HF waves heating ionosphere F-layer

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To predict and evaluate the effects of ionospheric modification quantitatively, the electron temperature and density perturbations are analyzed at different heating conditions, based on a developed model including momentum equation, continuity equation and energy equation. The results show that (1) powerful HF radio waves can cause the electron temperature to increase markedly, and the largest perturbation is near the reflection layer, but the electron density decreases at this area; (2) the lower neutral gas density in the ionosphere, the larger disturbance of the electron temperature and density; the higher radio frequency, the lower increment of electron temperature; and the higher radio power, the larger disturbance of electron temperature and density are caused, but there are no linear relationships between the radio power and disturbance amplitude; (3) the perturbations at nighttime are larger than at daytime when heated by HF radio waves with the same powers; the electron temperature perturbations in the solar minimum are larger than that in solar maximum; and the electron temperature perturbations in spring and autumn are larger than in winter and summer; (4) compared with the low-latitude, the mid-latitude has the smaller perturbations, the maximum electron temperature perturbation is ~30% (at daytime of winter), and the density is ~5%.

powerful HF waves, ionospheric heating, simulation

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The ionosphere is the main carrier and channels of radio waves; the conditions of ionosphere can strongly affect the quality of the satellite-ground and long-distance ground-ground radio wave communications. As for the ionosphere, it is a very complex system, and is not only influenced by the Sun and magnetosphere-driven processes [1–5], but also influenced by dynamical atmospheric processes. For example, lightning can heat ionosphere to result in modification of the electron temperature and number density [6,7]; earthquakes may produce pre-earthquake ionospheric anomalies [8–12]; typhoon or hurricanes can cause ionospheric TEC increase and foF2 to rise [13]; atmospheric waves (planetary, gravity, tidal and infrasonic waves) coming from below can significantly affect the lower ionosphere, both directly and indirectly (e.g. through major stratospheric warmings) [14–16].

Except for these natural ionospheric disturbances, many artificial methods can also cause the ionosphere to be dis-

turbed [17–19]. Since ‘Luxemburg effect’ was found in 1933, it has been known for many years that the ambient properties of the Earth’s ionosphere can be modified by the absorption of powerful HF waves launched by ground-based transmitters. With the merit of convenience, swift and notable heating effect and being friendly to environment, ground-based transmitters became one of the major ionospheric modification means. Especially after 1970s, USA, Soviet Russia and some European countries have established much experimental equipment. HAARP facility in Alaska now owns the largest power and antenna gain (the effective power could reach up to 1 GW), and can transmit strong electromagnetic energy flux to efficiently modify the ionosphere.

Powerful HF radio waves can modify the local electron temperature and density, and induce the change of plasma conductivity, dielectric constant and other plasma parameters. Heating the ionosphere not only has scientific research values, but also possesses practical objectives. For example, heating lower ionosphere (50–100 km) can cause ionization

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that forming ‘ionospheric mirror’ to reflect some particular electromagnetic waves; heating lower ionosphere by amplitude-modulated HF waves can efficiently produce radiation sources of ELF/VLF waves [20]; heating the upper ionosphere (150–500 km) could modify the electron density, form focusing and defocusing area that badly change or even disrupt the communication channel, and can also cause parametric instabilities and self-focusing instabilities to form various-scale field-aligned irregularities.

Because heating experiment is extremely expensive and heating is local and short-lived, all kinds of numerical models were developed with the increasing knowledge of the ionosphere physics [21–24]. Huang et al. [25] developed a model based on the achievement of other researchers, and the model is in accord with some experiment results. In this paper, we use this model to predict and evaluate the effects of ionospheric modification quantitatively, aiming to provide some guidance to the future experiments.

1 Physics of large-scale modifications

Under the well-justified assumption of ambipolar diffusion, the macroscopic dynamics of the F region plasma can thus be described by following equations:

Momentum equation

$$N_e V_e = -D \left[\frac{\partial}{\partial s} N_e k (T_e + T_i) + \sum_{\alpha} N_{\alpha} m_{\alpha} g \sin \theta \right] + N_e V_n \cos \theta, \quad (1)$$

Continuity equation

$$\frac{\partial N_e}{\partial t} = Q_0 - \beta N_e - \frac{\partial (N_e V_e)}{\partial s}, \quad (2)$$

