Design and flight of ANITA-3: An ultra-high energy cosmogenic neutrino detector

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Photo credit: TsungChe Liu
Contents

• Motivation:
  • Ultra-high energy cosmic rays and neutrinos

• ANITA-3 detector:
  • Askaryan Effect and ANITA detection strategy

• 2014-15 flight details:
  • Satellite connection and a telemetry prioritizer
  • Calibration RF pulser installed at WAIS divide

• ANITA “landing” and conclusions
The GZK mechanism: A guaranteed $\nu$ flux?

**GZK feature?** (Greisen, Zatsepin, Kuz'min)

If CRs are cosmogenic in origin then spectrum should steepen rapidly at $10^{19.5}\text{eV}$

**Cosmogenic Neutrinos:**
Carry away half the energy of the incident proton

$\nu_{\text{cmb}} + \nu_{\text{cmb}} \rightarrow \Delta^+ \rightarrow \pi^+ + n$

$\nu_e^+ \rightarrow e^- + \nu_e$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow \nu_\mu + e^+ + \bar{\nu}_e$
What could we learn from UHE neutrinos?

- Confirm GZK mechanism suppresses UHECR flux > $10^{19.5}$eV
- Identify source of highest energy cosmic rays

$10^{19.5}$eV neutrino has centre of mass energy > 100 TeV
Use earth as shield to make cross section measurements

Plot credit: Peter Gorham

**ANtarctic Impulsive Transient Antenna**

- **Satellite communication antenna**
- **GPS antenna array**
- **Instrument box** contains digitization electronics, computer, and hard disks
- 48 Custom made quad-ridge horn antennas angled down at -10°
- PV panels drop down to reveal a 3rd ring of antennas
The Askaryan Effect

Measured at SLAC ESA in 2006 by ANITA collaboration

Fired bunches of $10^9$ electrons at 28.5 GeV into 7000 kg of ice

Radio detection of neutrinos by ANITA

- Neutrino fluxes are low, need lots of ice
  - At ~38km altitude horizon is at 700km
  - Ice radio transparent $\mathcal{O}(1\text{km})$
  - Observing $\sim1.5$ million $\text{km}^3$ of ice
- SM cross section $\sim250\text{km}$ in rock
  - Earth skimming neutrinos
  - Pulse refracts through surface
  - Detected at ANITA
Satellite data rates

- ANITA-3 made use of new (faster!) OpenPort satellite communication: 20-25 kbps
  - ANITA-3 event size ~56 kB
  - Can send down 3 events per minute
  - Nominal ANITA-3 trigger rate is 50Hz

Can only telemeter very small fraction of data set (~0.1%) with such a low bandwidth connection!
Impulsive event

Should ANITA telemeter this impulse?
Cross correlation

Cross correlation used to identify time delay between signal in two channels

\[(\psi_a * \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m + n]\]
Cross correlation

Cross correlation used to identify time delay between signal in two channels

\[(\psi_a * \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m + n]\]
Cross correlation

Cross correlation used to identify time delay between signal in two channels

$$(\psi_a \ast \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m+n]$$

Channels 2TH and 2MH (2MH offset by $\delta t = 1.923077$)

Voltage of time aligned points (2MH offset by $\delta t = 1.923077$ ns)
Cross correlation

Cross correlation used to identify time delay between signal in two channels

\[
(\psi_a \ast \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m+n]
\]
Cross correlation used to identify time delay between signal in two channels

\[(\psi_a * \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m+n]\]
Cross correlation

Cross correlation used to identify time delay between signal in two channels

\[(\psi_a * \psi_b)[n] = \sum_{m=-\infty}^{\infty} \psi_a[m] \times \psi_b[m + n]\]
Use knowledge of payload geometry to generate expected $\delta t$ as a function of arrival direction for pairs of antennas.
Construct interferometric image

1 Antenna Pair
Construct interferometric image

2 Antenna Pairs

Elevation (Degrees)

Azimuth (Degrees)
Construct interferometric image

3 Antenna Pairs

Elevation (Degrees)

