MSU Seminar, 30 August 2011

ANITA & ARA RADIO NEUTRINO EXPERIMENTS

August 2011
ANITA measurements of neutrinos and cosmic rays

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Outline

• Neutrino & Askaryan motivation
• ANITA payload/instrumentation
• Neutrino analysis
• Cosmic ray analysis
• Future
  – ANITA & other balloons
  – ARA at the South Pole
  – SalSA-salt domes
Four crucial events from the 1960’s

1. **1961**: First $10^{20}$ eV cosmic ray air shower observed
   - John Linsley, Volcano Ranch, Utah

2. **1962**: G. Askaryan predicts coherent radio Cherenkov from showers
   - His applications? Ultra-high energy cosmic rays & neutrinos

3. **1965**: Penzias & Wilson discover the 3K echo of the Big Bang
   - while looking for bird droppings in their radio antenna

4. **1966**: Cosmic ray spectral cutoff at $10^{19.5}$ eV predicted
   - K. Greisen (US) & Zatsepin & Kuzmin (Russia), independently
   - Cosmic ray spectrum *must end* close to $\sim 10^{20}$ eV

\[ p, \gamma + \gamma(3K) \rightarrow \text{pions, e+e-} \]

\[ \text{“GZK cutoff” process} \]

\[ \downarrow \]

GZK neutrinos

**END TO THE COSMIC-RAY SPECTRUM?**

Kenneth Greisen
Cornell University, Ithaca, New York
(Received 1 April 1966)
Neutrinos as messengers

Study of the highest energy processes and particles throughout the universe requires PeV-ZeV neutrino detectors

To “guarantee” EeV neutrino detection, design for the GZK neutrino flux

Existence of extragalactic neutrinos inferred from CR spectrum, up to $10^{20}$ eV, and similarly, Galactic up to $10^{18}$ eV

Need gigaton (km$^3$) mass (volume) for TeV to PeV detection, and teraton at $10^{19}$ eV

Neutrino detection associated with EM sources will ID the UHECR sources

“EM Hidden” sources may exist, visible only in neutrinos.

Neutrino eyes see farther ($z>1$), and deeper (into compact objects), than gamma-photons, and straighter than UHECRs, with no absorption at (almost) any energy
GZK neutrino production

- GZK process: Cosmic ray protons \((E > 10^{19.5} \text{ eV})\) interact with CMB photons

\[
p + \gamma_{\text{cmb}} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e
\]
Askaryan Effect

In electron-gamma shower in matter, there will be $\sim 20\%$ more electrons than positrons.

Compton scattering: $\gamma + e^-_{(at\ rest)} \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-_{(at\ rest)} \rightarrow \gamma + \gamma$

In dense material $R_{\text{Moliere}} \sim 10\text{cm}$.

$\lambda << R_{\text{Moliere}}$ (optical case), random phases $\Rightarrow P \propto N$

$\lambda >> R_{\text{Moliere}}$ (microwaves), coherent $\Rightarrow P \propto N^2$

$$\frac{dP_{CR}}{d\nu} \propto \nu d\nu$$
• Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> avoid RF transition radiation
• RF backgrounds carefully monitored
  • but signals were much stronger!
• Measured pulse field strengths follow shower profile very closely
• Charge excess also closely correlated to shower profile (EGS simulation)
• **Polarization** completely consistent with Cherenkov—**can track particle source**
Signal particulars

- Strong signal, bandwidth limited
- Characteristics very different than other, anthropogenic, impulsive signals (e.g., linear pol, very broadband, scale-free)
- Difficult to make an Askaryan signal generator
Natural target material?

- Lunar regolith (20m attenuation length)
  Parkes Telescope; GLUE; WSRT; …
- Ice (100-1500m attenuation lengths)
  Forte (satellite); ANITA (balloon);
  ARA (englacial)
- Salt (100-500m attenuation lengths)
  SalSA (proposed, ensalted)
- Air is too thin
- Water is RF lossy, natural, outdoor, sand
  (as opposed to pure silica) is also lossy
ANITA

Overall height ~8m

Solar panels
Antenna array
ANITA Gondola & Payload

National Scientific Balloon Facility
FLOAT ALTITUDE: 120,000-130,000 FEET
PAYLOAD WEIGHT: 6,000 POUNDS

