# ARA TestBed background data analysis and neutrino sensitivity study


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## Abstract

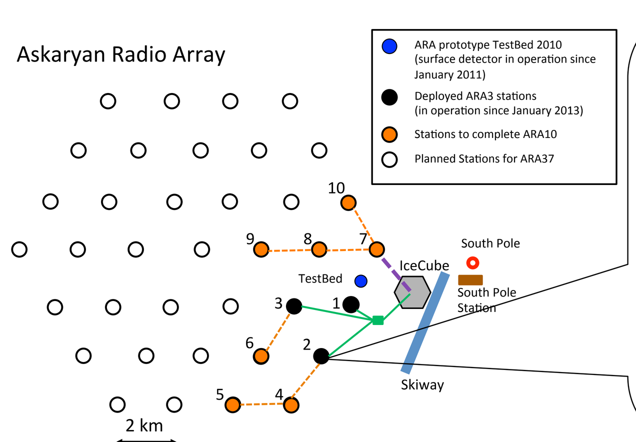
The Askaryan Radio Array (ARA) is an ultra-high energy (UHE) cosmic neutrino detector located at the South Pole. The cosmic ray flux cut off above primary energies of 1019.5 eV leads us to expect a UHE neutrino flux due to the Greisen-Zatsepin-Kuzmin (GZK) effect. The detection of these UHE cosmic neutrinos 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 by deploying radio frequency antennas 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 results of the first neutrino search with ARA, using data taken from 2011-2012 with the ARA TestBed station.

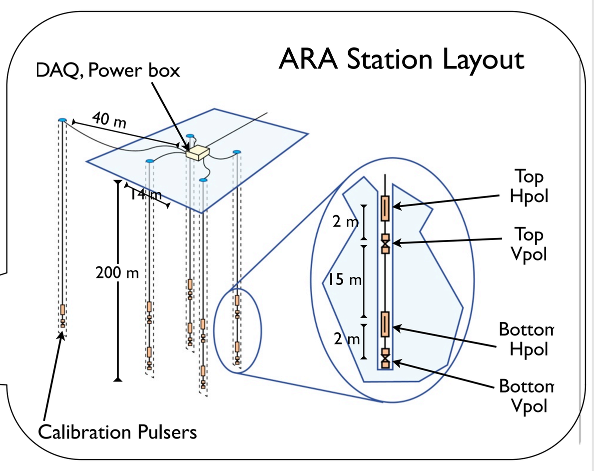

## Introduction

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

## Askaryan Radio Array (ARA)

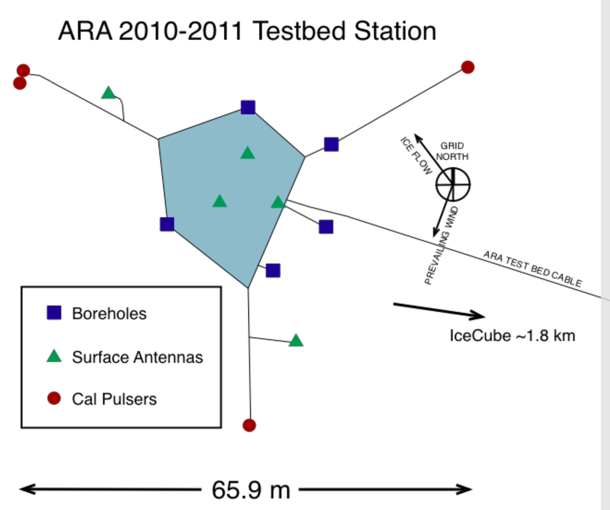
- ARA is an array of RF antennas in the ice sheet at South Pole
- 100 $km^2$ array would establish GZK flux
- Arranged in stations 200 m deep each consisting of
  - 8 Hpol and 8 Vpol antennas for event reconstruction
  - 3 calibration pulsers
- Currently deployed:
  - 1 prototype TestBed station and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

- Blinded analysis technique: 1 out of 10 events available for optimizing cut parameters and understanding backgrounds

Three complementary analyses of TestBed data:

