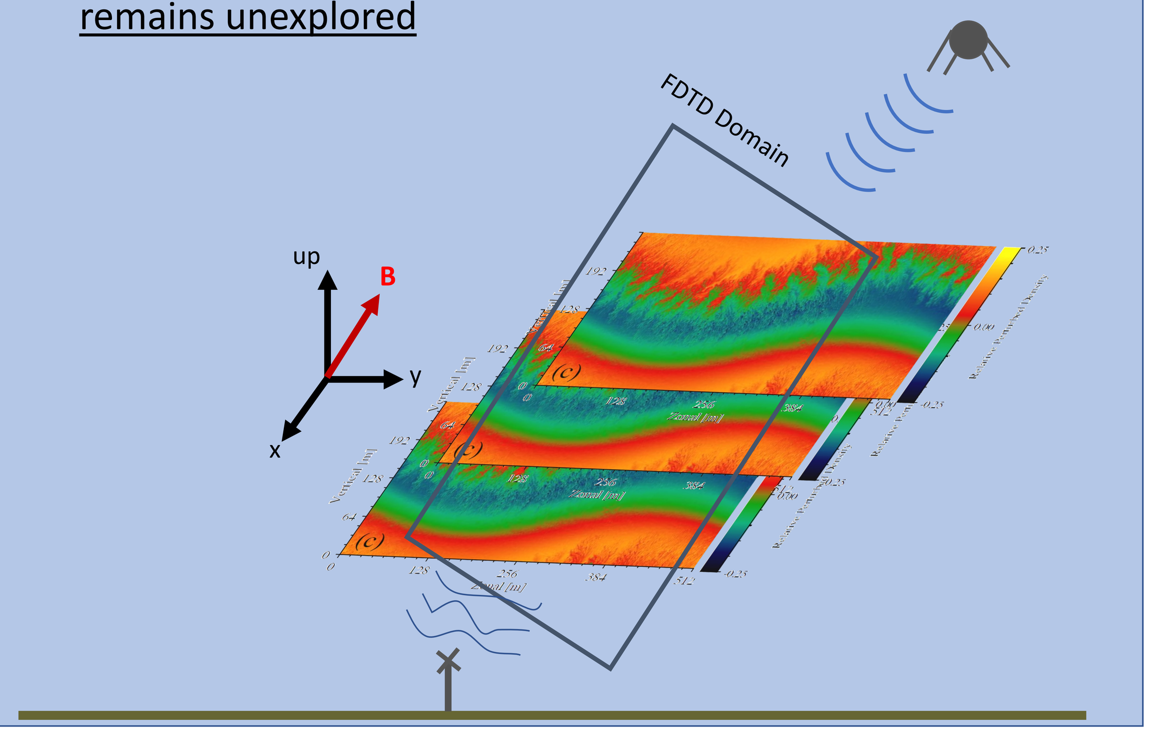
Simulating the Effects of Small-Scale Irregularities on HF Scintillation

Alexander Green[1], William Longley[2], Matthew Young[3], Yakov Dimant[1], Meers Oppenheim[1]
(1) Boston University, (2) New Jersey Institute of Technology, (3) University of New Hampshire

Motivation

Ionospheric Scintillation

- Frequently disrupts satellite communication
- One of the most regular and important forms of space weather
- Causes ranging errors and sometimes complete loss of signal (loss of lock)
- Short timescale amplitude and phase fluctuations of radio/GNSS signals
- Driven by ionospheric density irregularities and instabilities
- Observed primarily at edges of polar cap patches in high latitude ionosphere, associated with the gradient drift instability
- Scintillation by small scale ionospheric irregularities remains unexplored

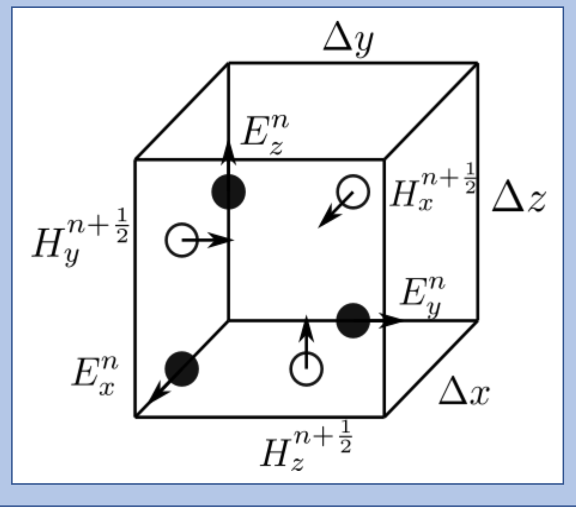


Finite-Difference Time-Domain Simulations

- Direct solution to Maxwell's equations on a spatial grid introduced by *Yee* (1966)
- Plasma effects coupled to FDTD simulation using momentum equation for electrons

