Wave-Optics Analysis of HF Propagation through Traveling Ionospheric Disturbances and Developing Plasma Bubbles

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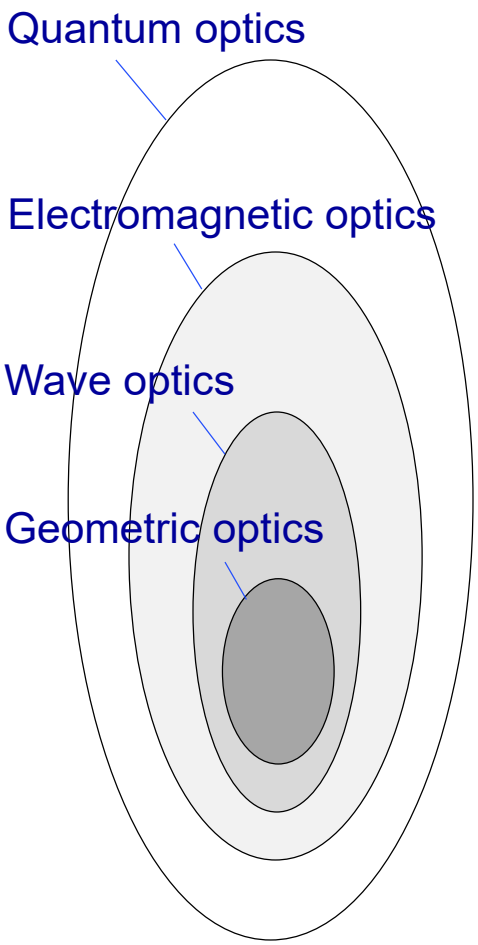
Overview

- We apply a wave-optics technique to model the propagation of high-frequency (HF) waves through simulated traveling ionospheric disturbances (TIDs) and developing plasma bubbles at low latitudes.
- Wave-optics is derived from a forward-propagation approximation of the Helmholtz equation governing the electric field in the frequency domain.
- It is implemented using the split-step approach commonly referred to as the multiple phase screen method (MPS).
- We use the angular spectrum (a byproduct of the computation) to generate angle-of-arrival "maps," which depict the spectrum of angle-of-arrival (AOA) everywhere on the ground.
- These AOA maps identify all radio propagation modes and their amplitudes. There is no need to 'home' rays to identify these propagation modes.
- Wave-optics can represent the interaction (via diffraction) between different propagation modes, which result in fading of the received HF signal. Ray-tracing techniques, by comparison, neglect these effects.

Hierarchy of Wave Propagation Theories



Wave Theory	Simplifying Assumption	Numerical Algorithms
Quantum optics	None(?)	
Electromagnetic optics (Maxwell)	Classical fields	Finite-difference time domain (FDTD)
Wave optics	Scalar waves	Forward propagation equation (FPE)
	Small-angle scatter	Parabolic wave equation (PWE)
		Multiple phase screen (MPS)
Geometric optics	Infinitesimally small λ, no diffraction or interference	Hamiltonian Ray-tracing
	Rays are lines	Snell's Law

