ARA TestBed background data analysis and neutrino sensitivity study

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Abstract

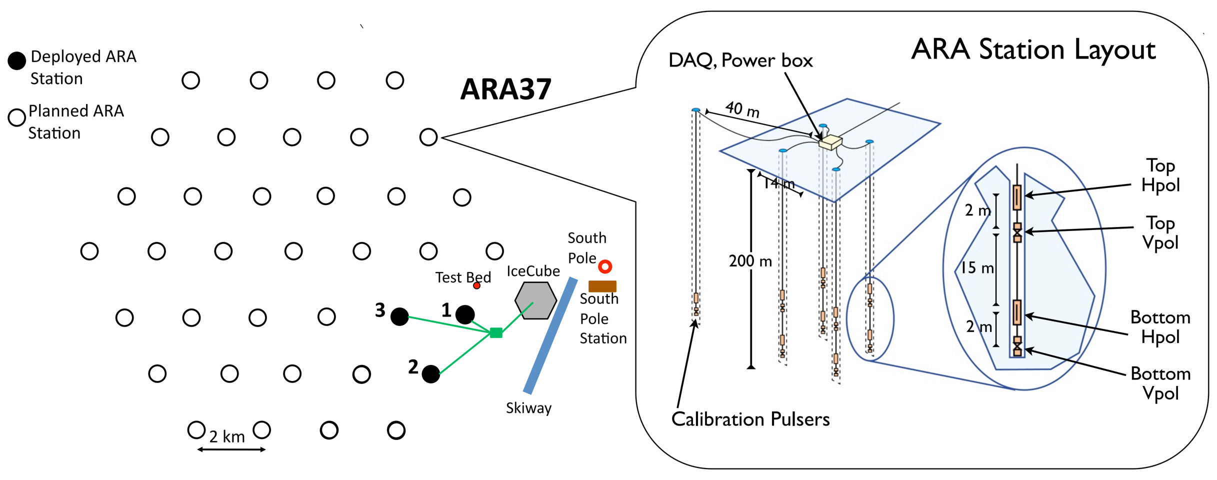
The Askaryan Radio Array (ARA) is an ultra-high energy (UHE) cosmic neutrino detector located at the South Pole. The cosmic ray flux cut off above primary energies of $10^{19.5}$ eV leads us to expect a UHE neutrino flux due to the Greisen-Zatsepin-Kuzmin (GZK) effect. The detection of these UHE cosmic neutrinos will add to the understanding of the sources and physics of UHE cosmic rays. The radio Cherenkov technique is the most promising technique for a long term program to investigate the UHE cosmic neutrino flux. ARA uses this radio Cherenkov technique with radio frequency antennas deployed at a depth of 200m in the Antarctic ice. A prototype ARA TestBed station was deployed in the 2010-2011 season and the first three ARA stations were deployed in the 2011-2012 and 2012-2013 seasons. We present the status of the first neutrino search with ARA, using data taken from 2011-2012 with the ARA TestBed.

Introduction

- Cosmic ray flux cutoff for primary energies above $10^{19.5}$ eV leads us to expect a UHE neutrino flux – Berezinsky-Zatsepin effect
- Electromagnetic showers induced by neutrino interactions create impulsive radio-frequency (RF) signals via the Askaryan effect

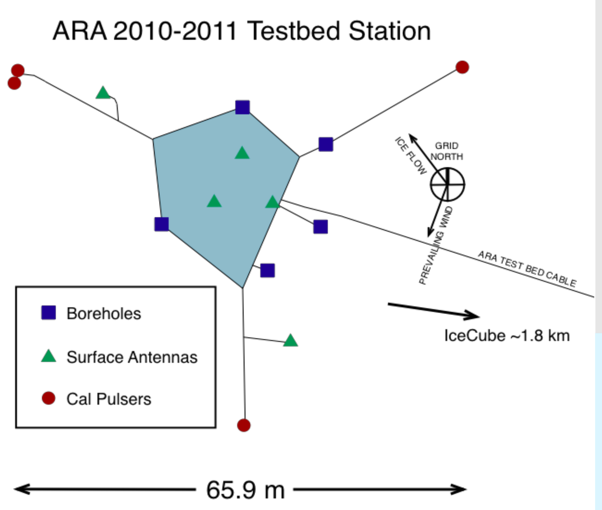
Askaryan Radio Array (ARA)

- ARA is an array of RF antennas in the ice sheet at South Pole
- 100 km^2 array would establish GZK flux
- Arranged in stations 200 m deep each consisting of
  - 8 horizontally (Hpol) and 8 vertically (Vpol) polarized antennas for event reconstruction
  - 3 calibration pulsers
- Currently deployed:
  - 1 prototype TestBed station and 3 design stations
- Full design array consists of 37 stations



