FDTD for Geophysical Applications

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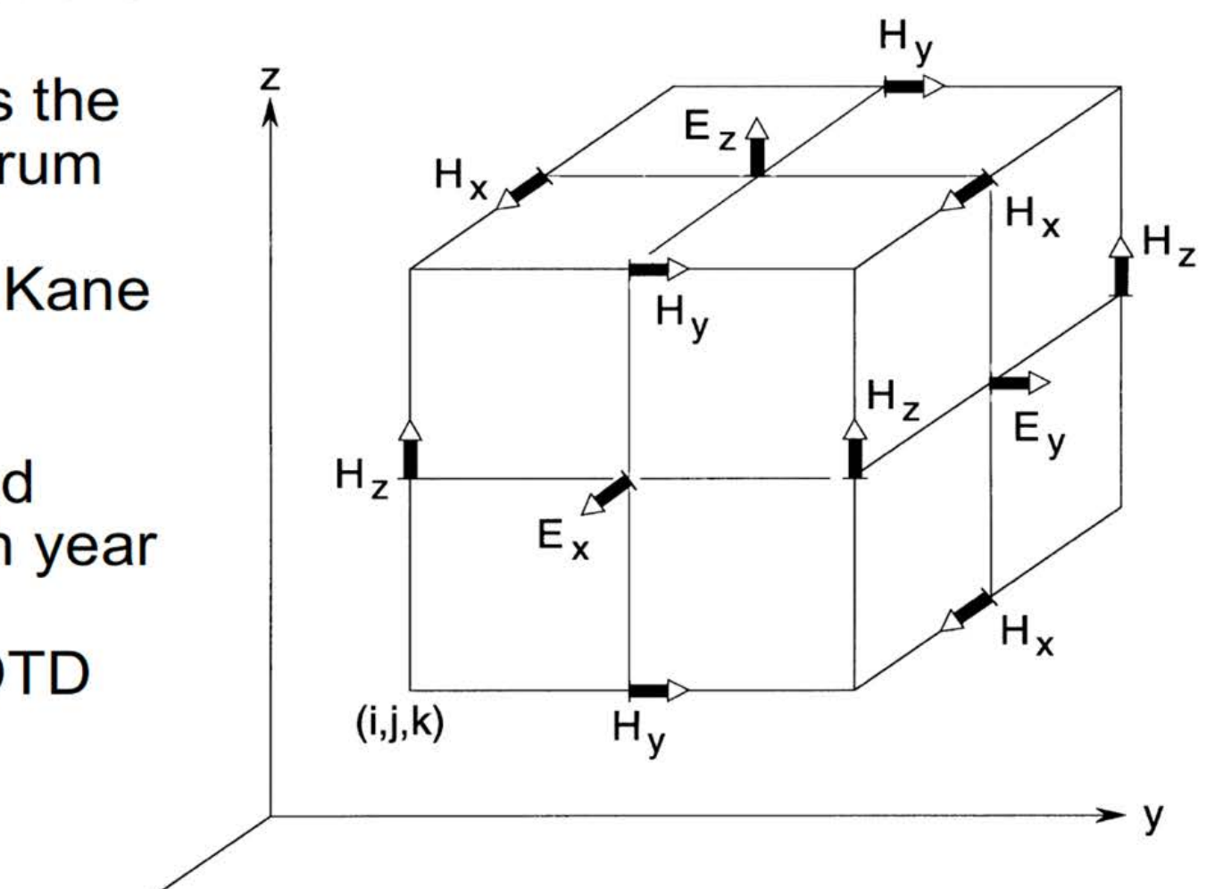
ABSTRACT

The finite-difference time-domain (FDTD) method is a robust method that solves Maxwell's equations in time and over a spatial grid. Our research group has developed FDTD models of electromagnetic waves propagating globally around the world in the Earth-ionosphere waveguide [2] and through the ionosphere [3]. This poster provides an overview of our modeling capabilities, and it highlight a recent research activity relating to power line emissions (PLE) and harmonic radiation (PLHR) propagating into and through the ionosphere.

INTRODUCTION

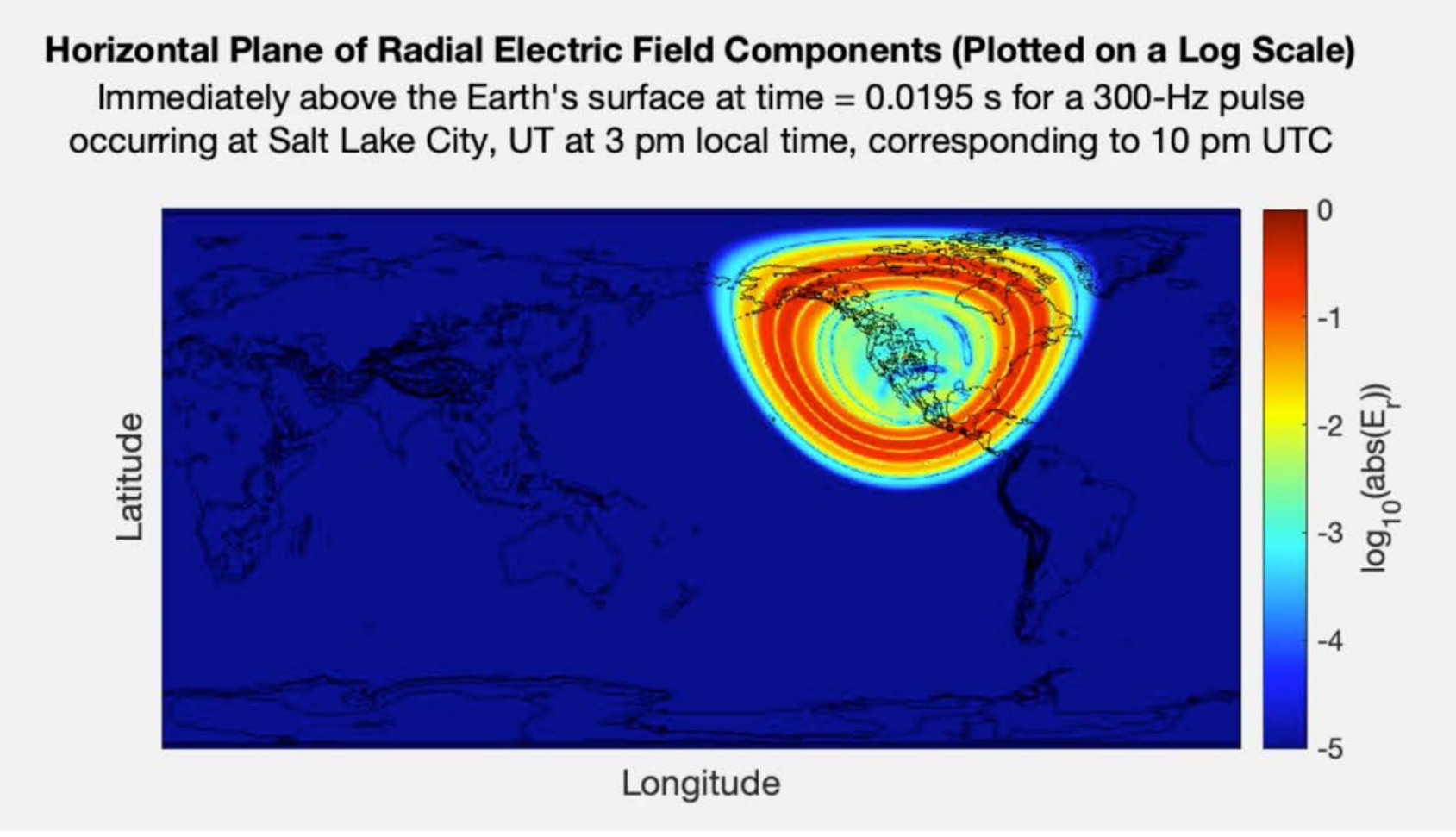
Finite-Difference Time-Domain (FDTD) Method

