Radiofrequency detection of UHECR (both protons & neutrinos) in Antarctica

- detection of RF photons as a CR-observation tool:
  \( L_{\text{atten}} \text{(ice,f=300 MHz)} \approx 1.8 \text{ km} \)

- History & Current Experiments
  - ANITA, ARA, ARIANNA

- Future Plans
Radio Wave EM shower detection (idealize pure EM shower)

- Neutrino-induced (e.g.) EM shower traveling through n>1 medium produces charge excess via
  - Compton scattering (atomic electrons) + Bhabha ($e^+$ depletion)
  - Charge excess about 0.25 electrons/GeV of primary
- Each charged particle radiates Cherenkov photons with $E \sim hf$
  - To detect single C-cone, target high-freq. (UV [pmt] vs. Radio, e.g.)
  - But shower gives NET E-field amplitude due to all shower particles
  - Electrons and positron Cherenkov largely cancel
  - Charge excess 'coherent' at wavelengths greater than transverse size (<1 GHz)
    - For smaller wavelengths, net E-field INCOHERENT sum
    - Finite width of shower=>C-cone 'thickness' (few degrees)
- Coherence compensates for hf/photon for $E > 1$ PeV
$t=0$ nanoseconds: Incident electron neutrino (from AGN, e.g.) strikes a neutron (in ice), resulting in the production of a proton plus an electron: \[
\text{neutrino} + \text{neutron} \rightarrow \text{proton} + \text{electron}
\]

One nanosecond (approx. 20 cm) later, the electron strikes a second proton, initiating the 'shower'. This shower develops over the next 20 nanoseconds (approx. 4 meters), sweeping up atomic electrons already in the ice (blue arrows). After 20 nanoseconds, there are approximately 10 million electrons moving forward along the shower 'front'.

(Multiwavelength) Cherenkov radiation; coherent at long wavelength (red)

These electrons move through the ice at velocities greater than the velocity of light in ice, resulting in a 'sonic boom' of radiation (Cherenkov radiation). It is this Cherenkov radiation which our radiowave sensors (antennas) are designed to detect and measure.
Basic mechanism, in pictures

Askaryan: $Q_s = N_{e^-} - N_{e^+} \sim \left(\frac{E_s}{4 \text{ GeV}}\right)$

Signal Strength details depend on
a) length of shower
b) charge excess
c) radial profile

$\theta_c = 56^\circ +/- 3^\circ$
Frequency/angle correlation: Cone width~FT of transverse charge; width 'fattens' as inverse of frequency
Signal height~total charge x 'tracklength'
- Some history
  RAND, RAMAND
- Present efforts:
  ANITA, ARIANNA, ARA
- Also lunar targets (GLUE, Puschino, LORD) and Jupiter/Saturn moon targets (PRIDE)

- Comparison of the two in-ice experiments

SALSA: in-salt, but RF attenuation length prohibitive
In the beginning...

- RAMAND:
  - Follows 1983 proposal by Markov and Zheleznykh to instrument surface array at Vostok
    - Aside: Vostok deeper (x1.4) than South Pole
    - Colder than South Pole (surface temp~5°C colder)
    - Firn layer 90 m
      - vs. 150 m at South Pole
  - Institute of Nuclear Research, Moscow (Zheleznykh and Provorov)
  - Tests at station Vostok by Provorov, 1988-1990
  - $1M rubles promised to continue research by CCCP on August 18, 1991.
Stations in Antarctica

RAMAND in 1984-1990

ANTARCTICA

Vostok station -78°28'S, 106°48'E

Two RAMAND prototypes (3 and 4 antennae) were tested

First background studies and Hydra

- 1985-1986:
  - noise studies w/ single module
- 1986-1987: Hydra
  - 3 broadband receiver channels
  - Pinger locations reconstructed
  - Man-made backgrounds investigated (sources coincide with station objects)
  - Upper limit on flux of impulse pulses from ice obtained

Side Note: Hydra antennas same as used for Barwick et al 2004 measurement of L_{atten} at South Pole

On the second day (1989-1992)...

- **RAND (South Pole):**

Three receiver Radio Neutrino Detector Array deployed at site 1.6 km from the South Pole (1990). The antennas are nearly buried in the ice to minimize the air attenuation of the radio signal.
“The Smoot Group has performed two preliminary tests of the feasibility of using the Antarctic Ice for radio detection in trips to the South Pole in 1989 and 1991-1992. The December 1991 - January 1992 expedition, under the acronym A.R.C.N.O. (Antarctic Radio Cherenkov Neutrino Observatory), utilized three broad-band receivers singly and in coincidence on the surface. These tests indicated that there was no insurmountable background to the radio detection. However, a surface array is not optimal for radio detector, as the earth is fairly opaque to very ultra-high energies and total internal reflection in the top layer of ice both limit the available observation solid angle.”
RICE: 20-ch dipole array: (200m)$^3$

- 1995- parasitic operation vis-a-vis AMANDA / IceCube... Limits on neutrino fluxes:

