ANITA: Current Status and Future Prospects

Ryan Nichol

Photo: H. Schoorlemmer, University of Hawaii
ANITA Collaboration

Ohio State University
University of Kansas
Washington University in St. Louis
University of Delaware
University of California, Los Angeles
Cal Poly, San Luis Obispo

University of Hawaii at Manoa
National Taiwan University
University College London
Jet Propulsion Laboratory
Stanford Linear Accelerator Center
University of Chicago
Why Antarctica?

- It is the coldest, driest, windiest place on Earth
- But...
  - Lots of Ice
    - Despite our best efforts
    - Over 4km thick in places
  - Also:
    - The only continent exclusively dedicated to scientific research
    - No indigenous (human) population
    - Home of NASA’s long-duration balloon program
Flashy Ice

From PRL 99, 171101 (200
• The ANtarctic Impulsive Transient Antenna
  – A balloon borne experiment
    • 32-48 dual polarisation antennas
    • Altitude of 37km (120,000 ft)
    • Horizon at 700km
    • Over 1 million km$^3$ of ice visible
ANITA Electronics and Trigger

• Need a low power (only solar energy), 90 channel, multi-GHz bandwidth oscilloscope.

• Split trigger and waveform paths
• Use multiple frequency bands for trigger
• ‘Buffer’ waveform data in switched capacitor array
• Only digitise when we have a trigger
ANITA Calibration

- There are ~12,500 capacitors in the analogue sampling array, each needs to be calibrated
- In addition the timing calibration depends on the temperature, event-by-event trigger jitter, pathologies of the clocks used for the calibration, …
• Lasted 35 days (the record is 42)
  – Three and a half sort of polar orbits
  – Recorded over 8 million triggers
ANITA-2 — 2008/9

• Launched Dec 2008
• Terminated after 30 days at float
• Little victories
  – Better flight path
  – Over 27 million events
  – Over 100,000 Calibration pulses
• Data fully recovered
  – Two students spent a week camping out at crash site
• Added an additional 8 antennas
  – Three equal rings of 16 antennas
• Added a new GPU-based software trigger
  – Allowing us to run at a higher rate with lower threshold
• “Improved” antenna design
• Lower noise RF front-end
• Added a low frequency antenna for cosmic ray characterisation
12/03/2014
The Weather Game

12/04/2014
The Weather Game

12/07/2014
12/11/2014
12/12/2014
The Weather Game

12/13/2014
The Weather Game

12/16/2014
The Weather Game

12/17/2014
ANITA-3 Flight

- Launched December 17th 2014
- Landed January 9th 2015
- Had to terminate the flight as payload was about to spiral off the continent
- Recorded over 80 million triggered events.
  - Best guess 0-5 neutrinos
  - Best guess O(200) cosmic ray events
- First step of the analysis was to retrieve the data…

GPU event source map
ANITA-3 End of Flight

Image: Josh F., Australian Antarctic Division
What happened to the data?
Aurora Australis icebreaker runs aground during blizzard in Antarctica

Crew and passengers all reported safe after Australian resupply ship broke free of moorings during storm with winds of more than 130km an hour

The Australian Antarctic Division's chartered icebreaker the Aurora Australis on a previous mission wedged in ice in Commonwealth Bay 10 nautical miles from Mawson's Hut in Antarctica. The ship has now run aground in Horseshoe Harbour after a blizzard. Photograph: Dean Lewins/AAP
Analysis: Narrowband Noise

Figure 6.1: Average power received by channel 1V as a function of time and frequency during a three hour period when the payload was close to McMurdo. The antenna sees CW from McMurdo in a number of bands, the strength as a function of time is caused by rotation of the payload, bringing the base in and out of view.

6.3.2 Interferometric imaging

The key tool used in the ANITA-2 analysis, particularly for thermal noise rejection, is the interferometric image. Using data from all active channels in a given polarisation, the interferometric image provides information both on signal strength and the direction from which a signal originates as a function of payload coordinates.

By taking the cross correlation of waveforms from antenna pairs, it is possible to map out how well matched two waveforms are for a given time shift. The correlation coefficient returned here will be proportional to the amplitude of the two waveforms being processed, using normalised waveforms will provide a normalised correlation coefficient (equation 6.3.4).

\[
C_{1,2} = \frac{\sum (x_1 - \mu_1)(x_2 - \mu_2)}{\sqrt{\sum (x_1 - \mu_1)^2 \sum (x_2 - \mu_2)^2}}
\]

Here, \(C_{1,2}\) is the normalised cross correlation between waveforms 1 and 2, while the normalisation of \(i\) is given by its RMS, \(\sigma_i\).

