Dynamic tunable notch filters for the Antarctic Impulsive Transient Antenna (ANITA)

P. Allison\textsuperscript{a}, O. Banerjee\textsuperscript{a, *}, J. J. Beatty\textsuperscript{a}, A. Connolly\textsuperscript{a}, C. Deacon\textsuperscript{a}, J. Gordon\textsuperscript{a}, P. W. Gorham\textsuperscript{b}, M. Kovacevich\textsuperscript{a}, C. Miki\textsuperscript{b}, E. Oberla\textsuperscript{a}, J. Roberts\textsuperscript{b}, B. Rotter\textsuperscript{b}, S. Stafford\textsuperscript{b}, K. Tatem\textsuperscript{b}, L. Batten\textsuperscript{b}, K. Belov\textsuperscript{c}, D. Z. Besson\textsuperscript{d,1}, W. R. Binns\textsuperscript{a}, V. Bugaev\textsuperscript{a}, P. Cao\textsuperscript{f}, C. Chen\textsuperscript{c}, P. Chen\textsuperscript{c}, Y. Chen\textsuperscript{c}, J. M. Clem\textsuperscript{d}, L. Cremonesi\textsuperscript{b}, B. Dailey\textsuperscript{a}, P. F. Dowkontt\textsuperscript{j}, S. Hsu\textsuperscript{i}, J. Huang\textsuperscript{g}, R. Hupe\textsuperscript{a}, M. H. Israel\textsuperscript{a}, J. Kowalski\textsuperscript{h}, J. Lam\textsuperscript{1}, J. G. Learned\textsuperscript{b}, K. M. Liewer\textsuperscript{c}, T. C. Liu\textsuperscript{i}, A. Ludwig\textsuperscript{g}, S. Matsuno\textsuperscript{b}, K. Mulrey\textsuperscript{f}, J. Nam\textsuperscript{i}, R. J. Nichol\textsuperscript{b}, A. Novikov\textsuperscript{d,1}, S. Prohira\textsuperscript{d}, B. F. Rauch\textsuperscript{f}, J. Ripa\textsuperscript{i}, A. Romero-Wolf\textsuperscript{f}, J. Russell\textsuperscript{f}, D. Saltzberg\textsuperscript{j}, D. Seckel\textsuperscript{f}, J. Shiao\textsuperscript{i}, J. Stockham\textsuperscript{c}, M. Stockham\textsuperscript{c}, B. Strutt\textsuperscript{j}, G. S. Varner\textsuperscript{b}, A. G. Vieregg\textsuperscript{g}, S. Wang\textsuperscript{c}, S. A. Wissel\textsuperscript{c}, F. Wu\textsuperscript{i}, R. Young\textsuperscript{i},

\textsuperscript{a}Dept. of Physics, The Ohio State Univ., Columbus, OH 43210; Center for Cosmology and Astroparticle Physics.
\textsuperscript{b}Dept. of Physics and Astronomy, University College London, London, United Kingdom.
\textsuperscript{c}Jet Propulsion Laboratory, Pasadena, CA 91109.
\textsuperscript{d}Dept. of Physics and Astronomy, Univ. of Kansas, Lawrence, KS 66045.
\textsuperscript{e}Dept. of Physics, Washington Univ. in St. Louis, MO 63130.
\textsuperscript{f}Dept. of Physics, Univ. of Delaware, Newark, DE 19716.
\textsuperscript{g}Dept. of Physics, Enrico Fermi Institute, Kavli Institute for Cosmological Physics, Univ. of Chicago, Chicago IL 60637.
\textsuperscript{h}Dept. of Physics and Astronomy, Univ. of Hawaii, Manoa, HI 96822.
\textsuperscript{i}Dept. of Physics, Grad. Inst. of Astrophys., Leung Center for Cosmology and Particle Astrophysics, National Taiwan University, Taipei, Taiwan.
\textsuperscript{j}Dept. of Physics and Astronomy, Univ. of California, Los Angeles, Los Angeles, CA 90095.
\textsuperscript{k}Dept. of Physics, Univ. of California, Irvine, CA 92697.
\textsuperscript{l}National Research Nuclear University, Moscow Engineering Physics Institute, 31 Kashirskeoye Highway, Russia 115409
\textsuperscript{m}SLAC National Accelerator Laboratory, Menlo Park, CA, 94025.
\textsuperscript{n}Dept. of Physics, California Polytechnic State Univ., San Luis Obispo, CA 93407.

