Simulations of Ionospheric Behavior Driven by HF Radio Waves at the Initial Stage

Jing Chen¹, ², Qingliang Li², Yubo Yan², Haiqin Che², Guanglin Ma², and Guang Yuan¹, *

Abstract—This study explores the variability in the electric field, plasma number density, and plasma velocity driven by high-frequency (HF) radio wave injected into the vertically stratified ionosphere at a millisecond time scale after switch-on of the radio transmitter. It was found that the mode conversion process of electromagnetic (EM) waves took place at the reflection heights of both the R-X (right-circularly polarized extraordinary wave, R-X) and L-O (left-circularly polarized ordinary wave, L-O) modes. The ionospheric electron number density was remarkably oscillatory. A depletion of ionospheric ion number density at the L-O mode turning point and two ion number density peaks on each side of the O-mode reflection region were discovered. The turbulent layer of the ion density peak at the bottom of the critical height shifted downwards, which qualitatively conforms to the observations made at the Arecibo and the EISCAT. The vertical electron velocity oscillated near the L-O mode reflection point. The vertical ion velocity remained positive above the reflection height of the L-O mode and remained negative below this height. These results, which were derived using realistic length scales, ion masses, pump waves, and other plasma parameters, are consistent with theoretical predictions and prior experimental observations, and should thus be useful for understanding the linear and nonlinear interactions between the HF EM wave and the ionospheric plasma at the initial stage.

1. INTRODUCTION

The ionosphere is a natural plasma laboratory, and as such, it is of significant interest both from geophysical perspectives and plasma physics [1]. Therefore, many different scientific and technological objectives have motivated the ionospheric modification using high-power and high-frequency (HF) transmitters [2–4]. A considerable number of active ionospheric experiments designed to investigate the F-region artificial ionospheric turbulence, including large-scale electron and ion temperature and density perturbations [5, 6], artificial field-aligned irregularities [7, 8], stimulated electromagnetic emissions [9–11], and Langmuir turbulence [12] have been performed. To explain the observed phenomena, studies of the associated physical mechanisms, such as ohmic absorption, oscillating two-stream instability, and parametric instability, have been developing rapidly [13–15]. A high-power radio wave can excite the particular wave modes and enhance plasma turbulence, which in turn causes the anomalous plasma heating [16–18]. It has been recognized that wave-wave interactions determine the characteristics of F-region modifications to a large extent [19]. As the primary mechanism of turbulence excitation, the parametric decay instability (PDI) involves the conversion of HF electromagnetic (EM) waves into Langmuir waves and ion-acoustic waves, which could lead to the development of solitons and the Langmuir cavitons under the existence of the vertical density gradient in the F-region [20–22].
One of the important features of the PDI caused by the nonlinear effects of wave and plasma interactions is that there is a limited electric field threshold [23–25]. High-frequency pump waves excite a noticeable standing wave pattern at the reflection points of ordinary wave (O-mode). The electric field strength of standing waves will then increase dramatically, and this is called the “swelling” of the electric field. When this electric-field amplitude of the standing wave exceeds the limited electric field threshold, other instabilities (i.e., Langmuir decay instability and oscillating two-stream instabilities) can be induced. Therefore, it is necessary to accurately calculate the variation within electric fields, plasma densities, and other parameters during the initial process in the reflection area. However, parametric instabilities are excited within a few milliseconds after a radio transmitter is activated [26, 27]. For instance, the EISCAT heating experiments showed the enhanced ion-lines induced by PDI within the initial 100 ms of heating [28], and the HF-induced small-scale plasma depletions have been detected instantly within 5 ms at the Arecibo [29]. Nevertheless, these observations provide very limited insights into the physical processes occurring within PDI over such short time intervals. Thus, numerical simulations are essential for studying the interactions between EM waves and plasma, and simulation results are of great benefit for understanding the physical phenomena that are difficult to observe by artificial ionospheric modification experiments at the millisecond time scale.

