# FDTD Modeling of Global Electromagnetic Wave Propagation in the Earth-Ionosphere Waveguide


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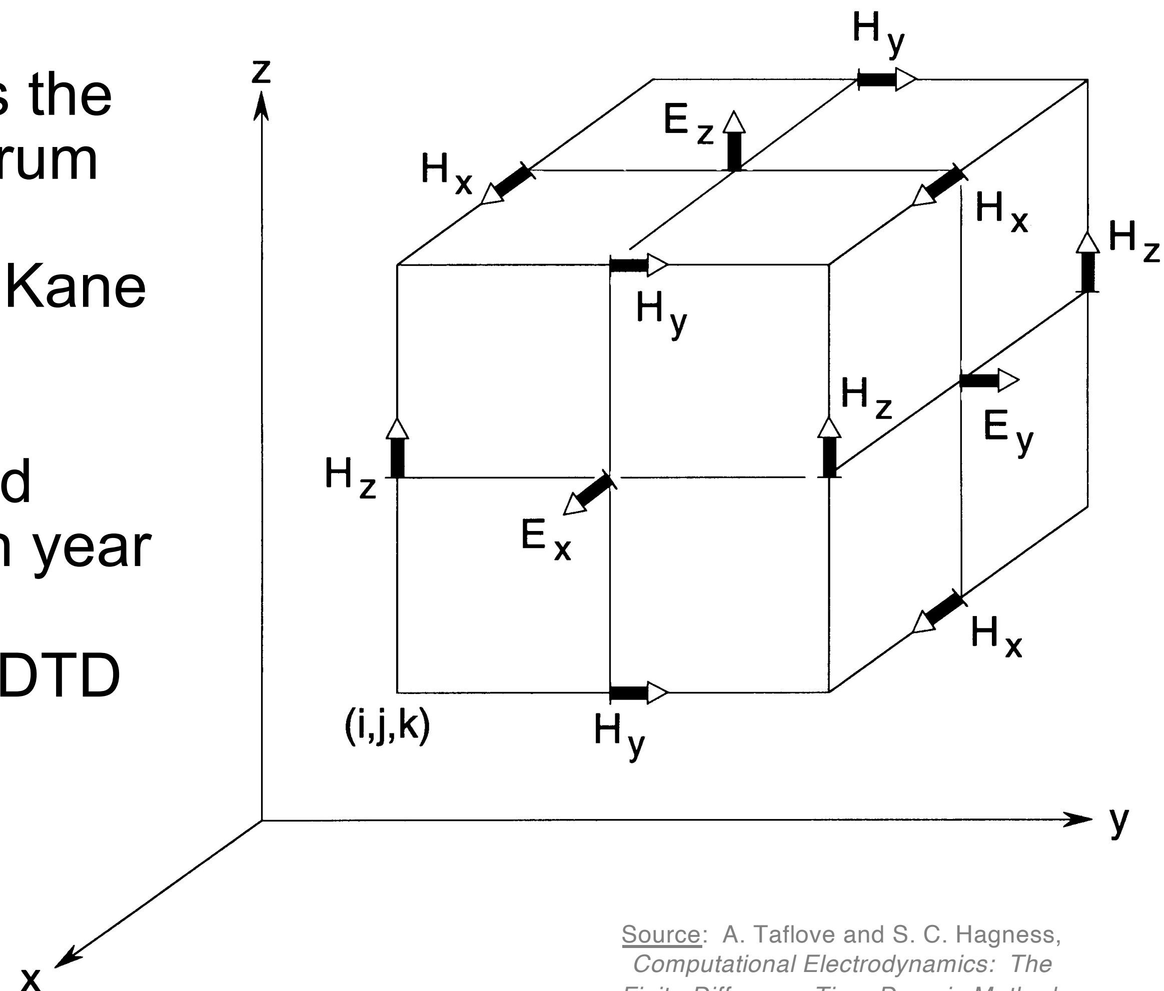
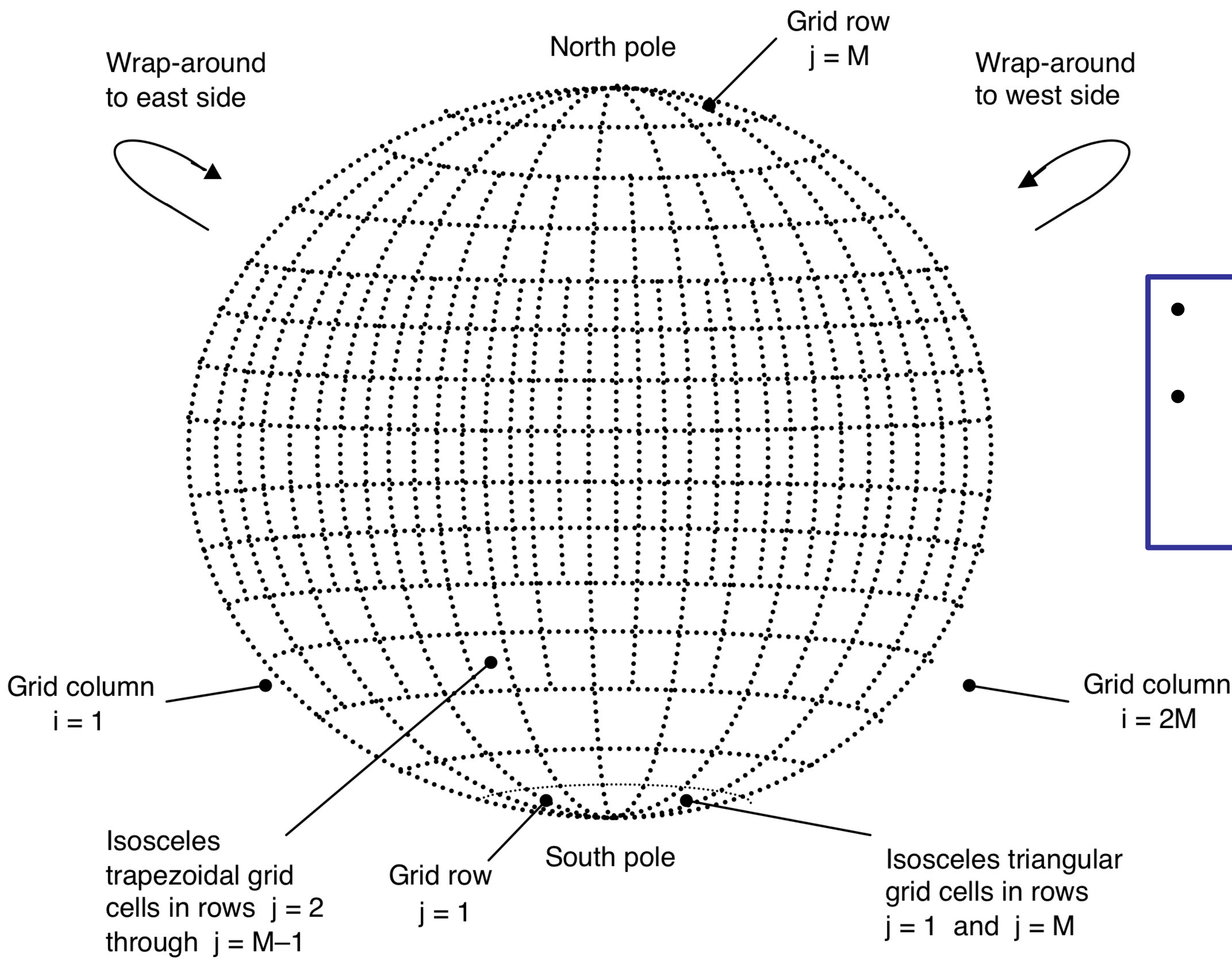
# Finite-Difference Time-Domain (FDTD) Method