\textsuperscript{*}Corresponding author
Email address: oindreeb@gmail.com (O. Banerjee)
Gamma Ray Burst: My favorite motivation

Broad motivation:

- Particle Physics at $E > 14$ TeV (Large Hadron Collider)
- Astrophysics at Nature’s most powerful, remote accelerators

\[ p + \gamma \rightarrow \Delta^+ (1232 \text{ MeV}/c^2) \rightarrow n + \pi^+ \text{ OR } p + \pi^0 \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \]

\[ \pi^0 \rightarrow \gamma\gamma \quad n \rightarrow p \ e^- \bar{\nu}_e \]

Potential ultra-high-energy (UHE) neutrinos
ANtarctic Impulsive Transient Antenna

- NASA long-duration balloon experiment
- Ultra-high-energy (>10^{18} eV) neutrino detector
- Looking for radio Cherenkov signal
- Four flights so far
- Recent flight 27.3 days long
Military satellite noise during ANITA-3

- 260 MHz
- 375 MHz

Plot by Ben Strutt

ANITA-3

FLTSAT, UFO satellites

MUOS satellites
ANITA-4 System Diagram

- **TUFF**
  - Amplification of ~45 dB by Tunable Universal Filter Frontend (TUFF) board
  - 200-1200 MHz Bandpass filters
  - Dual-polarization horn antenna

- **Internal Radio Frequency Conditioning Module (IRFCM)**
  - Notch filtering by TUFF
  - Notch filters at ~260, ~380 and ~460 MHz
  - 200-1200 MHz Bandpass filters
  - 3 dB splitter
  - 20 ns delay cable

- **Sampling Unit for RF (SURF)**
  - Level 1 and Level 2 triggers issued
  - 260x
  - 260x
  - 260x
  - 260x

- **Tunnel diode power detector**
  - 90 degree hybrid coupler, takes input RF from HPol and VPol channels, here showing only one input and output

- **PCI Bus**
  - Level 3 trigger issued
  - Trigger Unit for RF (TURF) also monitors trigger rate

- **Data archives**
  - 4TB Helium drives, 2TB SSD

- **GPU: Event Builder and Prioritizer**
  - Commanding Link

ANITA Instrument Box providing >= 80 dB EMI Faraday Housing
ANITA-4 Trigger

Trigger Logic:
- Level 1: LCP and RCP signal from same antenna above threshold
- Level 2: >1 antennas in same phi sector have Level 1 trigger
- Level 3: Adjacent phi sectors have Level 2 trigger

Trigger rate > ~50 Hz

Digitization Deadtime

Phi-masking

“Instrument Deadtime”
ANITA DATA

- An “event” is a 100 nanosecond snapshot of an incoming plane wave (voltage vs. time) that satisfies our trigger
  - ANITA-1 (06 - 07) — 8 million events
  - ANITA-2 (08 - 09) — 26 million events
  - ANITA-3 (14 - 15) — 77 million events
  - ANITA-4 (2016) — 97 million events

- Most events are noise
  - Thermal radiation by the ice
  - Anthropogenic or Human-made noise
    - Military satellites
TUFF board

Single TUFF channel

RF in

AMP 1

AMP 2

Microcontroller

Bias Tee

Notch 1

Notch 2

Notch 3

RF out

Circuit diagram
TUFF response

To combat Military Satellite Noise

To combat McMurdo and South Pole Station Noise

13 dB
TUFF notch operations during ANITA-4

Notch activation status vs. time

Notch 1: 260 MHz  
Military Satellite

Notch 2: 375 MHz  
Military Satellite

Notch 3: 460 MHz  
Base

Notch 3 off
TUFF notch operations during ANITA-4

Realtime notch tuning

![Graph showing Power Spectral Density (dBm/MHz) vs Frequency (MHz) with two traces: one before and one after notch tuning. The graph shows a significant reduction in power spectral density after re-tuning notch 2.]
Turning Notch 2 off... ouch
Digitization livetime

ANITA-3
74%

ANITA-4
92%

Level 1 and Level 2 triggers issued:
- 260x
  4 LABRADOR chips sample waveform data at 2.6 GSa/s until Level 3 trigger issued, then 1 LAB digitizes while remaining 3 continue to sample.

Sampling Unit for RF (SURF)
Phi-masking

ANITA-3

ANITA-4

Oindree Banerjee
“Instrument Livetime”

- ANITA-3: 32%
- ANITA-4: 91%

Digitization livetime × Fraction of unmasked phi sectors

2.8x live acceptance

Oindree Banerjee
Conclusions

• New tunable dynamic notch filters were successfully operated during ANITA-4
• Helped to increase per day “instrument livetime” by 2.8x
• With satellite noise under control, we can focus on improving other parts of signal processing
  • ANITA-5 trigger: continuous, low-resolution digitization to perform interferometry in realtime
• ANITA-4 flight is promising and data analysis is underway
  • Planned analysis includes
    • Diffuse search for UHE neutrinos
    • Search for UHE neutrinos from Gamma Ray Bursts
    • Evaluating sensitivity to Fast Radio Bursts
Backup slides
Radio detection of UHE neutrinos

Astronaut on balloon
ANITA

Radio signal

37 km altitude

Particle bunch emitting EM radiation

UHE neutrino

Antarctic ice sheet is lots of ice and it is radio transparent!
Threshold

Changing thresholds during the flight is a secondary method of reducing digitization deadtime.