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MODELING OF THE MODIFICATION OF THE NOCTURNAL HIGH-LATITUDE F REGION BY HF WAVES WITH DIFFERENT FREQUENCIES

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Abstract. The high-latitude F-region modification by high power radio waves is investigated using a numerical model of the convecting high--latitude ionosphere developed earlier in the Polar Geophysical Institute. The model is based on the numerical solution of the system of transport equations for ionospheric plasma. This system consists of the continuity equation, equation of motion for the ion gas, and heat conduction equations for ion and electron gases. Simulations are performed for the point with geographic coordinates of the ionospheric heater near Tromso , Norway, when it is located near the midnight magnetic meridian. The calculations are made for distinct cases in which high power waves have different frequencies. The results of modeling indicate that the frequency of HF wave influences significantly the F-region response to high power radio waves in the nocturnal high-latitude ionosphere.

Introduction

In recent years, the ionospheric plasma properties were successfully investigated by using experiments with high-power, high-frequency radio waves. Many interesting results concerning the ionosphere modification by a powerful HF wave were obtained. Moreover, the experimental investigations were accompanied by simulation studies of the ionosphere's response to HF heating. The majority of experimental and numerical investigations were mainly directed to study the mid--latitude ionosphere. It is natural because of the location of most high-power radio wave heaters in the mid-latitudes (Platteville, Arecibo, Nizhny Novgorod, etc). Nevertheless, few ionospheric heaters were built and utilized for the modification of the high-latitude ionosphere, for example, Monchegorsk (Russia) and Tromso (Norway). It can be noticed that the experimental studies of the high-latitude ionosphere just mentioned dealt with the lower ionosphere (D and E regions) only. The modification of the high-latitude F region by HF heating has yet to be achieved. On the contrary, the mid-latitude F region were successfully modified by powerful HF waves and many interesting results were obtained. It is obvious that there exist some specific features characteristics of the high-latitude F-region ionosphere which obstruct the observation of the F-layer modification. These specific features were established by numerical simulations [*Mingaleva and Mingalev*, 1996; 1997; *Mingalev and Mingaleva*, 1999]. It turns out that significant variations in the electron temperature profiles can be produced by powerful HF waves in the high-latitude F layer. The main fraction of the energy of the HF wave is to be absorbed at the level where the wave frequency is equal to the frequency of the electron hybrid resonance. The variations of the electron temperature profiles can ultimately lead to a detectable decrease in the electron concentration at the level of the F-region peak. However, the convection of the ionospheric plasma obstructs the observation of the disturbance caused by an HF wave. Minimal values of the electron concentration in the high-latitude ionosphere are not found right over an ionospheric heater but are displaced for a rather long distance from it. This displacement is the main specific feature that obstructs the observation of F-layer modification by HF heating in the high-latitude ionosphere.

In all of the simulation papers cited above, the results were obtained for fixed values of the wave frequency. To organize artificial modification experiments by HF radio waves in the high-latitude F-region ionosphere and to plan the operation of a diagnostic facility, it is instructive to examine how the wave frequency influences the expected ionosphere's response to HF heating. The purpose of this paper is to predict time variations of ionospheric quantities in the nocturnal high-latitude F region produced by the HF heating facility near Tromso, Norway for distinct cases in which HF radio waves have different frequencies.

