Refractive Index Measurement

Andrew Shultz
Ilya Kravchenko

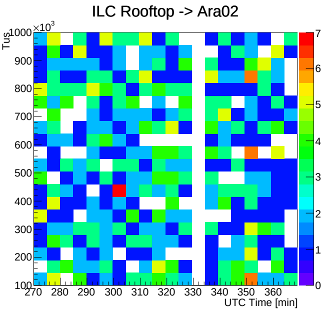
April 26, 2015

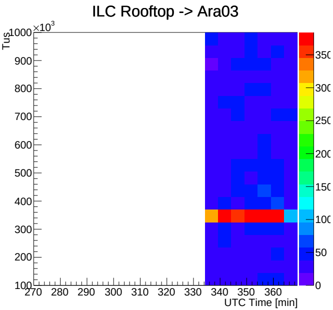
Brief History

- The goal of this study was to measure the index of refraction at the South Pole
- We were previously unable to take a measurement of the refractive index using ICL rooftop pulser data, as discussed here: `http://ara.physics.wisc.edu/docs/0011/001165/001/ICL_Rooftop_Pulser_Analysis_2013data.pdf`
- The main trouble was a large phi angle bias in reconstruction, which prevented the Minuit minimizer based measurement from converging (measurement unsuccessful)
- This presentation will discuss:
  - 1) Improvements in time finding and reconstruction
  - 2) Measurement procedure
  - 3) Measurement results

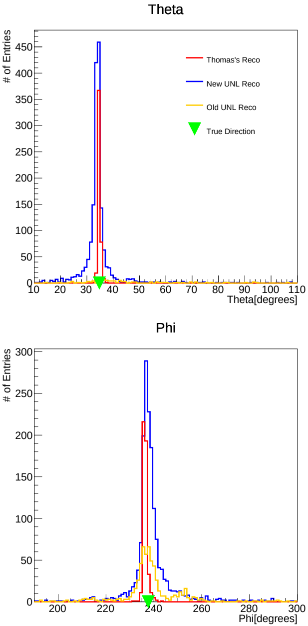
Triggering

- We expect to see a band of events, if the station is triggering on pulser events
- Below is a 2d histogram of trigger microsecond (Tus, microseconds from GPS second = 0) vs. the time of day in UTC
- For ARA03 there is a clear band during the times of ICL pulser activity
- ARA02 is missing this band and thus we will exclude ARA02's data from the measurement
- We will use the Tus band to discriminate between pulser and non-pulser events





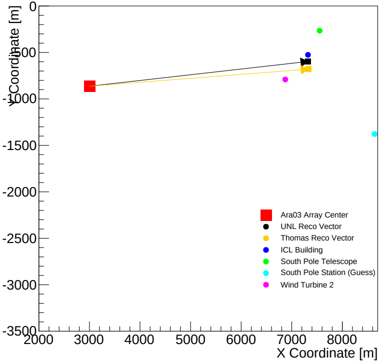
Reconstruction Results



- Here we see the reconstruction results for ARA03, yellow is UNL's previous reconstruction, blue is our current reco, and red is Thomas Meures' reco.
- Analytic sphere method (ASM) was used for yellow and blue, and red is Thomas's reconstruction using his analytic matrix method
- We used Thomas' reconstruction as a reference to understand why our reconstruction was greatly different from Thomas'
- After discussions with Thomas, we were able to improve our reco, using:
  - Station geometry corrections and cable delays from Thomas
  - A Correlation based time difference (dT) finder instead of a hit time finder (based off excursion over a threshold)

Reconstruction Before and After

- The plot shows a top view of the south pole (x-y plane)
- The vectors in the plot were found from the max bin of its corresponding reconstruction
- Our new reconstruction is about 1° off in the phi angle
- The improvement in reconstruction should make a measurement of the index of refraction possible