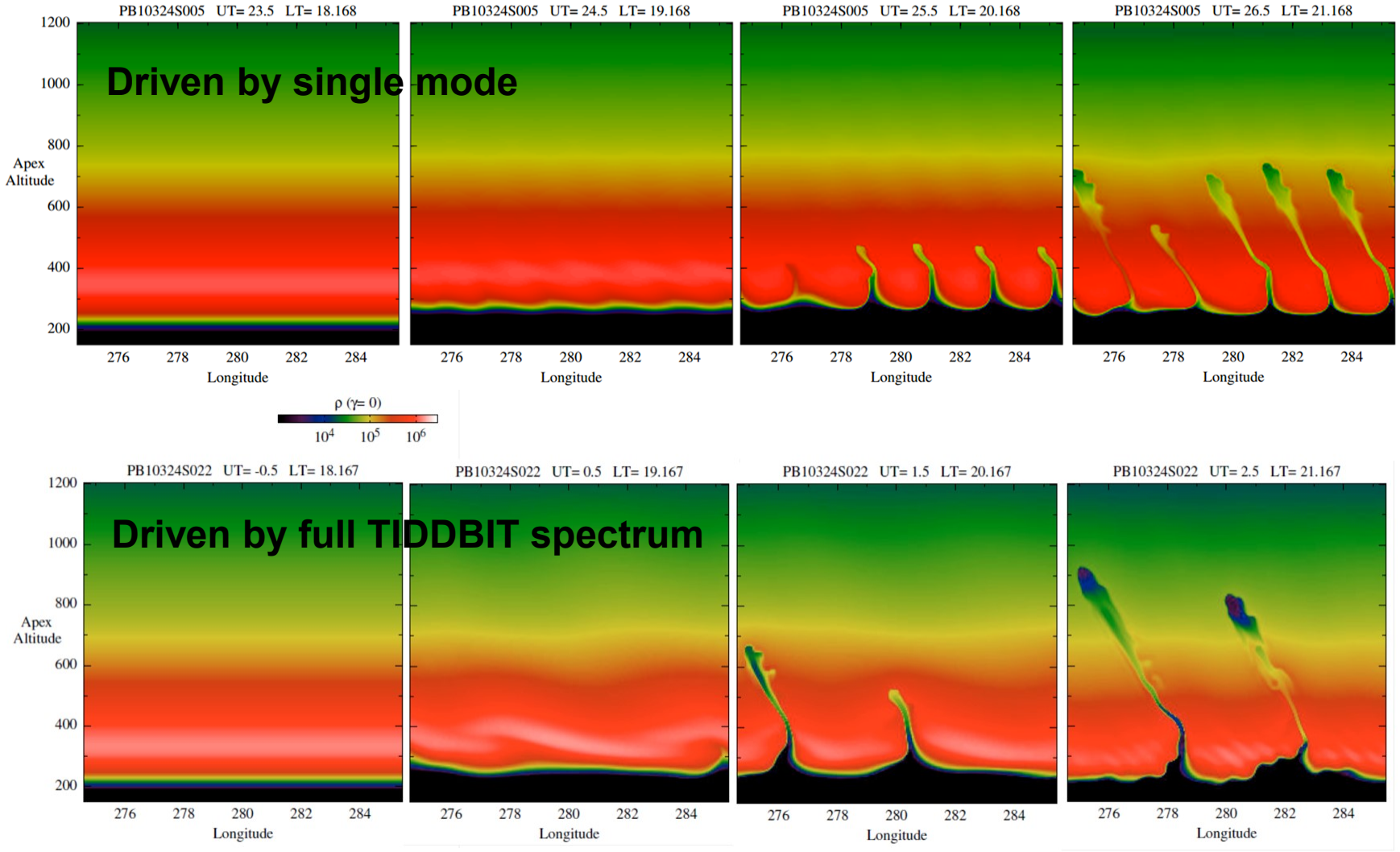
Decreasing Fidelity

HF Propagation through Large Scale Disturbances

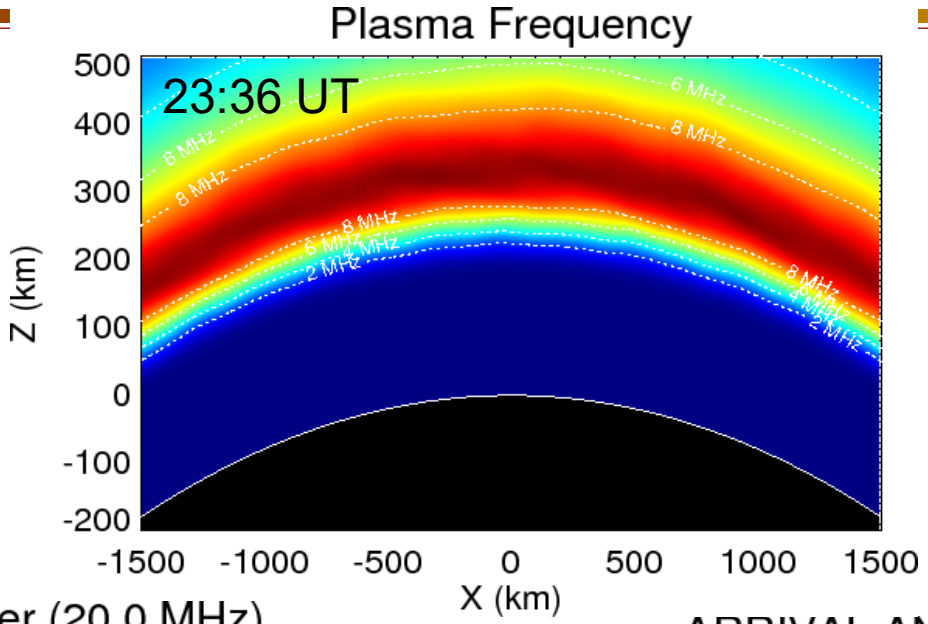
- Next few slides show PWE and ray-trace propagation through large scale plasma structures obtained via physics based simulation
- Measured neutral wind fields were used to initialize a physics based model (PBMOD), TIDs develop and seed R-T instability, producing spread-F plumes
- HF waves (20 MHz) were propagated through PBMOD data cubes in zonal direction at 4 time snapshots during the plasma evolution
- The propagation plots on slides 6-10 show
  - Plasma frequency (colors and contours)
  - Wave-optics (colors) and Ray-tracing (white curves) with plasma frequency contours
  - Spectrum of arrival angle at the ground (colors)

