Simulating the Effects of Small-Scale Irregularities on HF Scintillation

Alexander Green[1], William Longley[2], Matthew Young[3], Meers Oppenheim[1]

(1) Boston University, (2) New Jersey Institute of Technology, (3) University of New Hampshire

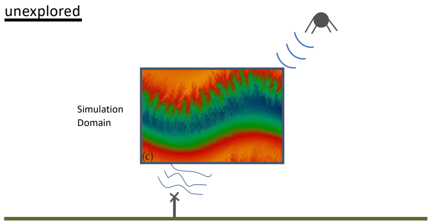
Abstract

Trans-ionospheric signals are regularly disrupted by interactions with plasma irregularities, leading to both phase and amplitude scintillation. The length scale of these irregularities can span several orders of magnitude from centimeters to kilometers. Modeling ionospheric radio wave propagation therefore necessitates an approach that is inherently multi-scale and that can evaluate both refractive and diffractive effects. We demonstrate the use of FARR, a new finite-difference time-domain (FDTD) code that solves Maxwell's equations, for evaluating HF scintillation. Because the FDTD method is a full vector solution of Maxwell's equations, we can explore both diffractive and refractive effects. Here we present simulations of HF communication through irregularities generated by the Farley-Buneman instability, which occurs regularly in the E-region ionosphere. We also demonstrate the ability to generate realistic scintillation spectra using FARR.

Background

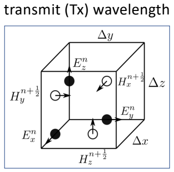
Ionospheric Scintillation

- Defined as: short timescale amplitude and phase fluctuations of radio/GNSS signals
- Scintillation frequently disrupts satellite and bottomside communication
- One of the most regular and important forms of space weather
- Driven by ionospheric density gradients and irregularities
- Observed primarily at edges of polar cap patches in high latitude ionosphere, associated with the gradient drift instability. Also generated by spread-F/plasma bubbles in low-latitude ionosphere.
- Scintillation by small scale ionospheric irregularities remains unexplored



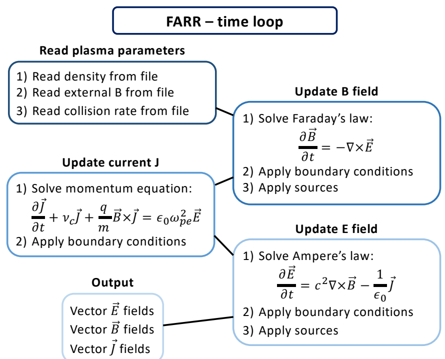
Finite-Difference Time-Domain Simulations

- Direct solution to Maxwell's equations on a spatial grid introduced by *Yee* (1966)
- Distinct from geometric optics/ray tracing methods
  - Captures all wave/plasma effects such as diffraction, Faraday rotation, phase/group delay, etc.
  - Allows us to evaluate effect of density irregularities at and below the transmit (Tx) wavelength



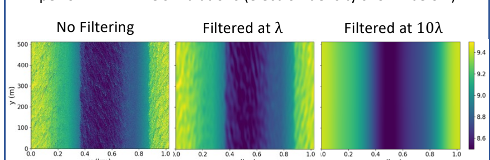
FARR Code

- 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 grid
  - Compute Radiation Patterns
- Realistic Antenna/Array sources for HF propagation
- Total field/ scattered field plane wave sources



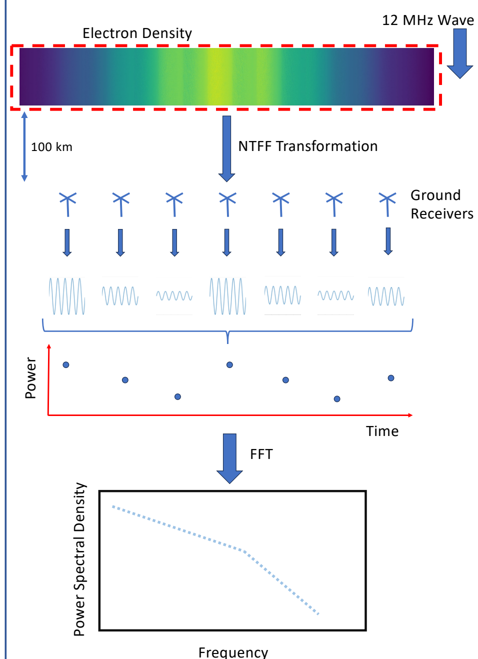
Plasma Conditions

- To model the interaction of radio waves with the ionosphere, we use external models of electron density
- Here we consider the secondary Farley-Buneman instability (FBI) associated with a primary gradient drift instability
- FBI is simulated using a well-tested hybrid particle-in-cell code, EPPIC, with fluid electrons and particle ions
- We consider an orientation in the low-latitude ionosphere, and perform 2D EPPIC simulations (electron density shown below)

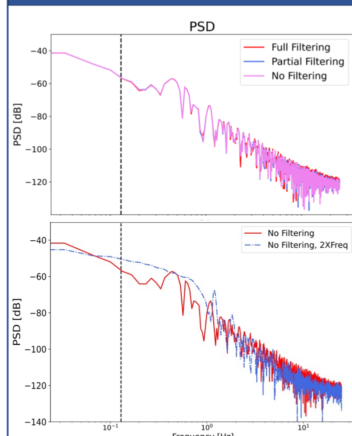


- For use in FARR, we filter the electron densities from EPPIC, with λ associated with either at 12 or 24 MHz Tx frequency
- Filtering allows us to separate the contributions from large-scale refractive gradients and small-scale diffraction caused by meter-scale turbulence

Making Scintillation Spectra



Results



- Power Spectral Density at 12 MHz and various levels of filtering
- Little diffractive scintillation observed for this case
- Power Spectral Density shows steeping at higher frequencies, and shallowing at lower

Conclusions

- FARR is a new open-source, high-performance FDTD code
- FARR is designed for radio wave propagation in magnetized, collisional plasmas like Earth's Ionosphere
- Using FDTD method, we can generate scintillation indices and power spectral densities expected on the ground
  - Allows for realistic, direct comparison with observations and theoretical frameworks
- Here, for HF frequencies (12, 24 MHz) we do not observe appreciable scintillation by Farley-Buneman instability

Future Work

- Evaluating scintillation caused by the gradient drift (plus secondary FBI) instability
- Evaluating scintillation at higher, VHF frequencies
- FDTD modeling with electron densities from other models, e.g. GEMINI
- Direct comparison with scintillation observed by the GEMINI-SIGMA model

Links

FARR is available on our Gitlab page: ***tinyurl.com/farr-code***

Get the paper here: ***tinyurl.com/farr-paper***

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