In recent decades, numerical simulation methods rather than purely numerical analyses of ionospheric heating have been shown to provide effective measures for understanding the interactions between ionospheric plasma and EM waves because the excitation and the development of parametric instabilities can be visualized by the simulations [30–32]. To better simulate this complex, nonlinear, and impulsive interactions in a natural way, it is critical to accurately describe the physical model and avoid distortions caused by numerical errors. The difficulty of simulating the parametric instabilities process is the accurate description of physical parameters enabling variation in the geomagnetic field, temperature characteristic, electromagnetic field and plasma collision frequency at different positions. The original finite difference time domain (FDTD) method, as a standard technique for numerically solving Maxwell’s equations, is considered a primary alternative to simulating PDI because the physical model involves Maxwell’s equations [33]. Additionally, the grid-based FDTD structures of Yee (1966) allow material properties (such as temperature, topography, and electron density) to be defined separately at each point [34]. Thus, this method can handle complex, nonlinear, and impulsive interactions between HF waves and the plasma in a natural way [35]. However, the original FDTD method lacks temporal and spatial discretization and is absence of the time advancement scheme of other physical quantities, such as plasma number density and velocity involved in simulating the PDI process. Hence, the classical FDTD method is insufficient for simulating this process. A few improved FDTD models described the radio waves propagation in plasma have been reported [36, 37]. More importantly, Young (1994) arranged plasma fluid velocity vector and electric field vector in same Yee grid in order to couple between the Maxwell equations and Euler equation [38]. Yu and Simpson (2010) developed a new three-dimensional FDTD model to simulate EM wave propagation in the anisotropic magnetized cold plasma by letting the current density and electric field share the same nodes [39]. Therefore, the schemes based on the FDTD method can feasibly simulate the variability in ionospheric parameters during the EM wave-driven ionospheric perturbation process. In this study, we investigate the variation in the electric field, plasma density, and plasma velocity driven by HF radio waves at the millisecond time scale according to plasma two-fluid theory and via numerical simulations based on an advanced FDTD method which improved the spatial and temporal arrangements and the time advancement scheme for the above-mentioned physical quantities. Such simulations, involving realistic scales of the ionosphere and wavelengths of the EM waves, are of great benefit for understanding the physical mechanisms of artificial ionospheric modification experiments.

2. METHODOLOGY

2.1. Physical and Mathematical Model

In this physical model, along the z-axis (vertical direction), a vertically stratified ionospheric layer was assumed. An HF EM wave was injected vertically into the ionosphere are shown in Figure 1. The downward-directed geomagnetic field $\mathbf{B}_0 = B_0 \left[ \hat{x} \sin(\theta) - \hat{z} \cos(\theta) \right]$ directed obliquely toward the density gradient and was tilted $\theta$, which is the complementary angle of the magnetic dip angle, to the z-axis.
Figure 1. Schematic showing the simulation model of the electromagnetic (EM) wave propagation in ionosphere: $\vec{B}_0$ is the geomagnetic field; $\vec{k}_{EM}$ is the propagation direction of the injected EM wave; $\vec{E}_x$ and $\vec{H}_y$ are the initial polarized direction of the electric field and magnetic field of the injected EM wave, respectively.

in the $x$-$z$ plane. It is necessary to define the geomagnetic field, which is of great importance to the plasma dynamics in F-region where collision frequencies between particles are low, because the motions of charged particles are influenced by the magnetic field [19].