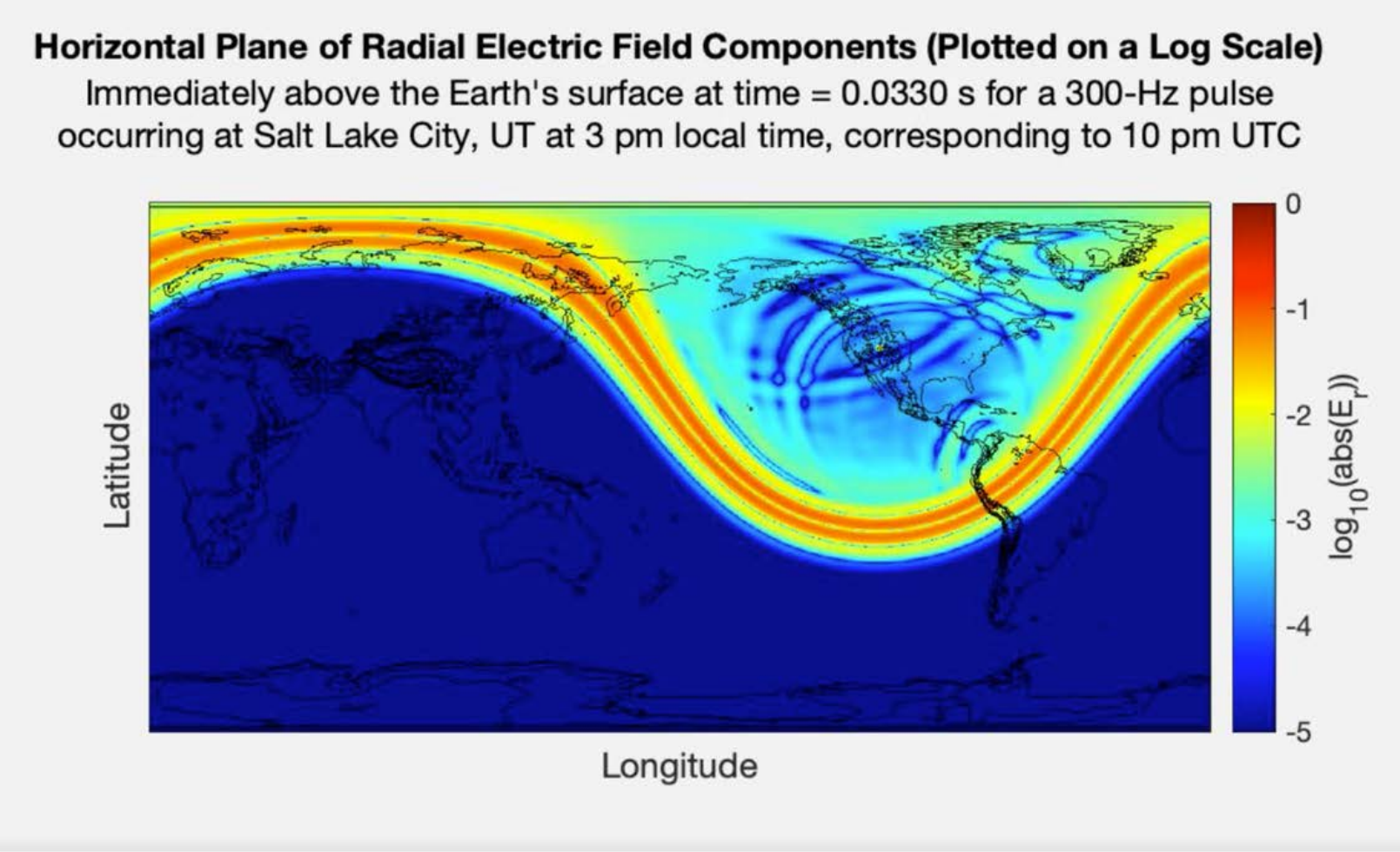
- Solves Maxwell's equations
- May be applied across the electromagnetic spectrum
- Introduced in 1966 by Kane Yee.
- 1000's of FDTD-related papers published each year
- 10's of commercial FDTD solvers available