- 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
- 100'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.

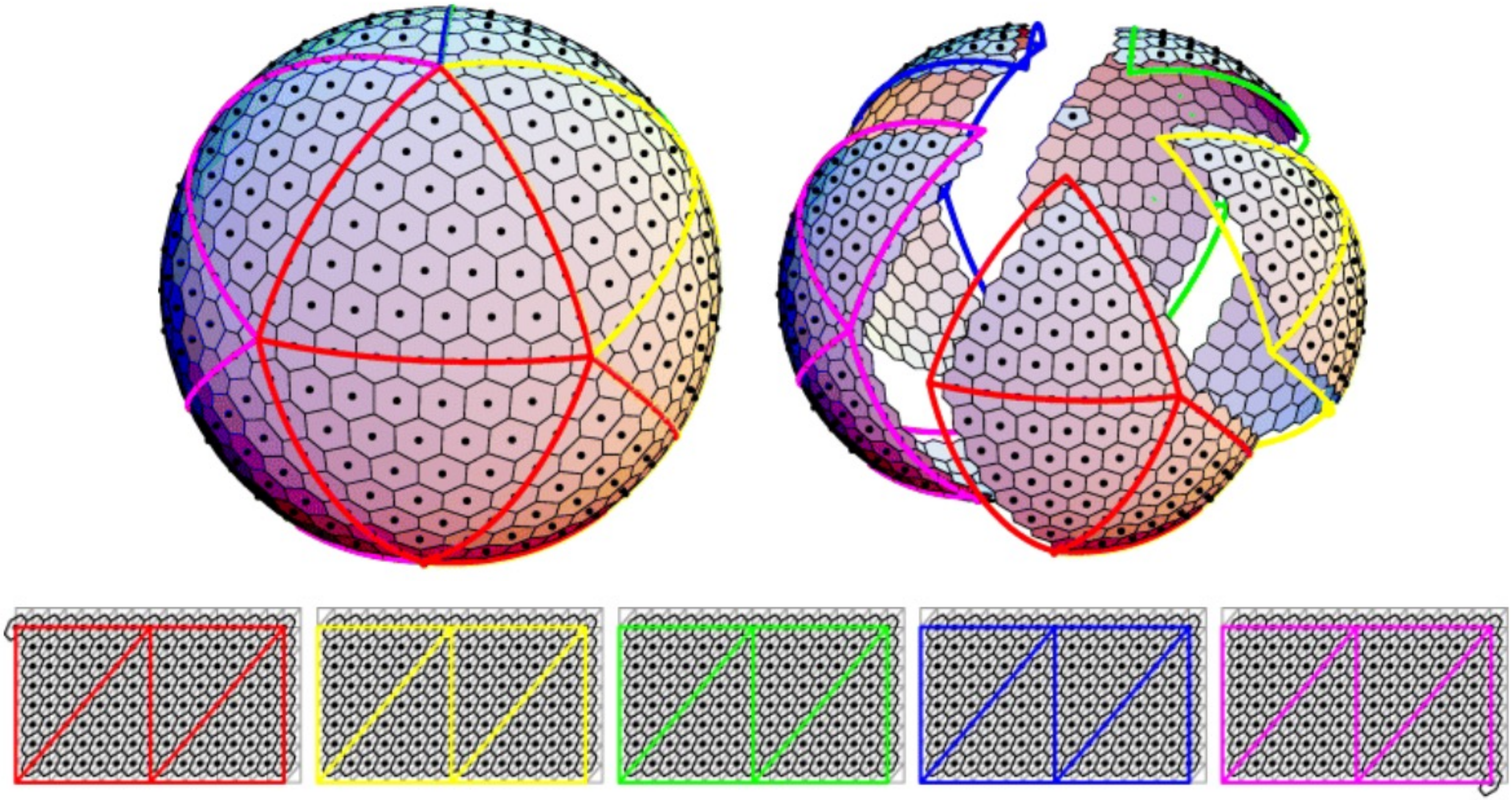
# Model Generation #1:
# A 3-D Latitude-Longitude Global Model




- 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.

