Reconstruction Studies at UNL 2014-2015

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Contents

Purpose:

- Overview the most important reconstruction developments from UNL from summer 2014 to summer 2015.

Contents:

- 1) Defining antenna noise RMS in the absence of a "noise event" flag
- 2) Improved time difference (dT) to distance difference (dD) approximation
- 3) Improvements to UNL's ray tracing tool
- 4) Index of Refraction measurement using ICL data
- 5) Reconstruction radial bias
- 6) Multistation reconstruction of the ICL

Part 1:

EDOK Based Tool for Noise Event Detection and

Defining Channel RMS

RMS Finding Overview

Motivation:

- Threshold based time finding requires the noise RMS for each antenna so that the threshold can be defined as: RMS $\times$ Threshold Multiplier
- If there is no flag to check if an event is a noise event (unbiased), then defining an accurate threshold can be difficult. If there is a flag, there is still some non-thermal noise contamination that can distort the RMS calculation.
- A tool called EDOK (Event Discovery and Organization Kit) can help bypass this difficulty
  - See previous presentation on EDOK: http://ara.physics.wisc.edu/docs/0010/001014/003/EDOK.pdf

Procedure:

- 1) Use EDOK to determine if there is signal in an antenna's waveform
- 2) If no signal is in the waveform, calculate the RMS of the waveform and include in an average RMS for the antenna

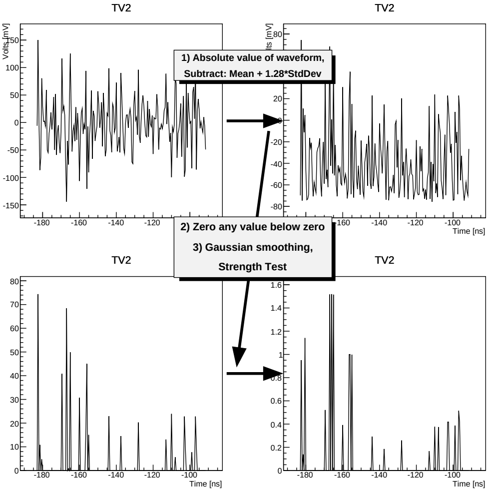
Previous Presentation:

- See previous presentation on RMS defining for full details: http://ara.physics.wisc.edu/docs/0011/001121/001/RMS_Study.pdf

"Noisy" Event Determination

For defining RMS we are concerned with 2 types of events:

- 1) Noise events: Events that have no signal (or signal is weak enough that it cannot be discerned)
- 2) Signal events: All other events



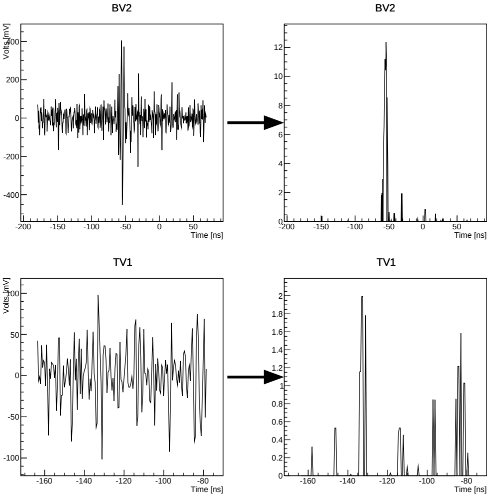
Determination of Noise Events:

- 1) The waveform's mean and standard deviation is calculated and mean+1.28*(standard deviation) is subtracted from the "absolute waveform" (absolute value of the waveform)
- 2) Every point of the waveform below zero is set to equal zero
- 3) Next the waveform is "Gaussian Smoothed" (method inherited from Guy Nir), the resultant graph shows areas of the waveform that have the highest power
- A waveform is "noisy" if no part of the resultant graph is above 2 (experimentally determined)

Noise vs Signal Events

Example of Performance:

