Transionospheric propagation of terrestrial VLF radiation

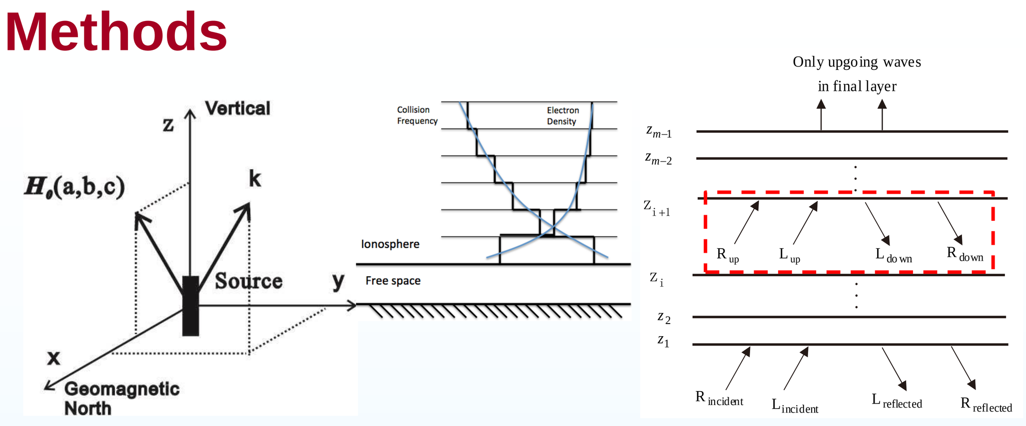
S. Zhao[1] L. Liao[2] X. Zhang[1] X. Shen[3]
1. Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China
2. Institute of geophysics, China Earthquake Administration, Beijing 100081, China
3. Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China

Introduction

Research on the transionospheric propagation of VLF signal is very useful in studying lightning and lightning location as well as man-controlled particles precipitation.

A full-wave model of transionospheric propagation of VLF waves has been constructed. Through comparing the calculated electromagnetic distribution excited by NWC with DEMETER satellite record, the model has been verified. The spatial distribution of electromagnetic field excited by VLF transmitters with different radiation frequencies and powers under different geomagnetic parameters and ionospheric parameters have been stimulated using the full-wave model.

Methods



The Maxwell equation is solved in Fourier (horizontal wave vector $\mathbf{k}_\perp$) domain:

①For each $\mathbf{k}_\perp = const$ (Snell's law) to find k_z in each layer for each of 4 plane wave modes: 2 up (**u**) and 2 down (**d**)

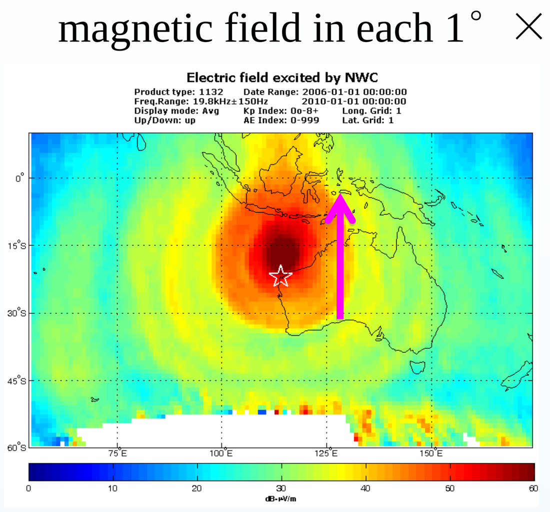
②Use continuity of $\mathbf{E}_\perp$ and $\mathbf{H}_\perp$ between layers to find reflection coefficients $\mathbf{R}^{u,d}$ and mode amplitudes **u, d**

- Recursion order $\mathbf{R}^u_{k+1} \rightarrow \mathbf{R}^u_k$ and $\mathbf{u}_k \rightarrow \mathbf{u}_{k+1}$ provides stability against 'swamping' of solution by evanescent waves
- Represent source currents as boundary conditions on $\mathbf{E}_\perp$ and $\mathbf{H}_\perp$ between layers

③Inverse Fourier transform from $\mathbf{k}_\perp$ to $\mathbf{r}_\perp$

Validation

Observation: Utilizing DEMETER electric and magnetic field spectrum data (1132, 1138) from 2006 to 2010; the energy within 19.8kHz±150Hz is summed to get the RMS electric and magnetic field in each 1° ×1° grid point excited by NWC.