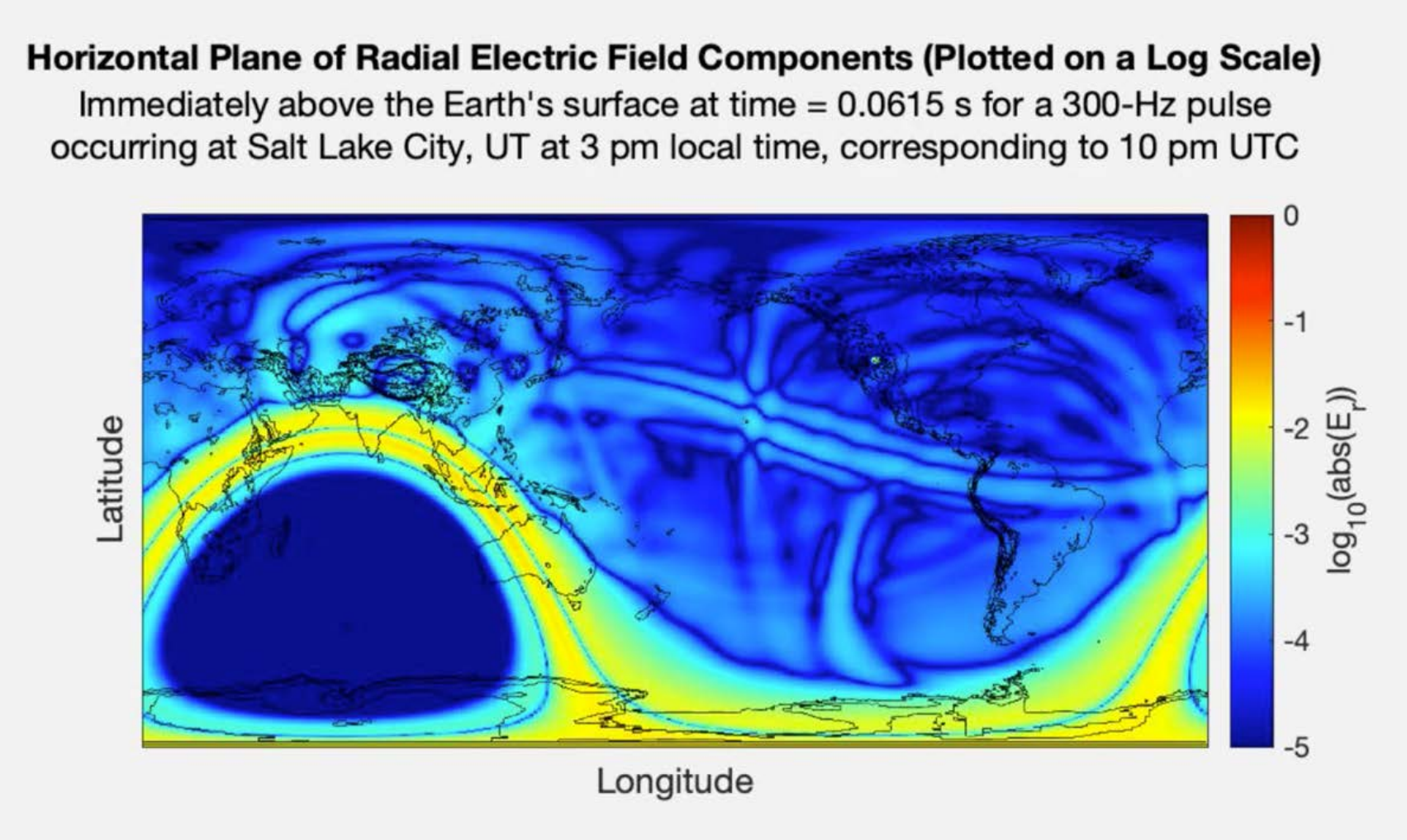


Source: A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method,* Norwood, MA: Artech House, 2005.

Example Applications:
1) Remote-sensing of localized ionospheric anomalies
2) Geolocation
3) Space weather effects on the operation of electric power grids
4) Scintillation in the Ionosphere


Horizontal Plane of Radial Electric Field Components (Plotted on a Log Scale)
Immediately above the Earth's surface at time = 0.0195 s for a 300-Hz pulse occurring at Salt Lake City, UT at 3 pm local time, corresponding to 10 pm UTC

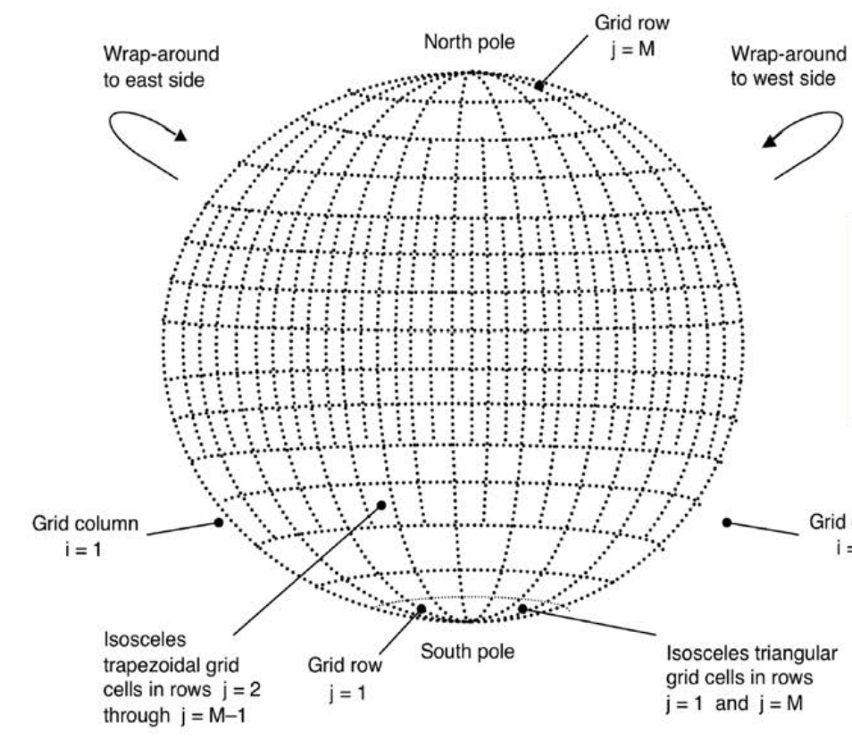

Horizontal Plane of Radial Electric Field Components (Plotted on a Log Scale)
Immediately above the Earth's surface at time = 0.0330 s for a 300-Hz pulse occurring at Salt Lake City, UT at 3 pm local time, corresponding to 10 pm UTC


Horizontal Plane of Radial Electric Field Components (Plotted on a Log Scale)
Immediately above the Earth's surface at time = 0.0615 s for a 300-Hz pulse occurring at Salt Lake City, UT at 3 pm local time, corresponding to 10 pm UTC

METHODS

There are three generations of models (1) a latitude-longitude grid; (2) a geodesic (hexagonal-pentagonal) grid; and (3) a Cartesian-based grid. A magnetized ionospheric plasma model has been incorporated into these grids.