The plasma component species in this simulation model of ionosphere were electrons and oxygen ions $O^+$. $O^+$ was considered as the major ionic component in F-region because the number of the $O^+$ ions is higher than that of other ions, such as NO$^+$ and O$_2^+$ [40, 41]. The plasma two-fluid theory was adopted to mathematically describe the ionospheric behavior driven by the EM waves propagation in the ionospheric plasma. The plasma two-fluid theory is essentially a macroscopic theory based on fluid equations of mass as well as charge, momentum and energy continuity together with the Maxwell equations. Because the $\partial T_\alpha / \partial t$ during 5 milliseconds is small enough that such the energy equation is not indeed calculated. Therefore, there are four equations to describe the initial ionospheric behavior. The magnetized plasma governing equations from this theory were cast in terms of Maxwell’s equations (Eqs. (1)–(2)) coupled to the continuity equation (Eq. (4)) and the momentum equation (Eq. (4)). These equations can be expressed as follows:

$$-\mu_0 \frac{\partial \vec{H}}{\partial t} = \nabla \times \vec{E}; \quad (1)$$

$$-\varepsilon_0 \frac{\partial \vec{E}}{\partial t} = \nabla \times \vec{H} - \sum_\alpha N_\alpha q_\alpha U_\alpha; \quad (2)$$

$$\frac{\partial N_\alpha}{\partial t} = -\nabla \cdot (N_\alpha U_\alpha); \quad (3)$$

$$N_\alpha m_\alpha \frac{dU_\alpha}{dt} = N_\alpha q_\alpha [\vec{E} + U_\alpha \times (B_0 + \vec{B})] - N_\alpha m_\alpha \nu_\alpha U_\alpha - \nabla(k_B T_\alpha), \quad (4)$$

where $\alpha$ represents the electron $e$ or oxygen ion $i$, and $\vec{x}$, $\vec{y}$, and $\vec{z}$ are the unit vectors in the $x$-, $y$-, and $z$-directions, respectively. $\vec{H} = \vec{H}_x + \vec{H}_y + \vec{H}_z$ and $\vec{E} = \vec{E}_x + \vec{E}_y + \vec{E}_z$ are the magnetic field and the electric field perturbation, respectively. $U_\alpha$ and $N_\alpha$ are the time-varying velocity and the number density of the plasma fluid, respectively. $T_\alpha$ signifies the electron or $O^+$ temperature. $\varepsilon_0$, $\mu_0$ and $k_B$ are the vacuum permittivity, permeability and Boltzmann’s constant, respectively. Here, $\nu_\alpha$ and $m_\alpha$ are the particle collision frequency and mass, respectively. Additionally, $q_i = e$ and $q_e = -e$ represent charge magnitude of the ion and the electron, respectively. It should be noted that the $dU_\alpha/dt \equiv \partial U_\alpha / \partial t + (U_\alpha \cdot \nabla)U_\alpha$ is the convective derivative in which $(U_\alpha \cdot \nabla)$ is a scalar differential operator.

These time-varying physical parameters, including the electric field, magnetic field, plasma number density, and plasma velocities exhibit a gradient of variation along each direction in space, as described by Eqs. (1)–(4). The transverse gradients of the parameters in F-region were much less than the vertical gradients owing to the presence of pump EM waves exhibiting spatial variation only in the $z$-direction.
during the millisecond ionospheric heating [27]. As a result, only the vertical gradient of variations was considered and the transverse variations were negligible in this model. Notice that the variation of \( k_B N_\alpha (\partial T_\alpha / \partial z) \), a part of the last term in right-hand side in Eq. (4), has negligible influence on Eq. (4) at a millisecond time scale. Hence, the electron and ion temperature in this model at a millisecond time scale were set to be constant when simulating the initial variations.

Based on this physical model, the developed FDTD scheme was applied to simulate the nonlinear interactions between HF waves and the ionospheric plasma through a complete spatial and temporal discretization scheme and the time-advancement equations for plasma number density and plasma velocity.

