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Simulation-based Analysis of the Impact of Large-Scale Field-Aligned Density Duct on HF Radio Wave Propagation

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In a horizontally stratified ionosphere, the high-frequency O-mode pump waves can propagate above their reflection altitude through the radio windows if transmitted at a Spitze angle. However, several observations show that transmission becomes maximum when the wave's inclination angle lies between the Spitze angle and the Earth's magnetic field instead of along the Spitze angle. Such viewpoints indicated the possibilities of two-dimensional inhomogeneities in the form of magnetic field-aligned irregularities (FAIs) and ducts. They are found in the polar ionosphere in a wide range of transverse and longitudinal spatial scales, i.e., meters to hundreds of kilometers. To understand the physical processes taking place in the ionosphere during active experiments, it is crucial to study the interaction of electromagnetic waves with the field-aligned irregularities and density ducts of different dimensions. In this work, our focus is on the large-scale field-aligned density duct to numerically study its impact on the propagation of high-frequency electromagnetic radio waves. We utilized a two-dimensional finite-difference time-domain (FDTD) approach to solve Maxwell's equations using a finite-difference approximation.

We examined two main cases: one in which the pump wave entered the density duct parallel to the magnetic field and the second in which the pump wave was inclined. Our findings indicate that both types of pump waves can propagate beyond the O-mode reflection height, but their spatial distribution of the electric field and energy transmission differ. When the pump wave entered the density duct at an angle, multiple reflections occurred within the plasma resonance of the duct, leading to the formation of eigenmodes inside the density duct. This resulted in more localized oscillations of the electric fields and less transmission through the plasma resonance but with a diverse angle of refraction. In contrast, there were no eigenmodes in the parallel incident waves, resulting in fewer plasma modes being excited and more waves being transmitted through the plasma resonance layer than the inclined pump wave.