$$\frac{\partial \vec{J_e}}{\partial t} + \nu_e \vec{J_e} = \epsilon_0 \omega_{pe}^2 \vec{E} - \overrightarrow{\omega_{ce}} \times \vec{J_e}$$

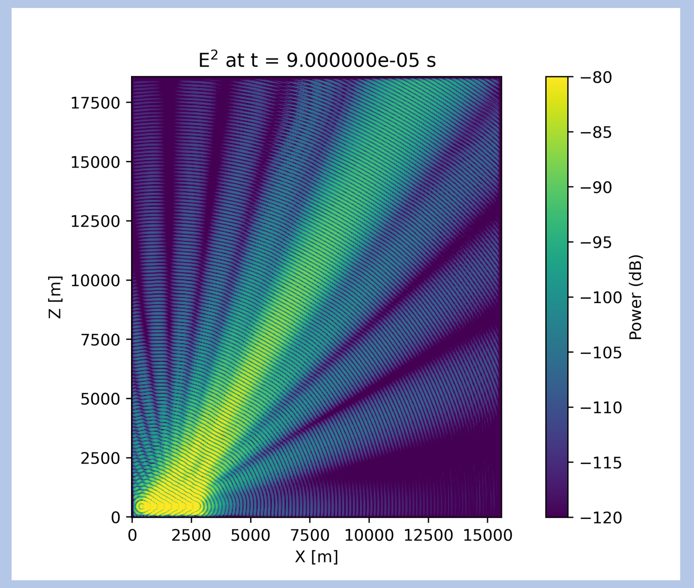
- Captures all wave/plasma effects such as refraction, Faraday rotation, phase/group delay, etc.



FARR Finite-Difference Time-Domain Code

FARR FDTD Core Features

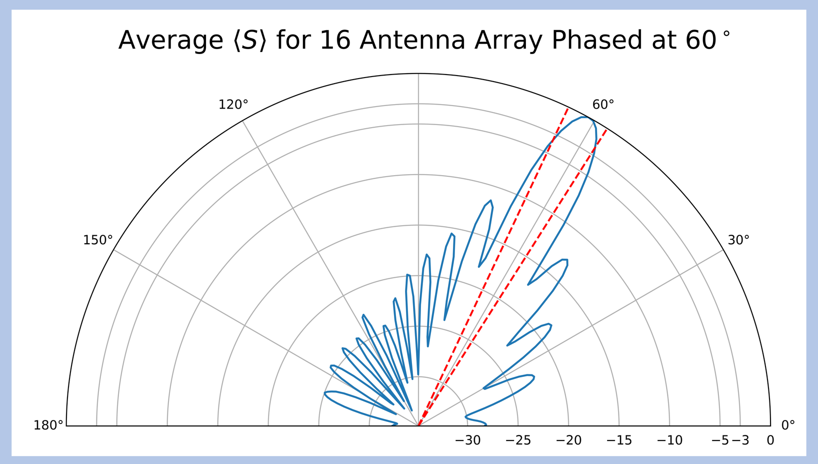
- 3D domain decomposition and MPI parallelization
- Perfectly Matched Layer (PML) absorbing boundary condition
- Effects of a magnetized, collisional plasma
- Easily couples to any external simulation/model
  - Reads in electron density array
- Near to far field transform (NTFF)
  - Time domain signal for E and B at any location outside main grid
  - Compute Radiation Patterns
- Realistic Antenna/Array sources for HF propagation
- Total field/ scattered field plane wave sources