### 2.2. Numerical Setup

The initial conditions of the simulation parameters relevant to experiments at the EISCAT facility are shown in Table 1. The simulated altitude ranged from 190 km to 340 km. We assumed the switched

| Table 1. Physical simulation parameters. |
|-----------------------------------------|
| **Parameter**                        | **Value**                        |
| Simulation range                       | 190–340 km                       |
| Simulation time                        | 0.667–6.667 ms                   |
| Switched work time of transmitter     | 0 ms                             |
| Density profile                        | \( N_0(z) = 2.5 \times 10^{11} \exp[-(z - 300 \times 10^3)^2/10^9] \) |
| Geomagnetic field using EISCAT a       | \( B_0 = 4.8 \times 10^{-5} (\vec{x} \sin(12^\circ) - \vec{z} \cos(12^\circ)) \) |
| Electron/ion temperature               | 1500 K                            |
| Electron collision frequency           | \( \nu_e = 400 \text{ s}^{-1} \) |
| Ion collision frequency                | \( \nu_{O^+} = 300 \text{ s}^{-1} \) |
| Frequency                              | 4.03 MHz                          |
| Wavelength                             | 74.37 m                           |
| Maximum amplitude                      | 1.5 V/m                           |
| Pulse type                             | sine                              |
| Polarization                           | time-varying linearly polarized   |
|                                        | \( E_x(t) = 1.5 \sin(\omega_0 t) \) |
| Injected height                        | 200 km                            |
| Theoretical critical altitude of X mode| 274.99 km                        |
| Theoretical critical altitude of O mode| 285.16 km                        |
| \( \Delta z \)                         | 2.48 m                            |
| \( \Delta t \)                         | \( 4.13 \times 10^{-9} \text{ s} \) |
| Number of time steps                   | 1,451,142                         |
| Time sampling resolution               | 750\( \Delta t = 3.101 \times 10^{-3} \text{ ms}/0.322 \text{ MHz} \) |
| Frequency resolution                   | 10\( \Delta t = 4.135 \times 10^{-5} \text{ ms}/24.184 \text{ MHz} \) |

\(^a\) European Incoherent Scatter Scientific Association (EISCAT)
work time of transmitter was 0 ms. The simulation began at $t = 0.667$ ms, because the altitude of EM wave source was set to be 200 km. The simulation time was from $t = 0.667$ ms to $t = 6.667$ ms.

According to the peak electron density $N_{\text{max}} = 2.5 \times 10^{11}$ m$^{-3}$, the peak plasma frequency $f_{\text{pe}} = \frac{1}{2\pi} \sqrt{\frac{N_e q_e^2}{m_e e_0}} = 4.489$ MHz can be calculated. Thus, the incident wave frequency was $f_0 = 4.03$ MHz ($w_0 = 2.53 \times 10^7$ s$^{-1}$), which is lower than the peak plasma frequency. According to the A-H equation, the theoretical altitude of the X-mode and O-mode for the incident wave were $h_X = 274.99$ km and $h_O = 285.16$ km, respectively. The cutoff of the O-mode is above the cutoff of the X-mode. The electric- and magnetic-field of the injected linearly polarized wave, which was a sinusoidal amplitude modulation wave, were set to $E_x(t) = 1.5 \sin(\omega_0 t)$ and $H_y(t) = E_x(t)/c_0$. Other electric- and magnetic-field components were set to zero.

The geomagnetic field, $B_0 = 4.8 \times 10^{-5} [\vec{x} \sin(12^\circ) - \vec{z} \cos(12^\circ)]$ T, was selected, which was in accordance with the EISCAT geomagnetic field. The electron and ion temperatures were set to 1500 K. Because the major ionic component was O+, the ion mass was set to $m_{O^+} = 16m_p$, where $m_p = 1836$, $m_e$ is the proton mass, and $m_e = 9.1 \times 10^{-31}$ kg is the electron mass.