Energy equation

$$\begin{aligned} & \frac{3}{2} k \left[N_e \frac{\partial T_e}{\partial t} + N_e V_e \frac{\partial T_e}{\partial s} \right] + k N_e T_e \frac{\partial V_e}{\partial s} \\ &= \frac{\partial}{\partial s} \left(K_e \frac{\partial T_e}{\partial s} \right) + S_Q + S_0 - L_e, \end{aligned} \quad (3)$$

with s the coordinate along the magnetic field; N_e the electron density; T_e and T_i the electron and ion temperature, respectively; V_e the field-aligned flow velocity; V_n the neutral wind velocity in the north to south direction; N_{α} the ion density (mainly consider O^+ , NO^+ and O_2^+); m_{α} the ion mass; k the Boltzmann constant; g the acceleration due to gravity; θ the magnetic field dip angle; and D , β , K_e and L_e the coefficients of density diffusion, recombination, thermal conduction and cooling, the conduction coefficient has an approximately $T_e^{5/2}$ behavior; S_Q the heating source due to radio waves; Q_0 and S_0 the local ionization source and energy absorption source in natural conditions respectively.

Heating can result from direct Ohmic absorption by the

bulk plasma electrons as well as from the slowing down of superthermal electrons accelerated by short-scale length waves excited by the HF pump. For simplicity, energy absorption is limited to a Gaussian centered at the reflection height [24,26,27], and the energy absorption at the reflection height can be written as [22]

$$\begin{aligned} S_{Q,\max} &= \frac{\varepsilon_0}{2} \left(\frac{f_p^2 \nu_e}{f_0^2} \right) E_{z_m}^2 + 16 \left(\frac{n_e T_e}{\omega} \right) \nu_e^2 \left(\frac{E_{z_m}}{E_t} \right)^4 \\ &= A \frac{\varepsilon_0}{2} \left(\frac{f_p^2 \nu_e}{f_0^2} \right) E_{z_m}^2 \quad (\text{J m}^{-3} \text{ s}^{-1}), \end{aligned} \quad (4)$$

where A is a constant, and it generally equals to 10 according to the experiments; ε_0 the dielectric constant; f_p the local plasma frequency; f_0 the radio frequency; ν_e the electron collision frequency, mainly include electron-neutral (ν_{en}) and electron-ion (ν_{ei}) collision; z_m the altitude of reflection point; E the electric field intensity; E_t the abnormal absorption excitation threshold. ν_{en} and ν_{ei} can derive from empirical equations as follows [28]:

$$\begin{aligned} \nu_{en} &= 9.32 \times 10^{-12} N_{N_2} (1 - 3.44 \times 10^{-5} T_e) + 1.21 \times 10^{-10} N_{O_2} \\ &\times (1 + 2.15 \times 10^{-12} T_e^{0.5}) T_e + 5.49 \times 10^{-10} N_O T_e^{0.5}, \end{aligned} \quad (5)$$

$$\nu_{ei} = 54 \frac{N_e}{T_e^{3/2}}. \quad (6)$$

The absorption energy at arbitrary ionospheric altitude z (km) is

$$S_Q(z) = S_{Q,\max} e^{-(z-z_m)^2/\sigma^2}, \quad (7)$$

where σ the half-width of Gaussian, generally assumes to 20 km. The electric field intensity of HF waves as a function of height can approximately be written as [29]

$$E(z) = \frac{\sqrt{30ERP}}{z}. \quad (8)$$

Here ERP is the transmitter effective radiation power.

The loss processes mainly include (1) elastic collisions with positive ions and neutral particles, (2) rotational excitation of O_2 and N_2 , (3) vibrational excitation of O_2 and N_2 , (4) electronic excitation of O , (5) fine structure excitation of O . Ref. [30] provides the detailed expressions.

2 Computational arithmetic

We use Crank-Nicolson method [31] to solve the equation (3); this method was developed by John Crank and Phyllis Nicolson in the mid 20th century. In numerical analysis, the Crank-Nicolson method is a finite difference method used for numerically solving the heat equation and similar partial

differential equations. It is a second-order method in time, implicit in time, and is numerically stable.

