# A Generalized Tool for Modeling Radio Wave Propagation in Earth's Ionosphere

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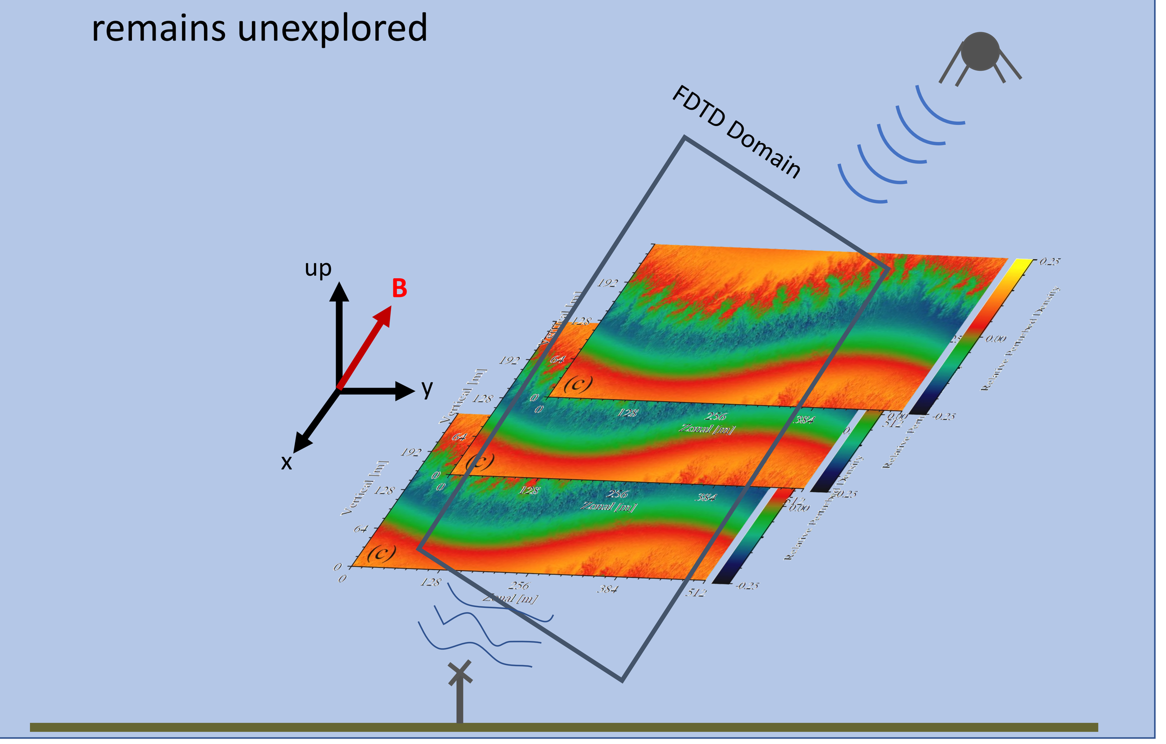
## Motivation

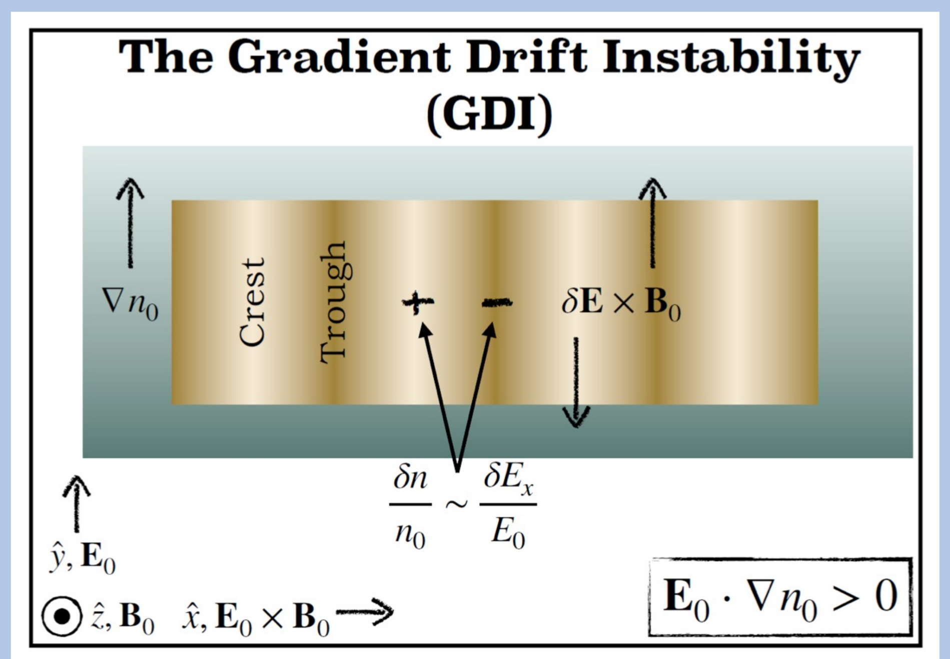
### Ionospheric Scintillation

- 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




### Gradient Drift Instability

- Electrostatic plasma instability driven by density gradients parallel to ambient electric field
- Occurs on very large spatial scales
- Can trigger secondary meter scale Farley-Buneman instability