Model Generation #1: A 3-D Latitude-Longitude Global Model



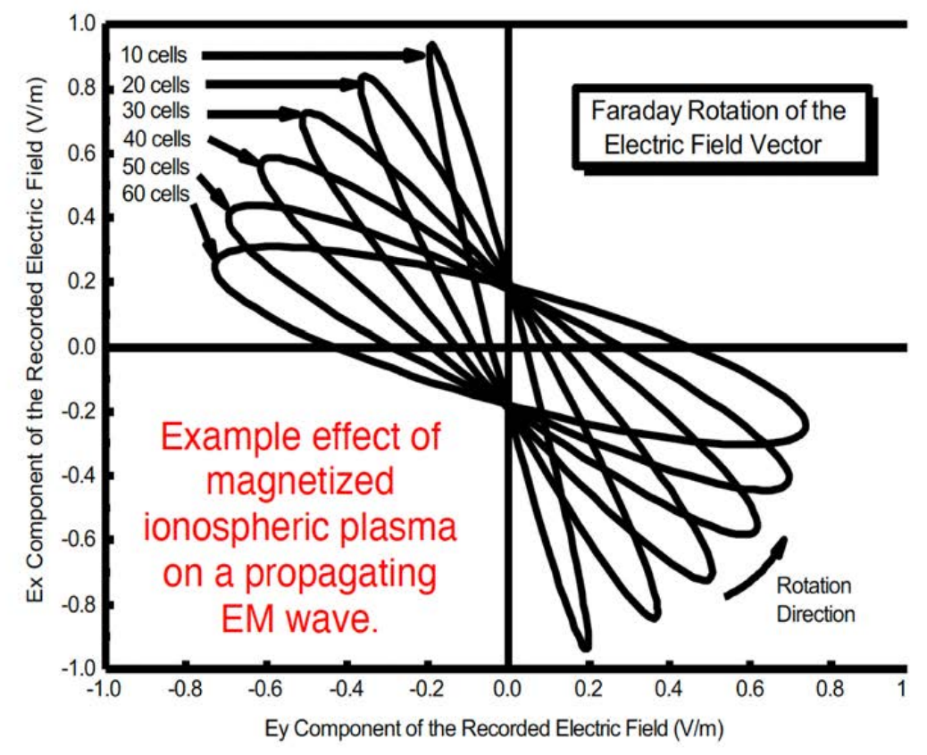
- Not drawn to scale.
- Can extend 100's of km radially from the Earth's surface.

Source: Simpson & Taflove, *IEEE Trans. Ant. Prop.*, pp. 443-451, 2004.

Magnetized Ionospheric Plasma

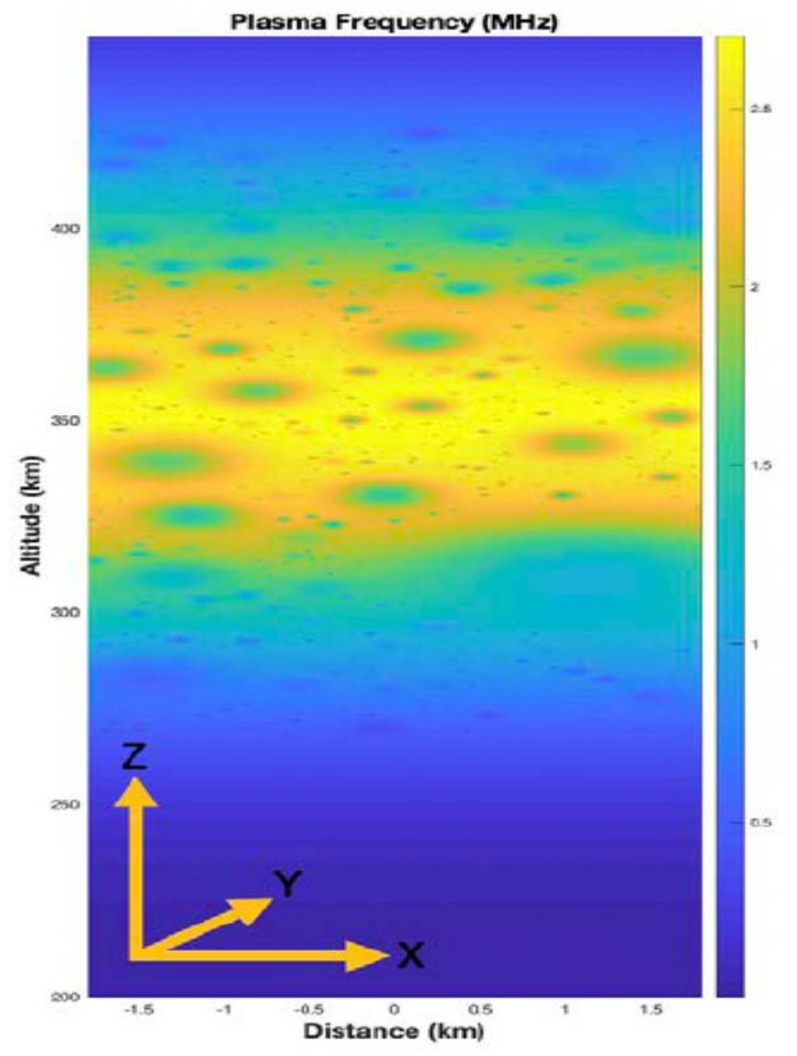
$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$
$$\nabla \times \mathbf{H} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}_I + \mathbf{J}_S$$
$$\frac{\partial \mathbf{J}_e}{\partial t} + \nu_e \mathbf{J}_e = \varepsilon_0 \omega_{Pe}^2 \mathbf{E} + \omega_{Ce} \times \mathbf{J}_e$$
$$\frac{\partial \mathbf{J}_p}{\partial t} + \nu_p \mathbf{J}_p = \varepsilon_0 \omega_{Pp}^2 \mathbf{E} - \omega_{Cp} \times \mathbf{J}_p$$
$$\frac{\partial \mathbf{J}_n}{\partial t} + \nu_n \mathbf{J}_n = \varepsilon_0 \omega_{Pn}^2 \mathbf{E} + \omega_{Cn} \times \mathbf{J}_n$$
$$\mathbf{J}_I = \mathbf{J}_e + \mathbf{J}_p + \mathbf{J}_n$$

e – *electron*
p – *positive ion*
n – *negative ion*
$\omega_{Pe}, \omega_{Pp}, \omega_{Pn}$ – *plasma frequency*
$\omega_{Ce}, \omega_{Cp}, \omega_{Cn}$ – *gyrofrequency*
ν_e, ν_p, ν_n – *collision frequency*



Sources: Yu & Simpson, *IEEE TAP*, 58(2), 469-478, 2010; Samimi & Simpson, *IEEE TAP*, 2015; Pokhrel *et al.*, *IEEE TAP*, 66:9, 2018.

