- field strength, mV/m
- atmosphere-skimming air shower
- time, ns

C. 39599205, -3.6°

- field strength, mV/m
- atmosphere-skimming air shower
- time, ns

D. 68298837, -36.7°

- field strength, mV/m
- normal, reflected air shower
- time, ns
caveats

- ‘Mystery’ based on only one observable (POLARITY)!
  - Neutrino possibility ruled out by Earth absorption
- Waveforms shown after unfolding ANITA detector response
  - All band-limited signals look identical
  - Mystery events otherwise indistinguishable from UHECR in FFT, etc.
- These routines are NOT C++ ROOT standard, and are custom codes!
- Antarctic surface (and sub-surface) not monolithic
  - Ridges, crevasses, etc.
- Radio from UHECR hitting surface is also accompanied by
  - “Transition radiation”
  - “Stopping radiation”
  - “There are more things in heaven and Earth than are dreamed of in your philosophy” (Hamlet)
HiCal (MEPhI/KU) calibrates surface reflections

Balloon-borne (barbeque-lighter) transmitter separated from ANITA by 200–800 km.

SPUNK Transmitter orientation measurements
Tagline: Wrong polarity likelihood < 1% per CR
Conventional explanation for mystery events

- Significant current arrives at air/ice boundary if:
  - Energies $\geq 1 \times 10^{17}$ eV and
  - Zenith angles $< 70$ degrees
- AND amount of charge increases dramatically with high surface elevations

- The transverse current, as well as the path itself, vanishes resulting in a strong shock in the potential
  - Producing the corresponding E-field
  - Polarized along geomagnetic
ANITA-4: 4 more ME (3.2σ (7/20))

- 4098827, -6.17 deg., Anomalous
- 9734523, -5.68 deg., Above-horizon
- 19848917, -6.73 deg., Anomalous
- 50549772, -6.43 deg., Anomalous
- 51293223, -5.47 deg., Above-horizon
- 72164985, -6.16 deg., Anomalous
Sub-surface reflectors?

Reflections on the anomalous ANITA events: the Antarctic subsurface as a possible explanation

Ian M. Shoemaker (a1), Alexander Kusenko (a2) (a3), Peter Kuipers Munneke (a4), Andrew Romero-Wolf (a5) ...
HiCal-2a $\rho =$ fractional power in waveform tail ($N_{\text{evt}} = 31897$)

$\rho_{\text{RMC}} / \rho_{\text{R}}$

HiCal-2b $\rho =$ fractional power in waveform tail ($N_{\text{evt}} = 31897$)

$\rho_{\text{RMC}} / \rho_{\text{R}}$
Triboelectric Effect? (see M. Mikhailova talk from Tuesday!)

- Analyze data from RICE and AURA experiments at South Pole
- Perform statistical correlation between trigger rates for each experiment and local wind speed
- Find:
  - Clear evidence for enhanced radio-frequency emissions during high wind times
  - Threshold $\sim 10$-12 meters/second
- Frequency spectrum analysis $\Rightarrow$ model/simulation under construction
  - Mikhailova/E. Bondarev
Radar detection of ultra-high energy showers

1) Beam Pipe

2) Beam Pipe

HDPE Target
Time-domain radar echo

![Graph of time-domain radar echo with data, FDTD, and RadioScatter waves.](image)
Data signal with right time and frequency structure!
Measured Power ($\omega$)

- 2.1 GHz, LPDA+dish (X offset: -2W)
- 2.1 GHz, Vivaldi (X offset: +2W)
- 1.75 GHz, LPDA+dish (X offset: -1W)
- 1.75 GHz, Vivaldi (X offset: +1W)
- 2.1 GHz RadioScatter
- 1.75 GHz RadioScatter
Future Experiments

- ANITA-IV = last flight in ANITA series
  - PUEO proposed as NASA ‘Pioneer Class’ mission
  - Beam-forming interferometry at trigger level
    - Reduce trigger threshold from $\text{SNR} \sim 6 \rightarrow \text{SNR} \sim 2$ based on ARA experience
  - Antarctic flight 2024
- RET radar, Taylor Dome, Antarctica 2024
2024+ IceCube Gen-2 radio (10 PeV–10 EeV)