Mylar Balloon
40 million cubic feet
24 miles of seams
13 acres of fabric

At launch Washington Monument At float altitude

South Atlantic Ocean

Cutaway View of Ice Sheet

Indian Ocean

Weddell Sea

Queen Maud Land

Enderby Land

Ross Sea

Victoria Land

McMurdo Station

Antarctica

West

East

Marie Byrd Land

Ross Ice Shelf

South Pole

Ross Sea

Victoria Land

McMurdo Station

Antarctica
ANITA concept

Ice RF clarity:
\~1.2\text{km} attenuation length

Effective “telescope” aperture:
\begin{itemize}
  \item \~250 \text{km}^3 \text{ sr} @ 10^{18} \text{ eV}
  \item \~10^4 \text{ } @ \text{ km}^3 \text{ sr} @ 10^{19} \text{ eV}
\end{itemize}
(compare to \~1 \text{ km}^3 at lower E)
ANITA scheme

NB: Only top of Cherenkov cone visible $\Rightarrow$ RF is vertically polarized!

38 km altitude

Antarctic Ice Sheet (Lots of ice, radio transparent)
ANITA as telescope (sim)

• Pulse-phase interferometer (~150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for arrival direction of radio pulse

• Neutrino direction constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle
ANITA & IceCube

volumetric aperture, $V_\text{eff}$, km$^3$ sr

$\nu_e + \nu_\mu + \nu_\tau$

cascades only

neutrino energy, eV

$10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$ $10^{21}$
The ANITA Instrument

- Launched from McMurdo Station Antarctica by NASA’s Long Duration Balloon Program

Instrument Overview:
- 40 horn antennas (both polarizations measured)
- Frequency range: 200-1200 MHz
- Direction calculated by timing delay between antennas
- In-flight calibration from ground
- Threshold limited by thermal noise
- Livetime limit from anthropogenic noise

Components of ANITA

- NASA Solar Panel Array
- Horn Antennas for Detecting Signal
- ANITA Instrument Box (computer, signal processing)
- ANITA Solar Panel Array
- GPS Antenna Array
- Bicone antennas for onboard pulsing
- NASA Science Instrument Package
- 8 Drop-down antennas (ANITA-II only)
ANITA trigger

Waveforms recorded on 80 channel 2.6GSa/s 1.2 GHz BW “oscilloscope”

- Horizontally Polarized Signal
- Vertically Polarized Signal

200-1200 MHz filter, Low noise amplifier, \( T = T_{\text{ice}} + T_{\text{sys}} \approx 280 \text{ K} \)

If trigger conditions met, save the raw data to disk

Pass the Trigger

L1: 3 of 4 Bands
L2: 2 of 3 Adjacent Antennas
L3: 2 of 3 of Upper, Lower, and Nadir Ring
Part-by-part + End-2-end calibration
**Sample noise event**

- **West Antarctica camp noise event**
  - Yellow, L1: multiple bands above thermal noise in one antenna; ~150 kHz
  - Green, L2: coincidence between adjacent L1 in the same ring; ~40kHz
  - Blue, L3: coincidence between L2 triggers in same phi sector; ~5Hz
Validation at SLAC

ANITA I beamtest at SLAC (June06): proof of Askaryan effect in ice
- Coherent (Power \( \sim E^2 \))
- Linearly Polarized

“Little Antarctica”
35 day ANITA-1 flight
ANITA-1 events & “activity”
April 2010

Red: payload position
Black: Reconstructed event position

Remove Base & Clustered Events
ANITA-I Neutrino Limit
ANITA-I end → ANITA-II begin
Improvements for ANITA-II

• Problems from first flight:
  – Unusual flight path
  – Repeated CPU crashing

• Improvements:
  – Lower Energy Threshold (x 3 events)
    • Reduce front-end amplifier temp (20%)
    • Improve trigger efficiency (30%)
    • 8 more antennas (30%)
  – Increased Exposure (x 2 events)
    • Directional trigger masking (30%)
    • Better flight path & more livetime (x 2)
  – Better clock sync

Total improvement: > 5 in neutrino event rate
Construction & Assembly – Palestine 2008
ANITA II Flight

- 30 day flight, Launched Dec 21st 2008
- 27 million events recorded
Ground Calibration at Taylor Dome

- 100 m deep borehole
  - discone antenna
  - fast, high voltage pulser
  - pulsing on GPS second

- Most important calibration tool. Used for:
  - antenna positions and system delays
  - pitch and roll
  - Pointing resolution
  - mis-reconstruction efficiency
  - surface roughness/ Fresnel effects
ANITA II Calibration Event
Pointing Events to the Ground