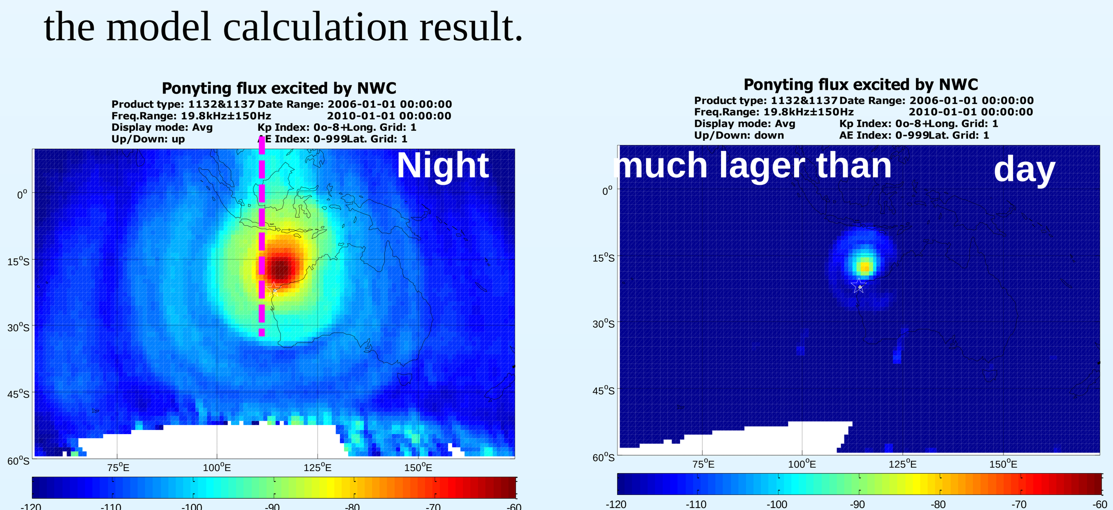


(1) A set of concentric rings, which may be caused by the mode interference in the wave-guide mapping into the ionosphere.

(2) The center of the concentric ring in the ionosphere has a longitudinal deviation relative to the source.

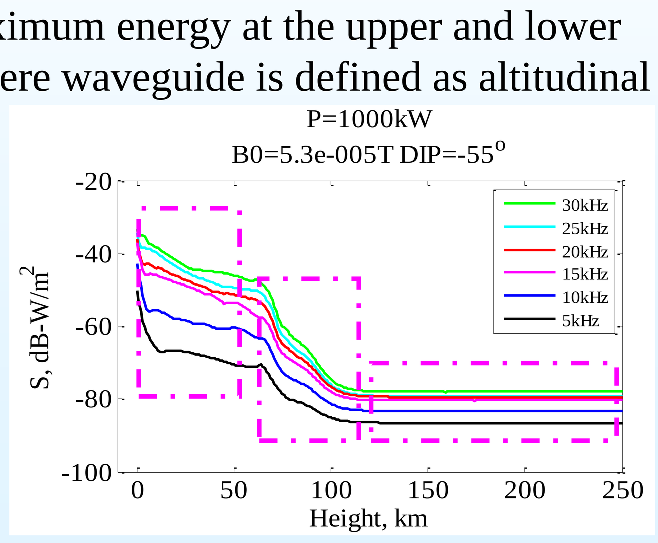
(3) The concentric ring is asymmetry in north and south, the side that magnetic force line points is larger which may be due to the influence of the geomagnetic dip angle.

Since DEMETER survey mode only records a horizontal component of both the electric and magnetic fields, it is possible to estimate the power flux in the ionosphere from VLF transmitters by assuming that the unmeasured component of both the electric and magnetic fields are equal in magnitude to the measured component, due to circularly polarized propagation. The data on the pink dash line is compared with the model calculation result.