If we treat RF signals reaching the ANITA-2 payload as plane waves then, for a given direction of incidence, there will be an offset between the time of arrival of the signal between any two given antennas. This timing difference varies as a function of antenna separation.
Analysis: Cross Correlation

~3.5m

~1m

waveform cross-correlation gives baseline delays

from A. Romero Wolf, Neutrino 2008

http://dx.doi.org/10.1016/j.astropartphys.2014.06.006
Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

Also calibrate out the tilt of the payload.

Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

Also calibrate out the tilt of the payload.

ELEVATION ANGLE

AZIMUTH ANGLE

from S. Hoover
Figure 6.16: Maps of the average correlation value of every event passing quality cuts for HPOL (top) and VPOL (bottom) with no event filtering.
Anthropogenic Backgrounds

- Use clustering algorithms to associate events with known bases and with other events
- Remove all events that cluster leaving only isolated events
- Remaining background is the number of unknown sites of anthropogenic noise which we have not identified... hard to quantify
ANITA-2 Results

Figure 4.20: All reconstructed events that are not associated with reverse soars or airplanes and are not in the hidden signal box. The red dots are known based on human activity, the black dots are Hot Spots (local maxima from Figure 4.11), and each cluster of events is given a different color/marker combination.
Neutrino Limits

- **ANITA-2 Results**

<table>
<thead>
<tr>
<th>Isolated v-pol events</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected background events</td>
<td>0.97 ± 0.42</td>
</tr>
</tbody>
</table>

- **Use calibration pulser and simulation to determine efficiency and set the best limit on UHE neutrino flux.**

DOI: 10.1103/PhysRevD.85.049901
10.1103/PhysRevD.82.022004

Also limits on magnetic monopoles and neutrinos from gamma-ray bursts.
What about Horizontal Polarisation?

- Askaryan signals from neutrinos strongly favour vertical polarisation
  - Only top of Cherenkov cone escapes TIR at surface
  - Fresnel coefficients transmit more V-pol than H-pol
- Reflections from above the horizon sources would favour H-pol over V-pol at the balloon
- What could the signal be?
ANITA-1 H-Pol Results

- ANITA-1 detected 16 isolated H-pol candidate UHECR events
- ANITA-2 did not trigger on the H-pol channels
  - Doh!!
- Still detected 5 UHECR candidate events

PRL 105, 151101 (2010)
• The 14 events that reconstruct to the surface (i.e. are reflections) have very similar waveforms.

• The 2 events that reconstruct above the surface have the opposite polarity.

• Consistent with some signal that is generated above the surface.

Are they really cosmic ray signals?

FIG. 3 (color). Top panel: Overlay of the 16 UHECR event H pol pulse shapes, showing the two direct events (red) and 14 reflected events (blue) with inverted phase. Inset: Average pulse profile for all events. Bottom panel: Flux density for both the averaged direct and reflected events, along with fits to an exponential. Errors at low frequency are primarily due to systematic uncertainty in the antenna gains, and to thermal noise statistics at higher frequencies.

FIG. 4 (color). Plane of polarization of UHECR events compared to the angle of the magnetic field local to the event and Lorentz force expectation (red line). Reflected events are corrected for surface Fresnel coefficients. Angles are from the horizontal.
• Magnetic field is nearly (but not) vertical in Antarctica

\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \]

\[ \chi^2 = 10.4 \text{ (16 DOF)} \]
ANITA-4

• Approved by NASA in 2014
• Complete new digitiser and trigger hardware
• Nominal flight date December 2016
• Busy times ahead

Figure 10: Left: 3D CAD model of the new digitizer cPCI board for ANITA-3 & 4. Right: ANITA receiver chain test impulse waveforms captured with the LAB4 prototype board, along with phase-aligned average waveform.
• The radio detection of high energy particles is undergoing a period of renaissance

• The first two flights of ANITA have been used to set the most stringent limits on the UHE neutrino flux
  – ANITA-1 did detect 16 UHECRs though
  – ANITA-3 should have recorded O(200) UHECR events

• The next generation of neutrino astronomy facilities may finally realise the ambition of probing the universe with “new eyes”.
  – Probing fundamental physics at energies beyond the reach of terrestrial accelerators.