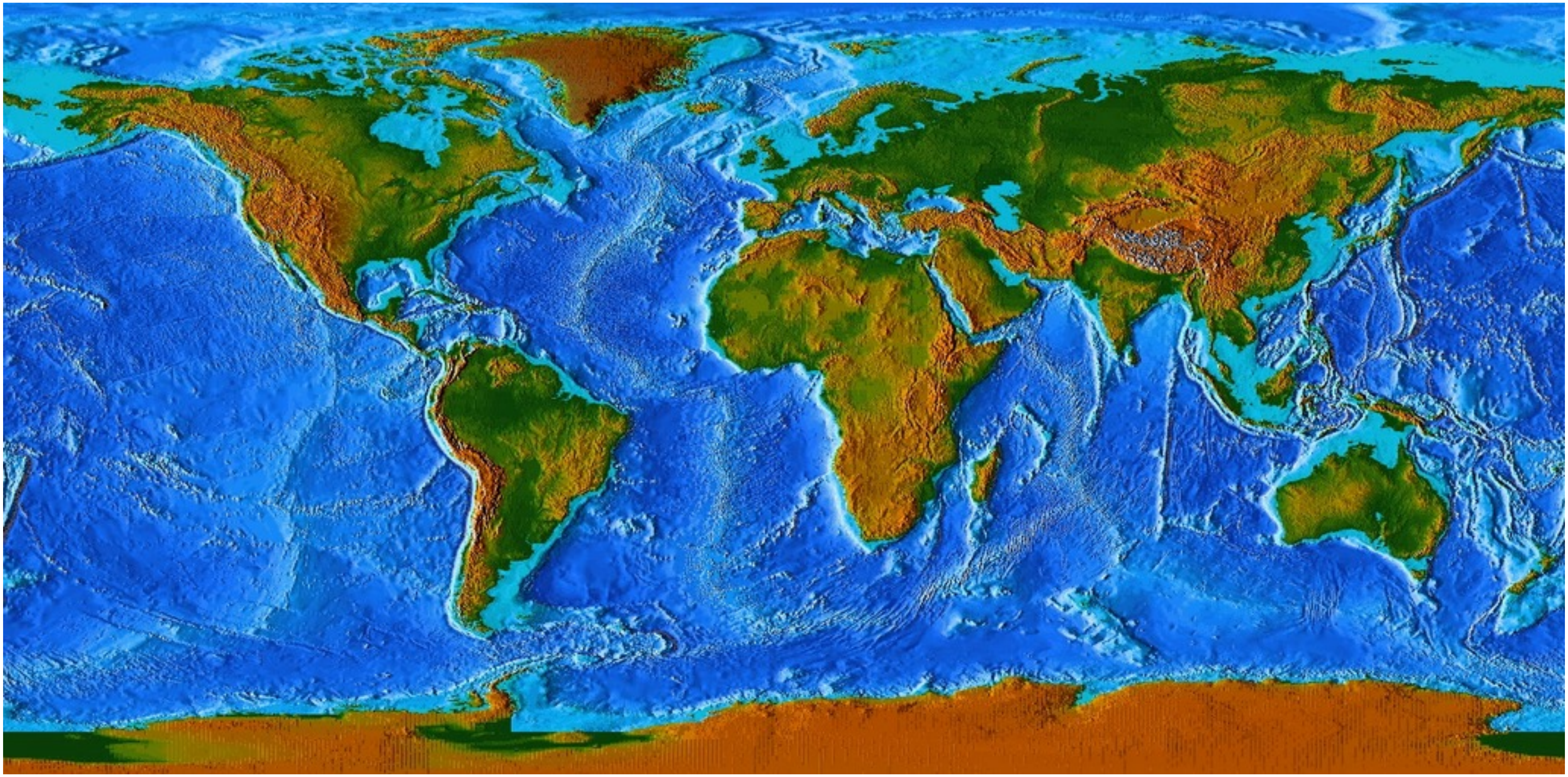
# Model Generation #2: An Efficient Geodesic Global Model



Unfolding of grid cells for parallel-processing on a supercomputer.