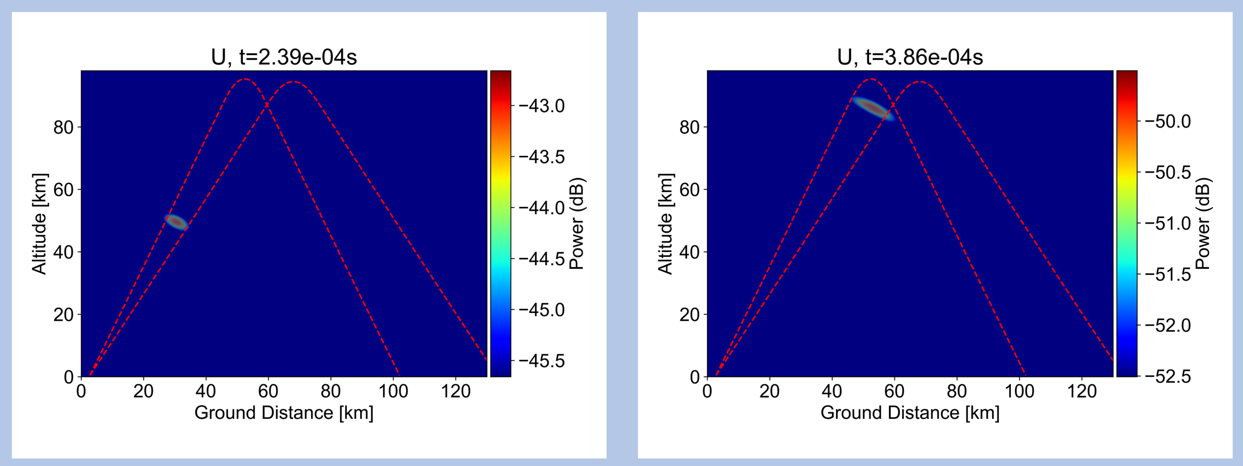
FARR FDTD simulation of a 1 MHz, 16 element array, phased at a 60° elevation angle. The simulation is run on 4 separate processors, demonstrating realistic beamforming and the perfectly matched layer boundary condition.

Comparison with Ray Tracing

- 1 MHz pulse launched at 60° elevation angle with background electron density from IRI
- Simulated using a 16-element phased array in FARR
- Numerically traced using PHaRLAP code with elevation angles spanning HPBW from FDTD simulation

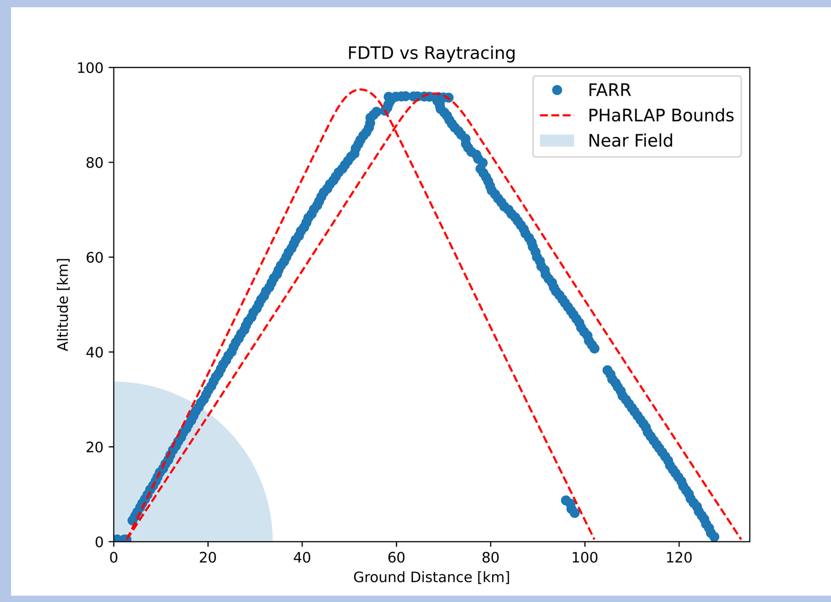


Radiation pattern for 16 element half-wave dipole array, phased at 60°, found using NTFF transform. Red dashed lines indicate the theoretical -3dB beamwidth



