Ionospheric Raytracing in a Time-dependent Mesoscale Ionospheric Model

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Introduction

- Electron Density Gradients from MSTIDs
  - Modify the path of HF rays in the atmosphere
  - Create multipathing
- Model a 3D MSTID (SAMI3/ESF)
- Simulate HF rays using a 3D raytrace code (MoJo)
- How do MSTIDs affect Quasi Vertical Ionograms (QVIs)?

  * Other than multipath effects

MoJo

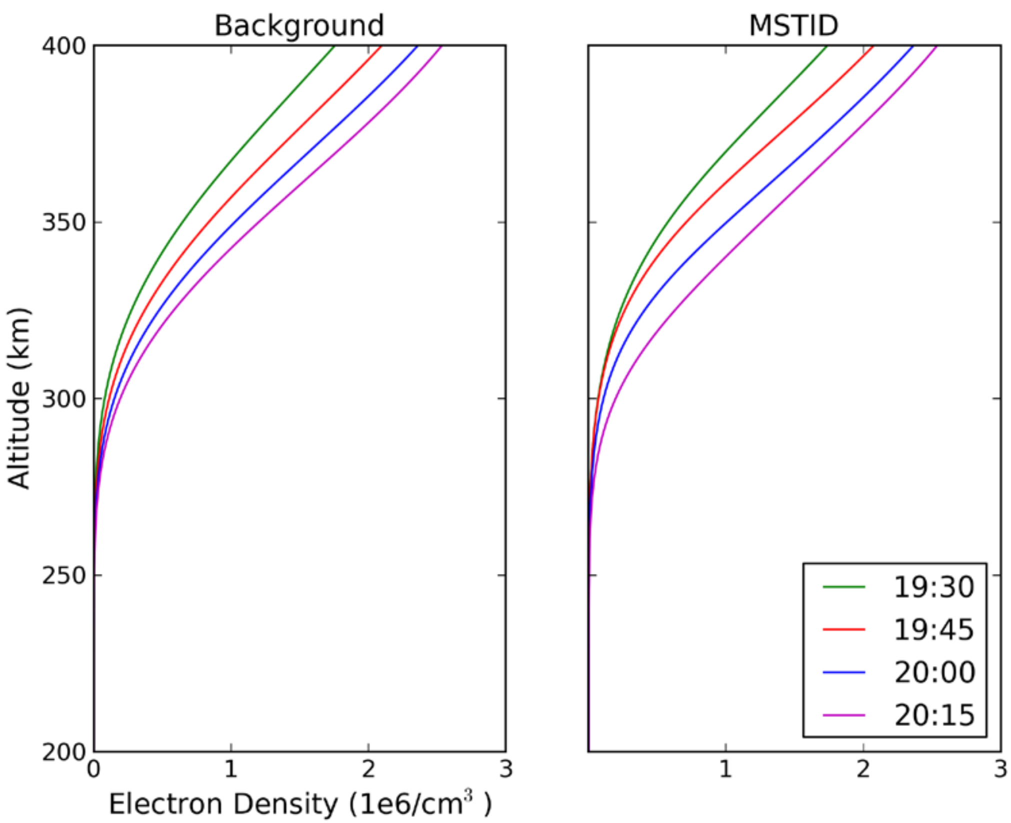
- Evolved from classic Jones-Stephenson raytrace code
  - Jones, R. M. and Stephenson, J. J. A versatile three-dimensional ray tracing computer program for radio waves in the ionosphere, U. S. Department of Commerce, OT Report 75-76, 1975.
- Made significant improvements/upgrades
  - Upgraded to Fortran 90
  - Fixed bugs
  - Efficiency improvements
  - Automation infrastructure and graphics
  - Updated the physics (absorption equation, collision frequency)

SAMI3/ESF

- 3D model, but limited in longitude to 4°
- magnetic field: non-tilted dipole magnetic field for simplicity (geographic and magnetic latitude are the same)
- interhemispheric / global (±89°)
- nonorthogonal, nonuniform fixed grid
- seven (7) ion species (all ions are equal): H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+
  - solve continuity and momentum for all 7 species
  - solve temperature for H^+, He^+, O^+, and e^-
- plasma motion
  - E × B drift perpendicular to B (vertical and longitudinal in SAMI3)
  - ion inertia included parallel to B
- neutral species: NRLMSISE00/HWM93/HWM07 and TIMEGCM
- chemistry: 21 reactions + recombination
- photoionization: daytime and nighttime

Ionospheric Parameters

- Simulation time: 19:30-20:30 LT
- Day of year: 80 (equinox)
- $F_{10.7} = F_{10.7}a = 150$ (moderate solar conditions)
- Ap = 4 (quiet time)
- Critical frequency ~ 14 MHz



Electron density profiles at 10° latitude, 0° longitude

SAMI3/ESF MSTID

- Traveling-wave electric field is added to the ExB drift:

$$(E_{TID} \times B)_{[p,h]} = -U_{TID} \frac{k_{[x,y]}}{k} \sin(k_x x + k_y y - \omega t)$$

- p: vertical direction
- h: horizontal direction
- x: longitude direction (=> vertical drift)
- y: latitude direction (=> horizontal drift)
- Limited to:
  - 200-400 km altitude (frequency range: .5 MHz – 11 MHz)
  - -1.5° – 1.5° longitude
  - 8° – 12° latitude

SAMI3/ESF MSTID

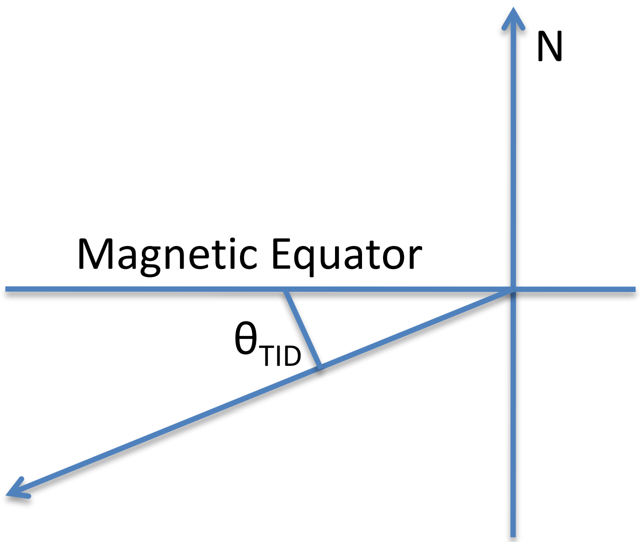
- Traveling-wave electric field is added to the ExB drift:

$$(E_{TID} \times B)_{[p,h]} = -U_{TID} \frac{k_{[x,y]}}{k} \sin(k_x x + k_y y - \omega t)$$