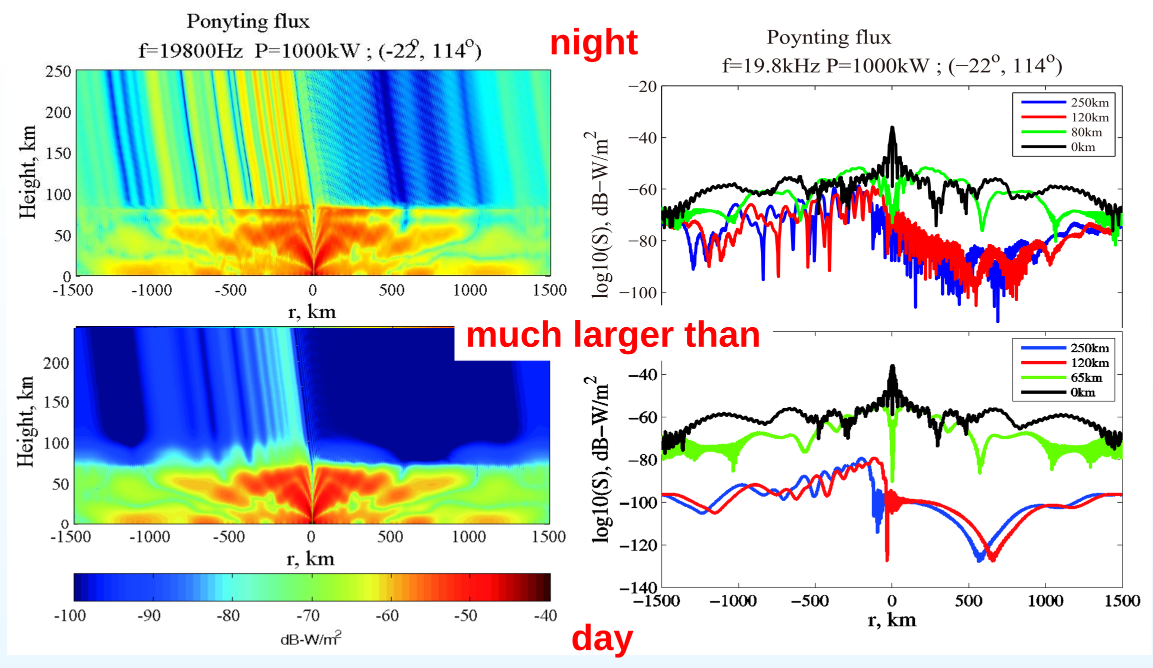


The energy attenuation is mainly in the earth-ionosphere wave-guide (0-65 km) and the D/E region of the lower ionosphere under 120 km. The energy would not change after penetrates the D/E region.

- The difference between maximum energy at the upper and lower boundary of the earth-ionosphere waveguide is defined as altitudinal attenuation in the waveguide.
- The difference between maximum energy at the upper boundary of the earth-ionosphere waveguide and 120km is defined as D/E region absorption.

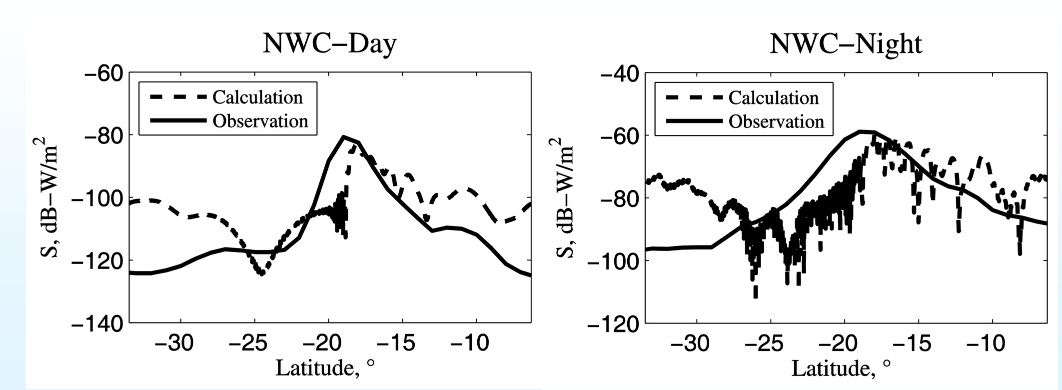


Calculation results in the meridian plane:



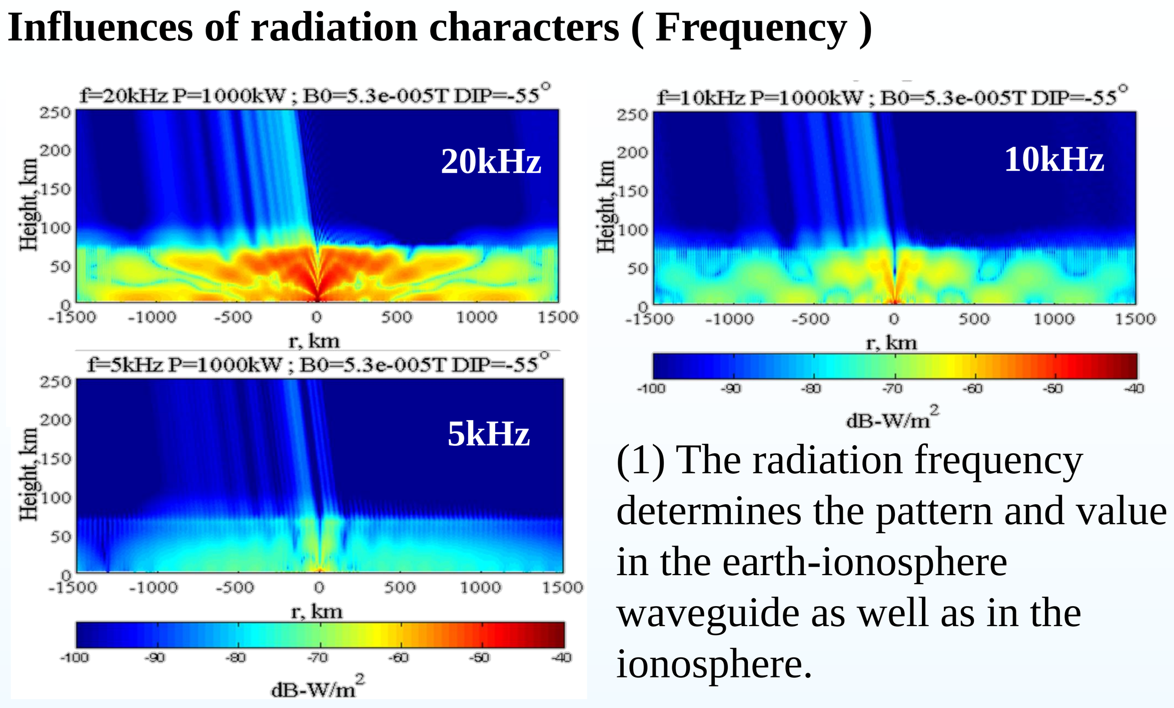
(1) Mode interference in the earth-ionosphere wave-guide can be clearly seen. The change of the energy at upper and lower boundary of the wave-guide are contrary.
(2) The energy which penetrates the D/E region would not change while propagates into the upper ionosphere and magnetosphere along the geomagnetic field line.
(3) The energy is gathered more at the side of the geomagnetic field inclines.

The calculation results match with observation:



Simulation

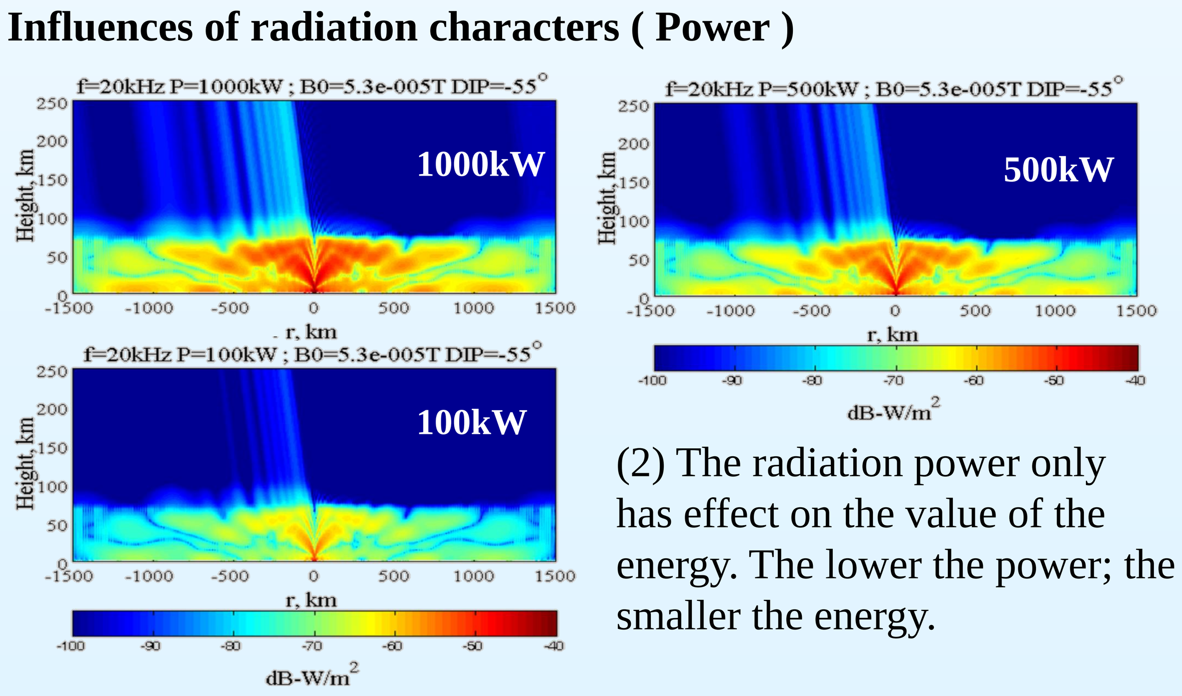
Influences of radiation characters (Frequency)



(1) The radiation frequency determines the pattern and value in the earth-ionosphere waveguide as well as in the ionosphere.

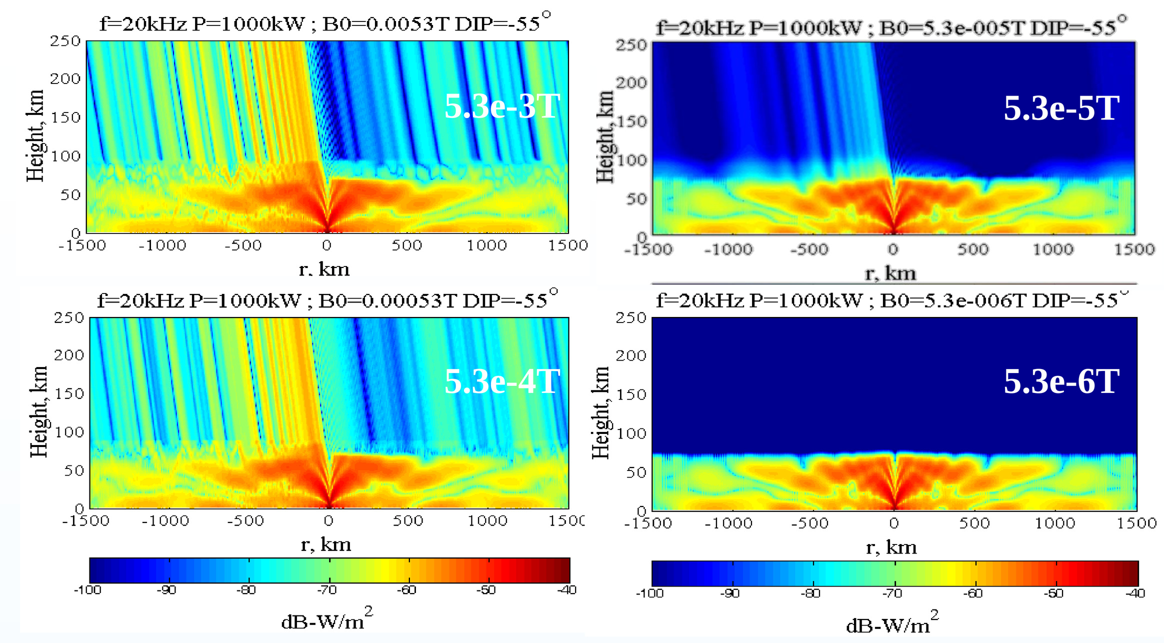
The lower the frequency, the energy in the waveguide and the ionosphere is smaller, and the energy in the ionosphere become two beams.