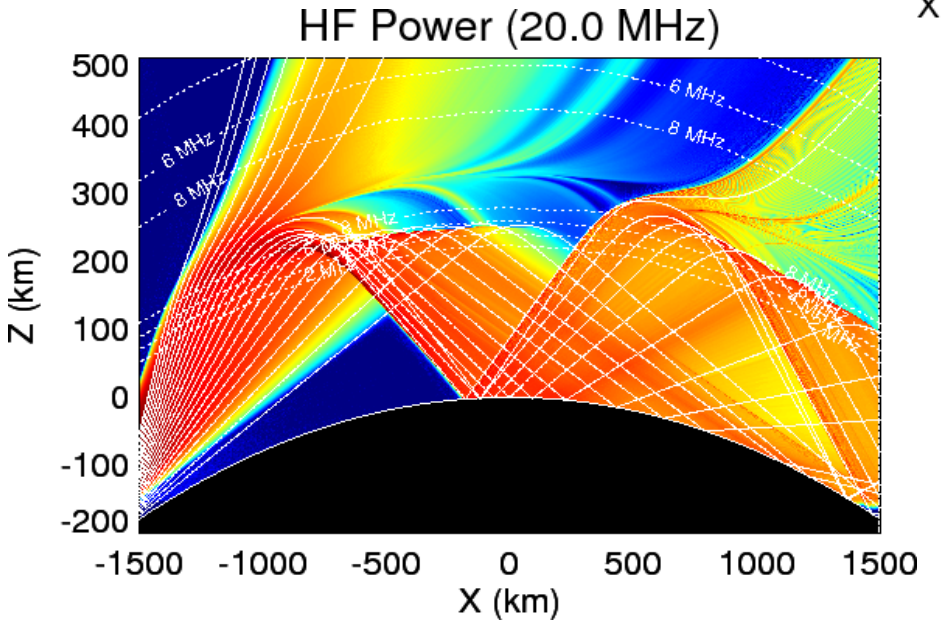
3-D Plasma Structures Driven by TIDDBIT

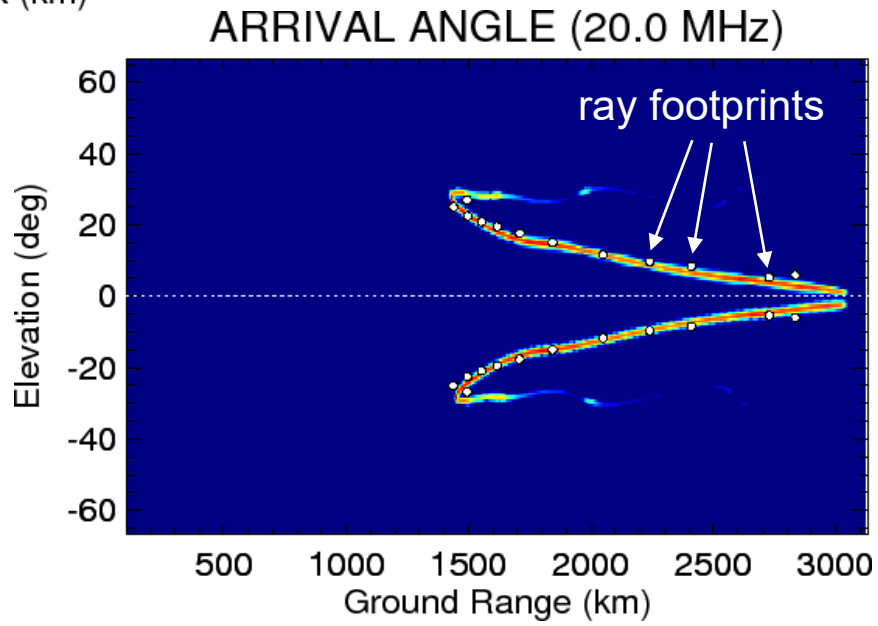
PBMOD simulations of the interchange instability in this event, showing plasma density in the equatorial plane. TIDDBIT data provided the neutral-wind perturbations.