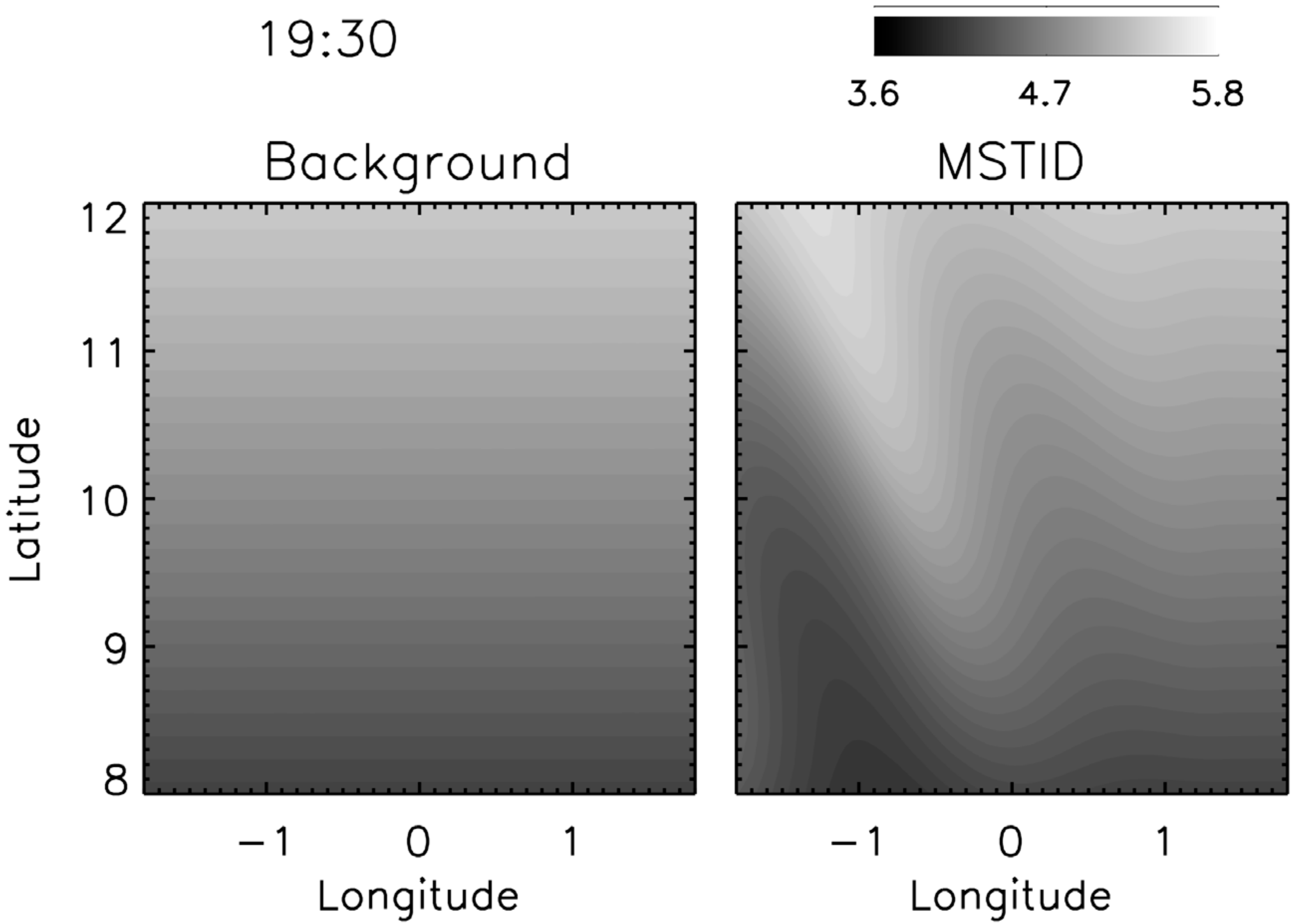
- k = 2π/λ (wave number)

  $$k_x = k\cos\theta_{TID} \quad k_y = k\sin\theta_{TID}$$

- λ = 250 km
- ω = 2π/T (frequency)
- T = 1 hour (period)
- θ_{TID} = 20° (propagation angle)
- U_{TID} = 50 m/s (drift velocity)

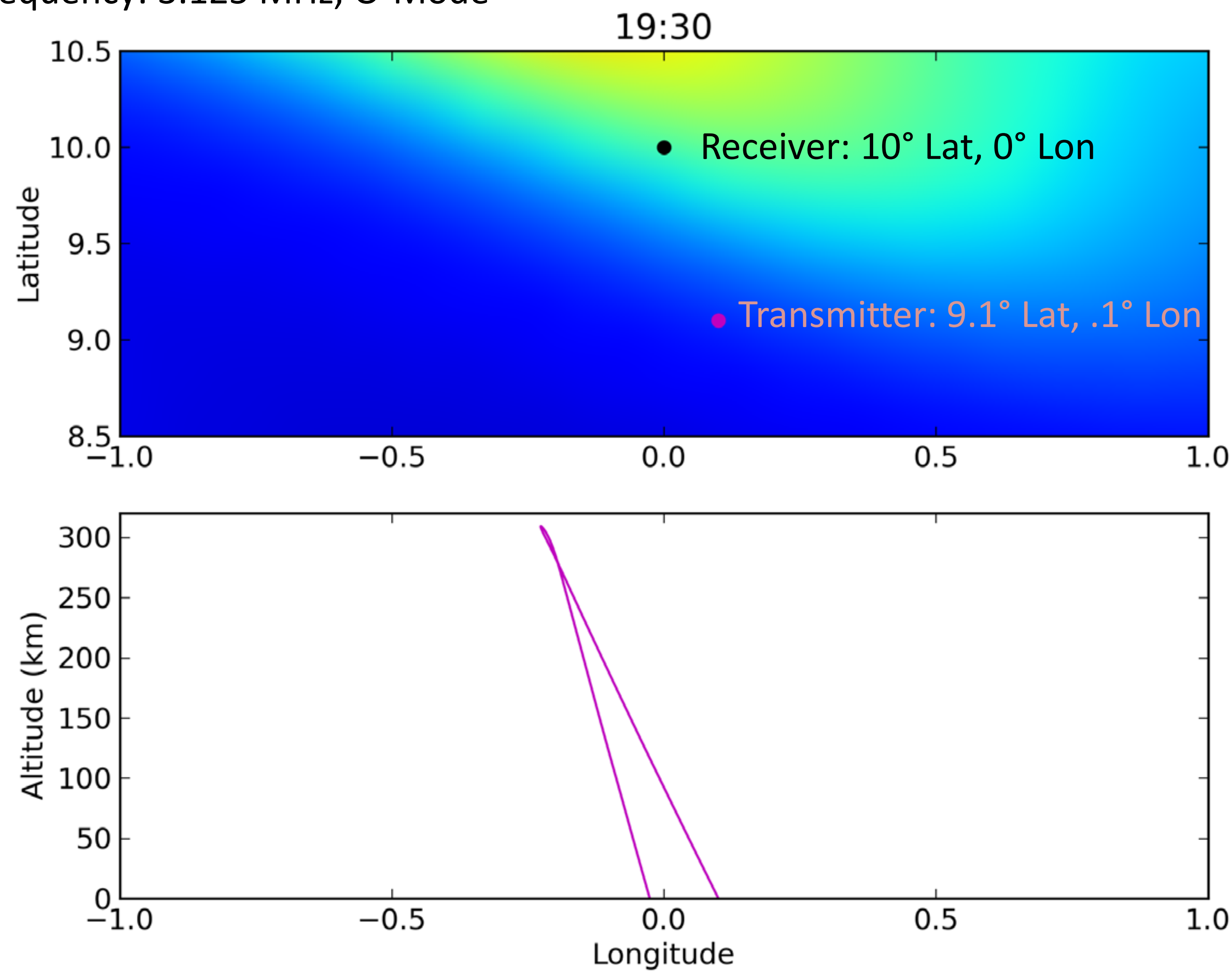


Log Electron Density at 300 km



Snapback Effect

Frequency: 3.125 MHz, O-Mode



Snapback Effect (20 deg TID)

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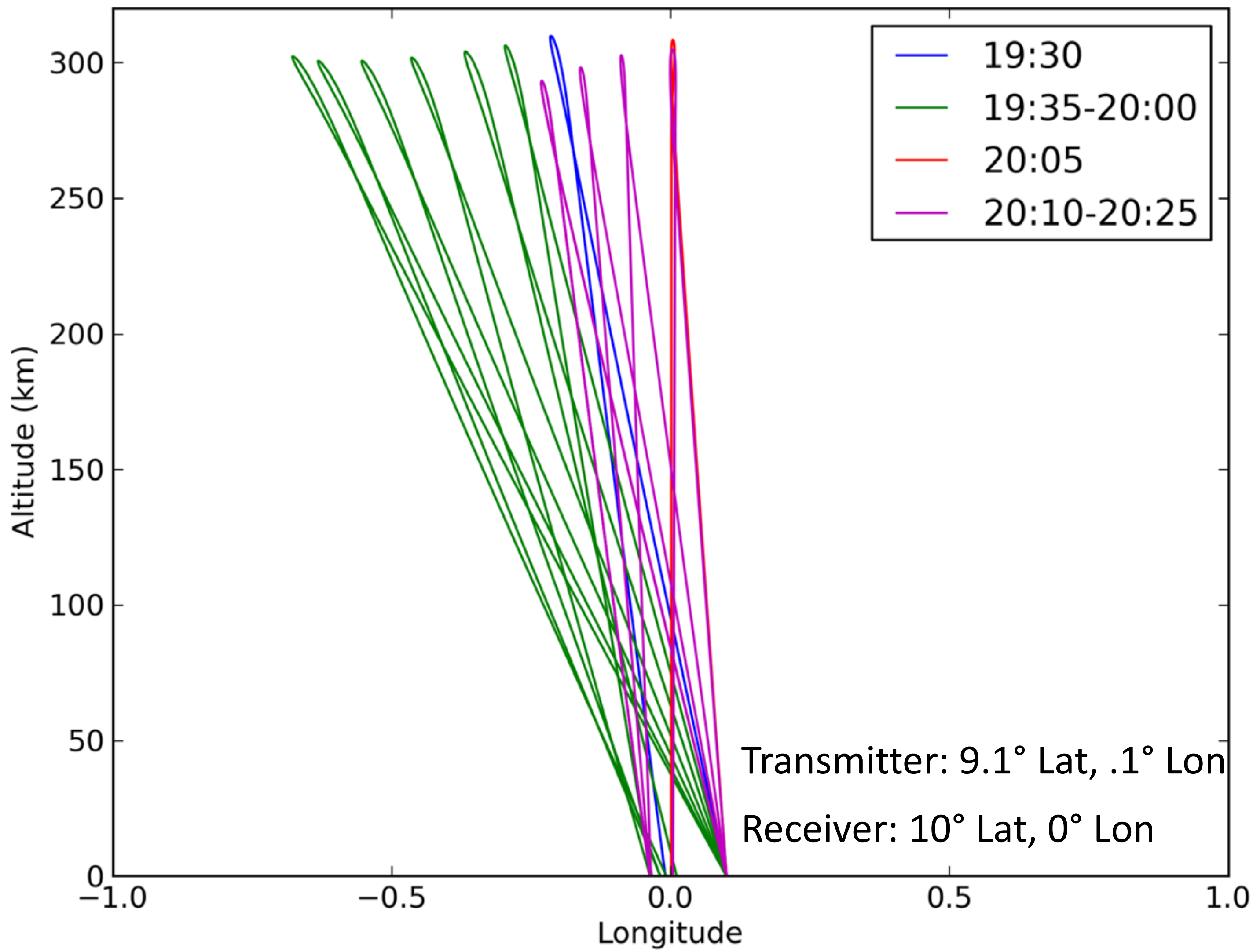
Frequency: 3.125 MHz, O-Mode