Numerical model

In the present study, the mathematical model of the high-latitude F-region ionosphere is utilized. Taken into account is the effect of HF heating in the model calculations by analogy with the study by *Blaunshtein et al.*[1992]. The utilized mathematical model has been developed earlier [*Mingaleva and Mingalev*, 1996; 1997] and applied for simulations of the high-latitude F-layer modification by HF waves with different powers [*Mingalev and Mingaleva*, 1999]. The model takes into account the convection of the ionospheric plasma, strong magnetization of the plasma at F-layer altitudes, and geomagnetic field declination. In the model calculations the temporal history of the ionospheric plasma is traced in the part of the magnetic field tube moving along the convection trajectory through the neutral atmosphere over an ionospheric heater. A part of the magnetic field tube of the ionospheric plasma is considered at distances between 100-700 km from the earth along the magnetic field line. It is known that the convection trajectories, around which the magnetic field tubes are carried over the polar region, are closed for a steady convection pattern. In the present study, the pattern B of the empirical convection model by *Heppner* [1977] is utilized which is a steady non-substorm convection pattern. Using this convection pattern, we calculate the plasma drift velocity along the convection trajectory, which intersects the F-layer volume illuminated by the HF heating facility near Tromso, Norway, when it is located near the midnight magnetic meridian. The plasma flow in the moving magnetic field tube is described by the system of transport equations, which consists of the continuity equation, equation of motion for ion gas, and heat conduction equations for ion and electron gases. The system of transport equations is numerically solved, and the profiles of ionospheric quantities versus distance from the earth along the geomagnetic field line are obtained. The utilized mathematical model takes into account the variations of ionospheric quantities produced not only by powerful HF waves but also by a natural spatial inhomogeneity of the ionosphere, which can take place in high-latitude F region.

Presentation and discussion of results

The heating facility near Tromso, Norway, provides a beamwidth of about 14.5^0 . Therefore, the half-power heated region diameter is approximately 75 km at 300 km altitude [*Stubbe et al*., 1982]. The available drift velocity of the ionospheric plasma at F2-layer altitudes is about 400 m/s. Hence, the time of about 190 s is the maximal period required for a plasma volume to intersect the region illuminated by the ionospheric heater at F2-layer altitudes. We suppose that the HF heater is turned on and operates during a time longer than 190 s. During this time, the considered plasma volume enters the illuminated region, intersects it, abandons it, and moves farther along the convection trajectory. The moment of the entrance in the illuminated region is the initial moment of our examination. We consider the temporal history of the ionospheric plasma in the magnetic field tube during the period of 1500 s. This period is sufficient for the magnetic field tube to be displaced for a distance of more than 600 km from the HF heater. In the initial moment the considered magnetic field tube is assumed to be on the magnetic meridian of 23.20 MLT.

The utilized mathematical model can describe different combinations of the solar cycle, geomagnetic activity level, and season. In the present study, the calculations are performed for autumn (5 November) and high solar activity ($F_{10.7}$ =230) conditions under the low geomagnetic activity ($K_p = 0$). The considered convection trajectory is assumed to lie across the center of the illuminated region. As it had been noted earlier, the natural spatial inhomogeneity of the high-latitude ionosphere may take place, which leads to horizontal variations of ionospheric quantities even without any HF heating. Therefore, we started by obtaining the variations of calculated ionospheric quantities along the considered convection trajectory under natural conditions without a powerful HF wave effect. The results of simulation indicate that appreciable variations of calculated profiles may take place in the polar ionosphere under natural conditions without HF heating, with the electron concentration at the level of the F-region peak decreasing along the considered part of the convection trajectory (corresponding to the period of 1500 s). As a consequence, the F-layer critical frequency decreases along the considered part of the convection trajectory approximately from 3.35 to 3.30 MHz.

To investigate how the wave frequency influences the expected ionosphere’s response to HF heating we calculate the variations of ionospheric quantities along the considered part of the convection trajectory (with time) following the entrance of the plasma volume in the illuminated region for distinct cases in which HF radio waves have different frequencies: 2.0, 2.5, 2.8, 3.0, 3.2, 3.35, 3.5, and 3.65 MHz.The part of power radiated by the HF heater, which is deposited in the ambient electron gas and lost for its heating, is called “effective absorbed power” or EAP. The EAP varies on condition that the plasma volume moves along the convection trajectory. The EAP arises, when the plasma volume enters the illuminated region, achieves the maximal value, when the plasma volume reaches the center of the illuminated region, decreases, when the plasma volume moves farther along the convection trajectory, and vanishes, when the plasma volume abandons the illuminated region. The maximal value of the EAP is assumed to be 30 MW that is quite attainable for the heating facility near Tromso.