1. Coherently Summed Waveform Analysis
2. Interferometric Map Analysis
3. Template-based analysis

## Coherently Summed Waveform Analysis

Creates a coherently summed waveform from signal timing

Only uses events triggered by the 8 deep antennas

Examined data taken from 1 January 2011 to 31 December 2012

### Coherently Summed Waveform (CSW)

- Signals arrive at antennas at different times
- Maximal cross-correlation between waveforms gives timing offset
- Sum the waveforms with timing offset → CSW

$$CSW(t) = \frac{1}{N}\sum_i \psi(t + \Delta t_{1,i})$$

- Cross-correlations after the first are performed against the CSW
- After all waveforms added, individual waveforms subtracted out and re-correlated against full CSW → mitigates initial biases
- CSW formed for vertically and horizontally antennas separately

## Interferometric Map (IM) Analysis

Cuts designed around ray-traced interferometric maps

Only uses events triggered by the 8 deep antennas

Examined data taken from 1 January 2011 to 31 December 2012

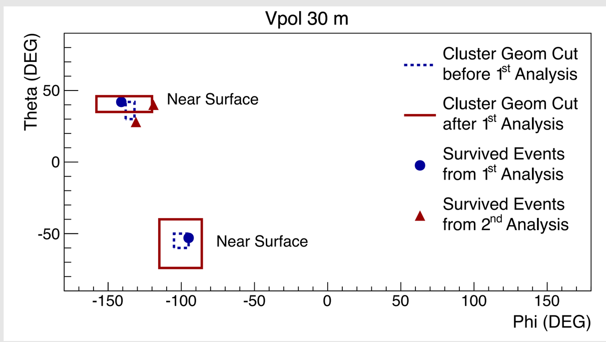
### Quality Cuts

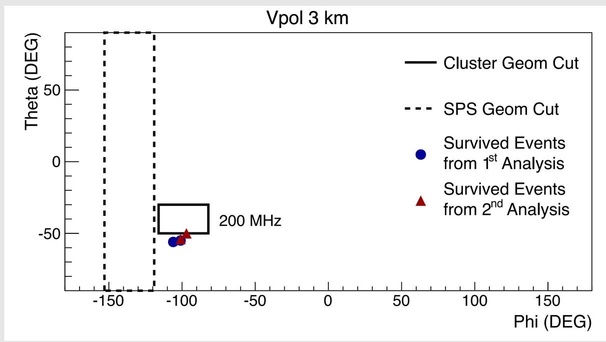
1. In-band power cut: 150-800 MHz
2. Timing cuts – electronics issues

### Geometric Cuts

- Reject events that reconstruct to:

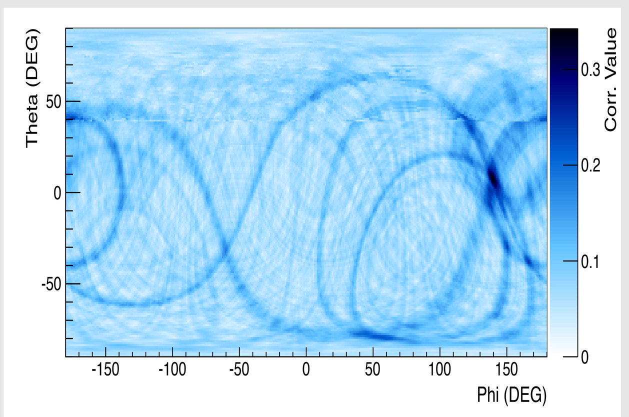
1. South Pole Station (SPS)
2. A calibration pulser
3. Signals from unknown but repeating sources
   - Three locations - likely mis-reconstructions of SPS events