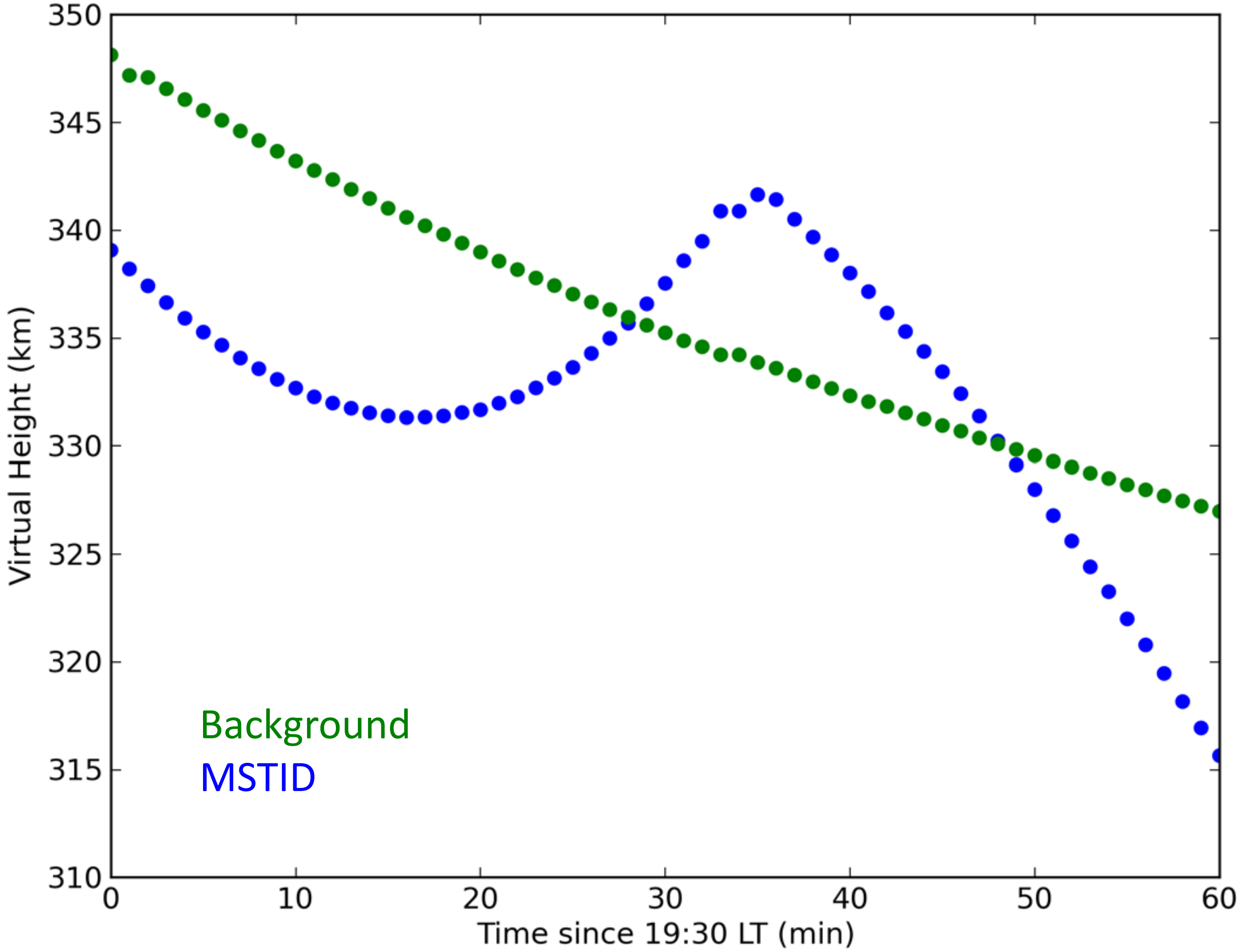


Change in Virtual Height (20 deg TID)