TestBed Station

- Layout differs from design stations for full array[1]
- 8 Hpol, 6 Vpol in the ice
  - 4 Hpol and 4 Vpol antennas buried at ~30 m
  - 4 Hpol and 2 Vpol antennas placed near the surface



- Up to 2 GHz sampling rate
- Bandpass filter of 150 MHz to 800 MHz is applied to input signal
- Event trigger condition:
  - Power must exceed a set threshold in 3 out of the 14 antennas within a 100 ns window
  - Threshold may be adjusted to obtain different trigger rates

Analysis Methods

- The ARA collaboration uses a blinded analysis technique
- Only 1 out of 10 events is not-blinded for preliminary analysis
  - Available for optimizing cut parameters and understanding backgrounds

Currently two complementary analyses of TestBed data:

1. Cut-based analysis
   - Combination of cuts designed to reject background signals and accept neutrino signals
   - Only uses events triggered by the 8 deep antennas instead of all 14
   - Examined not-blinded set from 20 February 2012 to 6 April and 12 May 2012 to 30 June 2012
2. Template-based analysis
   - Search for unique impulsive signals by comparison between events
   - Limited number of cuts
   - Uses events triggered by any of the 14 antennas
   - Examined not-blinded data from March 2011 to August 2011

Cut-based Analysis

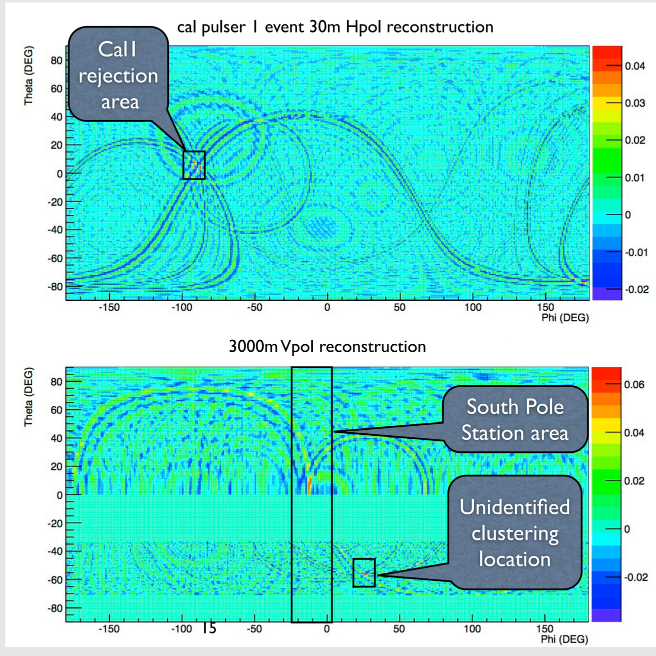
Quality Cuts

1. Timing cuts - eliminate known periods of anomalous electronics activity – less than 1% cut
2. Power in band cut
   - Require that 90% of power lies within frequencies of 150-800 MHz
   - Less than 1% of simulated neutrino events are rejected

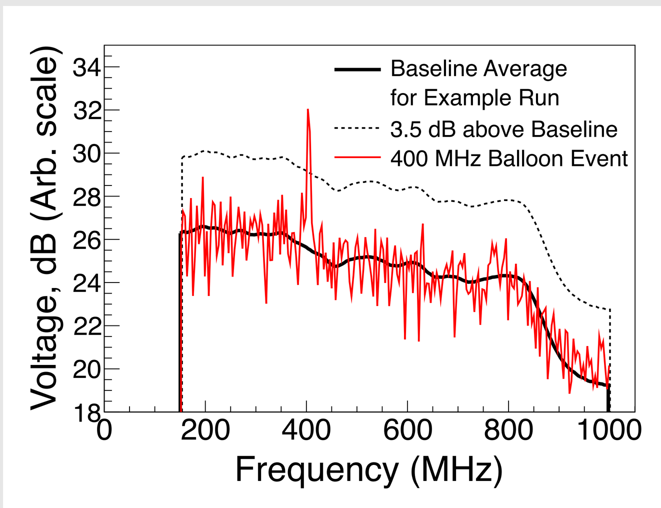
Geometric Cuts

- Based on interferometric reconstruction of event (including ray-tracing)
- Reject events that reconstruct to:
  1. South Pole Station (SPS)
  2. A calibration pulser
  3. Signals from unknown but repeating sources
     - Only one location - likely mis-reconstructions of SPS events
- ~ 10% of events cut

