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Ray Propagation Modeling for the Detection of Ultra-High Energy Neutrinos

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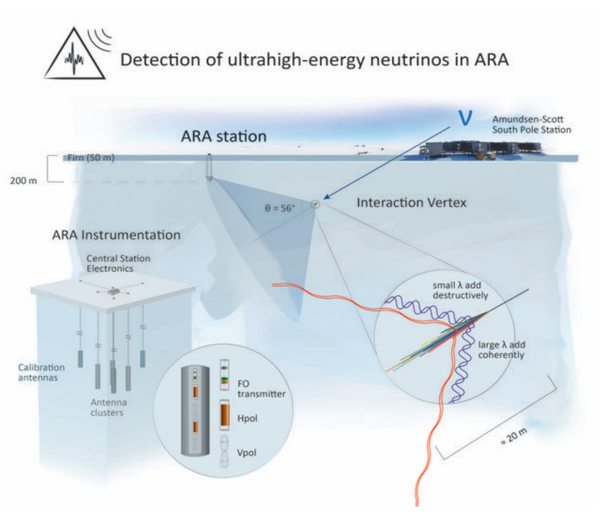
INTRODUCTION

What are neutrinos?

Neutral fermions with negligible mass. Ultra-High Energy (UHE) neutrinos (>10^{18} eV) are produced when cosmic rays interact with the cosmic microwave background (CMB).

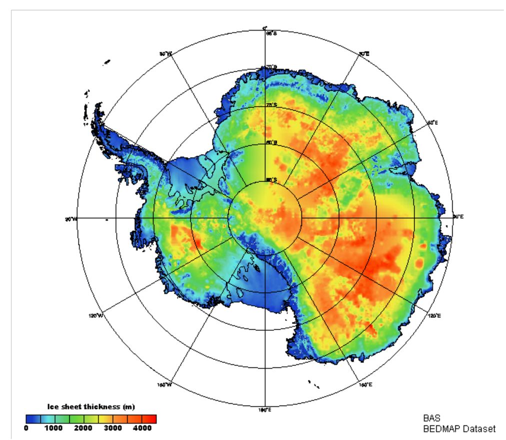
UHE neutrinos would point to some of the highest energy sources in the Universe.



Radio detection of UHE neutrinos:

When a UHE neutrino interacts with a dielectric medium, it produces EM radiation that is coherent in radio wavelengths.

Fig. 1. Neutrino detection by ARA (https://ara.wipac.wisc.edu/home)



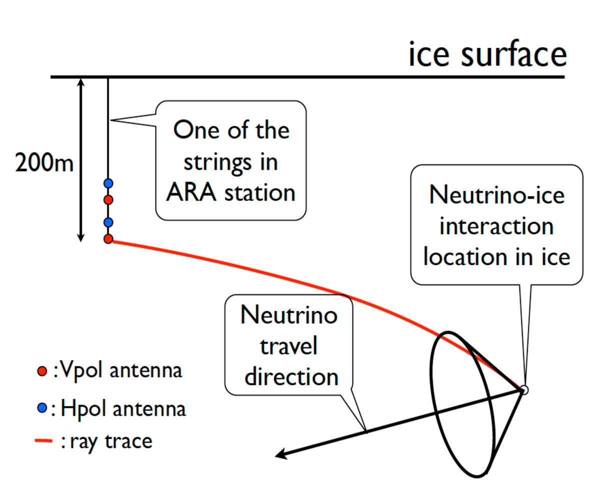
Why Antarctica?

- Covered with ~ 2000 m thick ice
- Radio attenuation length ~ 1 km

https://antarcticfudgesicles.wordpress.com/afsa-student-page/40-how-thick-is-the-ice-in-the-summer/

Raytracing:

Tracing path of rays in ice. Many efforts to do so by different collaborations. I've attempted to obtain a model that allows flexibility over many different ice locations.



Why model ray propagation?

- Study how rays travel under changing index of refraction.
- Distinguish between signal & background.
- Allows us to study impact of attenuation in ice on ray propagation.

