Observation of UHE Cosmic Rays from the ANITA Balloon-borne Radio Interferometer
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arxiv:1005.0035v2
ANITA-1 Trigger Design

Power Requirement

Level 0 Trigger:
The band power is $2.3\sigma$ above the noise level.

Spectral Requirement

Level 1 Trigger:
3 of 8 bands pass the L0 trigger condition.

Geometric Requirement

Level 2 Trigger:
A top or bottom cluster has two adjacent antennas with L1 trigger.

Geometric Requirement

Level 3 Trigger:
Top and bottom antennas in a phi sector have L2 triggers.
ANITA Event Recording

SURF (Sampling Unit for Radio Frequencies)
- 2.6 Gsa/s
- 0.385 ns/sample
- 100 ns waveform record length
- 260 samples per waveform
- 10 MHz spectral resolution

Payload View
L3 Trigger
L2 Trigger
L1 Trigger
ANITA-1 Flight Performance

- 35 day flight
- 17.4 days live time
- 8.2 million events
- Anomalous flight path
- but we did get some good quiet data.

ANITA-1 Flight Path

ANITA-1 Noise Temperature

ANITA-1 Average Ice Depth
Summary of UCLA ANITA-1 Analysis

79,358 Events
Reconstructed

14 EAS Events
+2 EAS events above horizon

No neutrino candidates.
Cosmic-Ray Candidate Event Locations

Figure from arxiv:1005.0035v2
Cosmic-Ray Candidate Event Pulses

(Instrument response deconvolved)

Figure from arxiv:1005.0035v2

Exponential fits fall with $180 \pm 13$ MHz

direct

reflected

Figure from arxiv:1005.0035v2
Geomagnetic Field Direction

Extended Air Shower Tests

- CR moves towards payload.
- $e^+$ and $e^-$ always curve away from each other due to dominant vertical B-field.
- H-pol emission always has the same polarization.

- V-pol magnitude and sign determined by the horizontal magnitude of the B-field.

Figures: Stephen Hoover and Eric Grashorn
Correlation of Polarization Angle to Geo-Magnetic Field Angle

\[ \Phi = \Theta_B - \frac{\pi}{2} \]

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

Interferometric image for a cosmic ray event

Figures from arxiv:1005.0035v2
Data Driven Energy Estimation

**Measured electric field model**

\[
\mathcal{E} = A_0 \left( \frac{E_{sh}}{10^{19} \text{ eV}} \right) \left( \frac{R_{ref}}{R + R_{X_{max}}} \right) F(\theta_{sh}) \cos(\theta_z) \frac{B_\perp}{B_{ref}} G(\nu, R) \mathcal{F}(\theta_z)
\]

- **Reference amplitude**
- **Radial falloff**
- **Shower radio Angular distrib.**
- **Magnetic field factor**
- **Fresnel Coeff.**

**Free parameters**

**Energy dependence**

**Obliquity factor**

**Roughness factor**
Angular Distribution

Angular dependence:
- Double Lorentzian based on fits to intrinsic synchrotron emission (from J.D. Jackson's *Classical Electrodynamics*)
- Overall power law imposed to account for first-order coherence effects
  - Center remains normalize, power function squeezes or stretches the distribution
  - Power varied from 0.2 up to 6

\[
F(\theta) = \left[ \left( \frac{1}{1 + (\theta / \theta_b)^p} \right) \left( \frac{1}{1 + (\theta / \theta_c)^q} \right) \right]^\alpha
\]
Likelihood function

\[ L = \prod_{n=1}^{14} p_n(R_n) \prod_{n=1}^{14} p_n(A_n) \times p(N_{total}) \times p(A|A_{prior}) \]

- \( R_n \) = distance to specular point for each event
- \( A_n \) = observed amplitude vs. frequency
- \( N_{total} \) = number of observed events (14) taken as a Poisson distribution.
- \( A \) = reference radio signal strength for model
- \( A_{prior} \) = distribution function for prior observed radio signal strength factors.
Likelihood Analysis

Results

Noise due to MC statistics

Best fit parameters:
Reference Amplitude $360^{+100}_{-250}$
angular exponent $3.9^{+0.4}_{-3.0}$
Event energies lie around the GZK cutoff. Ground based data favors higher energies but other parts of the model don't fit.
- ANITA exposure lies between declination of -35° to +5°
- AUGER exposure lies between declination of -90° to +25°
- 2° error ellipses
- Véron-Cetty AGN shown in gray.
- No correlation to Auger UHECR events nor V-C AGN.
- Intergalactic magnetic field deflection still significant for ANITA UHECR events.
ANITA acceptance increases with event energy.

Higher exposures could yield higher sensitivity to super-GZK events.

New 30 day flight with optimized trigger could yield 60-80 events above $10^{19}$ eV with ~10 above GZK cutoff.
ANITA-2 Cosmic Ray Events

Figures from Abigail Goodhue PhD Thesis
Potential for a UHECR Satellite

- Taurus Fairing Envelope
- Dual-polarized LPDA antennas
Scientific Potential

Compare to current gnd-based (Auger) after ~10 yrs exposure

5 yr mission gives factor of 40 improvement
~400 events above 100 EeV, compared to ~10 by year 2016

If spectrum rebounds above 300 EeV (as predicted) we would see much more

Assumed spectrum is conservative, source spectra can significantly raise tail of spectrum

Add to this ~10-15% more direct (eg, unreflected) events
Conclusions

- ANITA is able to self-trigger on geo-synchrotron cosmic ray events.

- Sensitivity to events near and above the GZK-cutoff.

Outlook

Simulations indicate that after trigger optimization a new 30 day flight could yield 60-80 events above $10^{19}$ eV and ~10 events above the nominal GZK cutoff.

Radio detection technique could yield the next level of sensitivity for super-GZK cosmic rays.
Backup Slides
FORTE Satellite

FORTE data provides RFI map.

Could have UHECR events in the data set. Potential for digging them out using geo-magnetic field and polarization angle correlation.

Provides clear evidence for VHF reflections off land and sea from lightning events.
Surface Roughness Model

Determined from Kirchoff physical optics on roughness estimated from Taylor dome, Radarsat
Event probability

Determining probabilities:

– Use MC to generate $R$, $A$ distributions, number of events from Auger spectrum

– Use fitted parameters to get observed event probabilities.

Figure: Peter Gorham

$p(R_n)$

Data

KS-test prob. = 0.66
Check to see that these distributions are plausible
Prior reference amplitude

• Prior distribution of reference amplitudes:
  – Allan 1971: 277 or 126 μV/m/MHz
  – Prah75: 64 or 29
  – HF 05 (REAS2?): 49 or 112
  – HEU 2008 (REAS3?): 165 or 390
  – LOPES 2009 (data): 37 or 78

• “Or” comes from spectral index used to scale to 265 MHz, two values prevalent

• Fit to lognormal distribution to provide a “Bayesian” prior