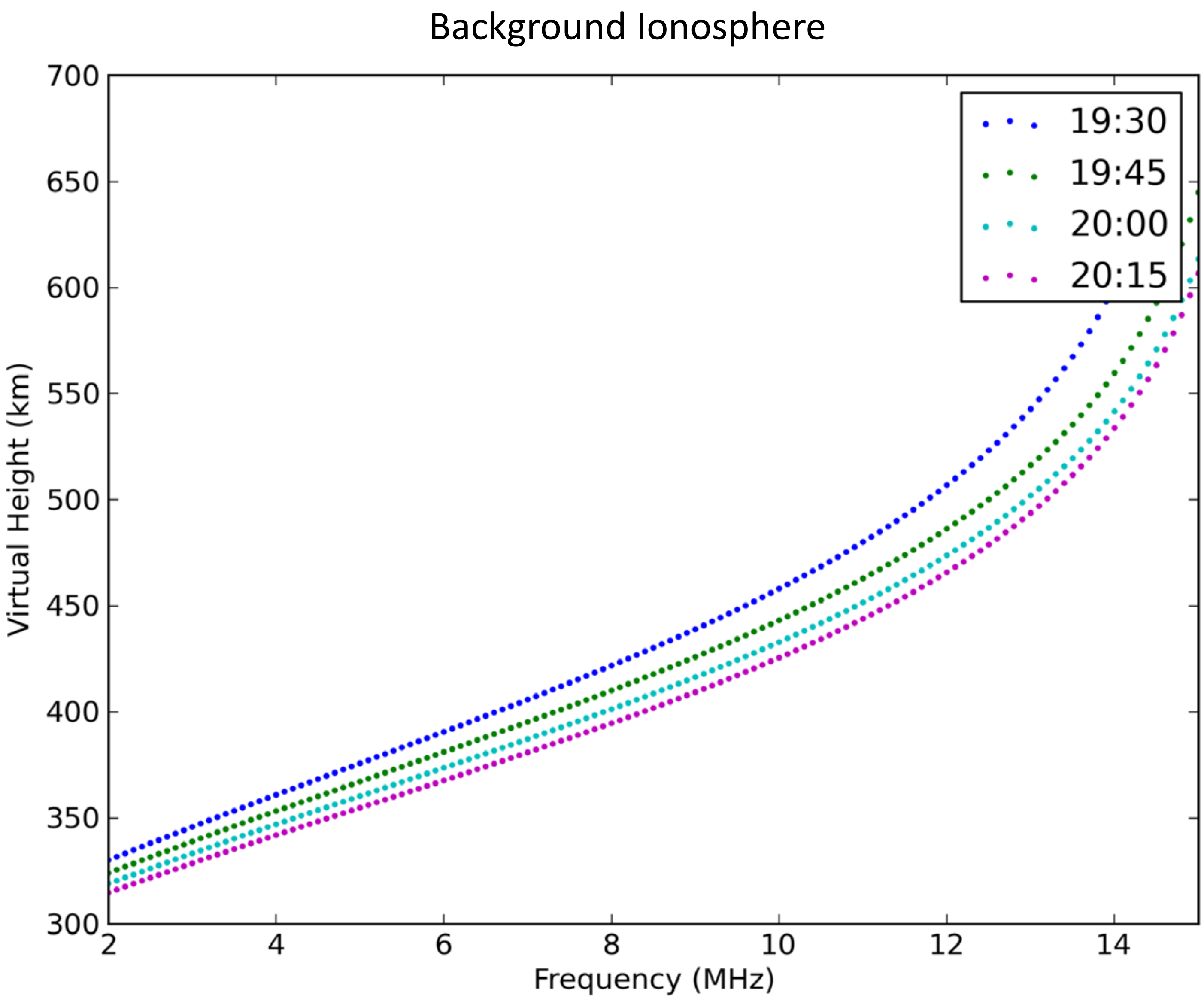
Frequency: 3.125 MHz

Transmitter: 9.1° Lat, .1° Lon

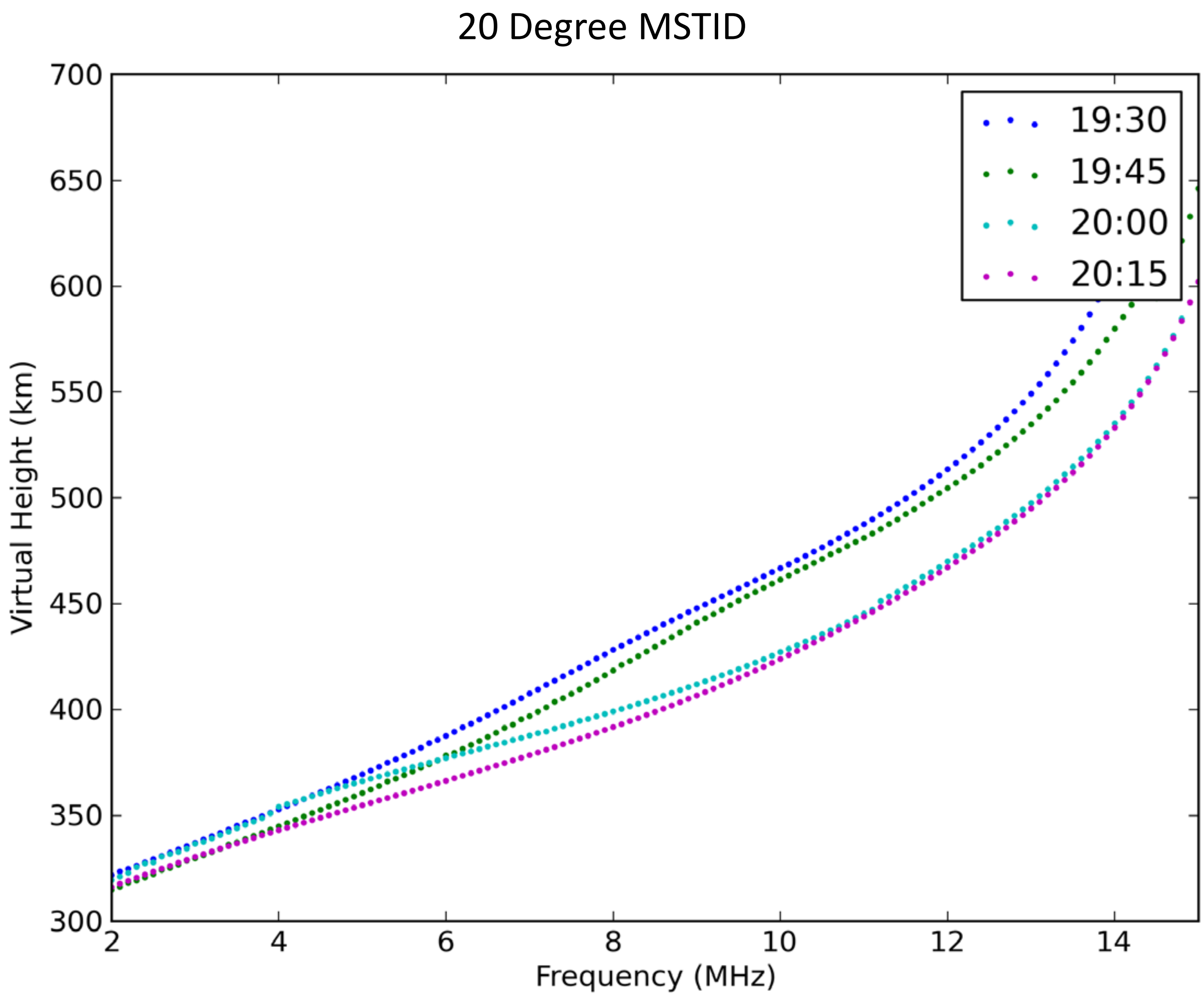
Receiver: 10° Lat, 0° Lon



Simulated QVI (O-mode)



Simulated QVI (O-mode)



Conclusions

- Cross range electron density gradients significantly alter the path of HF rays through the ionosphere
- These changes should be visible in QVI time series
- Next Steps:
  - Look at data
  - Multipath effects
  - Calculate Doppler
  - Extracting MSTID parameters from HF propagation observables

Acknowledgements

- This work was supported by the Chief of Naval Research (CNR) as part of the Bottomside Ionosphere (BSI) project under the NRL base program.

Snapback Effect (20 deg TID)

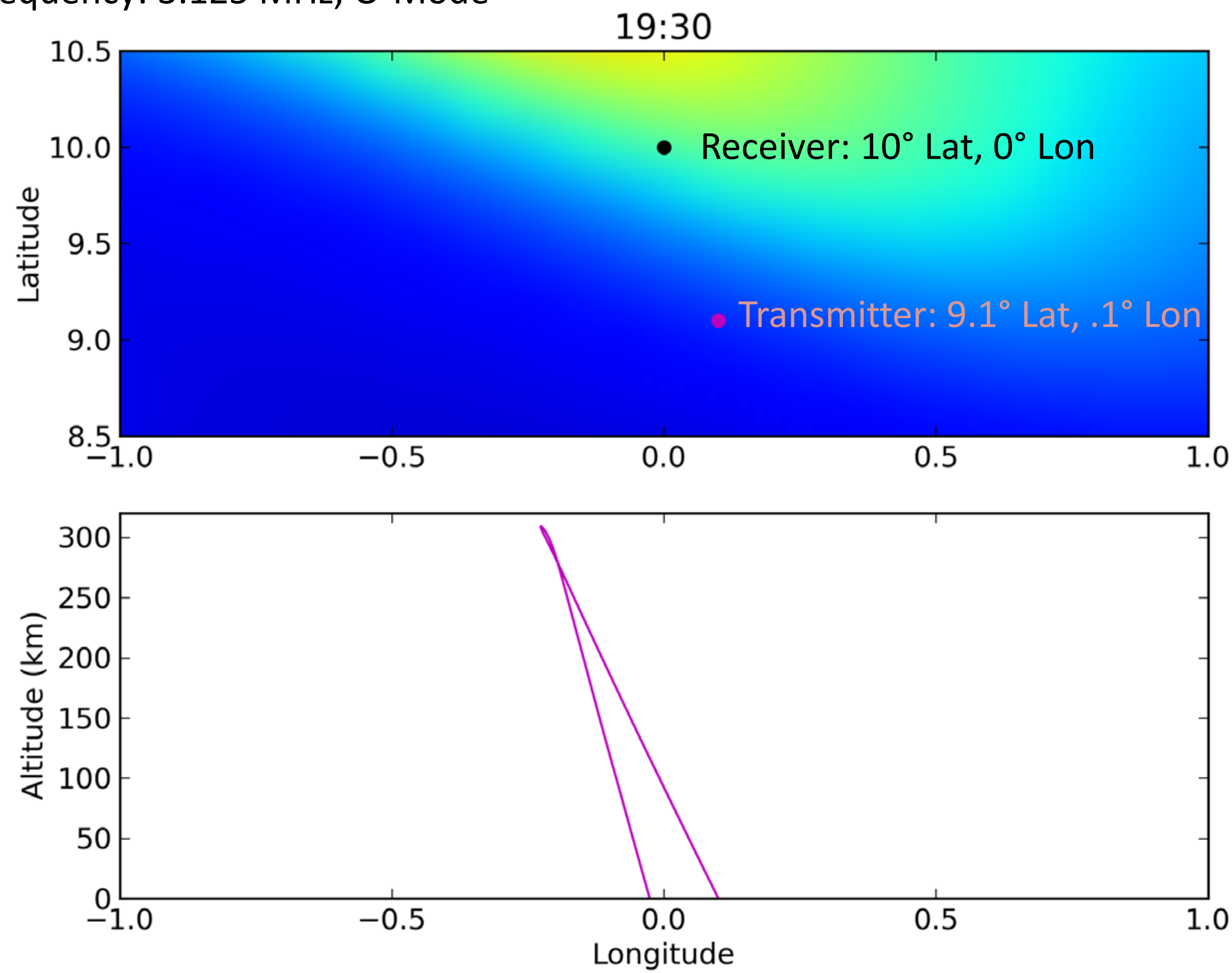
Frequency:

er: 9.1° Lat, .1° Lon

10° Lat, 0° Lon

Snapback Effect

Frequency: 3.125 MHz, O-Mode



Snapback Effect

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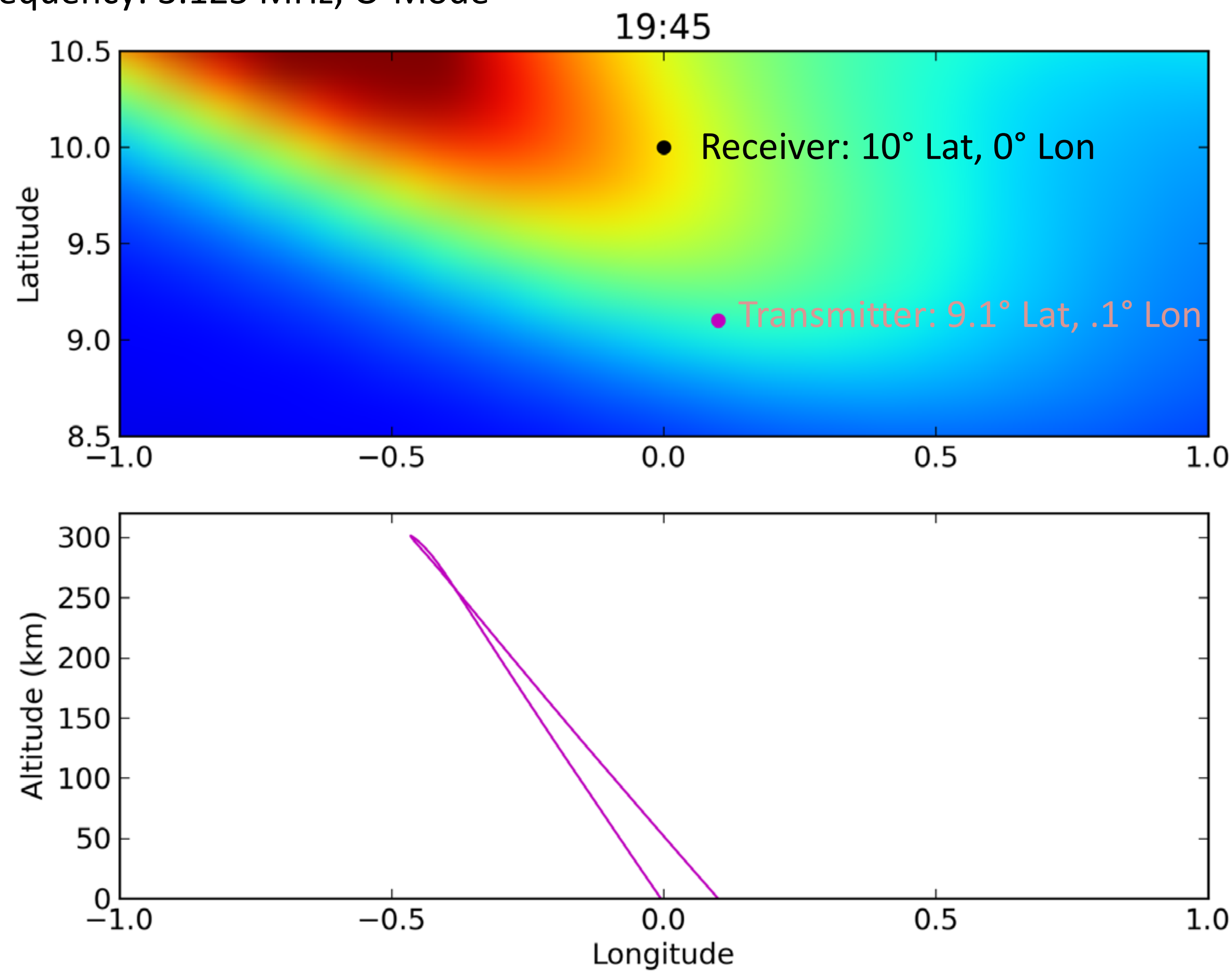

Snapback Effect

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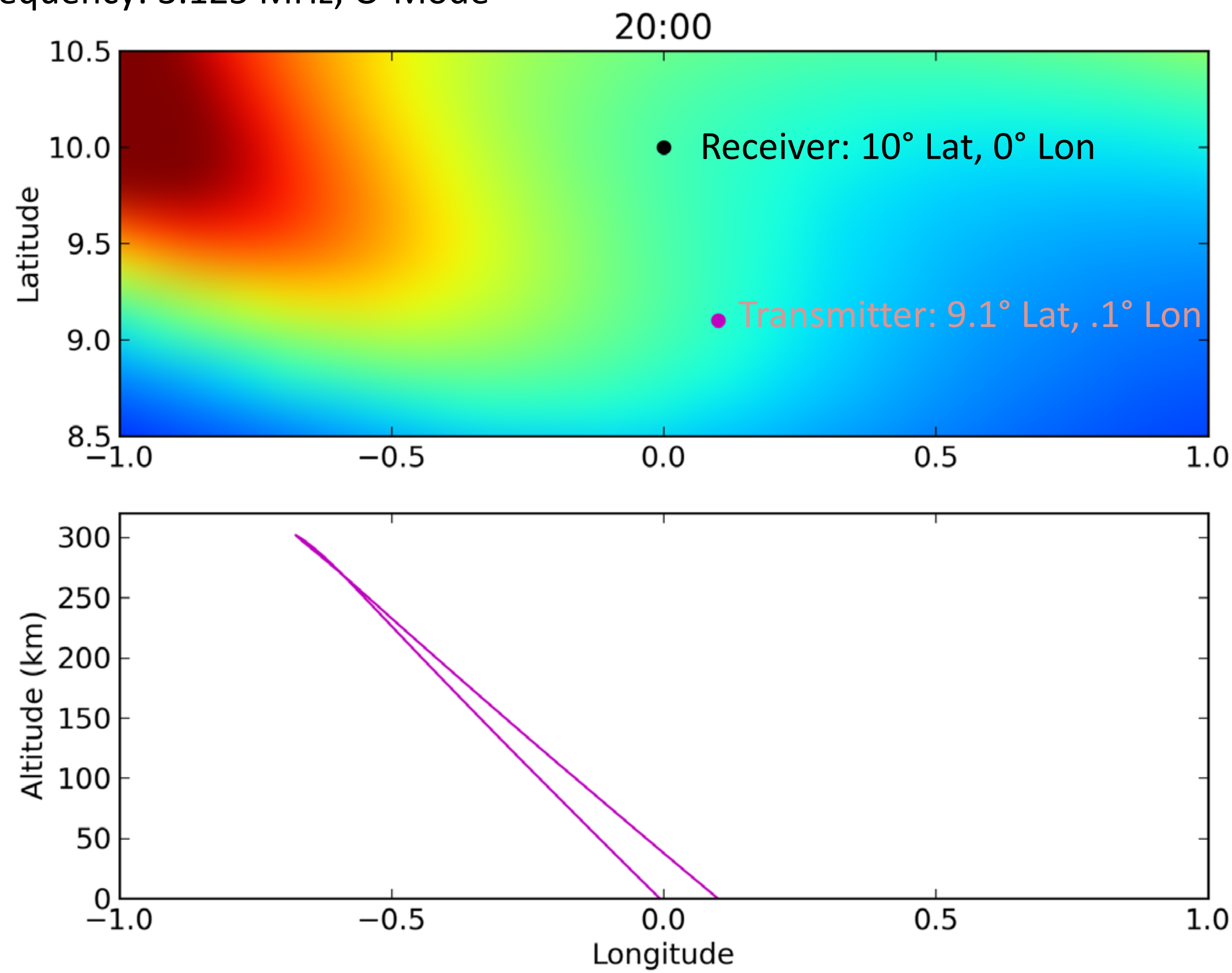
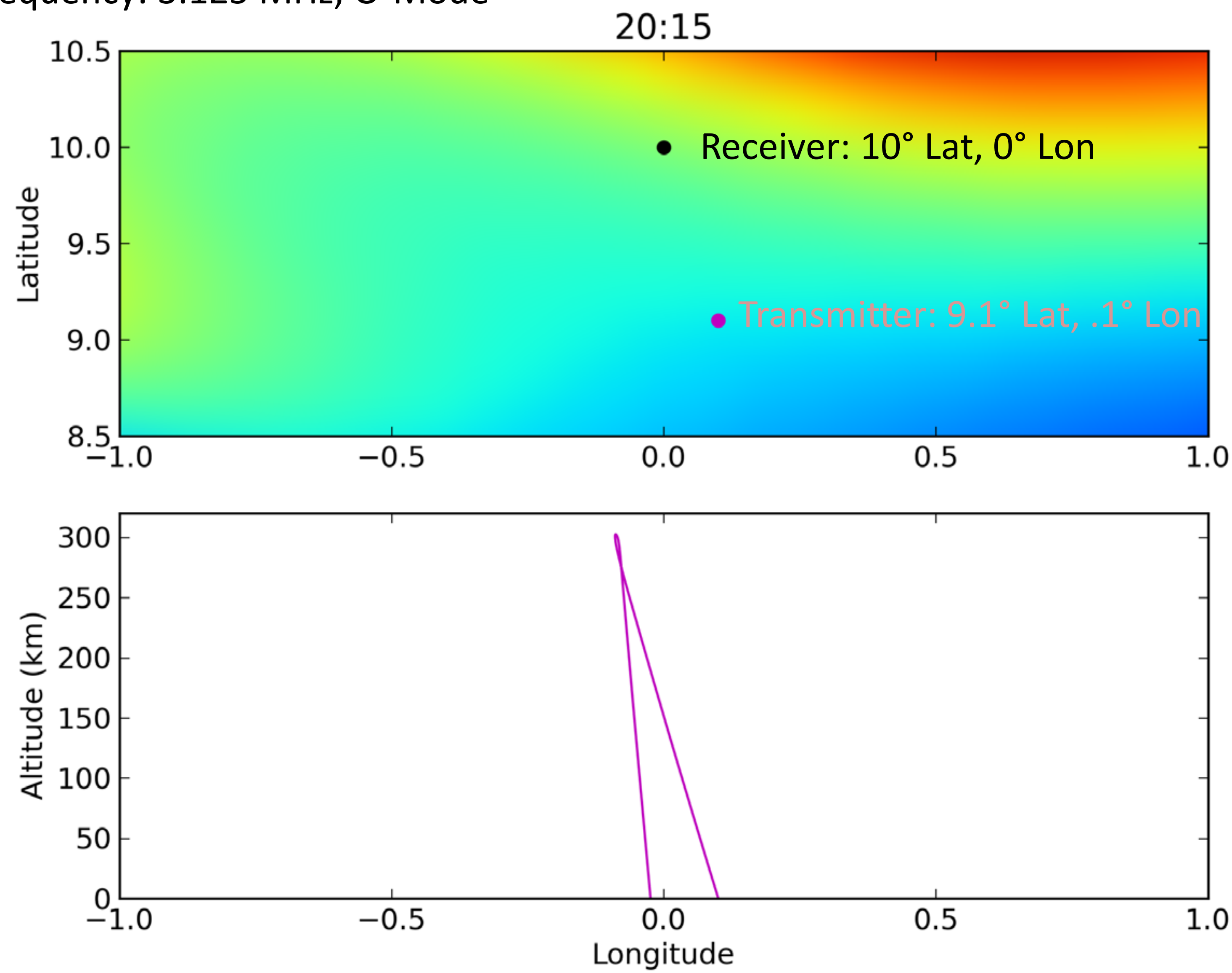