Fig. 2. Schematic of raytracing (Hong et al., 2013)

METHODS

Modeling the index of refraction of ice:

Since the index of refraction of the ice, n(z), in the top 200 m changes with depth, z, it is important to model this change. Results from previous experiments at both South Pole & non-South Pole locations show an exponential form of n(z).

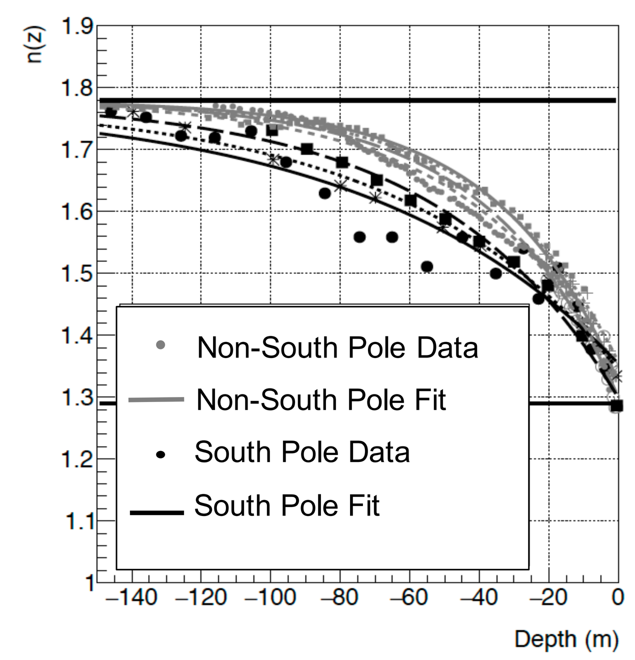


Fig. 3. Graph of refraction index of firn vs. ice depth for different ice locations in Antarctica by Prof. Jordan. C Hanson

Tracing the path of the ray:

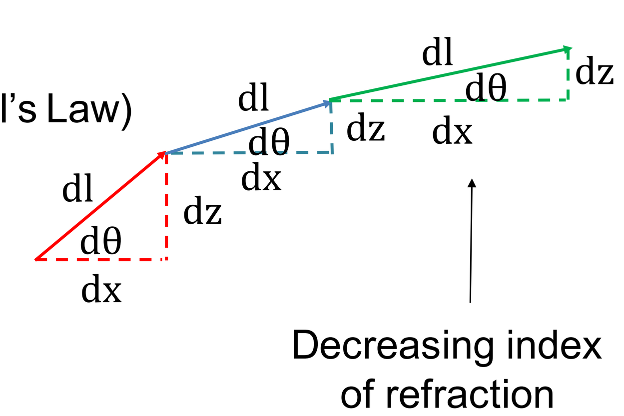
$\alpha = n(z)\cos\theta$ is constant(Snell's Law)

$\Rightarrow \frac{d\alpha}{dl} = 0 = \frac{dn}{dl}\cos\theta - n\sin\theta\frac{d\theta}{dl}$

$d\theta = \cos\theta \times \frac{c}{n^2}\cdot\frac{dn}{dz} \times dt$

$dx = \cos(\theta) \times dt \times \frac{c_0}{n}$

$dz = \sin(\theta) \times dt \times \frac{c_0}{n}$



Finding solutions as roots:

- Loop over many rays within a range of initial angles.
- Calculate the vertical miss distance from the detector.
- Interpolate vertical miss distance, z, as a function of initial angle.
- Solve the above function for z = 0.