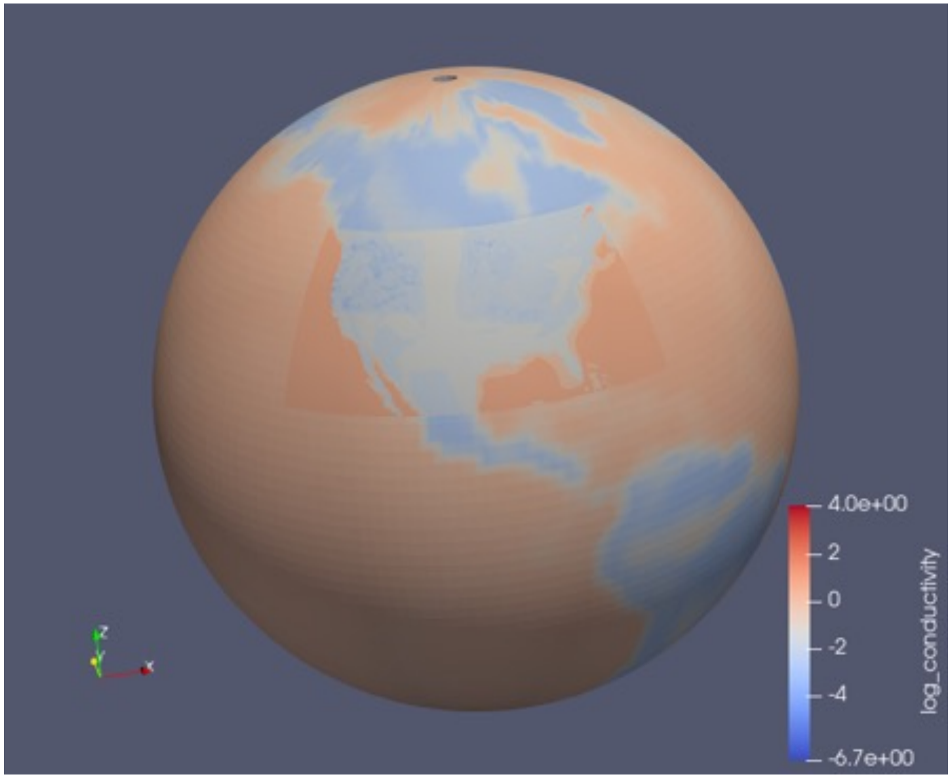
Sources: [1] Simpson & Taflove, *IEEE Trans. Ant. Prop.*, pp. 1734-1741, June 2006.
[2] D. A. Randall et. al., *Comput. Science and Eng.*, pp. 32 – 41, Sept./Oct. 2002.

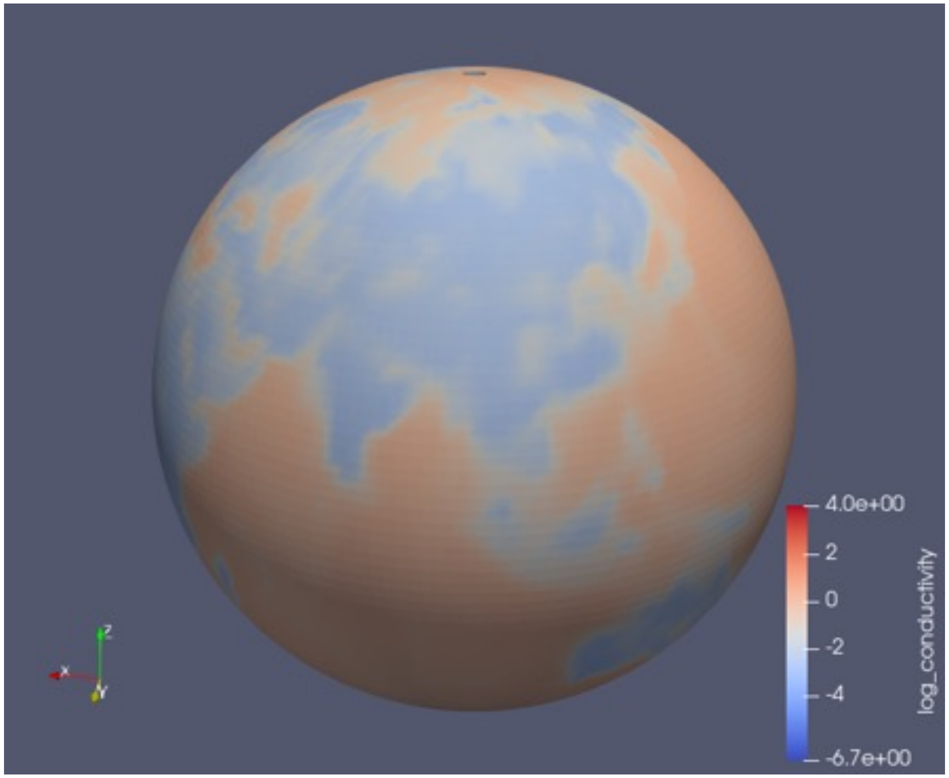
# Topography, Bathymetry, and Oceans Included



Source: *mapsnet.org and ngdc.noaa.gov/mgg/topo*
*(ETOPO 1 → 1 arc minute or ~1.9 km resolution at the Equator)*

