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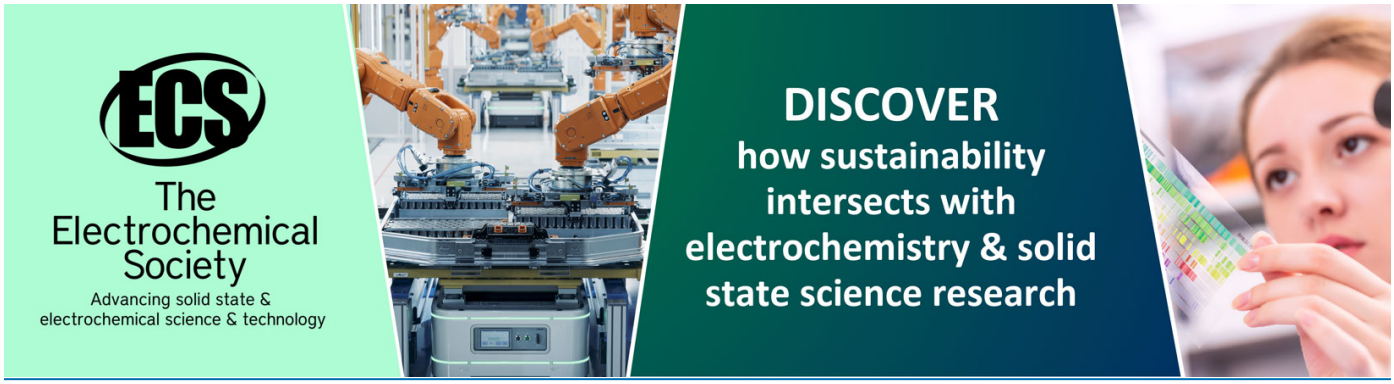

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Numerical Simulation of Oblique Heating of Ionosphere in East China

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Abstract. Compared with the vertical heating, the obliquely heated ionosphere has the advantages of high flexibility, wide influence range and convenient for practical operation. Considering the Ohm's absorption in a non- partial area, this paper establishes the physical models of ionospheric heating of with oblique radio waves. It also conducts the numerical simulation of oblique heating of ionosphere in east China using the background parameters provided by the experience models of IRI-2012 and NRLMSISE-00 to compare the disturb circumstances of the electron temperature and electron consistence of the ionospheres in the conditions that different elevation angles incidents and the same elevation backgrounds as well as the same elevation angles incidents and different elevation backgrounds. The results show that the wave heating effect increases with the increase of the incident angle; the heating effect in winter of the northern hemisphere is better than it in summer or low latitude areas.

1. Introduction

The fact that the electromagnetic waves of high power can make the ionosphere abnormality was in 1933 by B.D.H.Tellegen named "Luxemburg effect" [1]. Since then, scientists began to focus on the use of high power radio waves to change the local ionospheric environment. Based on the preliminary research, with the United States and the Soviet Union and some other European countries have established the ionospheric heating device and carried out a series of heating experiments after 1970s, many significant results have achieved.

The study of the heating of the ionosphere in China is relatively late compared with the United States and some European countries. But with the influence of artificial ionospheric studies pay more and more attention in recent years, China experts in theoretical and experimental aspects have made a lot of achievements. According to different processes of waves with different height of the ionosphere, Huang Wengeng [2] [3] established the theoretical models of radio wave heating of low ionosphere and high ionosphere, and calculate the change of electron temperature and density; Wu Jun et al [4] simulated the Arctic ionosphere low Ohm heating effect; He Fang et al [5] proposed a calculation method of ionospheric absorption loss and used ray tracing program to calculate the wave absorption of ionosphere radar; Wang Zhange [6] conducted the numerical simulation of the ionospheric heating effect and compared with the experimental results to verify the validity of the model.

It is worth noting that, most of the research on ionospheric heating has focused on vertical heating at present. The research of oblique heating which has the features of maneuverability and flexibility in practical applications is relatively little. However, the oblique ionospheric heating in practical applications is more and more. In 1980s, the former Soviet Union carried out the experiment of the oblique heating of the ionosphere. In the theoretical study, Ginzburg et al [7] compared the vertical

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and oblique heating absorption relations; Huang [8] studied the high power and high frequency radio waves to the less dense heating ionosphere theory. Chinese scientist Fang Hanxian and others [9] conducted the preliminary numerical simulation of the heating of the low ionosphere by the high power radio waves in specific locations.