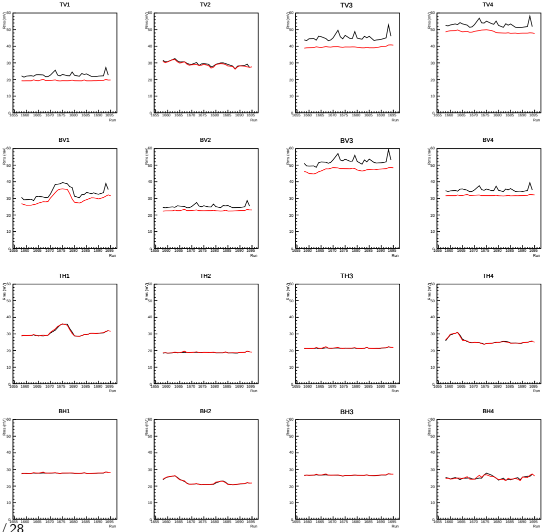
- Here are two examples of the outcome of using EDOK to determine noise events from possible signal carrying events
- The top plot has clear signal, which results in a peak far above 2
- The bottom plot is categorized as a noise event and passes the selection criteria by only 0.005, if the area around -130ns had a little more power the event would have failed. This is a good example of how "good" the noise event needs to be to pass the selection criteria



RMS Finding Results: 2013, Ara02

Results: 2013 Ara02 D6V Pulser:

- Ara02 pulser runs from 2013 do not have flag to see if the event was forced to trigger (noise event)



Two RMS finding methods:

- Use the triggering band of the D6V pulser to throw out any event that is outside the pulser trigger window (in this case Trig$_{\mu s}$ $<2000\mu s$ (black line)
- Use EDOK based RMS finding method (red line)

Results:

- For the top 8 plots (VPol channels) the RMS is more stable from run to run for the EDOK based compared to the trigger based method
- For the HPol channels there is little difference, which is expected since VPol signal should not budge HPol antennas very much
- Similar results for some antennas (HPol and TV2) verifies the EDOK based method as an accurate means to calculate the RMS
- The EDOK based method is very versatile, it requires no prior knowledge of the contents of a particular run

Part 2:

Improvements to dT to dD Conversion

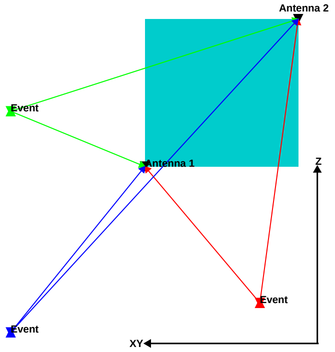
dT to dD Conversion Overview

Motivation:

- Many reconstruction methods rely on an accurate conversion from measured dT to dD (distance difference)
- The conversion calculation is often done using a constant Index of Refraction (n) ($\mathrm{dD} = \mathrm{dT} * \frac{c}{n}$), though what true value to use requires knowledge of source position

Previous Presentation:

- See: http://ara.physics.wisc.edu/docs/0010/001089/001/AnalyticImprovements2.pdf



Challenge:

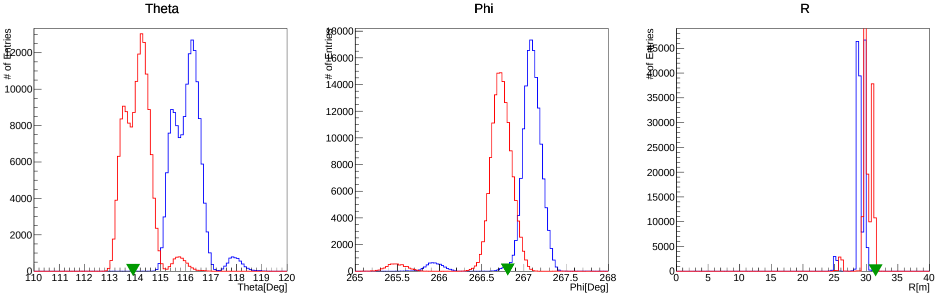
- The blue square in the plot represents the area where the majority of the time difference between the antennas will be seen
- Blue, Green, and Red events all require a different n based on location of the source
- Challenge: What is a good value to use for all 3 cases (source position would not be known)?