Making an Interferometric Image:

- calculate cross-correlation of antenna waveforms
- use timing delay given by direction
- sum over the whole payload
Better pointing resolution than ANITA-I (or design spec.)
→ Faster on-board clock
Efficiency of Reconstruction Cuts

• Includes Thermal Noise & Misreconstruction cuts
  – SNR → Neutrino energy from Monte Carlo

• Thermal Background:
  – 0.5 events

• Misreconstruction Background:
  – 0 out of 115,000 Taylor dome events
61% total efficiency on ESS neutrino spectrum
Total Background Estimate

- Thermal Noise Fluctuations:
  - 0.32 in H Pol and V Pol
- Man-made noise:
  - 0.65 +/- 0.39 V Pol
  - 0.25 +/- 0.19 H Pol
- Misreconstructions: 0 (hand scanned)

Background Estimate (Thermal + Man-made):
- V Pol (neutrino): 0.97 +/- 0.39 events
- H Pol (cosmic ray): 0.57 +/- 0.19 events
### ANITA-2 Unblinding

<table>
<thead>
<tr>
<th>Cut requirement</th>
<th>Passed</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vpol</td>
<td>Hpol</td>
</tr>
<tr>
<td>Hardware-Triggered</td>
<td>∼ 26.7M</td>
<td>-</td>
</tr>
<tr>
<td>(1) Quality Events</td>
<td>∼ 21.2M</td>
<td>320,722</td>
</tr>
<tr>
<td>(2) Reconstructed Events</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(3) Isolated Singles</td>
<td>2+1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total Efficiency</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Neutrino Bin**
- **Cosmic Ray Bin**
- **Analysis Efficiency**
12 Inserted Neutrino-like Events

- 9/12 reconstruct
  - Expected ~85% on low SNR events
- 1 single from a base
- 2 in large clusters
- 1 removed by aircraft cut
- 1 had Taylor Dome header
- 2 over the ocean
- 2 in the box (removed)
2 or 3 Neutrino Candidates?

- 2 candidate events pass hand inspection for problems

- 3rd event in the box has misreconstructed partner events in the same second
  - This event should have failed clustering cuts
  - Did not include 3rd event in setting a limit, and recalculated background & efficiency
2 Neutrino Candidates

Ev # 8381355

Ev # 16014510
New Limit on the UHE Neutrino Flux

- 2 events on a background of 0.97 +/- 0.39
- Feldman-Cousins 90% CL, including background uncertainty with a log-normal distribution
3 HPol Events – Cosmic Rays

3 HPol events consistent with cosmic rays seen by ANITA-I

Example ANITA-II deconvolved waveform:

Why so few HPol events?

→ Triggered only on VPol in ANITA-II
What about these cosmic rays?

- Firm detection of geosynchrotron emission from UHECRs, geometry agrees with B-field
- Detection of extremely “old” showers
- Characteristic time domain emission
- Direct, and ice-reflected, showers observed
- Work in progress
Cosmic Ray Observation

What is the excess of HPol Events??

Events in the HPol Box

→ 16 Total Cosmic Ray Candidates
→ ANITA I + II
→ New deeper analysis (non-blind) gives additional 12 events

Reflection

2 More Events Above Horizon
CR Geosynchrotron

- Cosmic ray radio emission observed since the 1960's
  - Largely abandoned until recently
    - Detection difficulties, theoretical uncertainties
    - Technological, theoretical advances have renewed interest
- Geosynchrotron model
  - Charged particles in geomagnetic field emit EM radiation
  - Electric field described by synchrotron equation (Jackson)

\[
E(x, t) = e \left[ \frac{n - \beta}{\gamma^2 (1 - \beta \cdot n)^3 R^2} \right]_{\text{ret}} \\
+ \frac{e}{c} \left[ \frac{n \times \{(n - \beta) \times \dot{\beta}\}}{(1 - \beta \cdot n)^3 R} \right]_{\text{ret}}
\]
Color scale is surface elevation in meters above WGS84 geoid
Hpol CR events piled up
CR Hpol direct events

from ice
from sky
Polarization Angle

**Measured vs. Expected V-pol content**

- Near south magnetic pole, so vertical component dominates and points everywhere up
- \( \mathbf{F} = q \mathbf{v} \times \mathbf{B} \)
  - e- *always* seen moving right, e+ *always* moving left
  - H-pol emission, always same polarity
- Predict Polarization Angle from Magnetic Field direction
  \( \rightarrow \) Matches well!
- Energy: order \( 10^{19} \) eV, work in progress
Full physics of reflected geosynch pulse