Snapback Effect

Frequency: 3.125 MHz, O-Mode



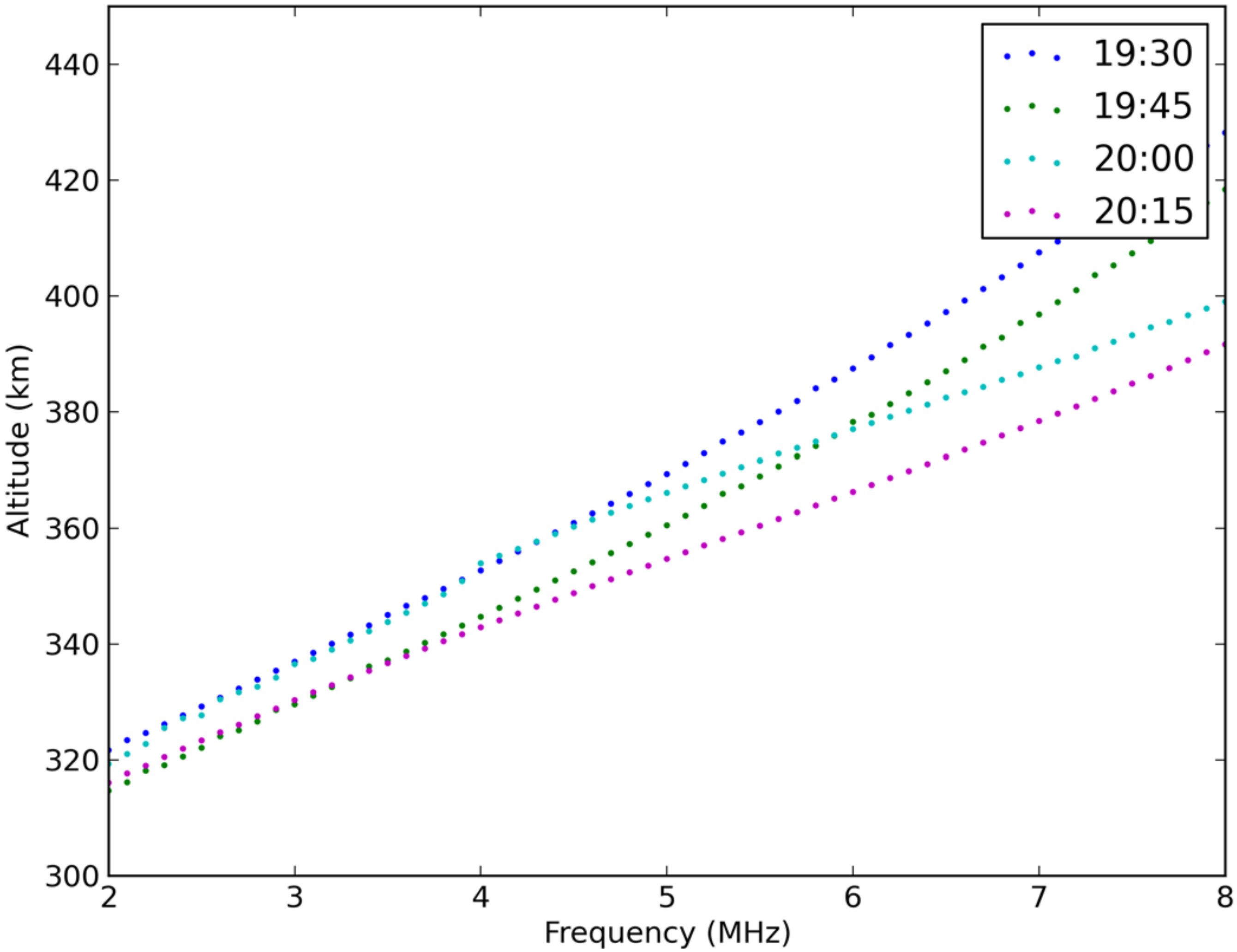
Extra Slides

Names

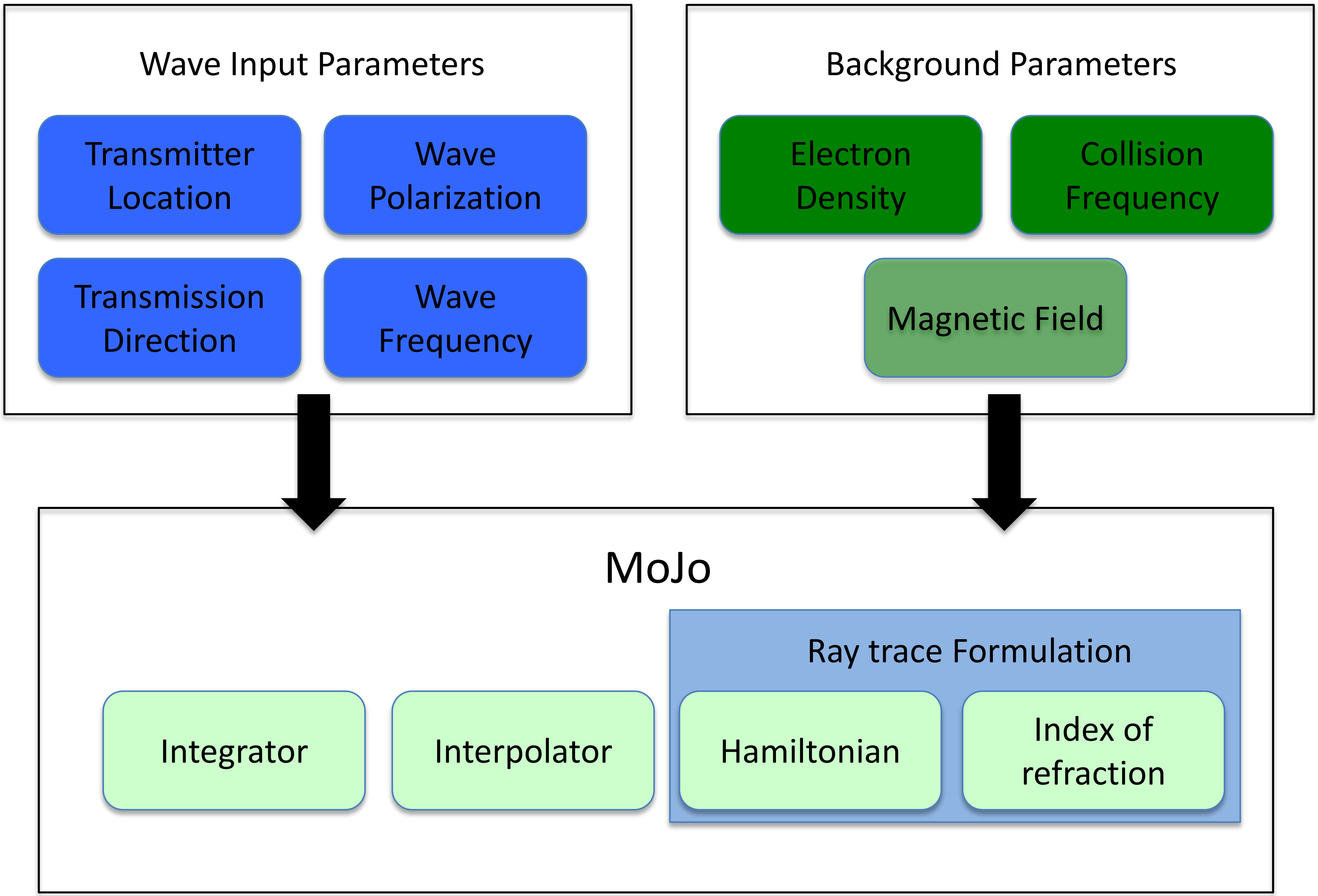
- MoJo
  - Modified Jones Code
  - Modernized Jones Code
- NAUTILIS
  - NAvy Usable radio Transmission for Long-range Ionospheric Systems
  - NAvy Utility for radio Transmission in Long-range Ionospheric Systems
- SAILFISH
- MARLIN
- SHARK
  - Simulated Hf Absorption and Raytracing Kit
- NAJ-C
  - Not Another Jones Code

Simulated QVI (O-mode)

20 Degree MSTID



MoJo



Wave Input Parameters
Transmitter Location
Wave Polarization
Transmission Direction
Wave Frequency
Background Parameters
Electron Density
Collision Frequency
Magnetic Field
MoJo
Ray trace Formulation
Integrator
Interpolator
Hamiltonian
Index of refraction

Hamilton's Equations

$$\frac{dr}{d\tau} = \frac{\partial H}{\partial k_r} \qquad \frac{dk_r}{d\tau} = -\frac{\partial H}{\partial r} + k_\theta \frac{d\theta}{d\tau} + k_\varphi \sin\theta \frac{d\varphi}{d\tau}$$

$$\frac{d\theta}{d\tau} = \frac{1}{r}\frac{\partial H}{\partial k_\theta} \qquad \frac{dk_\theta}{d\tau} = \frac{1}{r}\left(-\frac{\partial H}{\partial \theta} - k_\theta \frac{dr}{d\tau} + k_\varphi r\cos\theta \frac{d\varphi}{d\tau}\right)$$

$$\frac{d\varphi}{d\tau} = \frac{1}{r\sin\theta}\frac{\partial H}{\partial k_\varphi} \qquad \frac{dk_\varphi}{d\tau} = \frac{1}{r\sin\theta}\left(-\frac{\partial H}{\partial \varphi} - k_\varphi \sin\theta \frac{dr}{d\tau} - k_\varphi r\cos\theta \frac{d\theta}{d\tau}\right)$$

$$\frac{dt}{d\tau} = -\frac{\partial H}{\partial \omega} \qquad \frac{d\omega}{d\tau} = \frac{\partial H}{\partial t}$$

- Numerically integrated to calculate the ray path
- Lighthill (1965): Equations in 4 dimensions (including time)
- Haselgrove (1954): Equations in 3 dimensions (spherical coordinates)

Hamilton's Equations, cont.

H: Hamiltonian

k_r, k_θ, k_φ: components of the propagation vector

r, θ, φ: spherical polar coordinates of a point on the ray path

t: time

τ: parameter whose value depends on the choice of Hamiltonian

$\omega = 2\pi f$: angular frequency of the Wave