### Reconstruction Quality Cuts

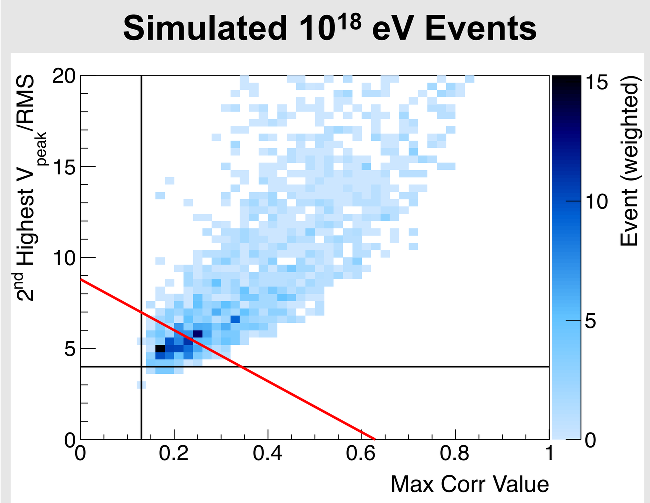
Example calibration pulser map

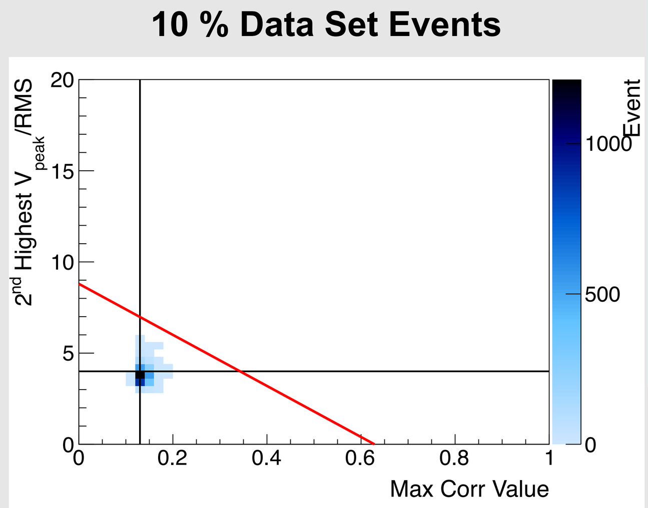



- Based on interferometric reconstruction of event (including ray-tracing)
- Use 30m, 3 km radius maps
- Use Hilbert envelope of correlation to smooth fringes
- Find area around peak, area on map at comparable strength; cuts based on these values
  1. 1 $deg^2 < A_{peak} < 50\ deg^2$
  2. $A_{total}/A_{peak} < 1.5$

### Peak/Correlation Cut

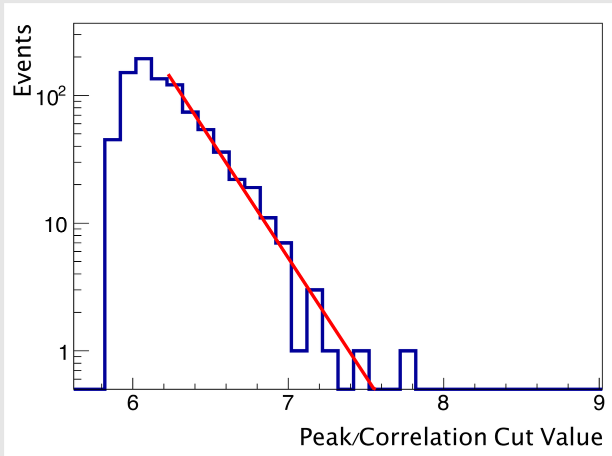
- Plot maximum correlation value from the Interferometric Map with $2^{nd}$ highest $V_{peak}$/RMS
- Designed to reject thermal noise (low signal and correlation)




### Cut Parameter Optimization

1. Assume all events that pass CW and other cuts in 10% sample are background
2. Fit distribution of events as an exponential function of Peak/Correlation to estimate background
3. Find the set of cuts that gives the best 90% confidence level limit on a model from Kotera *et al.*[3]