High frequency EM wave propagation into and through the ionosphere



2-D slice of the modeled 3-D perturbed ionosphere with a polar cap patch present with its irregularities (right profile) for F layer by DMSP satellite. The color scheme corresponds to the plasma frequency

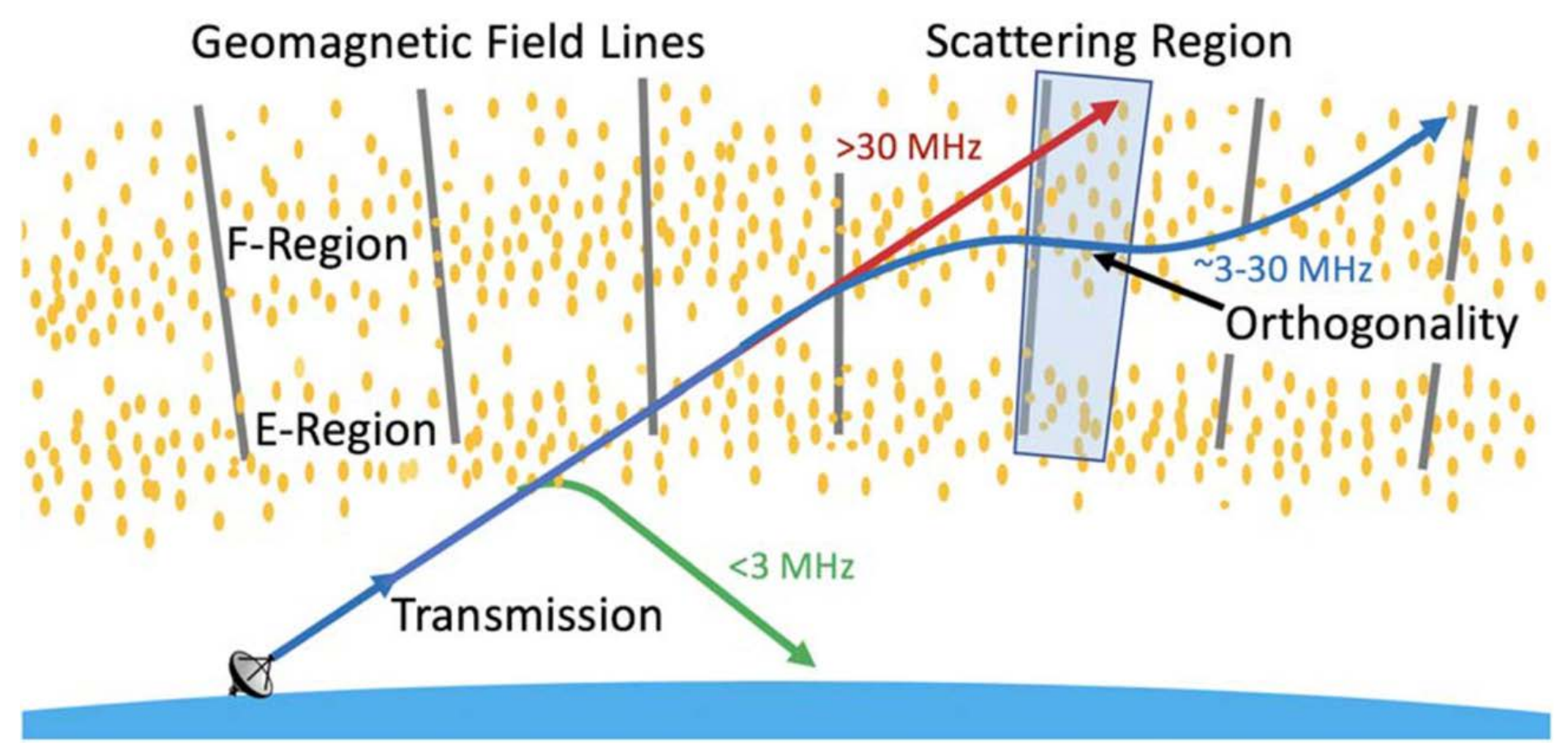
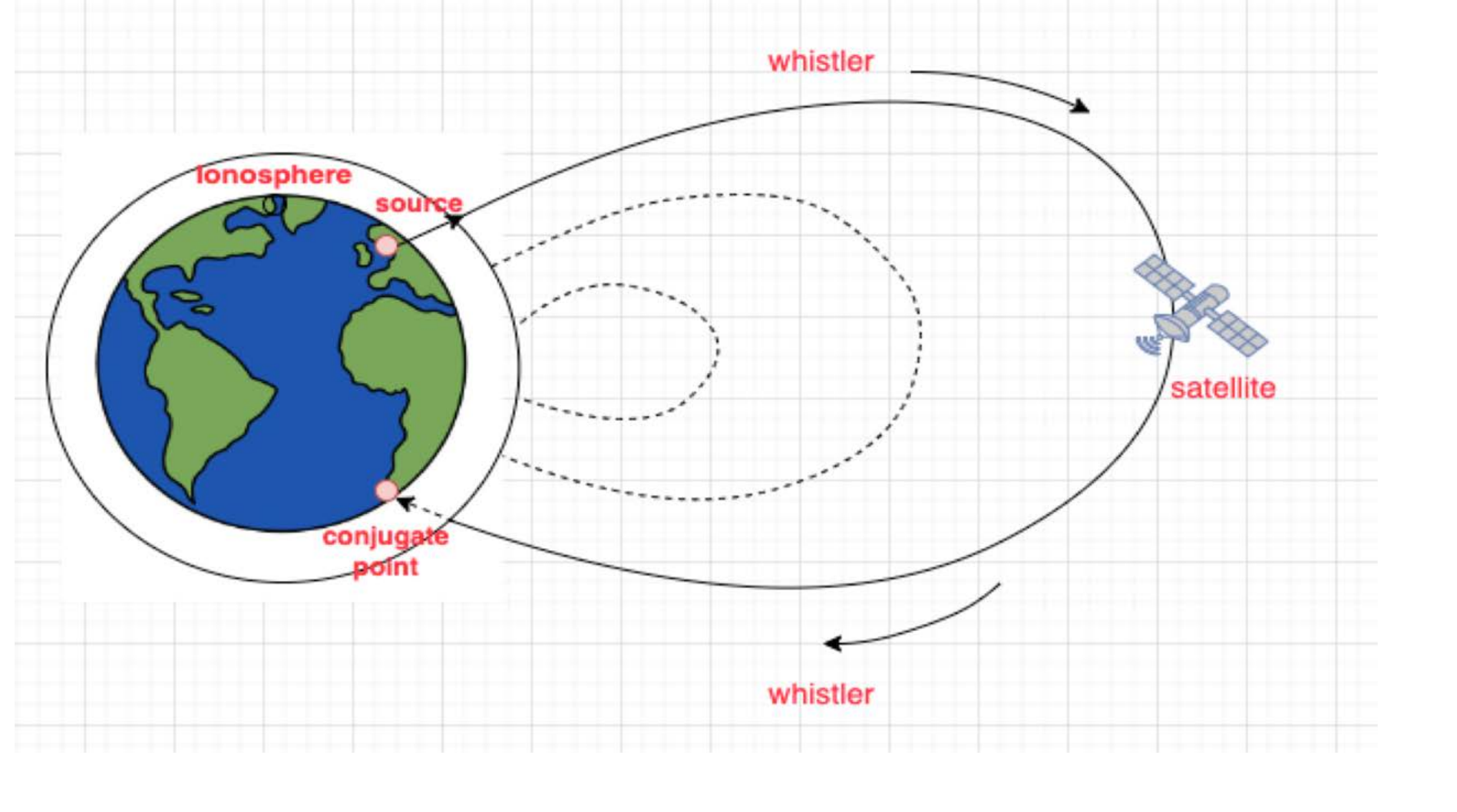