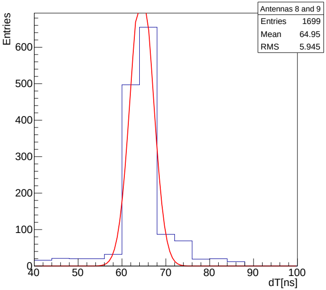
Measurement Procedure

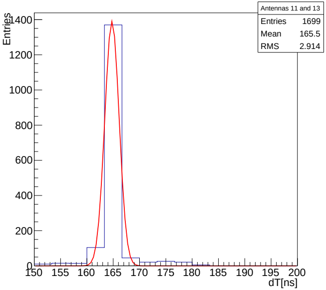
- To measure the Index of Refraction, the parameters of the current exponential decay model, n(z) $= A - Be^{Cz}$, will be minimized using Minuit
- The parameters will be minimized according to the function:

$$\chi^2 = \sum_{i=0}^{N_{ant}} \sum_{j=i+1}^{N_{ant}} \left(\frac{dT_{Meas_{ij}} - dT_{Exp_{ij}}}{\sigma_{ij}} \right)^2$$

- dT_{Measij} will be found from the maximum bin of a finely binned histogram of all dTs for each pair
  - Each dT will be found using a correlation based dT finder
- $dT_{Exp_{ij}}$ will be calculated using ray tracing
- σ_{ij} will be calculated by fitting a Gaussian to the dT distribution for each pair of antennas, the σ_{ij} is then equal to the σ of the Gaussian (see next slide)

dT Distribution

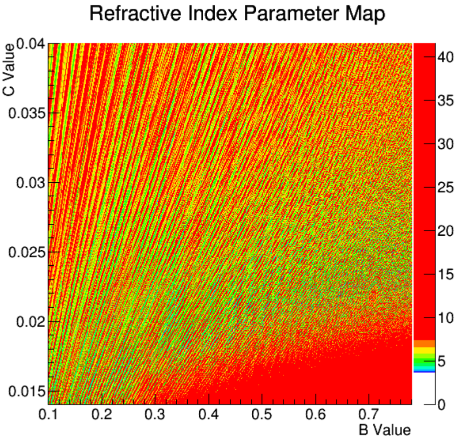




- To the left are 2 plots of 2 randomly selected antenna pairs, 8 and 9 (TH1 and TH2) as well as 11 and 13 (TH4 and BH2), each plot shows the Gaussian that was fit to the distribution in order to find σ_{ij}
- In this case $\sigma_{8,9}$ =2.624ns and $\sigma_{11,13}$ =1.362ns (see last slide for full list)
- $dT_{Meas_{ij}}$ is found from the same histograms, though with much finer binning

Minuit Fit Results

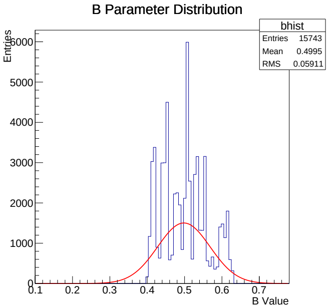
- Minuit would not converge on a minimum χ^2 if all 3 parameters are fitted for; parameter A defines the asymptotic value of the index at large depths and is well known to be 1.78+-0.005, B and C are not well defined, for this reason we will fix A and fit for B and C only
- Minuit converged to many different minima all with numerically close χ^2 values (at most 0.02 difference), depending on the initial values for B and C

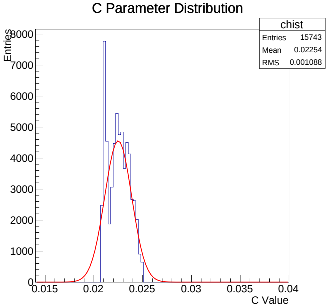


- To the left is a map of B vs C, which shows a striped pattern with many local minima
- The presence of many local minima explains why the fit result is dependant on the initial values of B and C
- A global minimum could not be definitively determined with Minuit since all convergences had very similar χ^2 values