Calculating the various parameters of ray solutions:

- Arrival time at the detector location
- Distance traveled by the ray up to the target point
- Surface reflection angles (if any)
- Initial angle
- Final angle

RESULTS

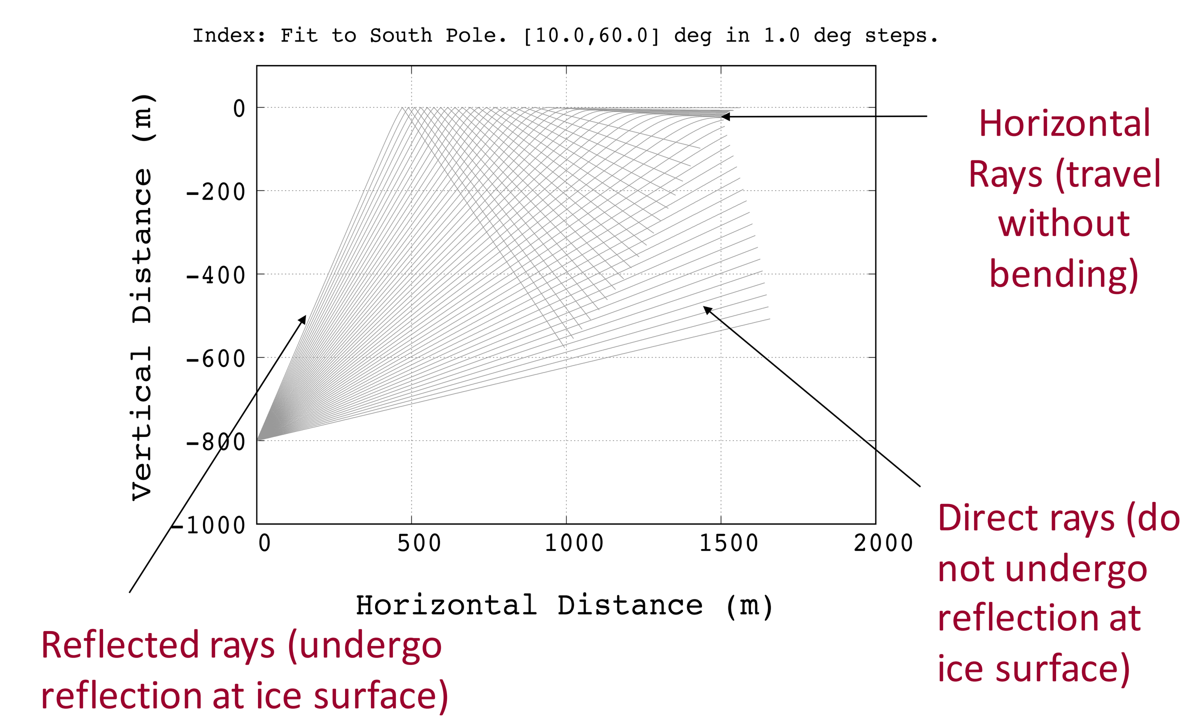


Fig. 4. Raytracing using the South Pole ice model. Plot also shows the 3 possibilities for ray propagation.

Making ray traces for an arbitrary ice model:

- Rays can hit detector directly or reflect off of the ice surface and then hit it.
- New data may indicate rays can travel horizontally from emitter to detector.

Plotting the vertical miss distance as a function of initial angle:

- Graph has two points where the vertical miss distance is zero
- Two solutions: one is direct ray, other is reflected ray.