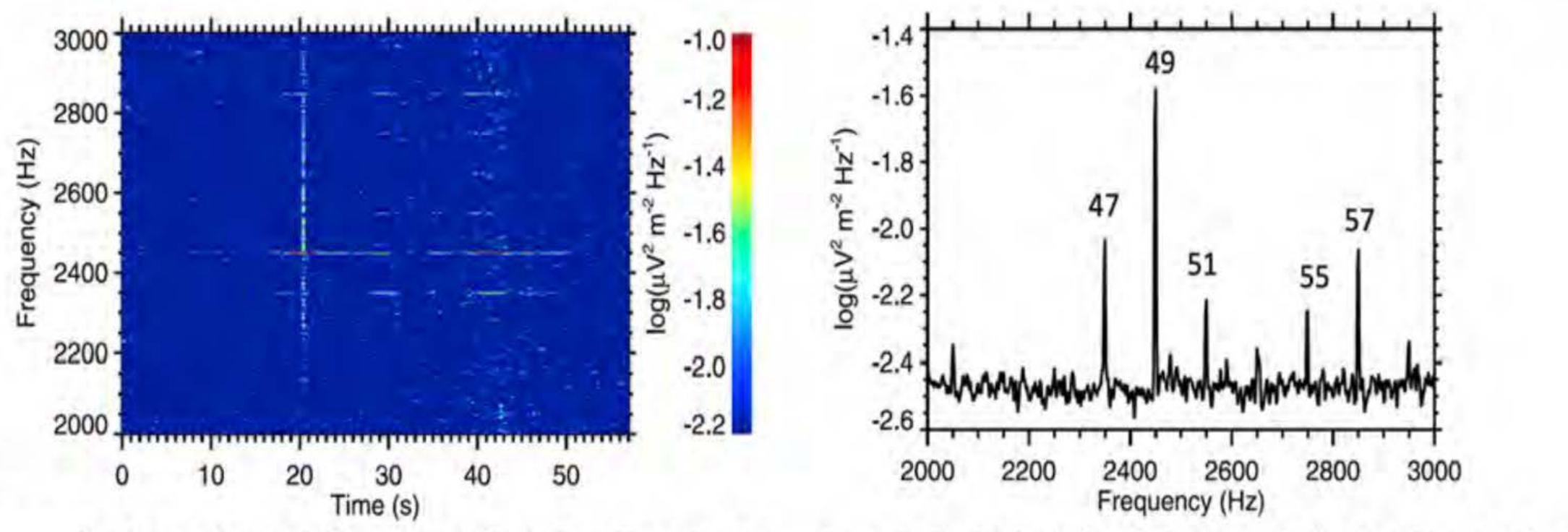
Illustration of how small scale irregularities that are comparable to the HF's wavelength affect the backscattering of the signal

Power line radiation detected by satellites

- Power line radiation propagates upwards due to the horizontal orientation of power lines and the presence of the ground.
- The figure on the right is an illustration of how an EM wave generated by a power grid can couple into the ionosphere and travel via geomagnetic field lines. The signals may then be detected by satellites and also by receivers at the conjugate point.