Note: MoJo uses P`=ct for the independent variable because the derivatives with respect to P` are independent of the Hamiltonian choice.

Hamiltonians

- Hamiltonian used by Appleton-Hartree and Sen Wyller:

$$H = \frac{1}{2}\left(\frac{c^2}{\omega^2}\left(k_r^2 + k_\theta^2 + k_\varphi^2\right) - real(n^2)\right)$$

- The Booker-Quartic uses the real part of the quadratic equation which has the Appleton-Hartree formula as its solution:

$$\begin{aligned} H = real\{&\left[(U-X)U^2 - Y^2U\right]c^4k^4 + X(k\cdot Y)^2c^4k^2 \\ &+\left[-2U(U-X)^2 + Y^2(2U-X)\right]c^2k^2\omega^2 - X(k\cdot Y)^2 \\ &+\left[(U-X)^2 - Y^2\right](U-X)\omega^4\} \end{aligned}$$

$$X = \frac{f_N^2}{f^2}$$

$$Y = \frac{f_{ecf}}{f}$$

$$U = 1 - iZ$$

Index of Refraction

- Appleton-Hartree and Booker-Quartic:

$$n^2 = 1 - 2X \frac{1 - iZ - X}{2(1 - iZ - X) - Y_T^2 \pm \sqrt{Y_T^4 + 4Y_L^2 (1 - iZ - X)^2}}$$

$$X = \frac{f_N^2}{f^2} \qquad Y = \frac{f_{ecf}}{f} \qquad Z = \frac{\nu}{2\pi f} \qquad Y_T = Y \sin\psi \qquad Y_L = Y \cos\psi$$

Ψ = angle between the wave normal and the earth's magnetic field

- Sen Wyller:

$$n^2 = 1 - \frac{2X(U - X) + 2AUX \sin^2\psi}{2U(U - X)(1 + A) + 2AUX \sin^2\psi - U(1 - BC)U + A(U + X))\sin^2\psi + RAD}$$

$$A = \frac{C + B}{2} \qquad B = \frac{F\left(\frac{1}{Z}\right)}{F\left(\frac{1 - Y}{Z}\right)} \qquad C = \frac{F\left(\frac{1}{Z}\right)}{F\left(\frac{1 + Y}{Z}\right)} \qquad F(w) = \frac{1}{(3/2)!} \int_0^\infty \frac{t^{3/2} e^{-t} dt}{w - it}$$

$$U = \frac{Z}{F(1/Z)} \qquad RAD = \pm\sqrt{U^2((1 - BC)U + A(U + X))^2 \sin^4\psi + U^2 (U - X)^2 (C - B)^2 \cos^2\psi}$$

Absorption

- Two types of absorption
  - Non-deviative: Typical D-region absorption
  - Deviative: Occurs when ray path turns in the ionosphere (not in Jones-Stephenson)
- Updated Absorption equation (from Davies, 1990):

$$L_a = -8.68 \int \kappa ds$$

κ: imaginary part of the complex propagation function k
ds: distance along the path

- Other factors we don’t include:
  - Source & Receiver functions
  - Geometric spreading
  - Nonlinear effects (multipathing)