Solution:

- "Best guess" is n at the average depth of the antenna pair (n_{ave}). This is because both rays from one event will travel similar paths up until the first antenna is hit, then the remainder (dT) will occur mostly within the blue square from the previous slide $\left(n = 1.78 - 0.4272 * e^{(0.016*[\text{Antenna Pair Average Depth}])}\right)$

Results:

- ASM reconstruction of 2011 TestBed (C2V Pulser) data using constant n at TestBed station center (n=1.45) (Blue) and n_{ave} (Red) (Green is real position)
- Using n_{ave} shifts the reconstructed position toward the true values



Part 3:

Ray Tracing Tool Improvements

Ray Tracing Improvement

Motivation:

- Ray tracing is a compromise of accuracy and processing time, if one is increased so is the other (step size decreases; number of calculations increases)
- In cases where accuracy is a concern, the processing time required can be quite large
- We maintain a ray tracer tool developed at UNL, it has also been integrated into the reconstruction framework under development by Christian and Guy.

Solution:

- In order to increase base accuracy and keep a reasonable processing time, the constant step size has been replaced with a variable step size
- Variable step size changes depending on the angular change induced by the step, if the angular change is larger than the maximum allowed then the step size is decrease by a factor of 2
- For in-air tracing, the step size does not decrease at all since there is no change in the direction of travel for the ray, the same applies when the ice reaches constant density

Current Ray Tracer Features:

- 1) Spherical earth model: accounts for the curvature of the earth
- 2) Variable step size: increases accuracy where ice density changes most

Part 4:

Refractive Index Measurement

Refractive Index Measurement Review

Motivation:

- An accurate model for the Index of Refraction (IoR) is essential for accurate reconstruction, which is in turn needed for an accurate measurement of the neutrino flux

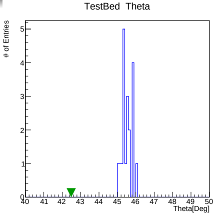
Challenges:

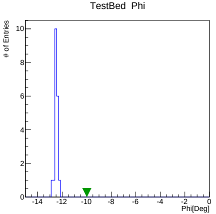
- The parameters of the usual exponential decay model (A+B*e^{C*z}) will be fit for using ICL rooftop pulser data
- To do a direction reconstruction we only need to know the IoR in the vicinity of the station since the rays travel similar paths up until the area of the station. Sensitivity to the IoR is limited to the area of the antenna array used
- The model is then degenerate for different values of A, B, and C (at z = depth of array)

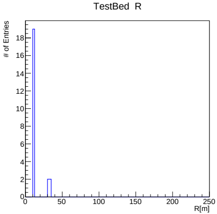
Initial Analysis:

- See previous presentation on first result of IoR measurement: http://ara.physics.wisc.edu/docs/0011/001191/001/IoR_Measurement.pdf

ICL Reconstruction





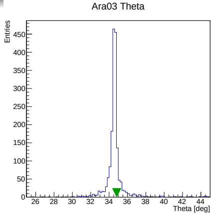


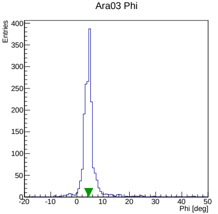
Reconstruction Goal:

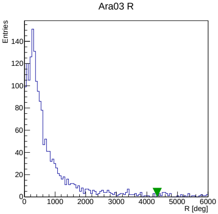
- If we are able to reconstruct the location of the ICL using the default IoR model reasonably well, a measurement of the IoR should be viable

Reconstruction Results:

- ASM Reconstruction of 2013 data:
  - TestBed: run 35478, VPol antennas, VPol mode ICL pulser
  - Ara03: run 64, HPol antennas, HPol mode ICL pulser
  - Green triangle is true direction/distance (for theta it is the receiving angle found from ray tracing)
- The ICL is reconstructed reasonably well for both stations, a measurement of the IoR should be possible