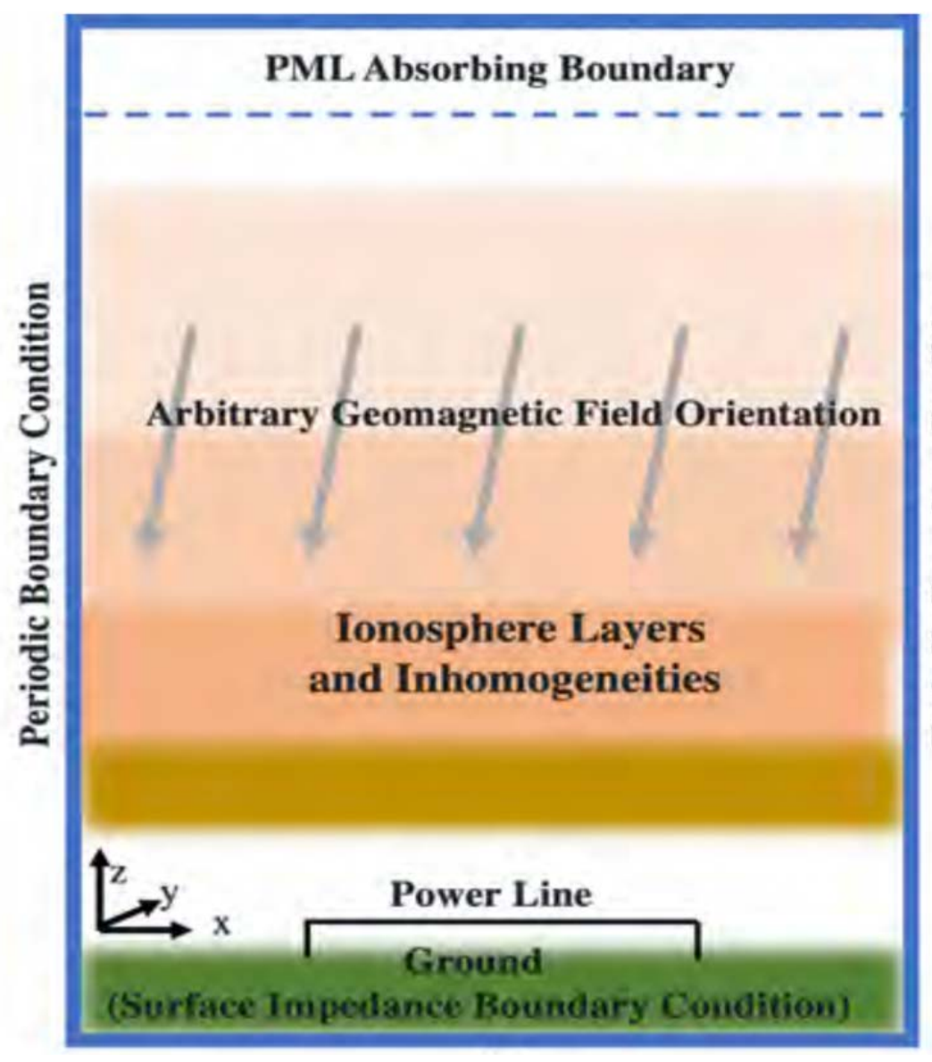


- Power line harmonic radiation is generated by power grids operating at 50 Hz or 60 Hz.
- In satellite data from DEMETER, we see harmonics of a 50-Hz base frequency, which has been correlated to underlying power grids.

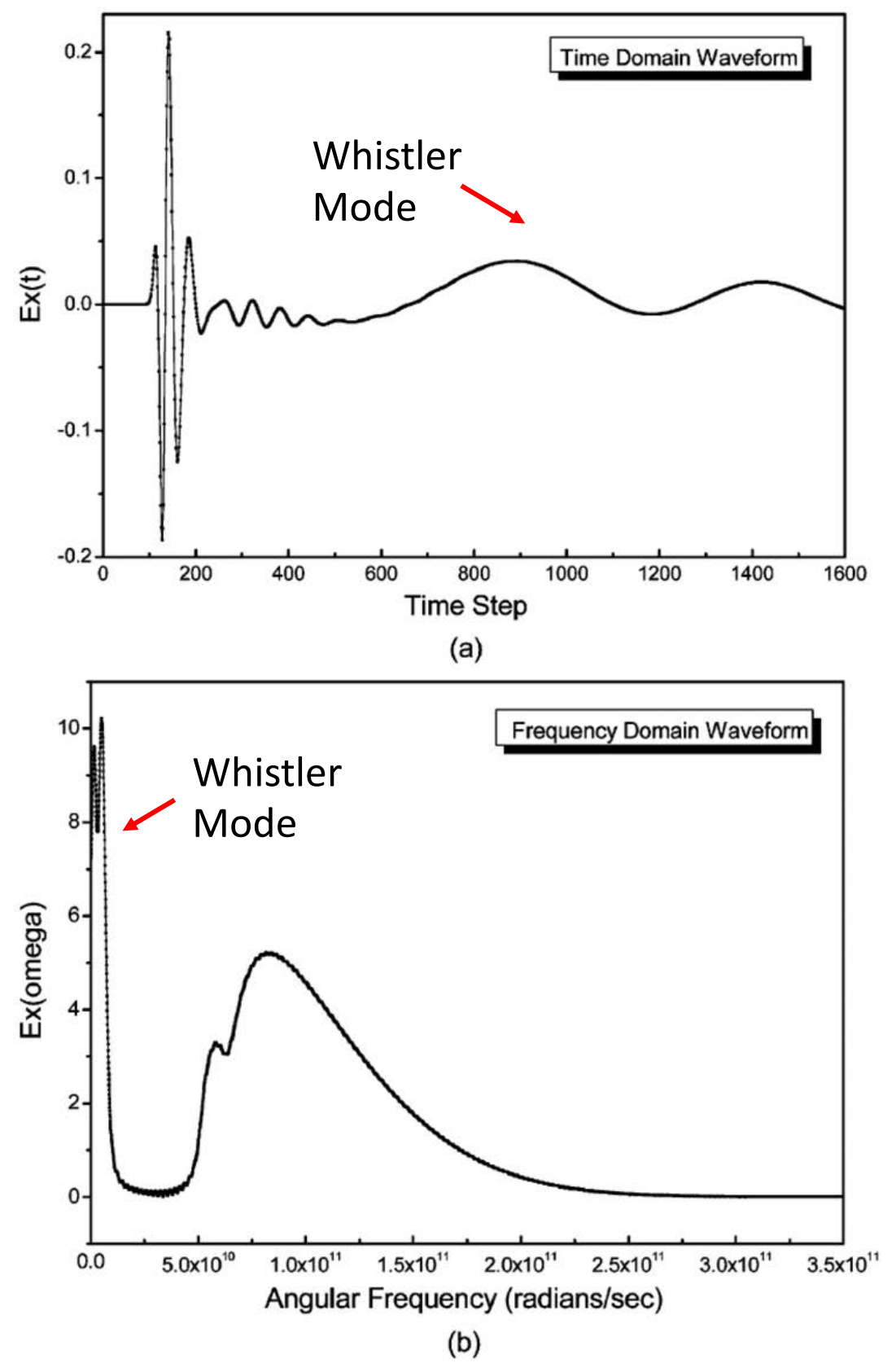


(Left) An example frequency-time spectrogram of the power spectral density of the electric field corresponding to a PLHR event on 3 Nov. 2009 after 1001:33 UT while DEMETER was passing over Europe. (Right) The corresponding power spectrum, with peaks located at 2350 Hz, 2450 Hz, 2550 Hz, 2650 Hz, 2750 Hz and 2850 Hz (corresponding to the odd harmonics of a 50-Hz base frequency; the harmonic factor is labeled above each peak) [7].