- Horizontally polarized signals come from above the ice
  - Radio emission reflected off the ice
  - Geosynchrotron emission from cosmic rays

- Important parameters
  - Magnitude of initial signal
  - Surface roughness
  - Distance from reflection to balloon
    - Contributes to area of detector
  - Fresnel reflection coefficient, angle off-axis
    - Contributes to aperture of detector

\[
E_{rcv}(\vec{R}_1, \vec{R}_2, \theta_2; \rho) = \frac{kF(\theta_2)}{2\pi} \cos \theta_2 \int_{b/\cos \theta_2}^{b/\cos \theta_2} dx \int_{-y_0(x)}^{y_0(x)} E_{src}(\omega, \theta) e^{ik\sigma^2(\rho)\cos^2 \theta_2} \frac{e^{i\vec{k}\cdot\vec{R}_1-\vec{p}}}{\vec{R}_1-\vec{p}} \frac{e^{i\vec{k}\cdot\vec{R}_2-\vec{p}}}{\vec{R}_2-\vec{p}} dy
\]

- Obliquity
- Geosynch beam
- Radial falloff
Closing in on energy...
UHECR acceptance

![Graph showing the acceptance of ANITA-1 and Auger for different energy levels.](image)
17.3d ANITA-1 10EeV nu
Sky map (Version 0.1)

(Cosmic Ray Acceptance Band Shown)
Future: ANITA-3

Crash of ANITA-2
+
Row of antennas
+
Hpol triggering
+
Lower Tsys
+
Faster prioritizer
Future: ANITA-3
Future: EeVA (EeV Antenna)
Future: Station-keeping

• ANITA could greatly improve duty cycle if payload could keep station above east Antarctica
  ~3-4 km ice depth, least anthropogenic activity

• Either tethered airship at ~80Kft (wind minimum) or station-keeping balloon possible

• With lightweighting of antenna arrays, other possibilities (e.g. High altitude UAV aircraft) also possible
Salt domes: found throughout the world

Qeshm Island, Hormuz strait, Iran, 7km diameter

Isacksen salt dome, Elf Ringnes Island, Canada 8 by 5km

• Rock salt can have extremely low RF loss: \( \Rightarrow \) as radio-clear as Antarctic ice
• \(~2.4\) times as dense as ice
• typical: \( 50-100 \text{ km}^3 \) water equivalent in top \(~3\text{km} \Rightarrow 300-500 \text{ km}^3 \) sr possible
Present: ARA at South Pole
All with primary aim at $\nu$…

- Above ground, also have option of seeing UHECRs
- But CRs are not entirely fashionable…
The Cosmic-ray Deflection Society of North America.
Signal chain
Sampling Unit for RF (SURF)
SURF & TURF (trigger share)

- Transition module TURF boards
- CPU
- PCI bus 1
- 7 drops max
- PCI bus 2
- 4 antenna SURF boards

April 2010
Original ANITA sketch
Original electronics
Cluster Multiplicity

<table>
<thead>
<tr>
<th>Cluster Multiplicity</th>
<th>Number of Clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Camp or Hot-Spot:</td>
</tr>
<tr>
<td>10-100</td>
<td>8</td>
</tr>
<tr>
<td>5-9</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Estimate man-made background using cluster multiplicities, polarization information, and distributions from bases
**Man-Made Background Estimate Using Sidebands**

Number of singles from bases * Number of small clusters not from bases \( \times \) Percentage of Events From Small Clusters That are VPol (or HPol) \( \times \) Number of small clusters from bases

<table>
<thead>
<tr>
<th></th>
<th>Single</th>
<th>Small Cluster &lt; 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>Not Base</td>
<td>?</td>
<td>3</td>
</tr>
</tbody>
</table>

\[
7 \times 3 / 17 \times 0.740 = 0.91 \text{ VPol} \\
7 \times 3 / 17 \times 0.226 = 0.28 \text{ HPol}
\]

Average 7 total similar methods with different variables:

\[
\rightarrow 0.65 \pm 0.39 \text{ VPol} \\
\rightarrow 0.25 \pm 0.19 \text{ HPol}
\]

April 2010