Let us consider the results of the simulation for the convection trajectory going across the center of the illuminated region. It turns out that the variations of the electron concentration, positive ion velocity, and ion and electron temperature profiles with time (along the chosen convection trajectory) following the entrance of the plasma volume in the illuminated region, obtained for such incident wave frequencies that are less than the F-layer critical frequency, are qualitatively very similar. The maximum energy input from the powerful HF wave is at the level where the wave frequency is equal to the frequency of the electron hybrid resonance. At this level, a pronounced peak arises in the electron temperature profile due to the great energy input from the powerful HF wave. At this peak, the electron temperature can increase for some thousands of degrees. As a consequence of the great increase in the electron temperature, the upward and downward ionospheric plasma fluxes arise from the level, where the electron temperature peak is located. Indeed, the increase in the electron temperature results in changes of the electron gas pressure. From the level where the electron temperature peak is located, the upward and downward electron gas fluxes arise. Due to the ambipolarity of the ionospheric plasma diffusion, the ion gas begins to move, too. Thus, ionospheric plasma fluxes arise from the level where the maximum energy input from the powerful HF wave takes place. As a consequence, the upward component of plasma velocity can achieve values of more than 100 m/s near the level of the F2-region peak. Visible changes of the electron concentration profile can be produced by the ionospheric plasma fluxes, with the electron concentration decreasing in the F2 layer at greater heights than the height of the maximum energy absorption from a powerful HF wave. The decrease of the electron concentration can be significant not only near the level of the maximum energy absorption from the powerful HF wave, but also near the F-region peak.

After the abandonment of the illuminated region by the magnetic field tube, the electron temperature decreases due to elastic and inelastic collisions between electrons and other particles of ionospheric plasma. Figure 1 presents the variations of the electron temperature along the considered part of the convection trajectory at the level near the F-layer peak. It can be seen that the amplitudes of variations of the electron temperature produced by powerful HF waves achieve the maxima at a point close to the back edge of the illuminated region (S ≈ 88 km), after which a region of the recovery of the electron temperature begins. The duration of the period of the electron temperature recovery after the HF heating is of about 3 min at F2-layer levels. For the cases in which incident wave frequencies are with confidence less than the F-layer critical frequency, the more the incident wave frequency is, the higher electron temperature variation amplitude, produced by the HF heating, ought to be.

Results of simulation indicate that the electron heating is possible when the transmitter operates at frequencies, which exceed the F-layer critical frequency, with the HF waves passing through the ionosphere without a reflection. However, the exceeding can only be less than 0.3 MHz. Indeed, the electron temperature variations, obtained at the frequency of 3.65 MHz which exceeds the F-layer critical frequency for 0.3 MHz, coincide with the results, obtained under natural conditions without a powerful HF wave effect. The maximal frequency of incident waves, at which the electron heating is possible, will be called the ‘threshold of incident wave frequency’ or TIWF. The TIWF depends on the F-layer critical frequency and slightly exceeds it.

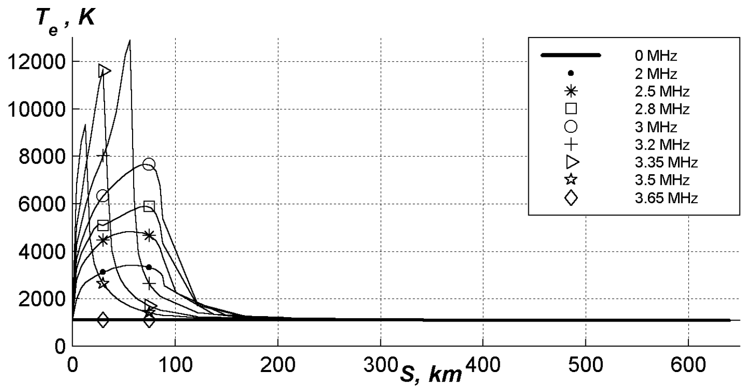

Fig.1. The variations of the of electron temperature (in absolute degrees) along the considered part of the convection trajectory at level h=350 km. The results are given for different HF wave frequencies: 2, 2.5, 2.8, 3, 3.2, 3.35, 3.5, and 3.65 MHz. The results, obtained under natural conditions without a powerful HF wave effect, are indicated by symbol 0 MHz. The distance from the beginning of the illuminated region S (in km) is shown on the horizontal axis. The center of the illuminated region, where the EAP achieves the maximal value, is located at S ≈ 44 km.