Schematic of the gradient drift instability adapted from *Young* (2019)

## FARR Finite-Difference Time-Domain Code

### 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

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

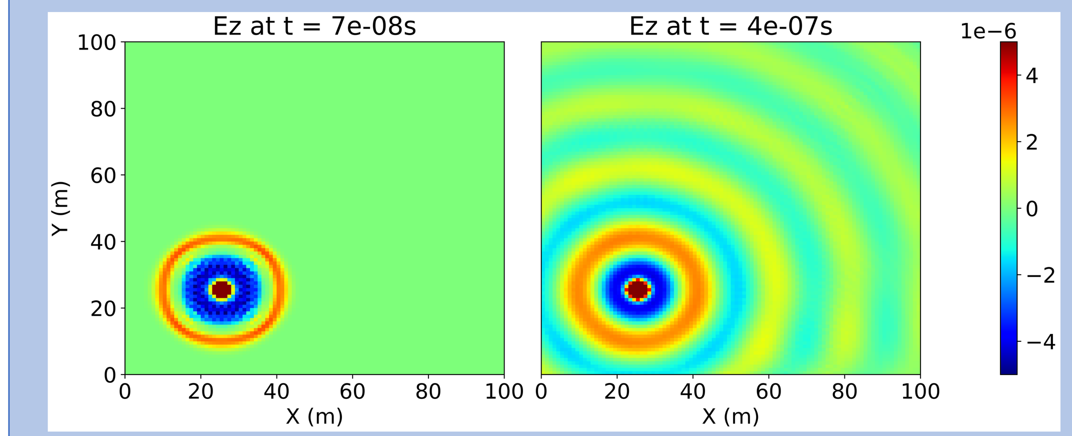
- Captures all wave/plasma effects such as refraction, Faraday rotation, phase/group delay, etc.

### Modeling High Latitude Scintillation

- Explore scintillation caused by irregularities with scale comparable to wavelength of radio signal
- Use 3D particle in cell simulations to model gradient drift and secondary Farley-Buneman instabilities
- Incorporate local plasma densities onto FDTD grid
- Time domain near to far field transform
- Compare waveforms and scintillation indices to existing data

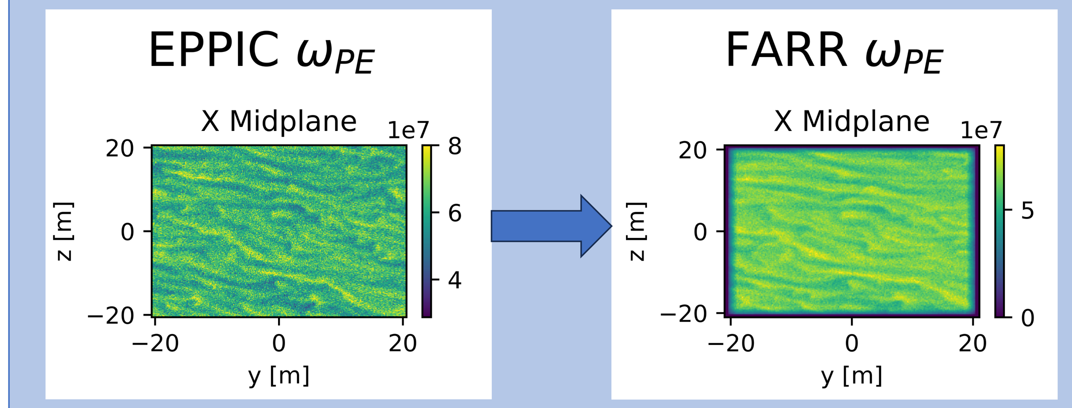
### FARR FDTD Core Features

- New high-performance FDTD code for radio wave propagation
- 3D domain decomposition and MPI parallelization
- Perfectly Matched Layer (PML) absorbing boundary condition
- Effects of a magnetized, collisional plasma