**RICE2011 (all flavors $\nu$ flux limit), 1751 d**

![Graph showing neutrino flux limits for various experiments and observations](image-url)

Log$_{10}$ $E_\nu$ [GeV] vs. $E_\nu^2 dN_\nu/dE_\nu$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
31 x 31 array  
[30 km x 30 km]

8 LPDA Rx  
110 MHz+  
All HPOL!  
Air showers?

ARIANNA  
US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631
reflected and direct events

Direct

Reflected

(much greater solid angle)

sensitivity to neutrino cross section!
The ARA Experiment at the South Pole
Expected ARA-37 reconstruction Performance: Neutrino Astronomy
ARA angular resolution: $0.2^\circ/0.6^\circ$ in $\phi/\theta$
<table>
<thead>
<tr>
<th></th>
<th>ARA</th>
<th>ARIANNA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>locale</strong></td>
<td>South Pole</td>
<td>MinnaBluff</td>
</tr>
<tr>
<td><strong>Trigger Rate</strong></td>
<td>5 Hz</td>
<td>0.1 Hz</td>
</tr>
<tr>
<td><strong>Trigger threshold:</strong></td>
<td>$4 \times 4 \sigma_{kT}$ over 256 ns</td>
<td>$4 \times 4 \sigma_{kT}$ over 60 ns</td>
</tr>
<tr>
<td><strong>Power Draw</strong></td>
<td>100 W/20 Rx + 2 Tx</td>
<td>10 W/8 Rx + 1 Tx</td>
</tr>
<tr>
<td><strong>Frequency band</strong></td>
<td>$4 \times 25-300$ MHz + $16 \times 110-900$ MHz</td>
<td>$8 \times 110-900$ MHz</td>
</tr>
<tr>
<td><strong>Hpol/Vpol</strong></td>
<td>Yes/yes</td>
<td>Yes/no</td>
</tr>
<tr>
<td><strong>Attenuation length</strong></td>
<td>1500 m</td>
<td>500 m</td>
</tr>
<tr>
<td><strong>$\delta\theta$ resolution</strong></td>
<td>$0.5^\circ$</td>
<td>$2.5^\circ$</td>
</tr>
<tr>
<td><strong>Air shower response</strong></td>
<td>Yes, via RASTARA</td>
<td>Not yet studies (AFAIK)</td>
</tr>
<tr>
<td><strong>Firn ray tracing</strong></td>
<td>Small (for 200 m deployment)</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Tx calibration</strong></td>
<td>1 Hz</td>
<td>Once/run</td>
</tr>
<tr>
<td><strong>Uncertainties (Z)</strong></td>
<td>Hpol:VPol response in situ</td>
<td>Antenna response near-surface; ray-tracing to Rx</td>
</tr>
<tr>
<td><strong>Future funding</strong></td>
<td>$7M$ OPP proposal (not yet)</td>
<td>$1 M$ MRI (funded)</td>
</tr>
<tr>
<td><strong>neutrinos</strong></td>
<td>50/yr/37 stations (20 Rx/station)</td>
<td>80/yr/961 stations (7 Rx/station)</td>
</tr>
</tbody>
</table>
The ANITA Experiment: Balloon-borne detection
ANITA concept

balloon at \( \sim 37 \text{km} \) altitude

cascade produces UHF–microwave EMP

antenna array on payload

antarctic ice sheet

1–3km

0.1–100 EeV neutrinos

earth

refracted RF

ice

cascade

1–3 km

56°

Cherenkov cone

\( \sim 700 \text{km} \) to horizon

observed area: \( \sim 1.5 \text{ M square km} \)
ANITA science

- Primary mission: “GZK neutrinos” caused by photo-production of UHECR on CMB: $\gamma N \rightarrow \Delta \rightarrow \pi X \rightarrow \nu X$
  - 2013 Observation by IceCube of first UHE non-atmospheric neutrinos (~PeV)!
  - Sub-GZK, but perhaps there is a high-energy tail that extends into ANITA sensitive energy range?

- Detection scheme: Coherent RF emitted by shower from $\nu N \rightarrow lN' +$shower in-ice collisions.

- Cylindrical shower has dimensions ~10 meters in length; ~20 cm in diameter; Cherenkov radiation coherent down to lambda~20 cm
  - Strategy pioneered by RICE experiment (1996-2012)
  - Signal verified in two SLAC testbeam experiments
ANITA +/-

Advantages of the ANITA strategy:

- Huge, RF-transparent target volume
- Triggering near thermal floor in RF quiet environment
- In-air receivers allow pre-flight calibration
  - Sub-degree resolution in both $\theta$ and $\phi$

Disadvantages:

- Poor depth perception (i.e., cannot tell if an event originated on the surface or sub-surface)
  - But have several handles on neutrino events, nonetheless!
- Typical distance-to-interaction point is $\sim$100 km
  - Neutrino must be energetic enough to produce detectable pulse!
  - Threshold $\sim$ 10,000 PeV (10 EeV)
- 35 day livetime
Flight History