Assuming the altitude z ranges from $z_{\min}$ to $z_{\max}$ and the time t from 0 to T . Divide $[0, T]$ into N equally spaced intervals at t values indexed by $l=0, 1, \dots, N$, and $[z_{\min}, z_{\max}]$ into I intervals at z values indexed by $i=0, 1, \dots, I$. The length of these intervals is Δt in the time direction and Δz in the z direction. We seek an approximation to the true values of T_e at the $(N+1) \times (I+1)$ grid points.

Focusing on an arbitrary internal grid point $(i, l+1)$, one could approximate the partial derivatives at that point by

$$\frac{\partial T_e}{\partial t} = \frac{T_{e,i}^{l+1} - T_{e,i}^l}{\Delta t}, \quad (9)$$

$$\frac{\partial T_e}{\partial z} = \frac{1}{2} \left[\frac{T_{e,i+1}^l - T_{e,i-1}^l}{2\Delta z} + \frac{T_{e,i+1}^{l+1} - T_{e,i-1}^{l+1}}{2\Delta z} \right], \quad (10)$$

$$\frac{\partial^2 T_e}{\partial z^2} = \frac{1}{2} \left[\frac{(T_{e,i+1}^l - T_{e,i}^l) - (T_{e,i}^l - T_{e,i-1}^l)}{(\Delta z)^2} + \frac{(T_{e,i+1}^{l+1} - T_{e,i}^{l+1}) - (T_{e,i}^{l+1} - T_{e,i-1}^{l+1})}{(\Delta z)^2} \right]. \quad (11)$$

Written in matrix form, eq. (3) provides the interior equations of

$$\begin{bmatrix} a_1 & b_1 & 0 & \dots & 0 \\ c_1 & a_2 & b_2 & \ddots & 0 \\ 0 & c_2 & a_3 & \ddots & 0 \\ 0 & \ddots & \ddots & \ddots & b_{n-1} \\ 0 & \dots & 0 & c_{n-1} & a_n \end{bmatrix} \begin{bmatrix} T_{e,1}^{l+1} \\ T_{e,2}^{l+1} \\ T_{e,3}^{l+1} \\ \vdots \\ T_{e,n}^{l+1} \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \vdots \\ D_n \end{bmatrix}. \quad (12)$$

This sort of system is efficiently solved by Gaussian elimination. It requires just $8I$ floating-point operations to determine the unknown T_e^{l+1} of all heights, and then update the parameters which are related to the electron temperature, and finally use eq. (2) to calculate the electron

density of all altitudes.

3 Simulation results

The background parameters of ionosphere are obtained from the model IRI2007, and neutral density profiles are from the model NRLMSISE-00. The boundary conditions are the same as that in [24]; that is, the grads of electron temperature and density keep invariability at the upper boundary, and the electron temperature and density remain constant over the course of the calculation at the lower boundary.

The ionospheric altitude ranges from 150 to 500 km, and heating at the midday of the winter in 2011 at Nanjing (geographic coordinate: 32°N, 118.5°E, dip angle: 47.3°). Under these conditions $h_m F_2$ is 275 km, and foF_2 is 11.5 MHz. The transmitter frequency is 5.54 MHz, ERP is 200 MW, heating duration 4 min, and the wave reflection height 195 km. The electron temperature and density disturbance profiles are displayed in Figure 1. The electron temperature increases evidently just after heating 2 s, and it is close to saturation when heating 10 s. The maximum disturbance is ~750 K, near the reflection area. The electron density decreases at reflection area, and it mainly depends on the grads of electron temperature which makes the plasma diffuse along the magnetic field. The saturation time of the electron density is longer than that of the electron temperature, and the electron density is still unsaturated after heating 240 s.

Figure 2 shows the disturbance profile of electron temperature and density when altering the background neutral density. We alter the neutral gas density to $0.8N$, $1.0N$, $1.2N$ (N is the original neutral density) respectively. Under $0.8N$ conditions, the disturbance amplitude is the largest, while $1.2N$ is the least. Therefore we can conclude that the lower background neutral density, the larger disturbance of electron temperature and density are caused.

To compare the disturbance amplitude of different heating

Figure 1 Profiles of electron temperature and density after disturbed.

Figure 2 Profiles of electron temperature and density when changing neutral background density.

conditions, we design four sets of experiments as follows.

Simulation 1 Choosing the different transmitter frequencies and powers to heat the ionosphere 4 min, the disturbance profiles are showed in Figure 3. Under the same power conditions, the larger radio frequency, the higher reflection altitude, and the lower disturbance of electron temperature. The higher radio power, the larger disturbance of electron temperature and density if the frequencies are

the same, but there are no linear relationships between the disturbance amplitude and radio power.