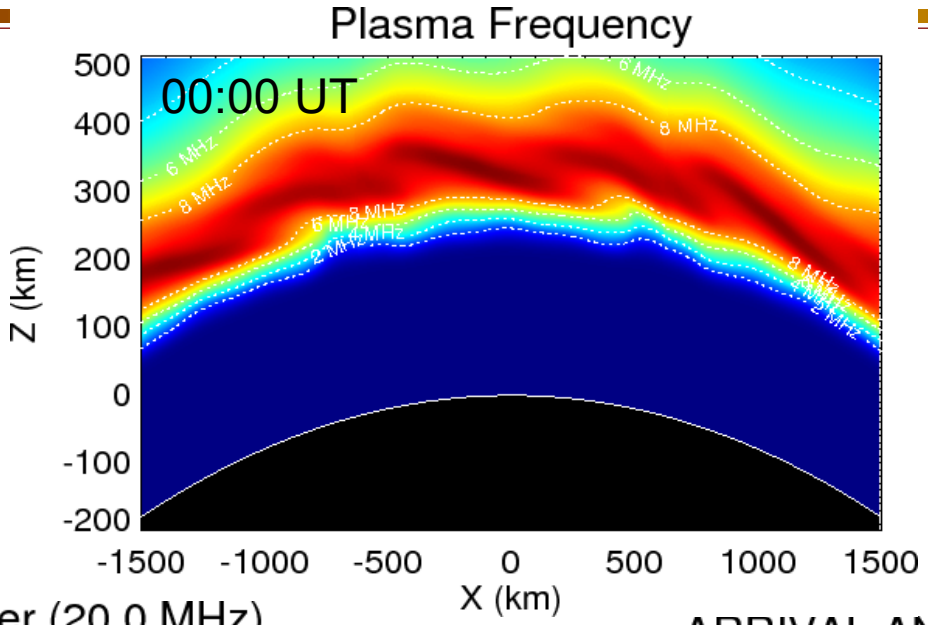
Propagation through Simulated TIDs

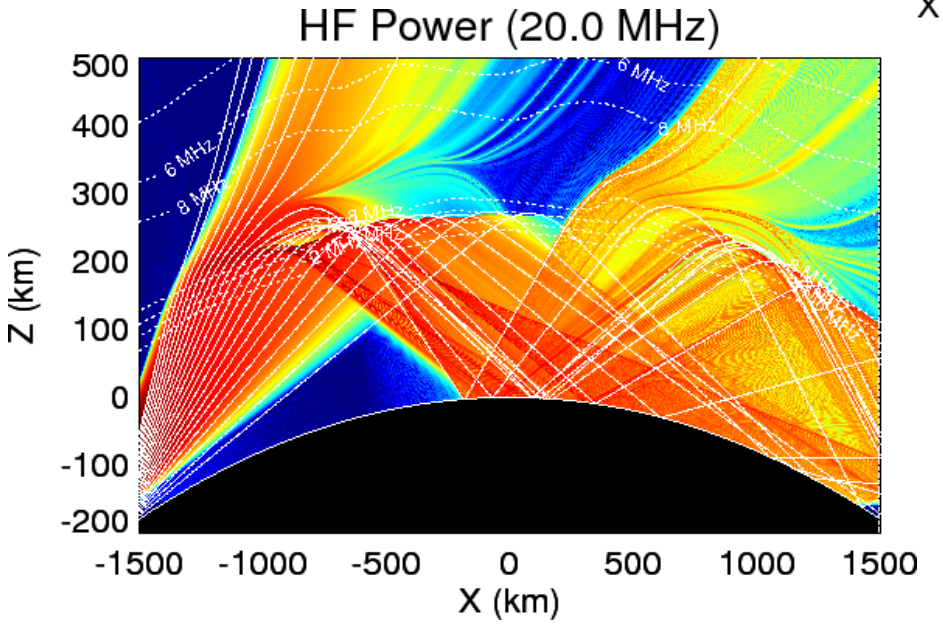


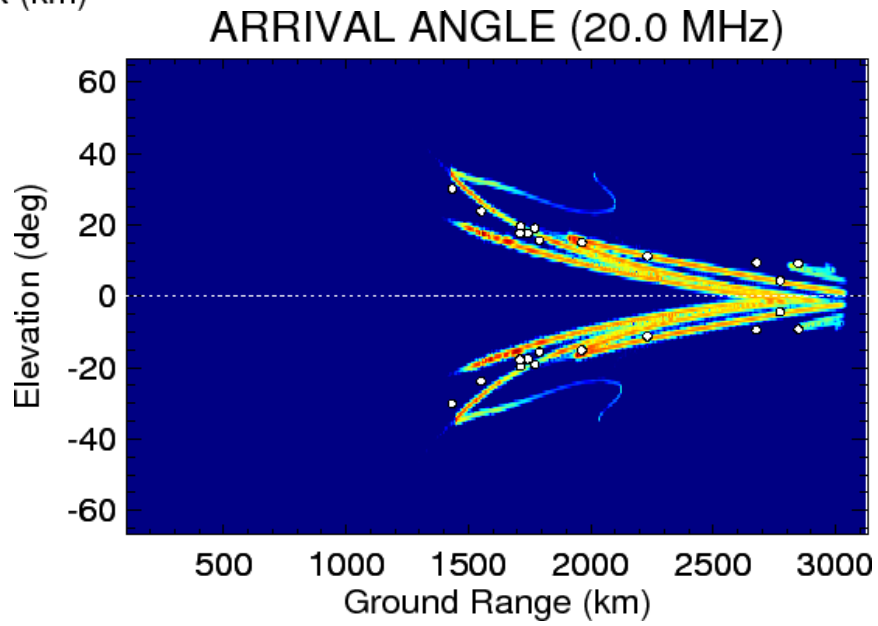




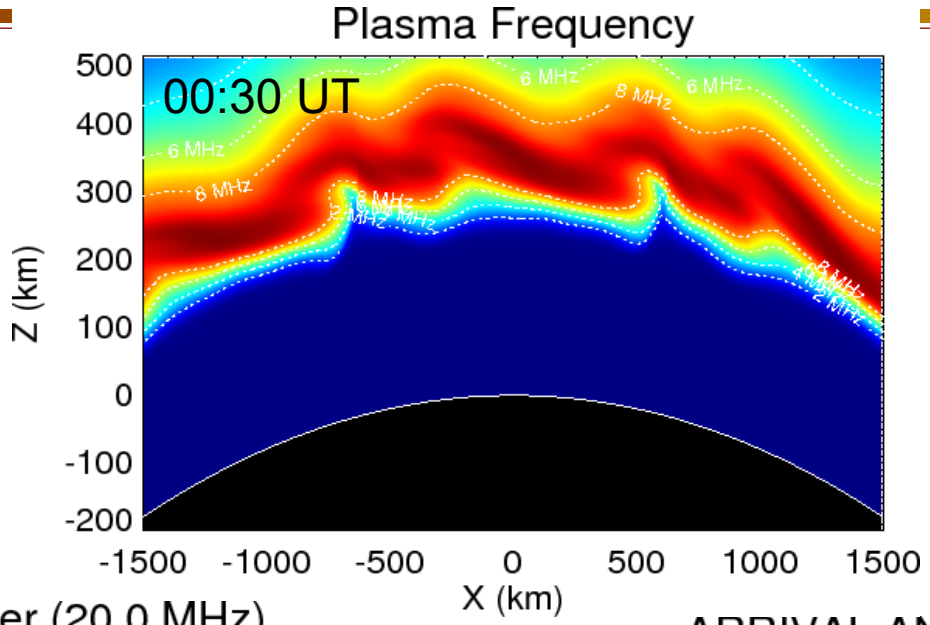
Propagation through Simulated TIDs

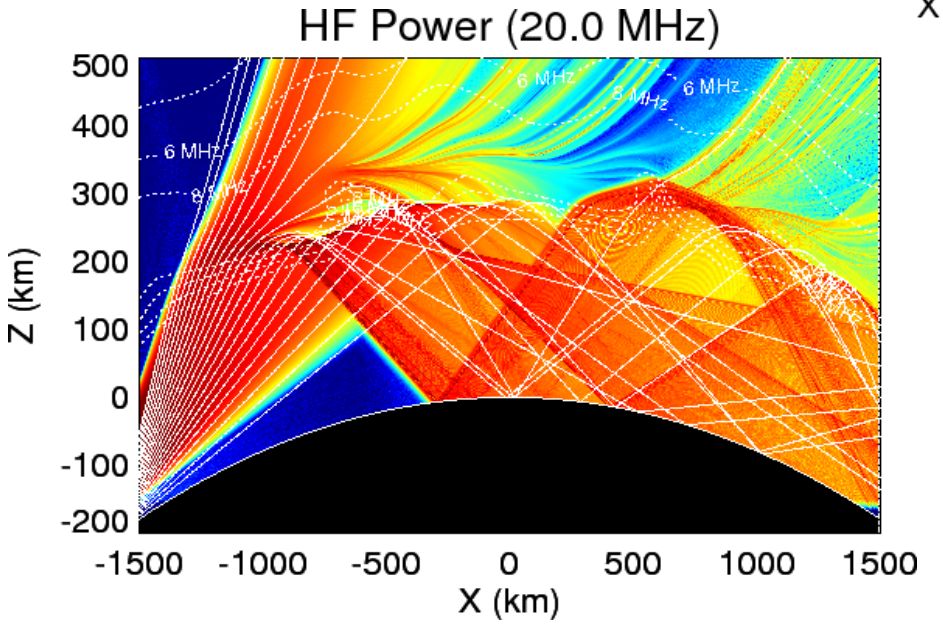


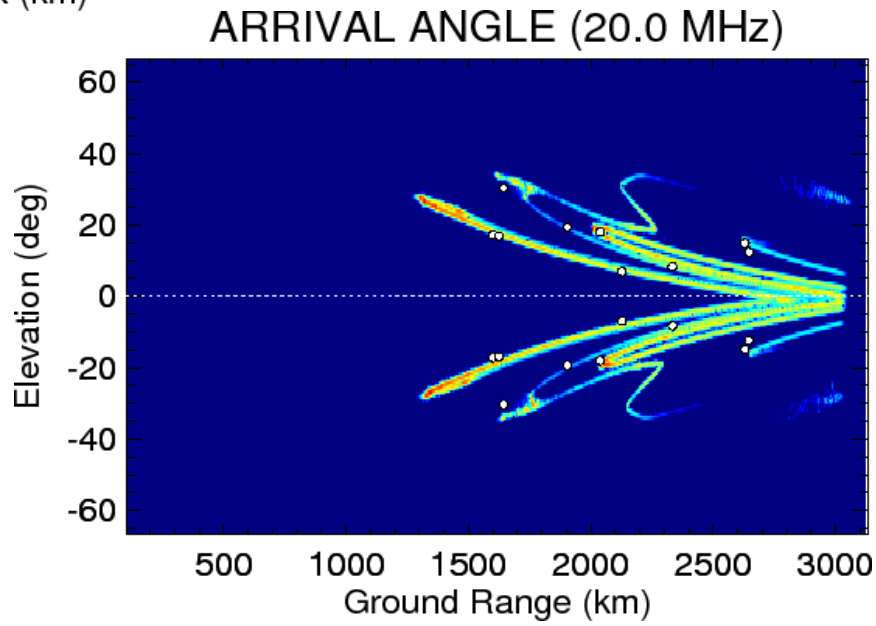




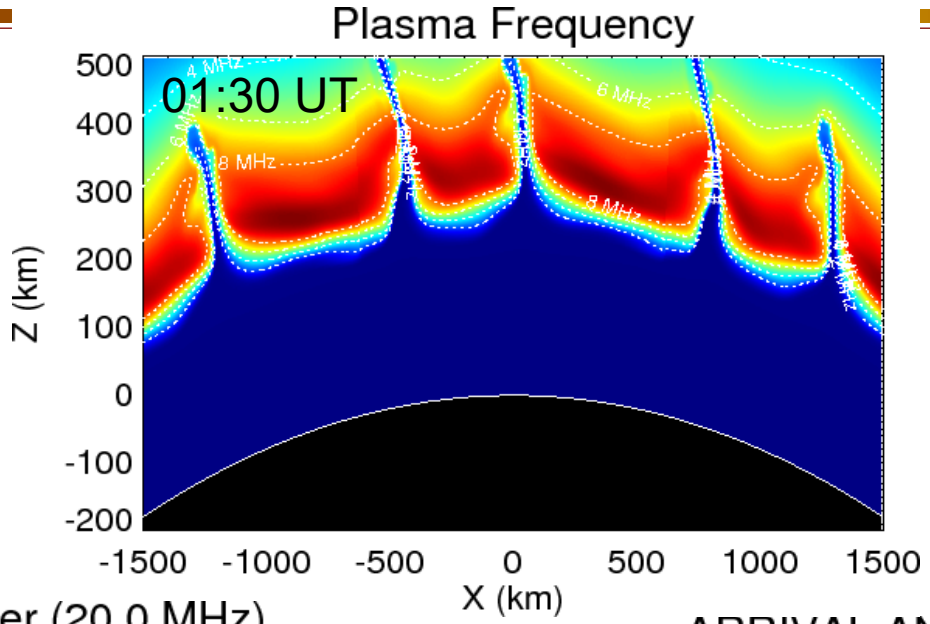
Propagation through Simulated TIDs



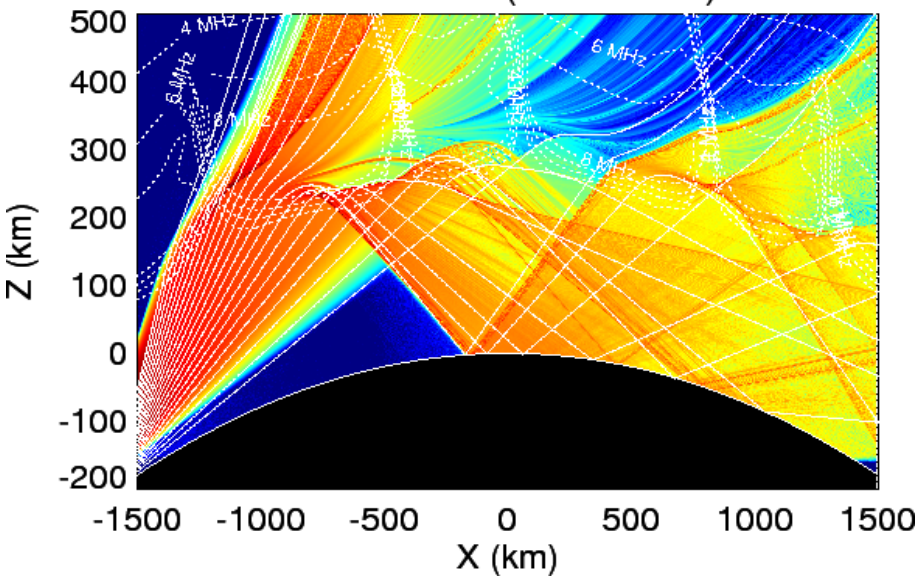