Based on the theoretical basis, this paper establishes the physical models of ionospheric heating of with oblique radio waves, calculates the change of the electron temperature and electron consistence in different conditions and analyzes the heating effect of different ionospheric backgrounds to provide a theoretical guide for the heating experiment to choose the most suitable incident wave in different time and places.

2. Fundamental Theory

The collision process is significant in the lower ionosphere; however, the transport process can be ignored. The Ohm heating effect plays a major role. When the electromagnetic wave passes, the energy losses is mainly electronic absorption, electronic and energy loss through collisions with ions and neutral particles, and achieve energy balance after a certain period of time, the temperature rises to a constant value. Correspondingly, as the electron recombination coefficient is a function of the electron temperature, the electron concentration in the heating process will change.

2.1. Equation of Electron Energy.

$$\frac{3}{2}k_b n_e \frac{\partial T_e}{\partial t} = Q(T_e, l) - L(T_e, l) \tag{1}$$

In the above formulation, k_b is the Boltzmann constant; $Q(T_e, l)$ and $L(T_e, l)$ are respectively the absorption term and the loss term.

The absorbed energy of unit volume with the height of l is:

$$Q(l) = 2\kappa S(l) \tag{2}$$

The energy flow of electric wave of the height of is:

$$S(l) = \frac{ERP}{4\pi l^2}\exp[-2\int_{l_0}^{l}\kappa(l')dl'] \tag{3}$$

ERP is the effective radiated power of the waves; $\kappa(l)$ is the wave absorption index and it can be expressed by:

$$\kappa = \frac{\omega}{c}\chi \tag{4}$$

In the above formulation, $\omega = 2\pi f$, f is the incident wave frequency and c is the light speed. χ is the imaginary part of acomplex refractive index in A-H formulation. The electron collision frequency in A-H formulation is determined by empirical formula:

$$\nu = 1.7\times10^{-11}[N_2]T_e + 3.8\times10^{-10}[O_2]T_e^{1/2} + 1.4\times10^{-10}[O]T_e^{1/2} \tag{5}$$

The geomagnetic field is applied to the central dipole field.

$$B = B_0(\frac{R_e}{R_e + h})^3\sqrt{1+3\sin^2\lambda} \tag{6}$$

In the above formulation, $B_0 = 3.085\times10^{-5}T$, R_e is the mean radius of the earth and λ is magnetic latitude; h is the height from the ground

The loss mechanism of the electron energy in the ionosphere is very complex, mainly through the collision process, the loss mechanism in common are: (1) the elastic collision of electrons and positive

ions; (2) the elastic collisions of electrons and neutral particles; (3) and rotational excited molecules; (4) molecular excitation and vibrational levels; (5) the excited atoms and the fine structure of the electronic level. The loss of electron energy is the sum of the various loss mechanisms. The specific expressions of each loss mechanism are in reference [11].

2.2. Continuity Equation.

Electron continuity equation is:

$$\frac{\partial n_e}{\partial t} = q - \alpha(T_e) n_e^{\ 2} \tag{7}$$

In that, q is the production rate; $\alpha(T_e)$ is the compound coefficient. We consider the dissociation-recombination of NO^+ and O_2^+ in low ionosphere. The compound coefficient can be achieved by the empirical formula:

$$\alpha(T_e) = 5\times10^{-7}[NO^+](300/T_e)^{1.2} + 2.2\times10^{-7}[O_2^+](300/T_e)^{0.7} \tag{8}$$

3. Numerical Simulation

The background parameters are obtained according to the empirical model of IRI-2012 and NRLMSISE-00. We studied the numerical simulation experiments are carried out to study the effects of wave incidence angle, seasonal and geographical position on the heating effect of the ionosphere. The incident wave frequency is $9MHz$; the effective radiation power is $200MW$; the range of the ionosphere height of the study is $65\sim120km$. The wave absorption under $65km$ is ignored. The space step in the direction of the electric wave propagation is taken as $1/\sin\alpha\, km$. α is the incident wave angle. The time resolution is $1\mu s$ and the heating time is $5ms$.