# Varying 3-D Lithosphere Electrical Characteristics According to Location and Depth




Global data is at 2° x 2° resolution;
the continental U.S. region is at 1° x 1° resolution

Source: Anna Kelbert, USGS, EMC-GlobalEM-2015-02x02 and
https://doi.org/10.1002/9781119434412.ch8

# 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*

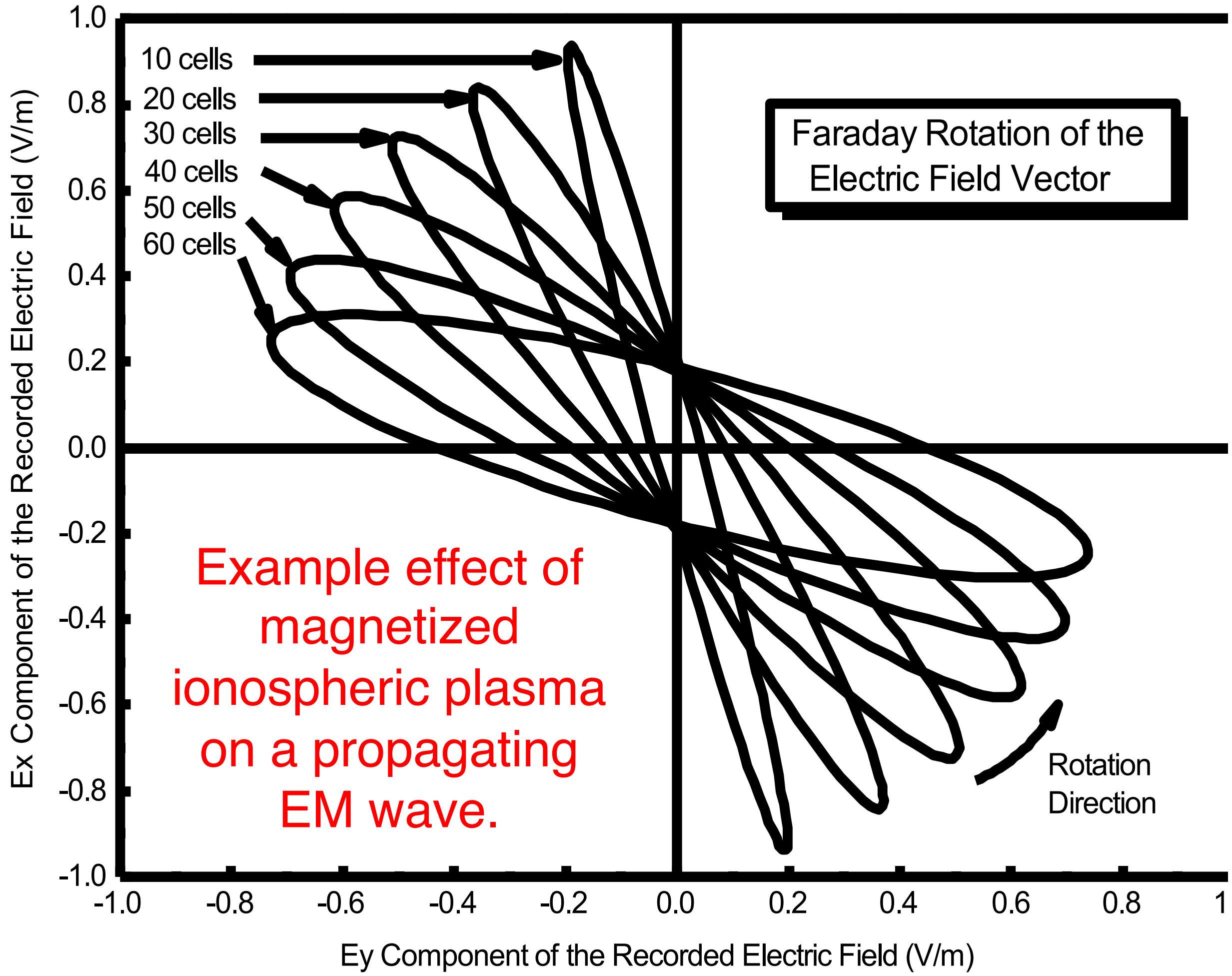