Azimuth (Degrees)
Construct interferometric image

5 Antenna Pairs
Construct interferometric image

10 Antenna Pairs

Elevation (Degrees)

Azimuth (Degrees)
Construct interferometric image

20 Antenna Pairs
Construct interferometric image

Normalized image

Now have direction of signal origin, with an implied set of $\delta$ts between antennas
Coherent sum of waveforms

Use map δts to sum waveforms in phase

Single phi-sector illustration, in reality sum from many adjacent phi-sectors
Prioritize telemetered data set

- In case of payload non-recovery
- Build parameter space out of hilbert envelope peak and interferometric map peak to decide what events to telemeter

<table>
<thead>
<tr>
<th>Telem Queue</th>
<th>Queue meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extremely impulsive</td>
</tr>
<tr>
<td>2</td>
<td>Very impulsive</td>
</tr>
<tr>
<td>3</td>
<td>Less impulsive</td>
</tr>
<tr>
<td>4</td>
<td>Weakly impulsive</td>
</tr>
<tr>
<td>5</td>
<td>Near thermal</td>
</tr>
<tr>
<td>6</td>
<td>Thermal</td>
</tr>
<tr>
<td>7</td>
<td>Panic queue!</td>
</tr>
<tr>
<td>8</td>
<td>Strong CW</td>
</tr>
<tr>
<td>9</td>
<td>Digitizer saturates</td>
</tr>
</tbody>
</table>

Tunable ellipse axis intercepts for priority bins

Most frequently telemetered

Least frequently telemetered
GPU programming for speed

- Interferometry is computationally intensive
- ANITA-3 has low power, single board computer
  - Move computation to graphics card!

Single $\phi$-sector, single polarization, GPU execution times - development over time
ANITA crashed after a 22 days 10 hours afloat in the polar vortex circling Antarctica with 85 million events written to disk.
Prioritizing WAIS divide pulses

Priorities near WAIS divide, runs 331-354

Low numbers sent back first

Wais pulsed on GPS second – see many events close to second start

Stacked histogram of events runs 330-356

GPU phi - Expected phi (+45) near WAIS divide, runs 331-354

Entries = 3745
Mean  -0.119
RMS   3.62
The waiting game...

Photo credit: Josh F/Australian Antarctic Division

Photo credit Unknown

Photo credit: Alex Kozyr

Conclusion

• ANITA-3 will have the best sensitivity to ultra-high energy neutrinos at GZK energies

• Implemented a GPU based interferometric prioritizer algorithm
  • Although less important now full data set is on the way (fingers crossed!)

• Currently waiting for a ship with some disks that fell 38km out of the sky, crashed into a remote ice sheet, were helicoptered to a remote base and are being shipped on a long voyage back to civilization…
Thanks for your attention

Any Questions?
Backup
Cosmic Ray Spectrum

10^{15}eV Knee: Accelerators in the galaxy have reached maximum energy. End of galactic confinement.

10^{18.5}eV Ankle: Higher energy extra-galactic flux dominates over galactic flux.

10^{20}eV GZK region: 1 per km^2 per century.

1 per m^2 per second 100 GeV.

1 per km^2 per year 10^{18.5} GeV.

What could we learn from these neutrinos?

Neutrinos point to Ultra-high energy cosmic ray source

What could we learn from these neutrinos?

50 Mega parsec

GZK horizon

E > E_{GZK}

E < E_{GZK}

CMB interaction

Magnetic field

Neutrinos point to UHECR source

Detector

Plot credit: Peter Gorham

log(particle or photon energy, eV)

highest observed p energy

\gamma \rightarrow e^+ e^- (IR+3K bkg)

\gamma \rightarrow \Delta^+ \rightarrow \pi^+ \nu

(protons)

Region not observable in photons or Charged particles

highest observed \gamma energy

galaxy

local group

Nearby clusters

AGN & QSOs

cosmology

Observable distance (Mpc)

P. Gorham
The Askaryan Effect

Detected power $P \propto N^2$ for frequencies < 1GHz where emission becomes coherent (photons along the shower length interfere constructively)


Movie credit: SLAC
ANITA-3 launched on the 17/12/2014

Movie credit: TsungChe Liu