3.1 The Heating Effects Simulation in the Conditions of Different Elevation Angles.

The background field of Figure 1 was Beijing ($39.5^\circ N$,$116.5^\circ E$) in LT1200 of December 1st in 2015. The angels of incidence of the radio waves are 45°, 60°, 75°and 90°. The electron temperature and electron consistence in the stable state are shown in Figure 1. We can see from Figure 1 that as the incident wave angle increases, the temperature fluctuation of electrons increases gradually. The maximum height of temperature increases due to the low elevation at the same height. The reached ionosphere path of the wave increase and the corresponding energy loss is bigger. Therefore, the wave energy acts on the ionosphere is relatively less. Similarly, the amplitude of the electron concentration, the height range and the height of the peak height increase with the increase of the incidence angle. However, it can be concluded that the ionosphere can be influenced by the oblique heating of the ionosphere. For example, at the height of $120km$, the 75° of the angle can make disturbance occur of the position where the horizontal distance between the emission spot and the position is $32.2km$. Therefore, the operation can be combined with the actual needs, considering the economic cost and operational feasibility and other issues to achieve the purpose of flexible use of oblique heating.

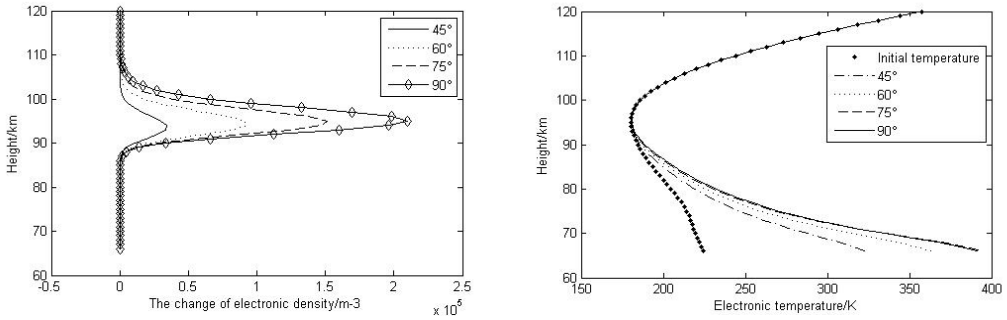

Fig. 1. Heating effects simulation of electron temperature and electron consistence in the conditions of different elevation angles

3.2 The Heating Effects Simulation in the Conditions of Different Seasons.

The heating spot was Beijing ($39.5^\circ N$,$116.5^\circ E$) in LT1200 of June 1st and December 1st in 2015, which represent summer and winter respectively. When the radio-wave's incident angel is 60°, the range of the electron temperature and electron consistence and the maximum of winter are bigger than them in summer. This is related to the seasonal variation of the background ionosphere. The electron concentration in the northern hemisphere is higher than that of the same altitude in winter. Correspondingly, the concentration of NO^+ and O_2^+ is relatively high. The initial time of composite coefficient, at the same time, the electron concentration larger and positive ion concentration will increase the loss mechanism in the energy equation. The electron density and electron temperature are in equilibrium state of high level in general. Therefore, the variation ranges of the two items are smaller when the wave is incident.

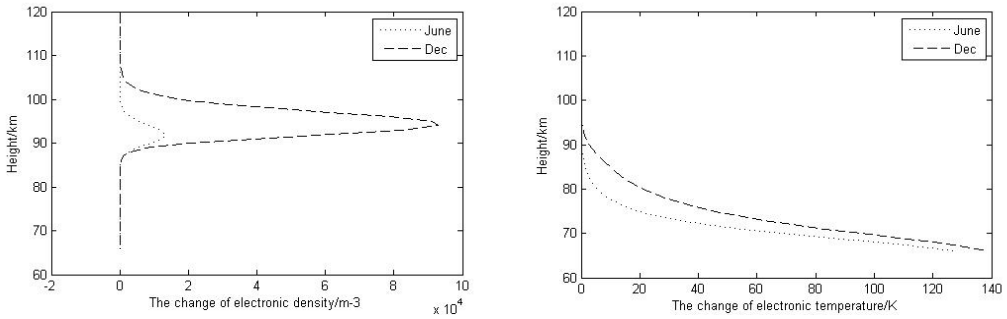

Fig.2. Heating effects simulation of electron temperature and electron consistence in summer and winter