$p$ – *positive ion*

$n$ – *negative ion*

$\omega_{Pe}, \omega_{Pp}, \omega_{Pn}$ – *plasma frequency*

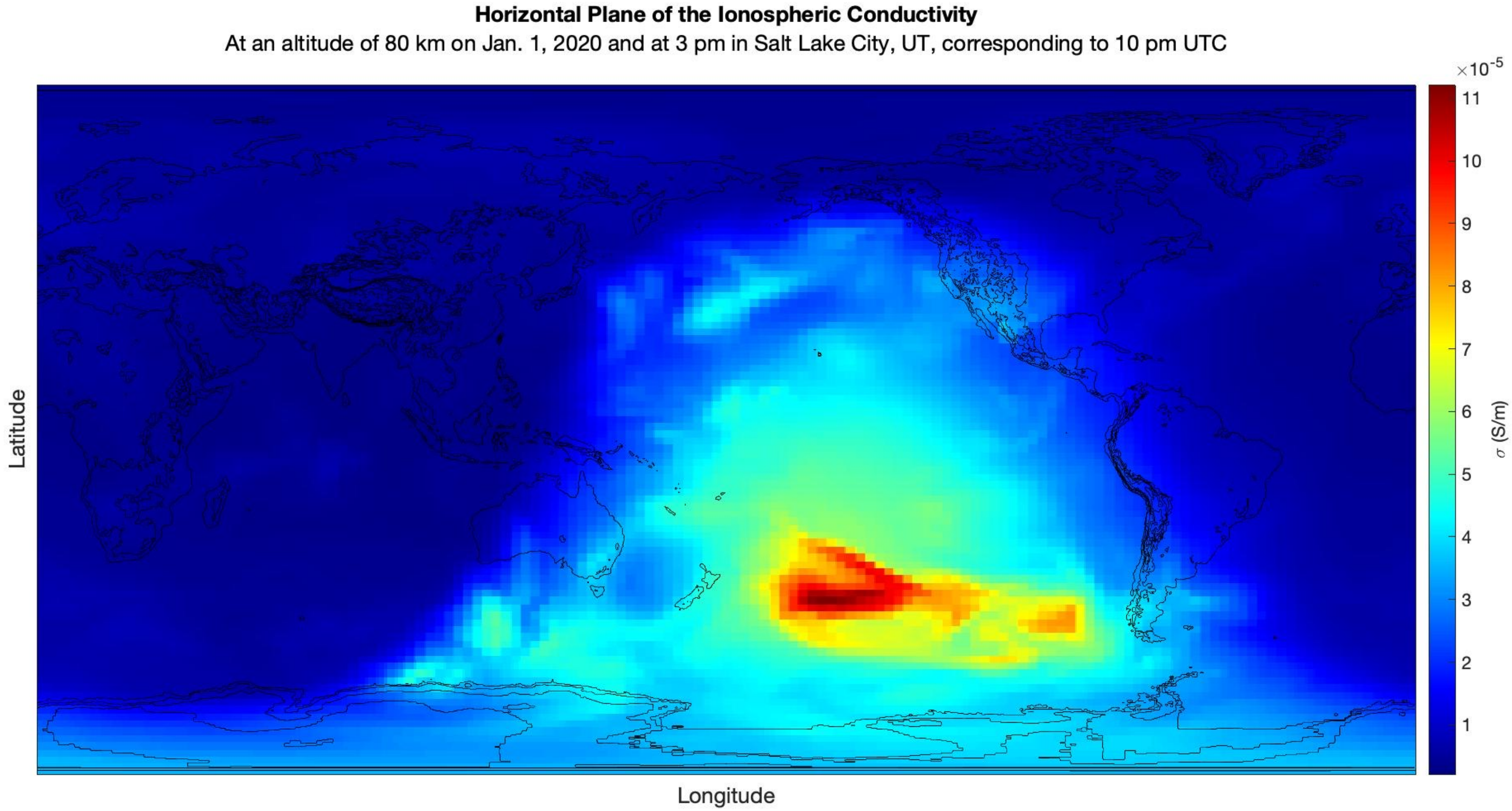
$\omega_{Ce}, \omega_{Cp}, \omega_{Cn}$ – *gyrofrequency*

$\nu_e, \nu_p, \nu_n$ – *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.