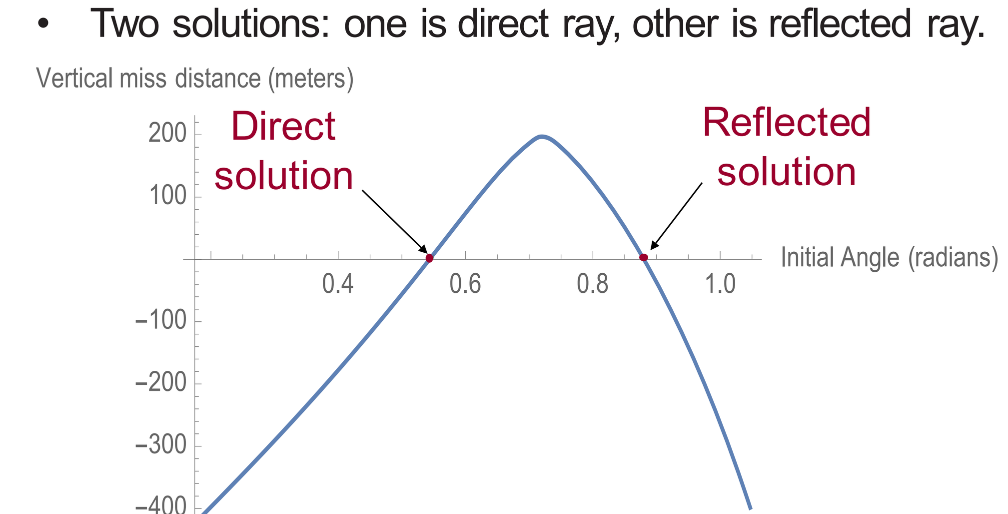


Fig. 5. Graph of vertical miss distance vs. initial angle

Making ray traces of the ray solutions:

- Each of the rays misses the detector by a few centimeters, which is reasonable.
- This shows our method works.

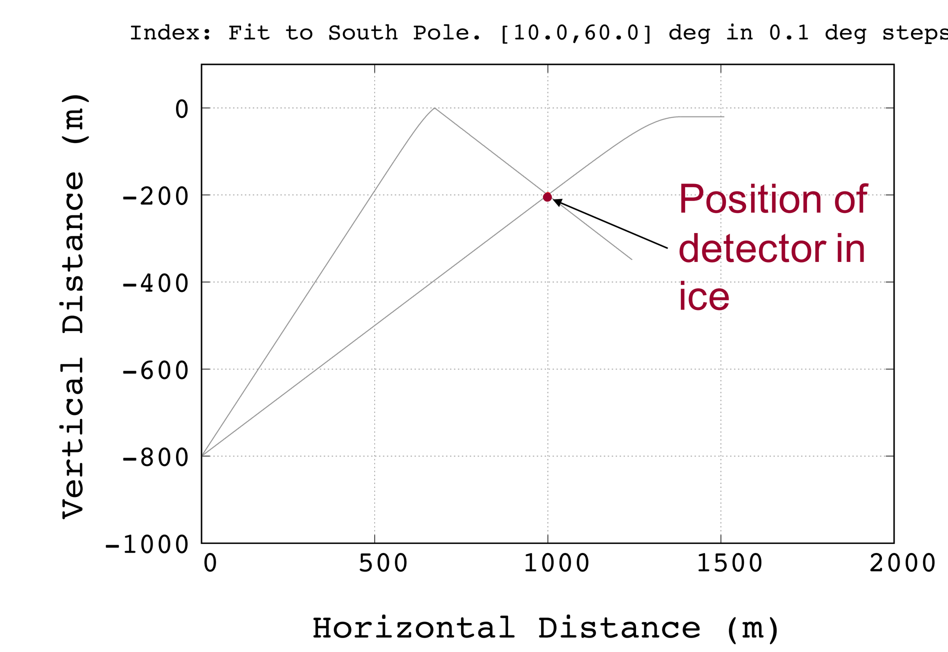


Fig. 6. Simulation of the two rays which served as the best solutions using this method

CONCLUSIONS

Ray tracing in ice allows us to study the propagation of rays in a medium with changing index of refraction. It also allows us to study the impact of attenuation in ice on ray propagation & to better distinguish between signal & background.

FUTURE WORK

We would like to be able to use this algorithm in our simulations, mainly to study the effect of different ice models on the detected number of neutrinos.

BIBLIOGRAPHY

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2. "Simulation of the ARA Experiment for the Detection of Ultra-High Energy Neutrinos," Eugene Hong, A. Connolly C.G. Pfender, *Proceedings, 33rd International Cosmic Ray Conference (ICRC 2013):Rio de Janeiro, Brazil, July 2-9, 2013.*

ACKNOWLEDGEMENTS

I thank the Summer Undergraduate Research Institute for offering me a generous scholarship to work on this over the summer. I would like to thank my advisor Prof. Amy Connolly for all the support. I would also like to thank Dr. Chris Weaver, who has helped me with this research as well. Many thanks to everyone else I work with in the lab, who have made this endeavor fun and worth while. Also, special thanks to the NSF Career Award 125557 and ARA Grant NNX15A20G.