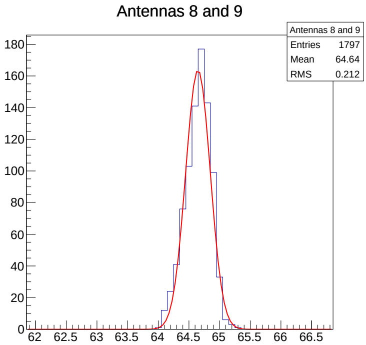


Refractive Index Measurement Procedure

Measurement Procedure:

- Parameter A is well defined as (1.78 ± 0.005), only B and C parameters will be fit
- A χ^2 is calculated for varied B and C values
  - $\chi^2 = \sum_{i,j=1\ldots N} \frac{dT_{ij}^{Measured} - dT_{ij}^{Expected}}{\sigma_{ij}}$
  - $dT_{ij}^{Measured}$ and σ_{ij} is found from fitting a Gaussian to the dT distribution for the antenna pair (dT = mean of Gaussian; σ = width of Gaussian) (See plot below)
  - $dT_{ij}^{Expected}$ is found from ray tracing

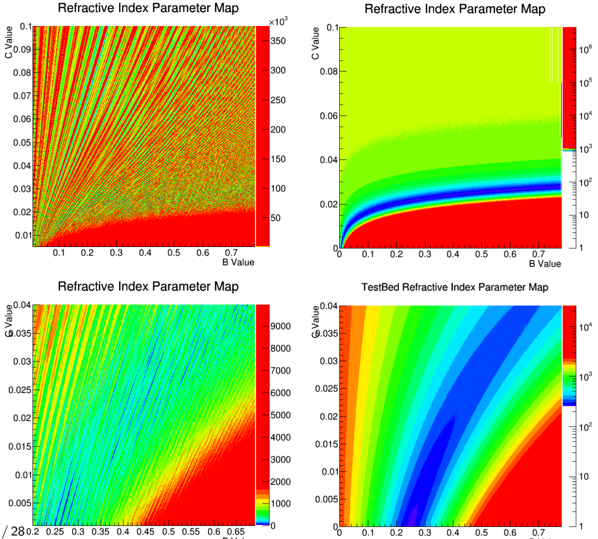
- From distribution $\chi^2 \geq \chi^2_{minimum}+1$ (with associated B and C) a distribution of IoR values can be calculated, which will then be fit with a Gaussian to obtain the IoR and error (mean and width of Gaussian) at the depth of the station used
- The TestBed and Ara03 HPol antennas will be used, which will give the IoR at 2 points, we will then fit the exponential decay model to these points to obtain a "final" result



Comparison of Previous Results to Current

- With improvements to ray tracing accuracy the previous IoR "maps" have changed significantly

← Previous | Current →

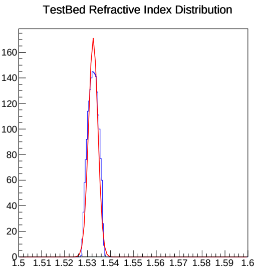


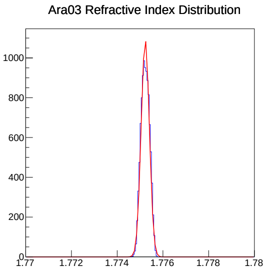
← Ara03

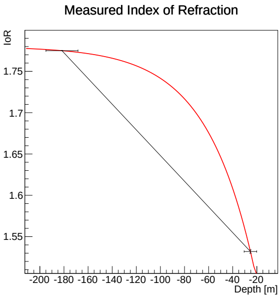
← TestBed

Refractive Index Measurement Results

- Every pair of B and C with $\chi^2 \geq (\chi^2_{\text{minimum}}+1)$ has been used to calculate an IoR value, the distribution of which is shown to the right, as well as the Gaussian fit to the distribution
- TestBed Result: 1.532 ± 0.0020
- Ara03 Result: 1.775 ± 0.0002
- Errors are statistical only, systematics have not been investigated