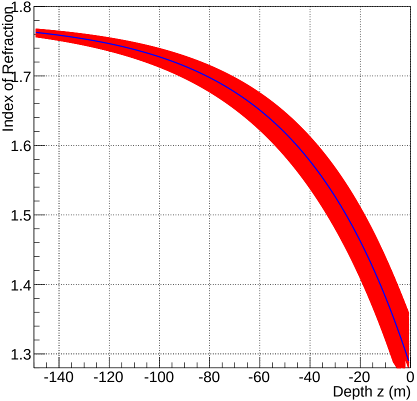
Parameter Map Minima

- To the right is the distribution of minima for B and C
- Since the local minimum values tended to be between 3.7 and 3.8 only B and C with χ^2 values between this range have been used to fill the histograms
- This distribution of minima is likely the result of error in time measurement, however we can use it to define the best values of B and C as well as the error in these parameters
- We will accomplish this by fitting a Gaussian to the distribution, the mean shall be the best value and the σ of the Gaussian will represent the error in the values for B and C





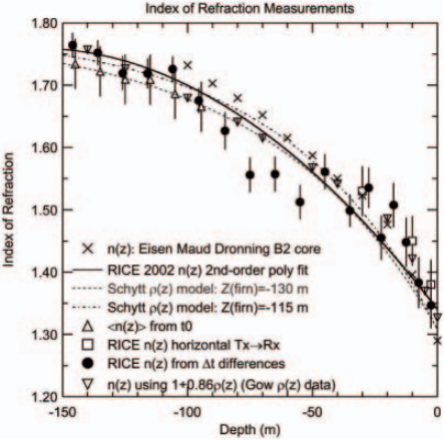
Measurement Results



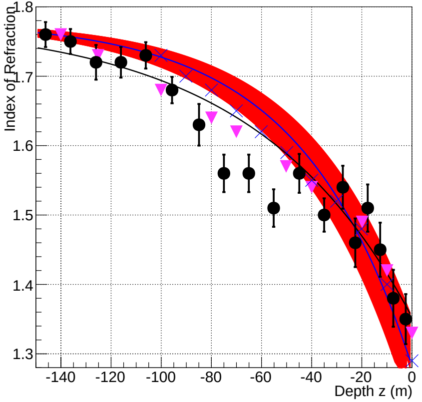
- The result of fitting a Gaussian to the minima distribution:
  - B $= 0.498 \pm (0.070)$
  - C $= 0.0225 \pm (0.0014)$
- The blue line is the measurement with a red band of error

Previous data

- 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`



Measurement Results



- The plot to the right shows previous data alongside our new index of refraction measurement
- The blue line is the new measurement with a red band of error
- The black line is the current model
- The B parameter implies a lower index at the surface which agrees well with the Eisen Maud Dronning B2 core (cyan X's)
- Our measured C parameter is larger than the current model which implies that the ice density increases faster at shallower depths and increases slower at deeper depths compared to the current model

Conclusion

- After reconciling the differences between our reconstruction and a previous reconstruction (Thomas), we decided to remeasure the index of refraction
- To measure the index, we used Minuit to find the parameters (B and C) that resulted in the lowest χ^2; parameter A needed to be fixed in order for the minimization to converge
- The presence of many minima lead to a initial value dependent convergence from Minuit
- From fitting a Gaussian to the distribution of minima we found the parameters of the current exponential decay model to be:
  - n(z)$= 1.78^{+}_{-}(0.005) - 0.498^{+}_{-}(0.070)e^{0.0225^{+}_{-}(0.0014)*\mathrm{z}}$
- Currently waiting on dedicated data from this year's pole season to expand upon our current findings

Extra - σ_{ij}

Antenna 1	Antenna 2	σ_{ij}
8	9	2.624
8	10	3.175
8	11	1.014
8	12	2.756
8	13	1.585
8	14	1.654
8	15	1.765
9	10	0.752
9	11	2.148
9	12	1.511
9	13	1.560
9	14	1.426
9	15	1.514
10	11	1.502
10	12	1.625
10	13	0.381
10	14	1.456
10	15	0.114

Antenna 1	Antenna 2	σ_{ij}
11	12	1.221
11	13	1.362
11	14	6.977
11	15	2.548
12	13	1.377
12	14	1.263
12	15	1.307
13	14	1.448
13	15	1.500
14	15	1.393