Advanced Propagation: Greenland Case Study and Parabolic Equations

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This talk covers two related topics related to “advanced propagation”

- The use of FDTD modeling to describe some measurements done in Greenland in 2013.
  - Paper: `https://inspirehep.net/literature/1675844`
  - Hopefully you already understand from the previous talk that FDTD (finite-difference time-domain) is a computationally-expensive way to solve Maxwell’s Equations on a grid.
- The potential of Parabolic Equation Methods for in-ice radio propagation modeling
  - Preprint: `https://arxiv.org/abs/2011.05997`

Summit Station 2013 measurements

- Downhole receiving antenna at variable depth
- Surface transmitting antenna, at varying distance, rotated to maximize received signal strength
- Surprisingly (at the time), signals received in "shadow region" (where there is no raytracing solution due to ray bending), albeit at reduced amplitude.
- Attempt to explain inspired use of FDTD methods for this problem. Using FDTD with empirical ice models qualitatively reproduces the results.

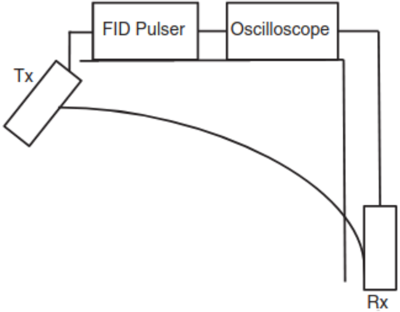
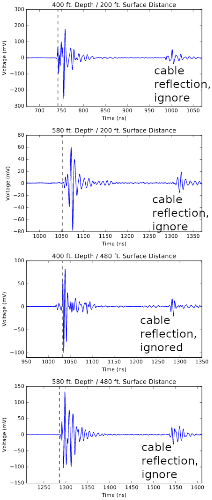


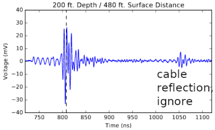
FIG. 9. A simplified schematic of the experimental setup, as deployed at Summit Station, Greenland. The receiving antenna was placed down a borehole that was filled with drilling fluid to ∼100 ft depth, and the feed of the transmitting antenna was placed ∼3 ft below the surface using an auger drill. The front-end electronics and triggering scheme are the same as in the in-air measurements shown in Fig. 7.

Measurements (from https://inspirehep.net/literature/1675844)

unshadowed

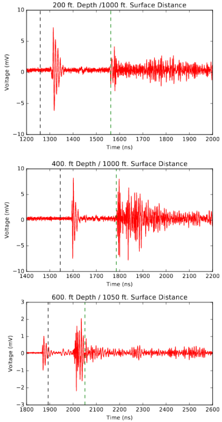


shadowed in some firn models



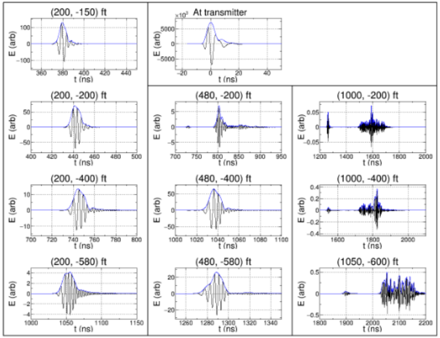
dashed lines show FDTD predictions for first/second pulse, averaged across firn models

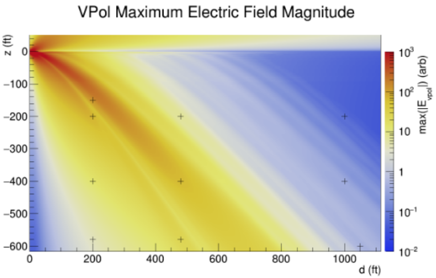
shadowed in all firn models



FDTD results

Movies at `https://users.rcc.uchicago.edu/~cozzyd/fdtd_movies/`!
Example waveforms below for one of the firn models (refraction index based on neutron scattering in top 30 m, fit to all models below 30 m()