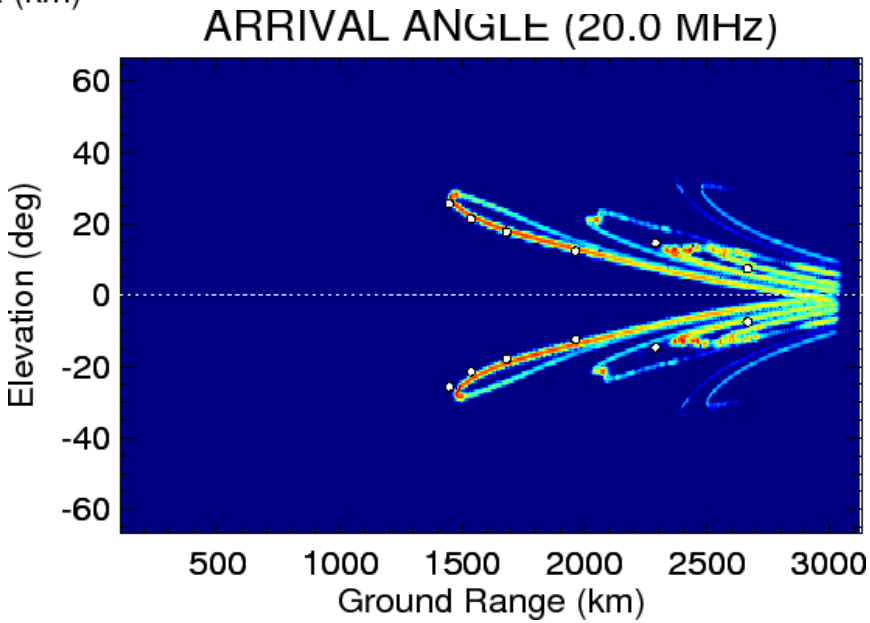


Propagation through Simulated TIDs



The number of propagation modes increases as the ionospheric structure develops. Ray-tracing results appear random, but wave-optics reveals systematic behavior of complex propagation environment





Conclusions

- Theory suggests wave-optics and ray-tracing should predict the same arrival angles when refractive processes are dominant e.g. when the scale sizes of the irregularities are much larger than the wavelength.
- Our PBMOD simulations support structure with scale-sizes of about 10 km. In the absence of sub-grid scale structure, we observed good agreement between wave-optics and ray-tracing, except in regions of strong focusing following caustics.
- Wave-optics provides more information than ray-tracing, as both the spectra of wave power and direction are available everywhere. This additional information is most useful when the propagation environment is multi-modal.
- Under these conditions, ray-tracing results become difficult to interpret because the footprints appear to be distributed randomly. The wave-optics results show that while the propagation environment is complex, it remains deterministic and systematic, with multiple modes of propagation clearly defined for all ranges.
- We believe the additional information afforded by wave-optics can be leveraged to improve OTHR performance.