• Hopefully soon we will have the first unambiguous detection of an UHE neutrino.
  – But in the mean time there are the UHECR
Me in front of the Royal Society Range

Photo: H. Schoorlemmer, University of Hawaii
Brief scientific timeline leading to ANITA

- **1912**
  - Victor Hess discovers cosmic rays, by flying balloons up to 3 miles above Austria

- **1930**
  - Wolfgang Pauli does “something very bad”... he postulates the neutrino

- **1962**
  - Gurgen Askaryan hypothesises coherent radio emission from particle cascades in dielectric media

- **1965**
  - Wilson and Penzias discover the cosmic microwave background
Kamiokande, IMB and Baksan detect neutrinos from a nearby supernova in 1987.

Greisen, Zatsepin & Kuzmin predict the end of the cosmic ray spectrum in 1966.


ANITA-I launches from Williams Field in Antarctica in 2006.
Why High Energy Neutrinos?

For Astronomers:
The Pretty Pictures Argument

For Particle Physicists:
The 300 TeV (CoM) Neutrino Beam Argument

<table>
<thead>
<tr>
<th>type</th>
<th>$L/E$</th>
<th>$t_{\text{proper}} \sim (L/c)(m_\nu/E)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN SpS/WANF</td>
<td>500 m/25 GeV</td>
<td>3 attoseconds</td>
</tr>
<tr>
<td>Stopped $\mu$ (LAMPF)</td>
<td>30 m/40 MeV</td>
<td>130 attoseconds</td>
</tr>
<tr>
<td>NUMI</td>
<td>735 km/4 GeV</td>
<td>30 femtoseconds</td>
</tr>
<tr>
<td>Reactor (KamLAND)</td>
<td>150 km/5 MeV</td>
<td>800 femtoseconds</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>10,000 km/1 GeV</td>
<td>2 picoseconds</td>
</tr>
<tr>
<td>Sun</td>
<td>150,000,000 km/5 MeV</td>
<td>800 nanoseconds</td>
</tr>
<tr>
<td>GZK</td>
<td>1 Gpc/100 PeV</td>
<td>50 milliseconds</td>
</tr>
<tr>
<td>SN-1987a</td>
<td>50 kpc/15 MeV</td>
<td>1 hour</td>
</tr>
</tbody>
</table>
Cosmic Ray Riddle

- Where do the highest energy cosmic rays come from?
- Nearby sources should point
- Faraway sources should be attenuated by the cosmic microwave background
- Could neutrinos solve the problem?
Aside: The GZK Effect

- Greisen-Zatsepin-Kuzmin (GZK) calculated cosmic rays above $10^{19.5}\text{eV}$ should be slowed by CMB within 50MPc.
- Berezinksy and Zatsepin realised this would produce a flux of neutrinos

$$\rho + \Upsilon_{\text{CMB}} \rightarrow \Delta^* \rightarrow n + \pi^+$$

$$\mu^+ + \nu_\mu$$

$$e^+ + \overline{\nu}_\mu + \nu_e$$

= “Guaranteed” Cosmogenic Neutrino “Beam”!

Figure 26.9: Expanded view of the highest energy portion of the cosmic-ray spectrum from data of HiRes 1&2 [101], the Telescope Array [103], and the Auger Observatory [104]. The HiRes stereo spectrum [112] is consistent with the HiRes 1&2 monocular results. The differential cosmic ray flux is multiplied by $E^{-2.6}$. The red arrow indicates the change in the plotted data for a systematic shift in the energy scale of 20%.

The experiments are consistent in normalization if one takes quoted systematic errors in the energy scales into account. The continued power law type of flux beyond the GZK cutoff previously claimed by the AGASA experiment [100] is not supported by the HiRes, Telescope Array, and Auger data.
In 1962 Gurgen Askaryan hypothesised coherent radio transmission from EM cascades in a dielectric:

- 20% Negative charge excess:
  - Compton Scattering: $\gamma + e^-(\text{rest}) \Rightarrow \gamma + e^-$
  - Positron Annihilation: $e^+ + e^-(\text{rest}) \Rightarrow \gamma \gamma$

- Excess travelling with, $v > c/n$
  - Cherenkov Radiation: $dP \propto \nu \ d\nu$
  - For $\lambda > R$ emission is coherent, so $P \propto E^2_{\text{shower}}$

Typical Dimensions:
- $L \approx 10 \text{ m}$
- $R_{\text{Moliere}} \approx 10 \text{ cm}$
• The Balloon
  – Just 0.02mm thick
  – Takes 100 million litres of helium (and several hours) to fill
Where is the Aurora Australis?