Appropriate spatial grid sizes and temporal steps chosen from the initial conditions can maintain the stability of the simulation. In an unstable simulation, small numerical artifacts may cause errors that rapidly grow with time, to the extent of altering or overwhelming the simulation results [35]. In order to satisfy the Courant-Friedrichs-Lewy condition $c \Delta t \leq \sqrt{[1-(\omega_p \Delta t/c)^2]/\sqrt{1/\Delta z^2}}$ [42], the fixed spatial grid length, $\Delta z = \lambda/30 = 2.48$ m, was determined by the incident wavelength and fixed temporal step was set to $\Delta t = \Delta z/c = 4.13 \times 10^{-9}$ s.

3. SIMULATION RESULTS

3.1. Full-Scale Simulations of Ionospheric Behavior

Typically, full-scale results of fluctuations in the electric field, plasma velocity, and plasma density are shown in Figures 2 and 3. The development processes modified by the HF EM waves can be divided into those of electric field swelling and the enhancement of plasma turbulence.

Figure 2 shows the variation of physical parameters during the process of electric field swelling. Before a pump wave reaches the O-mode reflection point, the electric field in the x direction $E_x$ propagates upward and maintains the sinusoidal wave shape. This phenomenon can validate the propagation model of EM wave. Meanwhile, the linearly polarized incident wave undergoes Faraday rotation and splits. Hence, $E_y$ have been excited, as can be seen at $t = 0.72$ ms and $t = 0.92$ ms.

It is obvious that the X- and O-modes both have cutoffs (turning points) at $t = 0.955$ ms. According to the A-H equation, the theoretical reflection heights of the X-mode and O-mode are $h_X = 274.99$ km and $h_O = 285.16$ km, respectively. In our simulation, the altitudes of the X-mode and O-mode were $h_X = 274.90$ km and $h_O = 285.23$ km, respectively. The errors for the reflection heights of the X-mode and O-mode were within an acceptable error range. Hence, the simulation results for the turning point corresponded well with the theoretical predictions. The EM waves arrived at the cutoffs of the X-mode and O-mode at $t = 0.917$ ms and $t = 0.951$ ms, respectively. $E_z$, at the O-mode turning points exhibited obvious swelling, while that at the reflection point of the X-mode exhibited no significant change, as shown at $t = 0.995$ ms. Hence, the electric field strength of the standing wave pattern grew at the reflection point of the X-mode, but its swelling was much weaker than that of the O-mode wave. At $t = 1.115$ ms, the $E_z$ was raised up to 16 V/m near the altitudes of the O-mode $h_O$ because the EM wave underwent mode conversion to a large-amplitude electrostatic wave, which could lead to the development of strong Langmuir turbulence [20]. Therefore, the electric field of each direction changed most obviously near the reflection points when compared with other regions.

At $t = 1.12$ ms, the electron vertical velocity on the order of $10^4$ at $h_O$ was affected by the propagation of EM waves, and the ion vertical velocity on the order of $10^0$ changed slightly due to the ion-electron mass ratio equaling 29376. The electron density exhibited significant variation near $h_O$, which was closely related to the electric field, especially $E_z$. However, the ion density was remarkably unchanged at the same order of magnitude near the $h_O$. 

\[ \text{Progress In Electromagnetics Research C, Vol. 95, 2019 157} \]
Figure 2. Fluctuations in the electric field, plasma velocity, and plasma density during electric field swelling at times: $t = 0.72\text{ ms}$ (upper panel), $t = 0.92\text{ ms}$, $t = 0.955\text{ ms}$ (middle panel), $t = 0.995\text{ ms}$, and $t = 1.115\text{ ms}$ (lower panel).
Figure 3. Fluctuations in the electric field, plasma velocity, and plasma density during plasma density enhancement at times: $t = 1.2$ ms (upper panel), $t = 2.2$ ms, $t = 3.2$ ms (middle panel), $t = 4.6$ ms, and $t = 6.2$ ms (lower panel).
After $t = 1.2\,\text{ms}$, it was found that the amplitudes of $E_x$ and $E_y$ at $h_X$ were greater than those at $h_O$, which demonstrates that the energy in $x$- and $y$-directions on the X-mode critical point are higher than that on the O-mode critical point. From $1.2\,\text{ms}$ to $6.2\,\text{ms}$, it was obvious that $E_z$ at $h_O$ maintained a relatively stable, large-amplitude oscillation, which was close to $20\,\text{V/m}$. Meanwhile, the vertical electron velocity $U_{ez}$ at $h_O$ continued to oscillate, which means the electrons near the O-mode reflection point migrated upward or downward. In all regions, the vertical ion velocity $U_{iz}$ had non-zero values, which can be explained by ions in the simulated ionosphere being affected by the propagation of HF EM waves. The noticeable maximum of the electron and ion density fluctuations were at the O-mode reflection point. The variations in density reached up to 7 orders of magnitude.