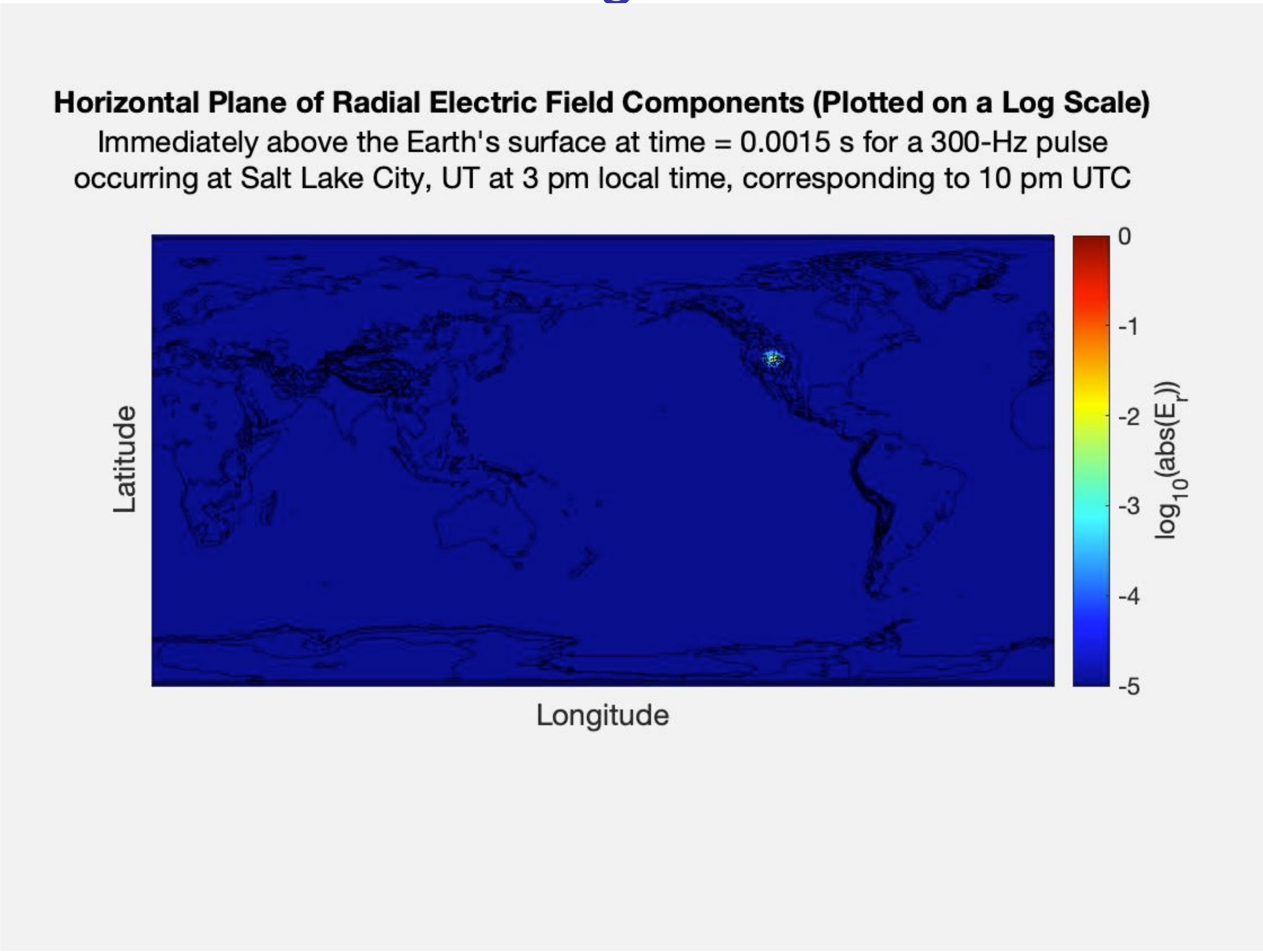
# Ionospheric Conditions assumed for the Propagation Scenario on the Next Slide






Sources: Data provided by Prof. Reichler

# FDTD-Calculated Global Propagation of an Electromagnetic Wave






Animation created by Kaiser Niknam

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I am always looking for excellent students to join our group!


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