Influences of radiation characters (Power)



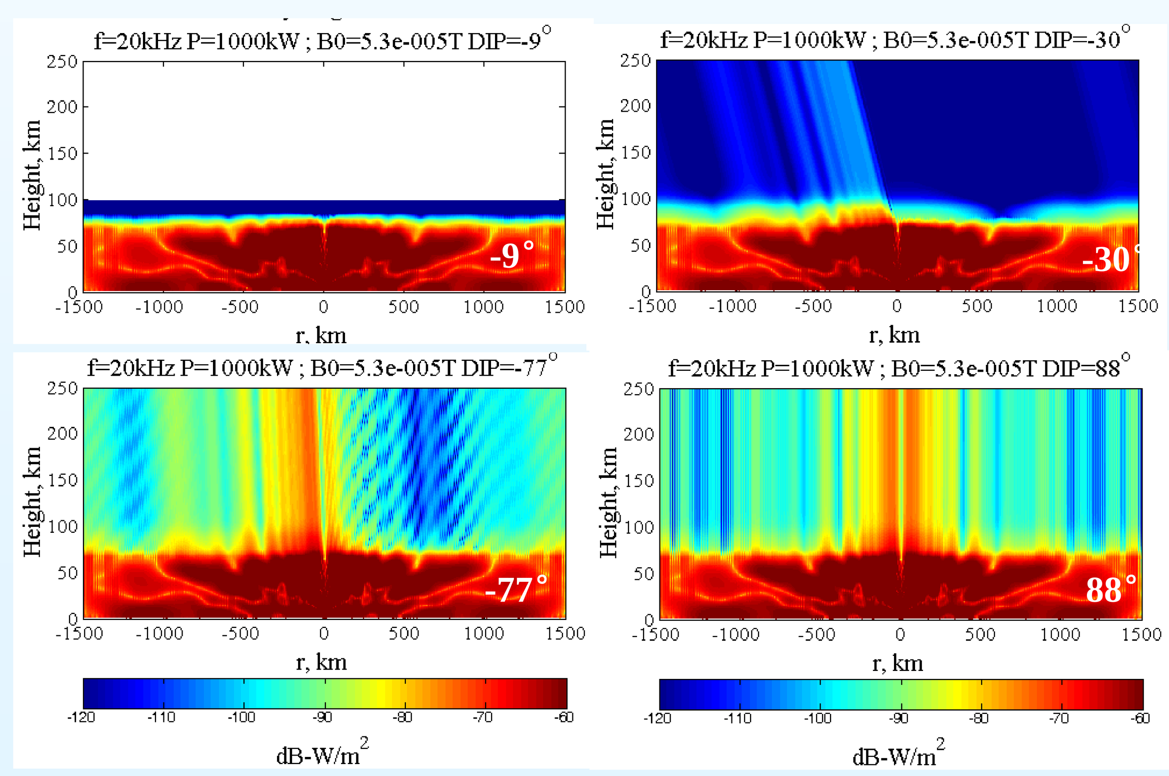
(2) The radiation power only has effect on the value of the energy. The lower the power; the smaller the energy.

Influences of geomagnetic characters (Intensity)