### 3.2. Mode Conversion of Electric Field

To clearly present the variation in the electric field at the reflection region, the electric field from 270 km to 290 km was extracted between 0.65 ms and 6.65 ms (Figure 4). It is notable that the amplitudes of $E_x$ and $E_y$ at $h_X$ were larger than at $h_O$. The maxima of $E_x$ and $E_y$ at $h_X$ both exceeded $3\,\text{V/m}$. Swelling of the $E_z$ amplitude could be generated at $h_O$ and at $h_X$, which indicates that parametric instability was excited both at the X-mode and O-mode turning points. However, the swelling of the $E_z$ amplitude at $h_O$ was greater than at $h_X$. The maximum of $E_z$ at $h_O$ exceed $16\,\text{V/m}$. Therefore, the pump electric field $E_x$ at $h_X$ and the excited electric field $E_z$ at $h_O$ exhibited the most obvious changes.

![Figure 4. Simulations of the spatial evolution of the electric field in the: (a) $x$-, (b) $y$-, and (c) $z$-directions from 0.65 to 6.65 ms.](image)

To investigate the frequency matching conditions of the PDI, $E_z$ near $h_O$ from $1.02\,\text{ms}$ to $1.12\,\text{ms}$ were extracted. The frequency spectrum of the $E_z$ is shown in Figure 5. The frequency $E_z$ at $h_O$ was $4.03291\,\text{MHz}$ near the frequency of the pump wave $4.03095\,\text{MHz}$, which met the frequency matching
Figure 5. Frequency spectra of $E_z$ near the turning points of the O-mode using data from 1.02–1.12 ms.

Figure 6. Wave spectrum of $E_z$ at time $t = 5.85$ ms.
3.3. Variation in Plasma Velocity

To predict the behavior of plasma movements, the plasma velocity in the $z$-direction is of particular concern and can be used to infer upward or downward motions. These movements lead to variations in the vertically stratified ionosphere, which can be mirrored on the incoherent radial observations of the spectral features known as cascades, collapses, and outshifted plasma lines [44]. The evolutions of $U_{iz}$ and $U_{ez}$ are presented in Figure 7, which reveals that the electron and ion velocities were on the order of $10^4$ and $10^0$, respectively, and were affected by the propagation of EM waves. The amplitude of the plasma vertical velocity at the reflection point of the O-mode was larger than in other regions.

![Figure 7](image)

**Figure 7.** Simulations of the temporal evolution of the plasma velocity near the O and X-mode turning point for: (a) $U_{ez}$ and (b) $U_{iz}$, and magnifications of these patterns through the condensing of $z$ (km), (c) $U_{ez}$ and (d) $U_{iz}$.

Closeups of the region of the O-mode turning point are displayed in Figures 7(c) and (d). It is notable that $U_{ez}$ is either positive or negative with turbulence near the O-mode turning point, which implies that the electrons are oscillating. It is also noteworthy that the oscillation frequency of $U_{ez}$ is high near the O-mode turning point, which suggests that the electrons here oscillate rapidly. Hence, the variation of electrons over a fast time scale can be observed with difficulty, and the change of electrons on the slow time scale can be traced by the movement of ions because the ambipolar electrostatic force makes both electrons and ions move in phase with the ion-acoustic waves.