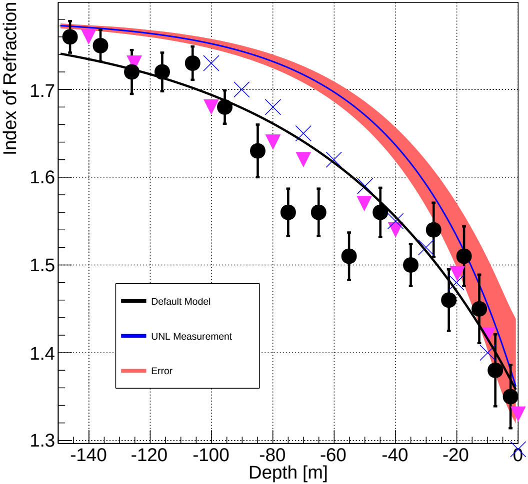




Result:

- A fit to the exponential decay model yields $B = 0.467$ and $C = 0.025$
- Current: $B = 0.4272$ and $C = 0.016$
- The fit result predicts a lower IoR at the surface and a steeper gradient toward saturation than the current model

Comparison to Previous Data

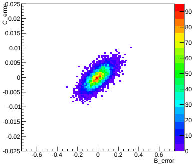


Previous Data:

- Black dots are from RICE
- Magenta triangles are from Gow density data
- Crosses are from Eisen Maud Dronning B2 core

Our Measurement:

- Blue line with red error band
- B and C errors are correlated:



- Error band is preliminary

- Previously taken index of refraction data, was obtained from *Kravchenko et al.*, The Journal of Glaciology Vol. 50, No. 171, 2004, pgs. 522-532, found here: http://icecube.wisc.edu/~mnewcomb/radio/index/rice_refraction.pdf

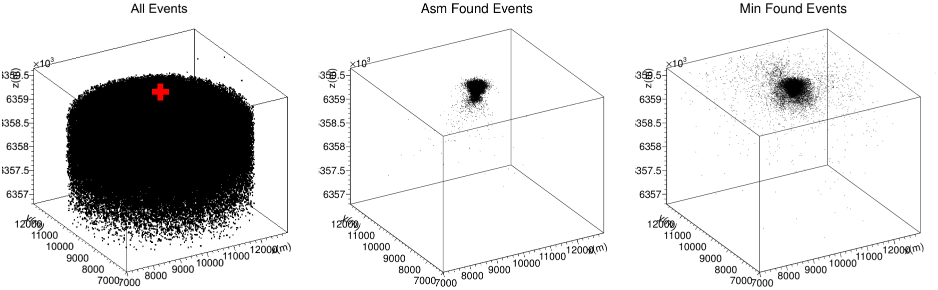
Part 5:

Radial Bias of Distant Sources

Radial Bias

Motivation:

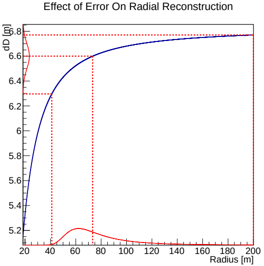
- After reconstructing an 100k event AraSim sample for an ideal station with neutrinos spread uniformly 3km around the station, we noticed that the majority of reconstructed distances were found much closer to the station than the true distance
- Both ASM and Minuit reconstruction methods observe this effect



Previous Presentation:

- See: http://ara.physics.wisc.edu/docs/0011/001126/001/RadialBiasStudy.pdf

Radial Bias

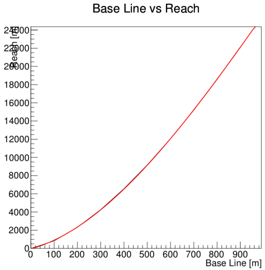


Source of Effect:

- As radial distance is increased the distance difference (dD) approaches an asymptotic value (blue curve), this non-linearity compounded with error on dT (analogous to dD, (red distribution on y-axis)), leads to a higher probability to reconstruct close to the station

Reduction of Radial Bias:

- We define the reach of a station as the distance (radius) where dD becomes asymptotic ((dD+error) $\geq$ asymptotic value)
- Using a toy simulation the reach average (from all directions) was calculated and plotted to the left
- From the reach plot, using 2 or more stations should drastically reduce the radial bias effect (increased base line)