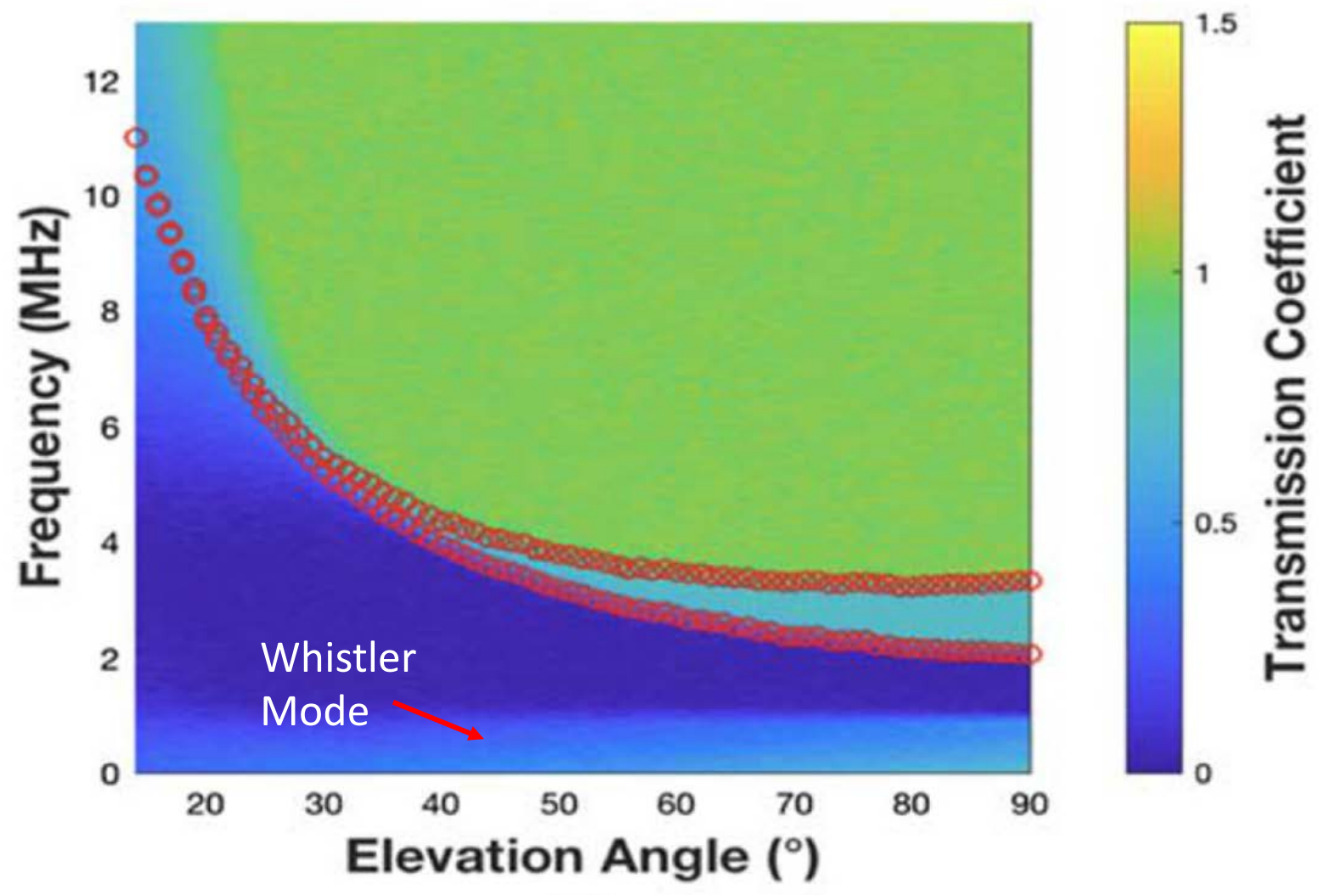
2-D vertical slice of a 3-D FDTD grid having the ground, geomagnetic field, magnetized ionospheric plasma, and a power transmission line.



EXAMPLE RESULTS/DISCUSSIONS



Electric field observations a short distance into a homogenous magnetized plasma that Is excited by a broadband Gaussian EM plane wave pulse. A) Time-waveform; and (b) Frequency-domain waveform calculated by performing a discrete Fourier transform DFT on the data from (a). The Whistler and LHP and RHP modes are visible.



Plots of the FDTD-calculated transmission coefficient as a function of frequency and elevation angle for an unperturbed spatially-varying ionosphere with background magnetic field of 50 μT. For comparison, analytical results are shown as red circles. The red circles follow two lines representing the left-hand polarization (LHP) and right-hand polarization (RHP) waves.

We are using the model described in the Methods section to determine characteristics of PLR/PLHR coupling from the atmosphere into the ionosphere

CONCLUSIONS

- **Our model may account for arbitrary source time-waveforms (as could occur from man-made antennas as well as naturally-occurring ionospheric currents or lightning strikes) and complex 3-D geometries (e.g. variable ground topography and 3-D lithosphere/ionosphere compositions).**
- **We are starting to obtain results for the coupling of PLHRs into the ionosphere. This will help science missions by helping them better identify and remove PLHR signatures from their measured data.**

REFERENCES

1. Simpson, J. J., (2012), Eos Trans.AGU, 93(29), 265.
2. S. Pokhrel, (2018), IEEE TAP.2018.2847601.
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5. F. Nemec, (2005), J Geophys Res-Space, vol. 120, no. 10, pp. 8954-8967, Oct 2015,