Example interferometric maps



Continuous Waveform (CW) Cut

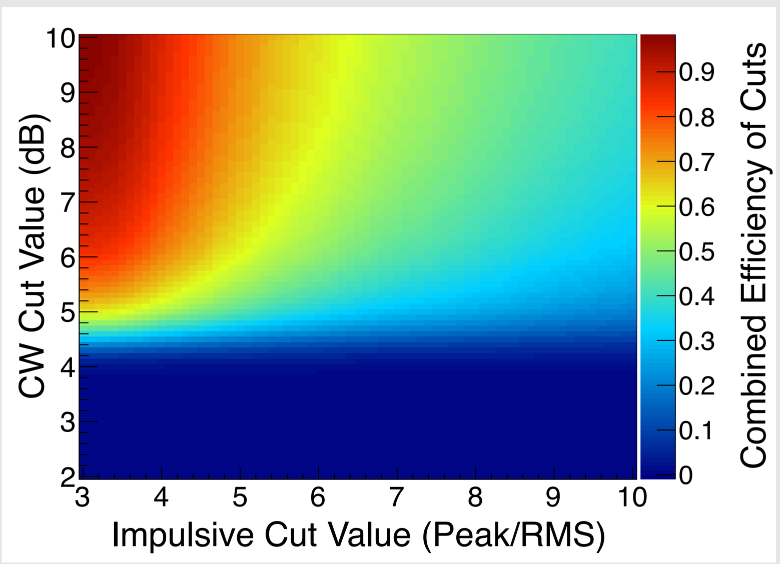


- Based on ANITA heritage
- Find average spectrum for antenna → "baseline"
- Baseline adjusted from event to event to help compensate for shifts in background
- Event is cut If event spectrum has V/Hz > X dB above the baseline for 3 or more antennas at the same frequency
  - Will eventually keep event and insert noise

Impulsive Cut

- Designed to reject thermal noise
- Waveform voltage must exceed a multiple of VRMS
  - Two antenna coincidence

Cut efficiency for the energy of maximal sensitivity ($10^{17.5}$ eV) as a function of CW and impulsive cut parameters

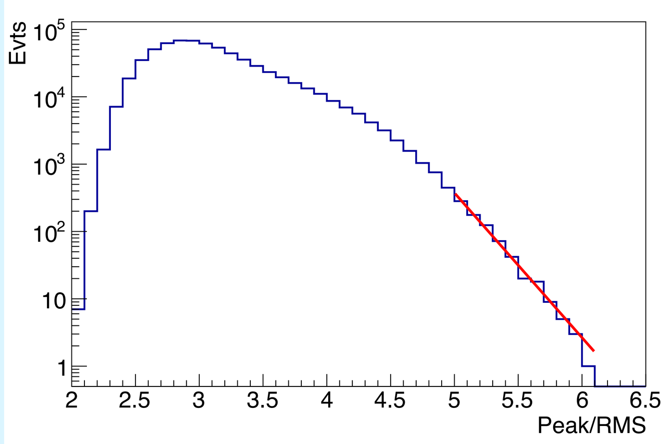


Cut Parameter Optimization

Impulsive and CW cuts will be optimized for best neutrino limit

Estimating background:

1. Assume all events that pass CW and impulsive cuts in 10% not-blinded sample are background
   - Fit distribution of events as an exponential function of Peak/RMS value to estimate expected background



Optimization Procedure:

3. Find the set of cuts that gives the best 90% confidence level limit on a model from Kotera *et al.*[3]

$$1-\alpha = \frac{\int_{-\infty}^{s_{up}} L(n\,|\,s)\,\pi(s)\,ds}{\int_{-\infty}^{\infty} L(n\,|\,s)\,\pi(s)\,ds}$$

Where:

$\pi(s) = 0$ for $s < 0$

$\pi(s) = 1$ for $s \geq 0$

$$L(n\,|\,s) = \frac{(s+b)^n}{n!} e^{-(s+b)}$$

Set n = b

s = number of expected signal events
b = number of expected background events
n = number of observed events

4. Obtain s from a set of simulated neutrinos[2] with energies weighted by a flux model

Template-based Analysis

Event Selection Method

- Background is defined as any repetitive waveform or antenna hit pattern – based on RICE experience[4]
- Events must pass the following cuts:

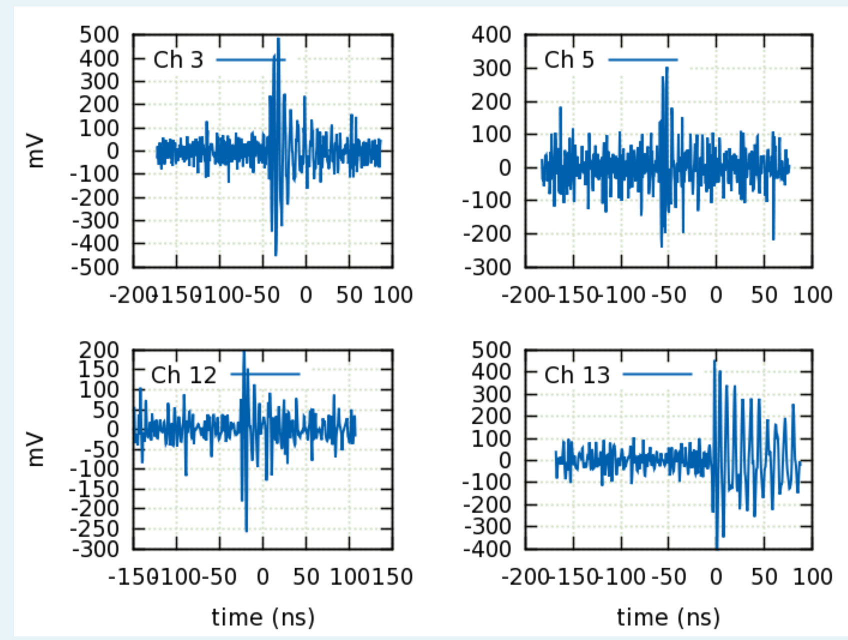
1. Require 4 antennas with voltage larger than 6 times the root-mean-square (RMS) voltage, σ_V, of the antenna
2. Require a well-reconstructed, single-source vertex point
   - Minimizing the least-square fit of arrival times

Minimized to get reconstruction location: $$\chi^2 = \sum_i \left(t_S - t_i + \frac{|\vec{r}_S - \vec{r}_i|}{c} \right)^2$$

- t_S is the expected propagation time to the antenna
- t_i is the observed time for the antenna
  - Time at which the voltage magnitude exceeds $6\sigma_V$
- r_S is the putative source point location
- r_i is the known antenna location

3. Reconstruction location must not be consistent with a calibration pulser
4. Similar events are rejected – determined by:
   - the dot-product of the two event waveforms
   - the timing pattern of the hit antennas

After cuts, one event was found for the time period examined:

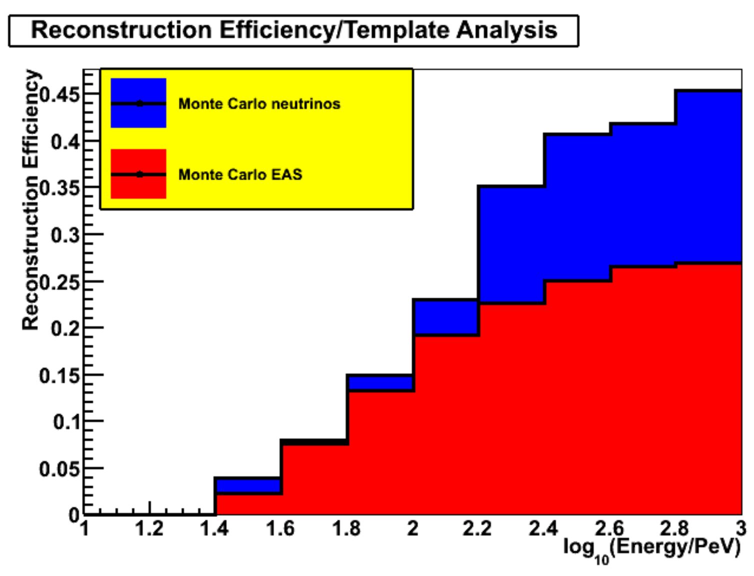


Waveforms from triggered antennas for the single passed event

Flux Limit Method

Three more inputs needed for an neutrino flux upper limit

1. Effective volume as a function of neutrino energy
   - Simulated neutrino waveforms superimposed on TestBed noise data to fully sample the *in situ* noise environment



Reconstruction efficiency from Monte Carlo simulation

Blue – neutrinos
Red – air showers

2. The livetime of the array during the period of data taking
   - Use the fraction of times the calibration pulser is observed (1 Hz firing rate) - **yields 98.4% livetime**
3. A rigorous accounting of the trigger efficiency - currently being examined

Conclusions and Further Work

- First upper limits on neutrino flux from ARA TestBed by the end of the year
- Currently 2 analysis methods to identify neutrino events
  1. Cut-based analysis
     - Cut parameters will be optimized
     - Improvements being made to cut algorithms
  2. Template-based analysis
     - Trigger efficiency being analyzed
- Methods will be applied to full TestBed data set

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References:
[1] P. Allison et al. [ARA Collaboration], Astroparticle Physics 35, 7 (2012) 457-477.
[2] E. Hong et al. [ARA Collaboration], paper 1161, these proceedings.
[3] Use mixed composition upper bound model found in Figure 9 of K. Kotera, D. Allard and A. V. Olinto, JCAP 1010, 013 (2010).
[4] I. Kravchenko et al. [RICE Collaboration], Phys. Rev. D 85 (2012) 062004.