- 2004: ANITA-Lite flies 2-chs. Piggyback on TIGER – Full verification of DAQ, backgrounds!
- 12/06–1/07: ANITA-1 = First full mission
- 12/08-1/09: ANITA-2 = ANITA-1 + lots of 10-30% improvements to give overall doubling sensitivity!
- 12/14: ANITA-3 = ANITA-2 + significant changes to DAQ, triggering, hardware – targets UHECR detection & extends low-frequency reach
- 12/16: ANITA-4 (proposed)=final ANITA flight; ~ANITA-3
ANITA launch; steps 1→6
ANITA also detects $\sim 10^{19}$ eV CR

ANITA-III optimized for UHECR as well as $\nu$ flew over Antarctica in 2014-15
2 direct UHECR
20 surface-reflected
surface roughness from stereoscopic photos

FIG. 1: Antarctic topography along Vostok route (I)
FIG. 2: Antarctic topography along Vostok route (II)
FIG. 3: Antarctic topography along Vostok route (III)

1/14 Data taken by AARI, St. Petersburg – reconstruction of point-clouds in progress
Calibrating surface roughness via Solar albedo

Vpol, Direct Sun v. Reflection

Hpol, Direct Sun v. Reflection
Agreement with Fresnel Coefficients as $f(\text{incidence angle})$

**Avg and rms Reflection Coefficients**

![Graph showing the relationship between reflection coefficient and elevation angle.](image)
HiCal-trailer balloon to measure roughness
More precise surface reflectivity probe

- 12/14: ANITA HiCal: Pathfinder class balloon, launched after main ANITA-3 launch
  - Tx emits both direct + surface-reflected signal

- Hardware:
  - “custom” transmitter that mimics EAS spectrum (ignition coil or piezo sparker [$10 from WalMart]) fed into a RICE-type dipole antenna
RF transmitter

Brinkmann | Model # 812-7221-S | Internet # 203016481 | Store SKU # 211787

Universal Push Button Ignitor

$12.97 / each

Ship to Home FREE with $45 Order
Estimated Arrival: APR 22 - APR 24
See Shipping Options

Pick Up In Store FREE
Available for Pick Up: Today

1 ADD TO CART

PayPal

Item cannot be shipped to the following state(s): AK, GU, HI, PR, VI

IN STOCK AT YOUR SELECTED STORE

Cumberland #121
Atlanta, GA 30339

In Stock
Aisle 51, Bay 012
HiCal sparker at 5 mB
HiCal schematic

- To balloon
- Eyebolts at corners
- MIP
- GPS
- 9V MIP battery
- HICAL
- Timing board
- 48-hr battery
- Actuator
- Piezo
- Nylon attachment plate and sleeve
- Long distance
- Dipole

Legend:
- Green: Signal
- Red: Power
- Blue: Mechanical

NASA Long Duration Balloon (LDB) Site at Willy Field, McMurdo Station
2014-2015 Antarctica Operations
(With Support from NSF and USAP)

Balloon Tracking
*Current Revolution in Red*

ANITA III  ANITA HI-CAL  SPB/COSI  SPIDER
Flight 2
Event 1 - HiCal observed from 750 km!
HiCal Event-2 (at float)
Also, surface reflections observed!
EVA: The balloon is the antenna

Reflectors guide RF to Inner feed array

<table>
<thead>
<tr>
<th>BZ neutrino models</th>
<th>Events, ANITA-II, 28d</th>
<th>Events, EVA, 50d</th>
<th>ratio, EVA/ANITA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed UHECR composition [30]</td>
<td>0.05</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td>Minimal, no evolution [3, 32, 33]</td>
<td>0.3-0.9</td>
<td>9.2-38</td>
<td>~ 40</td>
</tr>
<tr>
<td>$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, Standard model [3]</td>
<td>0.7</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>Waxman-Bahcall $E^{-2}$ flux (minimal) [34]</td>
<td>0.49</td>
<td>6.5</td>
<td>13</td>
</tr>
<tr>
<td>GRB UHECR-sources [46]</td>
<td>1.44</td>
<td>66</td>
<td>46</td>
</tr>
<tr>
<td>Strong source $z$-evolution [3, 31, 33]</td>
<td>2.2-5.3</td>
<td>40-60</td>
<td>11-18</td>
</tr>
<tr>
<td>Maximal, saturate all bounds [31, 33]</td>
<td>16-25</td>
<td>180-220</td>
<td>~ 10</td>
</tr>
</tbody>
</table>
EVA – the future: the medium is the message

-10m high reflective region

outer balloon diameter 112m
29 Mcft 'pumpkin'

inner membrane

focal plane

incoming plane wave

-6 to -13 degrees below horizontal
Summary

- ARA2+ARA3 + ARA4+ARA5 (2016-17)
- ARIANNA now has 7 working stations (summer only)
- ANITA-3 data analysis in progress
- In addition to enhanced neutrino sensitivity, effort to maximize UHECR sensitivity AND reduce systematic errors on UHECR energy estimate
  - Target 25% overall energy error
- ANITA-4 (we hope) flies again in 2 years, then..EVA!