Collision Frequency

- Old Collision Frequency Equation:

$$\nu_e = \nu_0 / e^{A(H-H_0)}$$

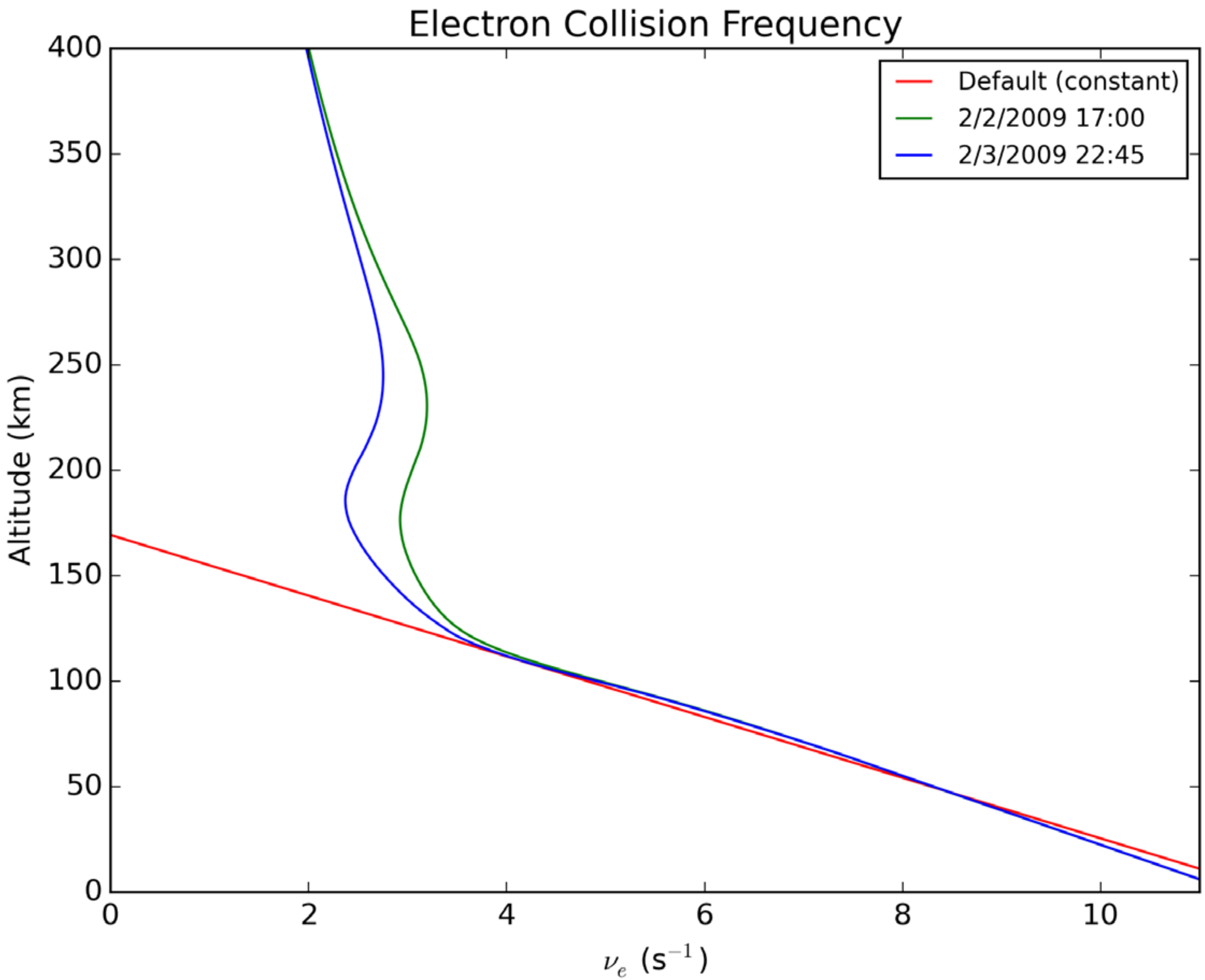
$H_0 = 70$
$A = 0.16$
$v_0 = 8e6$

- New Collision Frequency Equation:
  - From *The Earth's Ionosphere* (Kelley, 2009)
  - Use MSIS for neutral densities/temperature
  - Use SAMI3 for electron density/temperature

$$\nu_e \equiv \nu_{en} + \nu_{ei}$$

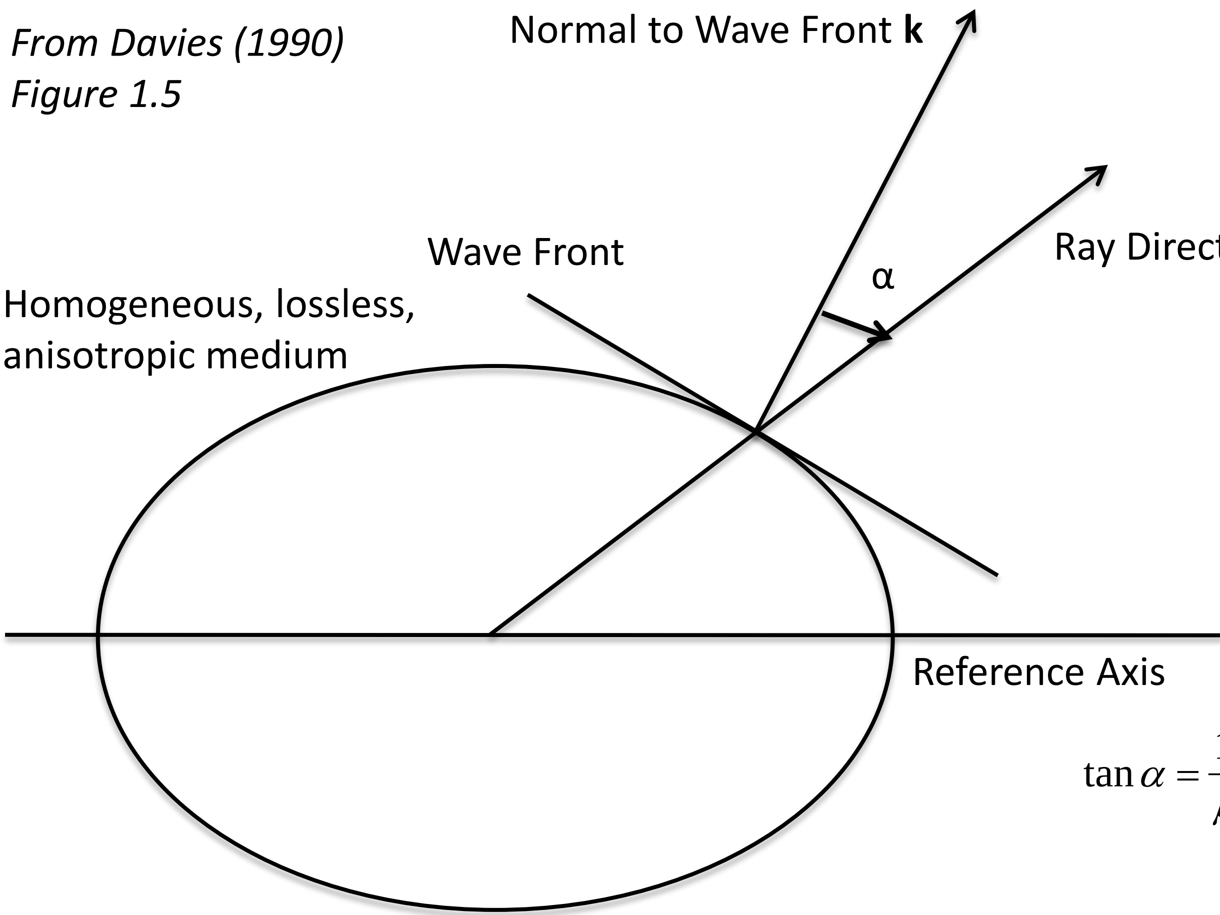
$$\nu_e = 5.4 \times 10^{-10} n_n T_e^{1/2} + \left[34 + 4.18 \ln(T_e^3 / n_e)\right] n_e T_e^{-3/2}$$

Collision Frequency



Wave Propagation (anisotropic medium)

From Davies (1990)
Figure 1.5



The energy propagation (**S**) is not in the same direction as the phase propagation (**k**)

$$\tan\alpha = \frac{1}{\mu}\frac{d\mu}{d\theta} = \frac{1}{2\mu^2}\frac{d\mu^2}{d\theta} = \pm\frac{(\mu^2-1)Y_T Y_L}{[Y_T^4 + 4(1-X)^2 Y_L^2]^{1/2}}$$

(assuming no collisions)

- The level of reflection of the wave normal (**k**) generally won't be the same height as the ray reflection height (**S**)
- The angle α depends on the angle (θ) between **k** and $\mathbf{B_0}$
- Discontinuity (spitze) at reflection when X=1, θ=0 condition reached before the wave normal (k) is horizontal