3.3. The Heating Effects Simulation in the Conditions of Different Magnetic Latitude Areas.

The spots of the experiments were selected in Sanya (18.2°N,109.5°E), Beijing (39.5°N,116.5°E) and Mohe (53°N,122.5°E). The experiment time was December 1st in 2015. The incident angel of the wave is 60°. We observed the change of the electron temperature and electron consistence. The magnetic latitude is 13.1°, 34.2° and 47.6°. It can be seen from the Figure 3, the electron density and electron temperature increased with the increase of magnetic latitude. The electron concentration perturbation peak height and electron temperature and electron density perturbation of maximum height increased gradually. This is reduced by the fact that the electron concentration in the northern hemisphere at the same height decreases with increasing latitude. The low latitude area electron density and electron temperature in high latitudes in dynamic equilibrium more quickly in response to

the same degree, affecting the external stimulation. The disturbance of the electron density and electron temperature were small in the same conditions and height of the disturbance was also small.

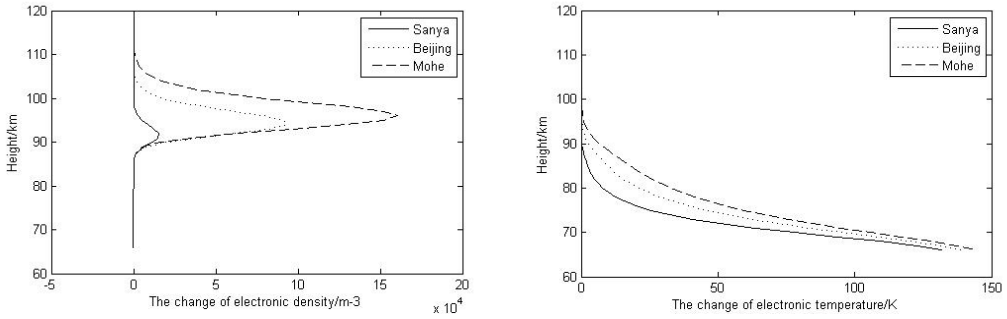

Fig.3. Heating effects simulation of electron temperature and electron consistence in different magnetic latitude areas

4. Conclusion

We assumed that the ionospheric level is uniform and applied the Ohm heating effect, ignoring the anomalous absorption and conduction and diffusion process. We established physical model of low ionospheric oblique heating of high power high frequency electric wave. Then, the change of electron temperature and concentration of different ionospheric background is numerically solved. We can draw the following conclusions by comparing the disturbance of the electron temperature and electron consistence in the conditions of the same incident and different backgrounds:

1) high frequency wave incident ionosphere through collision absorption so that the electron temperature and electron density perturbation, heated to a stable state in the same incident wave parameters under the condition of the electron temperature and concentration increase and disturbance can reach the height of the incident angle increases. The maximum increase can be achieved at normal incidence, and the maximum of the electron temperature and the concentration disturbance can be achieved.

2) The ionization degree of the lower ionosphere in the northern hemisphere is higher than that in winter. The electron density in the same altitude is larger than that in winter. It is higher in winter than that in summer when the height is low than about $95km$. It is higher in summer than that in winter when the height is higher than $95km$.The disturbance amplitude and maximum height of electron density and electron temperature are higher in winter than that in summer under the same conditions.

3) The electron consistence of low latitude region is greater than that of the high latitude in the same height. The electron density and electron temperature in the low latitude region are in a dynamic equilibrium reaction rate, which have small disturbance in the same external stimulation. The artificial high frequency heating effect in high latitudes is better than that in low latitude area.

The research process of this paper only considers the heating process of non-partial area. The wave travels in a straight line in the non- partial area. But, it cannot be established in the partial area. It needs to determine the radio wave track by ray tracing. In addition, it is not suitable to only consider the Ohm's absorption effect. As the background ionosphere and neutral atmospheric parameters obtained by the experience model of the IRI-2012 and NRLMSISE-00 will have certain deviation of the actual atmospheric conditions, although these will not affect the qualitative results, will affect the accuracy of quantitative calculation, so it also needs to be improved by using the measured data.

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