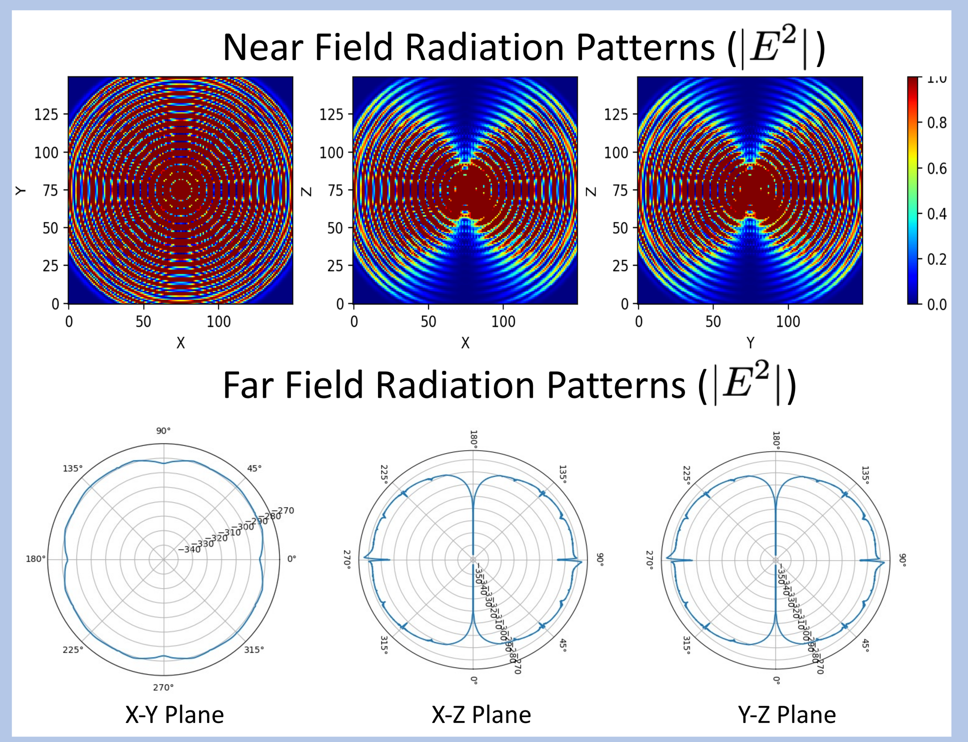

FARR FDTD simulation of a sinusoidal perturbation in Ez at early (left) and late (right) times. The simulation is run on 4 separate processors and shows the perfectly matched layer boundary condition.

- Easily couples to any external simulation/model
  - Preprocessing Python routine
  - Reads in electron density array
  - Standard input into FDTD



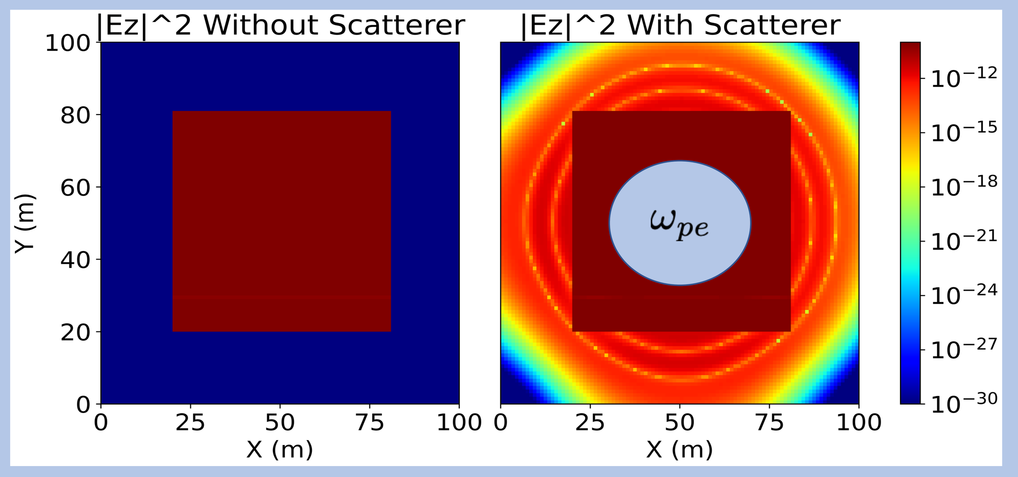

An example of taking an external electron density model from a particle in cell code (EPPIC) and applying the Python preprocessing routine to generate a standard input for the FARR Finite Difference Time Domain code.

- Near to far field transform
  - Time domain signal for E and B at any location outside main grid




Radiation pattern from a dipole antenna (z polarized), modeled using FARR. The top row shows the near field $|E^2|$ , and the bottom row (log scale) shows the far field at a radius of 6 km, generated using the near to far field transformation.

- Total field/ scattered field wave sources
  - Novel technique for TF/SF sources in a magnetized, collisional plasma




FARR simulation of a sinusoidal plane wave introduced with a TF/SF source for two different scenarios. The figure on the left is free space, and the right shows scattering from a spherical, overdense region of plasma at the center of the domain.

## 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
- Adaptable for a variety of background plasma conditions
- Core routines are implemented

### Next Steps

- Explore scintillation by irregularities with scale near wavelength of radio signal
- Simulate radar scattering off ionospheric instabilities
- Desired satellite-ground geometry and outputs
- Further validation

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

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