It was found that the ion velocity was lower than the electron velocity by approximately four orders of magnitude, which indicates that the amount of electron movement can be separated into HFs and slow time scales, and that ions are stationary at HF scales. At the turning point of the O-mode, $U_{iz}$ remains positive above the reflection height and remains negative below the reflection height. This will lead to enhanced diffusion and the subsequent movement of ions away from the region of interaction.

3.4. Change of Plasma Density

The simulated temporal and spatial evolutions of the plasma density are shown in Figure 8. It is obvious that the variation in electron and ion density near the O-mode reflection region was larger than that near the X-mode reflection region in Figures 8(a) and (b). In particular, the electron density near the X-mode reflection height almost unchanged. Hence, it is crucial to study the evolution of plasma density in the O-mode reflection region during the parametric instabilities process.
Simulations of the temporal evolution of the plasma density near the L-O mode turning point, where $\Delta N_e$ is the electron density fluctuation; $N_e$ is the initial electron density; $\Delta N_i$ is the fluctuation in the electron density, and $N_i$ is the initial electron density: (a) $\Delta N_e/N_e$, (b) $\Delta N_i/N_i$, and magnifications of these patterns through the compressing of $z$ (km), (c) $\Delta N_e/N_{e0}$ and (d) $\Delta N_i/N_{i0}$.

Figure 8. Simulations of the temporal evolution of the plasma density near the L-O mode turning point, where $\Delta N_e$ is the electron density fluctuation; $N_e$ is the initial electron density; $\Delta N_i$ is the fluctuation in the electron density, and $N_i$ is the initial electron density: (a) $\Delta N_e/N_e$, (b) $\Delta N_i/N_i$, and magnifications of these patterns through the compressing of $z$ (km), (c) $\Delta N_e/N_{e0}$ and (d) $\Delta N_i/N_{i0}$.

4. CONCLUSIONS

To summarize, a full-scale numerical simulation was performed to study the ionospheric behavior driven by HF radio waves during the initial process based on an FDTD scheme of the plasma two-fluid model at EISCAT. The temporal and spatial evolutions of the physical parameters, including the electric field, plasma density, and plasma velocity were obtained. The mode-conversion process of the incident EM wave was visualized at the reflection points of both the R-X and L-O modes. The results indicated that
the electric field strength of the standing wave pattern at the reflection point of the X-mode grew, but its swelling effect was much weaker than that of the O-mode wave. The vertical ion velocity remained positive above the L-O mode turning point and remained negative below this reflection height. The ionospheric electron number density rapidly oscillated with the small-scale HF electric field near the L-O mode reflection region. The ion density depletion created at the L-O mode turning point and two ion density peaks formed on each side of this reflection region were observed. This turbulent layer of the ion density peak at the bottom of the O-mode critical height was shifted downward, which is consistent with the observations made at both the Arecibo and at EISCAT. Future extensions of this work may consider the effects on parametric instability in the ionosphere due to the presence of different ponderomotive forces and the exciting condition in the governing equation, allowing for the improvement of the kinetic model of plasma dynamics. The scheme will be developed to extend the model to more complex situations and to more than one dimension in space.

ACKNOWLEDGMENT

We are grateful to Haiying Li, Shucan Ge, Jingfan Gao, Musong Cheng, Cheng Wang, Wen Yi, Ting Zhu and Moran Liu for their selfless assistance, and we would like to thank everyone who has contributed to this work.

Funding: This work was supported by the National Natural Science Foundation of China [Grant No. 41476082], the Innovation Foundation of the China Electronics Technology Group Corporation [Grant No. KJ1602004], and the Foundation of the National Key Laboratory of Electromagnetic Environment of China Electronics Technology Group Corporation [Grant No. 201803001].

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