Part 6:

Multi-station Reconstruction

Multi-station Reconstruction Review

Motivation:

- Reconstruct source position (ICL) using 2 stations (TestBed and Ara03)
- Demonstrate that increased base line can reduce the radial bias effect

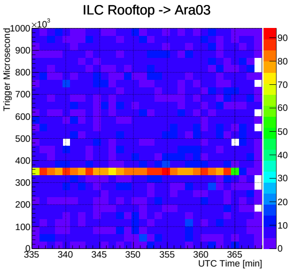
Challenge:

- The main challenge was in matching TestBed events to Ara03 events

Previous Presentation

- See previous presentation on multistation reconstruction: http://ara.physics.wisc.edu/docs/0012/001207/001/GlobalReconstruction.pdf

Multistation Reconstruction Details

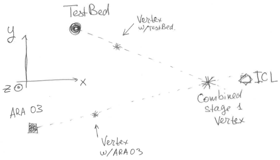


Event Matching:

- To match events, the "triggering band" (top left plot (Ara03)) for the TestBed and Ara03 was used to define the time delay between each station "capturing" the event
- Matching Criteria: TestBed and Ara03 events must land on the same GPS second and observe a time delay matching the delay found from the triggering plots

Reconstruction Procedure:

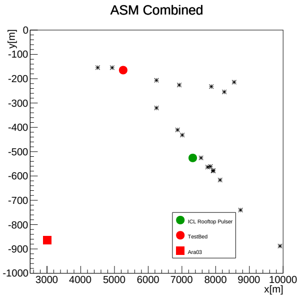
- Step 1: Pre-reconstruct both stations using ASM (analytic reconstruction)
- ASM "combined" multistation reconstruction is the intersection of the TestBed and Ara03's individual reconstructions (see bottom right plot)
- Step 2: Use minuit method to fit for the location of the lowest global χ^2

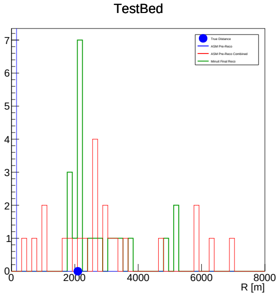


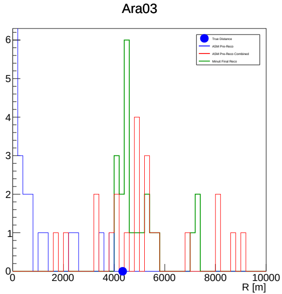
$$\chi^2_{Global} = \chi^2_{TestBed} + \chi^2_{Ara03}$$
$$\chi^2_{Station} = \sum_{i,j=1...N} (dT_{ij}^{Predicted} - dT_{ij}^{Measured})^2$$ (every antenna pair)

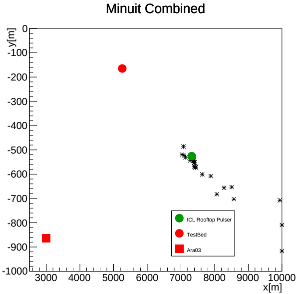
Results:

- Majority of "final" reconstructed positions are reconstructed close to the ICL
- Ara03 shows a better constraint than the TestBed
- Radial bias effects have been greatly reduced with the final reconstruction









Summary

- A versatile and accurate method to define antenna noise RMS has been developed
- Found its better to use the IoR at the average depth of an antenna pair to convert measured dT to dD for that pair, rather than the IoR at the station center
- Improved my ray tracing algorithm to use variable step sizes, in order to increase accuracy and speed
- Converging on a publishable result for the IoR measurement
- For distant sources ($\geq \approx$150m), events are reconstructed closer than their true position (radial bias). ASM and Minuit reconstruction methods have been confirmed to exhibit this effect, currently looking into radial bias effects seen by Jonathan's CSW method.
- Multi-station reconstruction helps to eliminate radial bias effects and increases accuracy of reconstructed of events

Backup: RMS Finding

2013 Ara03 D6V Pulser Runs:

- Runs 1658-1695