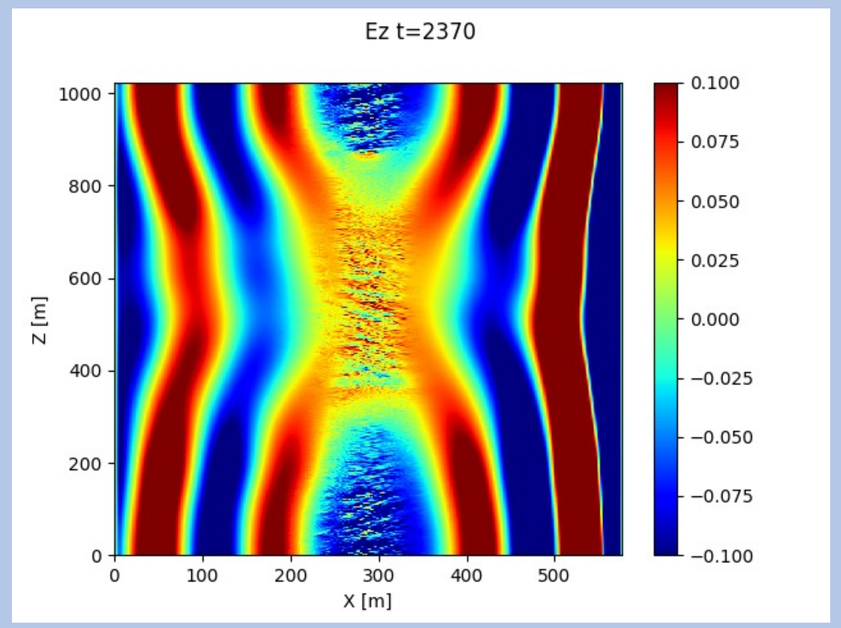
FARR FDTD simulation of a 1 MHz, 16 element array, phased at a 60° elevation angle. The simulation is run on 4 separate processors, demonstrating realistic beamforming and the perfectly matched layer boundary condition.

IRI Electron Density Profile



Comparison of 1 MHz ray path in FARR vs PHaRLAP. Blue dots indicate the location of maximum energy in the main lobe at each timestep in FARR (tracing the ray path). Red dashed lines indicate bounds of the -3dB beamwidth from rays launched in PHaRLAP.

Next Step, Adding Density Irregularities



Vertical, 1 MHz plane wave incident on meter-scale Farley-Buneman irregularities in E-region (100 km). Significant distortion of the original wavefront is observed. Background electron density is an IRI profile with altitude increasing from left to right.

Conclusions

Summary

- Developed a new high-performance Finite-Difference Time-Domain code
- Designed for radio wave propagation in magnetized, collisional plasmas like Earth's Ionosphere
- FDTD matches raytracing with large scale gradients, but provides far more information
- Small scale irregularities cause significant distortion of the original signal

Next Steps

- Further explore scintillation by irregularities with scale near wavelength of radio signal
- Characterizing backscatter from ionospheric instabilities such as gradient drift and Farley-Buneman
- Large scale runs to reconstruct scintillation indices on the ground

Note: Movies of some figures are available online at ***tinyurl.com/farr-fdtd***

Acknowledgements

This work was supported by NASA LWS grant 80NSSC21K1322. The authors acknowledge the Texas Advanced Computing Center (TACC) at The University of Texas at Austin for providing HPC resources that have contributed to the research results reported here (NSF grant ACI-1053575).

References

Luebbers, R. J., Kunz, K. S., Schneider, M., & Hunsberger, F. (1991). A finite-difference time-domain near zone to far zone transformation (electromagnetic scattering). *IEEE Transactions on Antennas and Propagation*, *39*(4), 429–433. doi:10.1109/8.81453

Samimi, A., & Simpson, J. J. (2015). An Efficient 3-D FDTD Model of Electromagnetic Wave Propagation in Magnetized Plasma. *IEEE Transactions on Antennas and P ropagation*, *63*(1), 269–279. doi:10.1109/tap.2014.2366203

Taflove, A., & Hagnes, S. C. (2005). *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (3rd ed.). Artech House Inc.

Yee, K. (1966). Numerical solution of initial boundary value problems involving maxwell\textquotesingles equations in isotropic media. *IEEE Transactions on Antennas and Propagation*, *14*(3), 302–307. doi:10.1109/tap.1966.1138693

Young, M. A., Oppenheim, M. M., & Dimant, Y. S. (2017). Hybrid simulations of coupled Farley-Buneman/gradient drift instabilities in the equatorial E region ionosphere. *Journal of Geophysical Research: Space Physics*, *122*(5), 5768–5781. doi:10.1002/2017ja024161