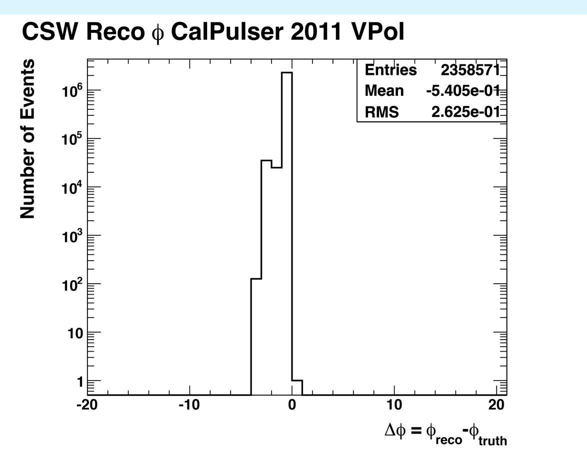


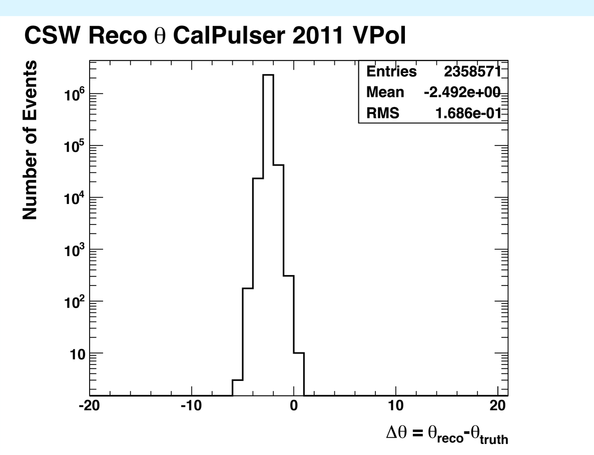

### Reconstruction

- Find expected timing delays for all signal arrival directions
  - R, θ, φ relative to the center of the station
- Use the timing delays from the CSW to form a pseudo-$\chi^2$

$$\chi^2 = \sum_i \left(\Delta t_{1,i,\exp}(R,\theta,\varphi) - \Delta t_{1,i,CSW}\right)^2$$

- Reconstruction location where pseudo-$\chi^2$ is minimized
- R sampled in log space from 15m to 3 km; θ, φ bins = 1 deg




### "Powherence" Cut

- Maximum voltage in a waveform ($V_{max}$)– measure of power
- Correlation value of waveform with CSW – measure of coherence
  - Sum for all waveforms - Σc
- Form linear combination of $V_{max}$ and Σc – "Powherence"
- "Powherence" maximizes separation between thermal noise events and signal-like events
  - Thermal – incoherent and low-power

## Template-based Analysis

Search for unique impulsive signals by comparison

Uses events triggered by any of the 14 antennas

Examined data taken from March 2011 to August 2011

### 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, $\sigma_V$, of the antenna
2. Require a well-reconstructed, single-source vertex point
   - Minimizing the least-square fit of arrival times

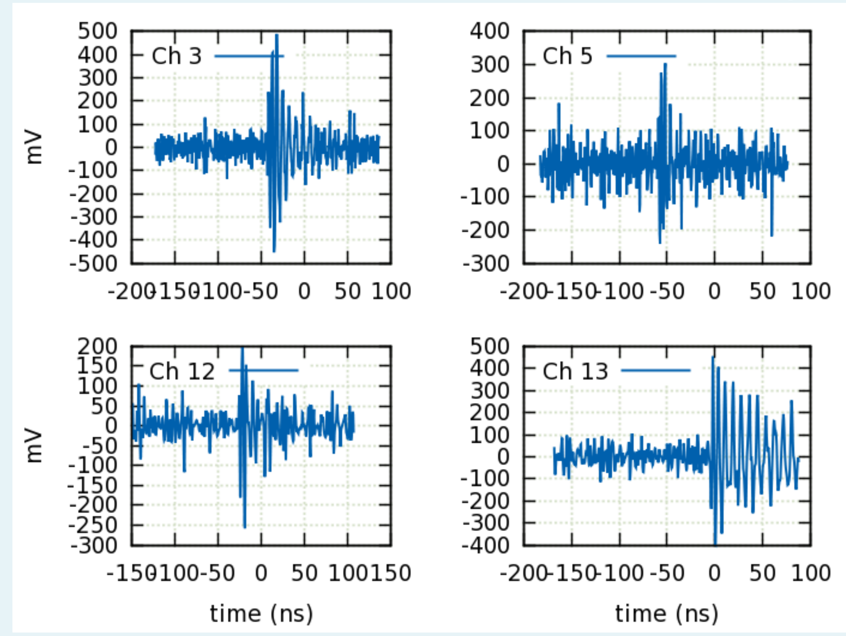
Minimized to get reconstruction location:

$$\chi^2 = \sum_i \left( t_S - t_i + \frac{|\vec{r_S} - \vec{r_i}|}{c} \right)^2$$

- $t_S$ 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

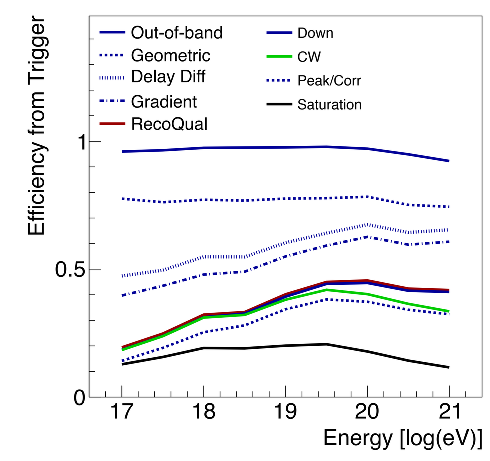
3. Reconstruction location must not be consistent with a calibration pulser
4. Similar events are rejected – determined by:
   - the dot-product of the two event waveforms
   - the timing pattern of the hit antennas