FDTD Discussion

- The main utility here is probably not because we expect it to matter for neutrinos observations (though we might need to consider what happens near the surface or at caustics), but to better understand how RFI can reach our antennas.
- Matching qualitative effects has been demonstrated. Quantitatively matching measurements is hard because you need to model the ice and antennas properly.
- Simulations like this at this scale or larger only tractable with cylindrical symmetry
  - Can push to a few km radius, but becomes more complicated (massive multi-day MPI job)
  - Clever use of reciprocity and lookup tables may be useful for analysis/simulation.
- In 3D, maximum achievable volume much smaller, but simulation becomes more interesting for physics:
  - Doing a 3D FDTD simulation of Askaryan emission in a changing index of refraction medium or of an impacting air shower would probably be very useful to understand near-field effects and how non-homogeneity affects things
  - This is on the edge of the computing resources I have available, and something that's perenially on my plate...
  - Such a study has been done with cylindrical symmetry in a homogeneous medium already (`https://arxiv.org/abs/1012.5155`)

Parabolic Equation Methods

- Parabolic Equation (PE) methods are an approximate way to solve the wave equation in the "paraxial case" that allows for a computationally-efficient "marching" solution, where each range step only depends on the previous one.
- "Paraxial" means that the propagation is mostly in one direction; the farther you stray from the main direction of motion, the less accurate the solution.
- Commonly used in e.g. undersea acoustics, seismic waves, atmospheric radio propagation.
  - Came across it in the context of ANITA and refraction in the troposphere.
- In the literature, PE is only applied to very shallow index of refraction gradients much less sharp than the firn transition (and the surface-to-air transition!).
- But... Steven Prohira tried it in-ice anyway to see what happens, comparing to FDTD as a reference
  - `https://arxiv.org/abs/2011.05997` describes the first attempt at this (some things still very much *ad hoc*, there is still plenty left to figure out)
  - Qualitatively has many similar features to FDTD, capturing wave-like phenomena not captured by raytracing, but details of phases and such are not completely captured

Example in shadow zone

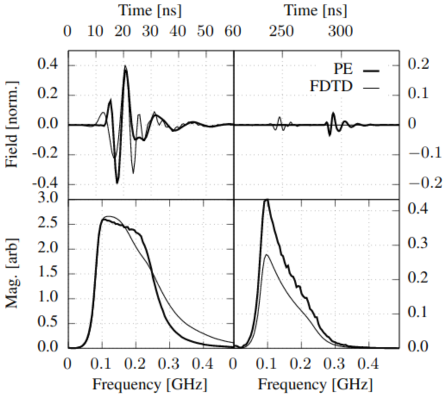


FIG. 12. Time domain (top) and frequency domain (bottom) comparisons between PE (thick solid line), and FDTD (thin solid line) for a source at $x, z = (0, -30)$ m and a receiver at $x, z = (250, -2)$ m, with a functional $n(z)$ profile for the South Pole. The columns in the time and frequency domain plots correspond to the first and second signals, respectively.

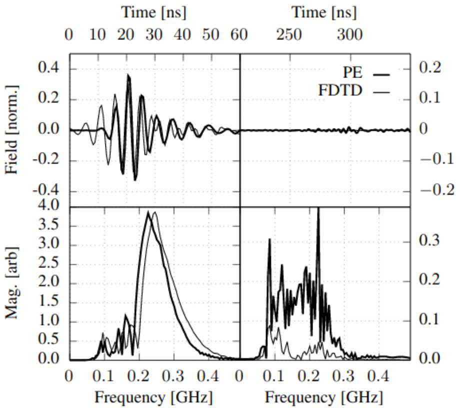


FIG. 13. Time domain (top) and frequency domain (bottom) comparisons between PE (thick solid line), and FDTD (thin solid line) for a source at $x, z = (0, -30)$ m and a receiver at $x, z = (250, -2)$ m, with $n(x, z)$ corresponding to a linear interpolation between SPICE core 1 at $x = 0$ and SPICE core 2 at $x = 300$. The columns in the time and frequency domain plots correspond to the first and second signals, respectively.

PE Discussion

- My goal here is mostly to let you know that this exists and is being developed.
- Occupies an intermediate position between FDTD (very accurate, very slow) and raytracing (no wave-like effects, very fast).
  - In 2D this is nice, but not necessarily critical because FDTD is feasible (but very inconvenient) at up to a few km with cylndrical symmetry
  - But, PE may be fast enough that it can be interfaced directly in simulations with some degree of practicality, offering an opportunity to supplant raytracing
- And, PE should be tractable in 3D, allowing for modeling of e.g. distant Askaryan radiation, signals in shallow LPDA antennas,potential non-cylindrical symmetry in the ice, etc..
  - That said, this isn't something that's implemented at all yet
- As they say, "stay tuned"