Calibration

Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

Also calibrate out the tilt of the payload.

Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

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ELEVATION ANGLE

AZIMUTH ANGLE

from S. Hoover

Measured azimuth (degrees)
• Using signals from multiple antennas it is possible to measure the direction of arrival of radio pulse to $\sim 0.5^\circ$ in elevation and $\sim 1.5^\circ$ in azimuth (based on ANITA-lite calibration data).

• The neutrino direction can vary around radio pulse direction but is constrained to $\sim 2^\circ$ in elevation and by 3-5$^\circ$ in azimuth by polarization angle.
A coherent event should display a clear and unique peak in an interferometric image.

Self-triggered blast in the upward-pointing noise sample passed all thermal cuts, but would have been set lower were it not for the leakage of self-triggered blast events (figure 6.7).

In order to best match the real ANITA-2 data, the scaling value for this was found using slightly lower than that of the minimum-bias and upward-pointing noise events with incoherent thermal noise event and a coherent calibration signal.

Figure 6.5: Average peak correlation coefficient for minimum bias events as a function of azimuthal angular separation between event pointing and Solar position. Dashed lines indicate the mean correlation value.

Figure 6.6: Summed and averaged interferometric images for HPOL (VPOL).

ANITA can “see” the Sun. Thermal noise is the dominant source of noise in the data sets.

As the upward-pointing noise events only represent a fraction of the ANITA-2 analysis data sample, the final cut is extrapolated by assuming a power law fit to the fraction of thermal events passing this final cut value. The fits shown are of the form $P < 10^{20}$, with the same scaling value used for both VPOL and HPOL events.

An error on the expected background of thermal events is calculated using the fraction of simulated and thermal noise passing the combination cuts from figures 6.13 and 6.14. The fits shown are of the form $P < 10^{20}$ for VPOL events from Taylor Dome calibration signals (colour histogram) and $P < 10^{18}$ for VPOL and $P < 10^{27}$ for HPOL.

For the VPOL analysis, the peaks are 41.40 for events with thermal cuts, the upward-pointing noise sample is used. The peak correlation values from simulated noise are scaled by 1.025 in minimisation, with the same scaling value used for both VPOL and HPOL events.
8.2. Point source limits

Figure 8.7: ANITA-2’s exposure at $10^{20}$ eV, using data from B. Mercurio and the icemc simulation.

8.2.1 Reflected neutrino search

Figure 8.8 demonstrates that the ANITA-2 experiment was optimally sensitive in the declination $\theta$ band $13^\circ < \theta < 15^\circ$. However, the only currently published neutrino point source limits for AGN in the $E_\nu > 10^{19}$ eV regime are for Centaurus A (a nearby AGN) and Sagittarius A* (the Galactic centre) [113]. Both of these sources are outside of ANITA-2’s optimal declination band, with $\theta < 13^\circ$. However, ANITA-2 was still sensitive to this region via reflected RF from down-going neutrinos.

The ANITA-2 analysis described in chapter 6 contained a cut on elevation of $\theta > 35^\circ$. This cut was intended to remove events to which the antenna response was degraded. The elevation cut also reduced sensitivity to neutrino events viewed in reflection, particularly reflected signals from highly down-going neutrinos that would provide most of ANITA-2’s sensitivity to sources with $\theta < 13^\circ$.

In order to place point source flux limits on sources that ANITA-2 was only sensitive to via reflected RF, further analysis was run with events passing all thermal analysis other than the elevation cut. All other thermal and clustering cuts remained unchanged. A summary of the downward-pointing ($\theta < 35^\circ$) events passing cuts and the results of event clustering is shown in table 8.1.
The observed voltage $V_{\text{obs}}$ is proportional to the neutrino energy $E_\nu$:

$$V_{\text{obs}} \sim E_\nu y h_{\text{eff}} R^{-1} \exp \left( -\frac{\beta^2}{2\sigma} - \alpha d \right)$$

$y$ is the fraction of neutrino energy in the cascade
$h_{\text{eff}}$ is the effective height of the antenna (gain)
$R$ is the range to the cascade
Gaussian in $\beta$ from observer position on Cerenkov cone
(estimated from RF spectrum)
Exponential is attenuation in ice at depth $d$.
(estimated from RF spectrum and polarization effects)

Gives: $\Delta E_\nu / E_\nu \sim 1.9$ (60% of which is intrinsic from $y$)