After cuts, one event was found for the time period examined: Mis-reconstructed calibration pulser event




Waveforms from triggered antennas for the single passed event

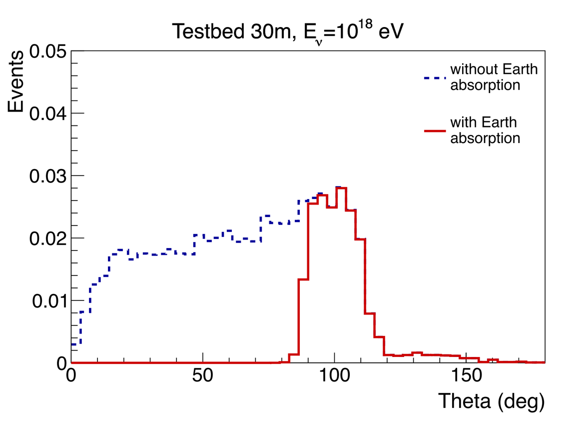
### Efficiency and Comparison to Deep Stations

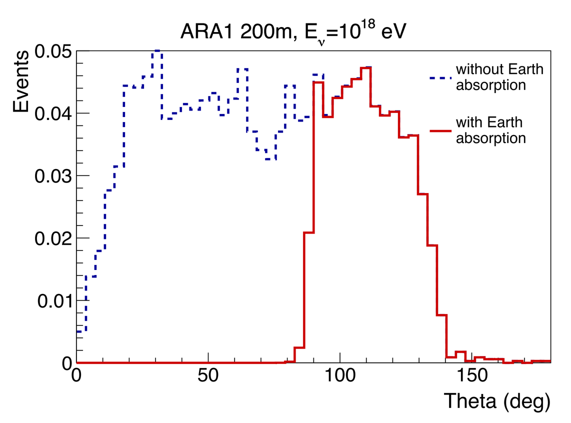



- Analysis efficiency ~ 10% overall
- Improvements for A2/3 analysis

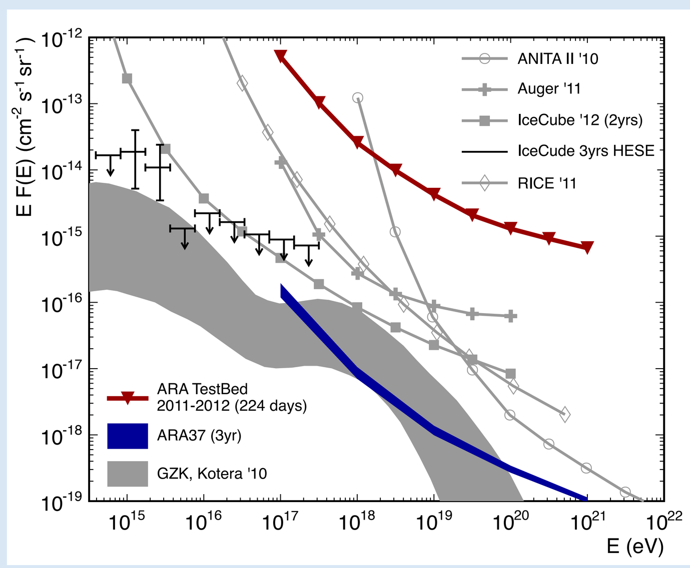
From the Testbed to ARA37 at $10^{18}$ eV

| | $A\Omega_{eff}$ [$km^2$sr] | Accumulative factor |
|---|---|---|
| Testbed analysis | 1.5E-4 | 1 |
| Testbed trigger | 1.5E-3 | 10 |
| ARA one-station trigger | 4.1E-3 | 28 |
| ARA37 trigger | 1.3E-1 | 900 |




## Conclusions and Further Work




- No valid candidate events found for any of the 3 analyses
- First upper limits on diffuse neutrino flux from ARA TestBed
- The proposed ARA37 is projected to place competitive limits
- CSW and IM methods yield the same limit
- See submission 1293 for more details on A2/3 analysis
- Full Testbed results can be found in
  - Astropart. Phys. V 70, Oct 2015, 62-80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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.