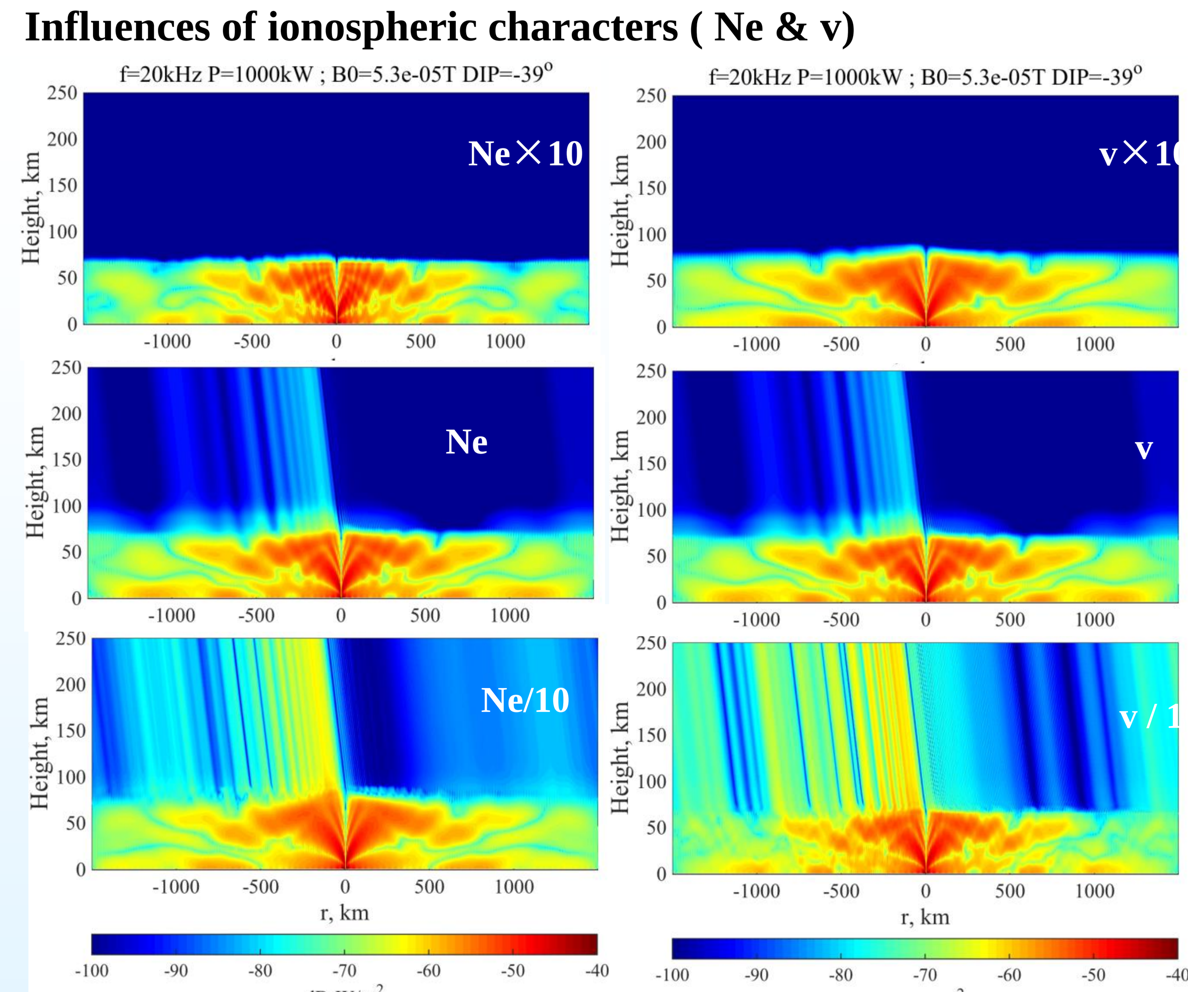
(3) The geomagnetic intensity has no effect on the value and pattern in the waveguide, but has huge effect on the energy distribution in the ionosphere. The smaller the geomagnetic intensity; the smaller the energy which can penetrate into the ionosphere.

Influences of geomagnetic characters (Intensity)



(4) The geomagnetic Dip angle also only has effect on the energy distribution in the ionosphere. The absorption is large at equator, where the energy can hardly penetrate into the ionosphere. The DIP also decides the inclination of the energy beam.

Influences of ionospheric characters (Ne & ν)



(5) The electron density and total collision frequency also have slight effect on the energy distribution pattern and value in the waveguide, but has huge effect on the pattern and value in the ionosphere. The smaller the density and collision frequency; the larger the energy which can penetrate into the ionosphere.

In summary

The full-wave model constructed is reliable. Focusing the attenuation in the earth-ionosphere waveguide and absorption in the D/E region of the ionosphere, it can be concluded that

- Attenuation of VLF radiation in the waveguide is only affected by the wave frequency in the near field which decreases with the increase of the wave frequency, while the D/E region absorption and total attenuation increase with wave frequency. The variation of the radiation power has no effect on the attenuation in the waveguide and the D/E region absorption.
- The geomagnetic and ionospheric parameters all have no effect on the energy distribution in the waveguide.
- The D/E region absorption decreases with the increase of the geomagnetic field. The dip angle of the geomagnetic field is larger; the inclination energy beam in the ionosphere is larger and the D/E region absorption is also smaller.
- The D/E region absorption increases with ionospheric electron density and collision frequency.