Simulation 2 Choosing the different moments to heat the ionosphere. The transmitter frequency is set to near the foF2, radio power is 200 MW, and the results are shown in Figure 4. The electron temperature increases at all heights, the maximum amplitude at daytime is ~20%, and the nighttime can reach up to ~300%; while the electron density

Figure 3 Profiles of electron temperature and density under the simulation 1 conditions.

Figure 4 Profiles of electron temperature and density under the simulation 2 conditions.

at daytime is $\sim 4\%$, and the nighttime is $\sim 20\%$. By comparison, the disturbance at nighttime is larger than at daytime when heated by HF radio waves. This is in accordance with the experiments [32,33], and many experiments are conducted at nighttime. Possible reason is that the nighttime has lower plasma parameters than the daytime, when the radio waves with the same power interact with the ionosphere, more energy could transport to the electrons and induce larger ionospheric disturbance at nighttime.

Simulation 3 Choosing the different latitudes to heat the ionosphere. The latitude ranges from 0°N to 90°N (10° spacing), the ERP of transmitter is 200 MW, and radio frequency is $\sim \text{foF}_2$, heating duration is 4 min. At low latitude, the electron temperature disturbance amplitude could reach up to $\sim 80\%$, and electron density $\sim 20\%$. While compared with the low latitude, the mid-latitude has the smaller disturbance, the electron temperature is $\sim 30\%$, and the electron density is $\sim 5\%$, but it can still cause the large ionospheric disturbance.

Simulation 4 Heating the ionosphere during the solar maximum (2002) and solar minimum (2008). The ERP of transmitter is 200 MW, and radio frequency is $\sim \text{foF}_2$. Figure 6 shows the disturbance of the electron temperature and density under the above heating conditions. At the solar maximum, the temperature disturbance of spring and autumn can reach $\sim 40\%$ and $\sim 50\%$ while the winter and summer are $\sim 20\%$ and $\sim 30\%$ respectively. At the solar minimum, the temperature disturbance of spring and autumn can reach $\sim 80\%$ while the winter and summer are $\sim 65\%$ and $\sim 50\%$ respectively. The electron temperature disturbance in the solar minimum is larger than that in solar maximum and the disturbances in spring and autumn are larger than that in winter and summer.

4 Conclusions

Under the well-justified assumption of ambipolar diffusion, we solve the momentum equation, continuity equation and

energy equation with Crank-Nicolson method, and calculate the change of electron temperature and density at different heating conditions. Main conclusions are shown as follows.

(1) Powerful HF radio waves can cause the electron temperature to increase markedly, and the largest increment is near the reflection layer. The electron density decreases at this area because of the grads of electron temperature makes the plasma diffuse along the magnetic field.

(2) The lower density of neutral background gas in the ionosphere, the larger disturbance amplitude of electron temperature and density; the higher radio frequency, the lower disturbance of electron temperature; and the higher radio power, the larger disturbance of electron temperature and density are caused, but there are no linear relationships between the radio power and disturbance amplitude.

(3) The disturbance at nighttime is larger than at daytime when heated by HF radio waves with the same powers. Possible reason is that the nighttime has lower plasma parameters than the daytime, when the radio wave with the same power interacts with ionosphere, more energy could transport to the electrons and induce larger ionospheric disturbance at nighttime.

(4) Compared with the low latitude, the mid-latitude has the smaller disturbances, the electron temperature is $\sim 30\%$, and the density $\sim 5\%$, but it can still cause large ionospheric disturbance.

(5) The electron temperature disturbance in the solar minimum is larger than that in solar maximum, and the spring and autumn are larger than that in winter and summer.

Simulation results show that the background neutral parameters have great influence on the heating results, but the outcomes from the empirical model IRI-2007 and NRLMISISE-00 are not the same as the true atmosphere parameters. Besides, the empirical equations are different from the theoretical equations. These make the differences between the quantitative calculations and experiment results, but have little effect on the qualitative conclusions in this paper.

Figure 5 Profiles of electron temperature and density under the simulation 3 conditions.

Figure 6 Profiles of electron temperature under the simulation 4 conditions. Upper panel is the solar maximum (2002) and the lower panel is maximum (2008).

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