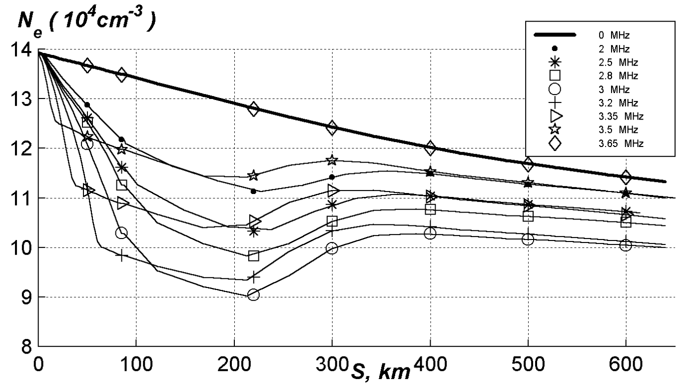

Fig.2. The variations of the electron concentration (in units of 10^4 cm^{-3}) along the considered part of the convection trajectory at level h =350 km. The captions are the same as in Fig.1.

The variations of the electron concentration along the considered part of the convection trajectory at the level near to the F-layer peak are shown in Fig.2. It is seen from results presented that the appreciable decrease of the electron concentration along the considered part of the convection trajectory takes place under natural conditions without HF heating. For the cases in which the HF heater operates, more appreciable decreases of the electron concentration along the considered part of the convection trajectory are produced by the energy input from the powerful HF waves. It is seen that the electron concentration decreases not only in the illuminated region but also after the magnetic field tube abandons it. For the cases in which incident wave frequencies are with confidence less than the F-layer critical frequency, the electron concentrations at the level of the F-region peak achieve the minima at a distance from the ground-based HF heater of about 160 km, besides, the more the incident wave frequency is, the less values of the electron concentration turn out to be. A powerful HF wave should lead to a decrease of more than 27% in electron concentration at the level of the F-region peak when the incident wave frequency is 3 MHz.

As a consequence of the decrease of the electron concentration conditioned by a powerful HF wave, the F-layer critical frequency decreases along the considered part of the convection trajectory. Therefore, the effect of the powerful HF wave on the plasma volume can be broken off due not only to it abandoning the illuminated region, but also to the decrease of the TIWF below the incident wave frequency even though the plasma volume continues to remain in the illuminated region. It is seen from results presented that to obtain the maximal effect of HF heating on the electron concentration at the level near the F-layer peak, the ionospheric heater has to operate at a frequency slightly less than the F-layer critical frequency. The difference between these frequencies ought to be about 0.35 MHz in the nocturnal high-latitude F region on condition that the F-layer critical frequency is 3.35 MHz. Figure 3 presents profiles of the electron concentration calculated for the point of the convection trajectory near the point in which the minimal values of the electron concentration at the level of the F-region peak are achieved.

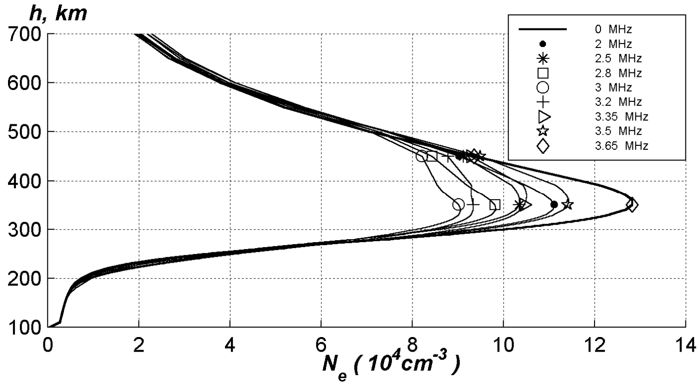

Fig.3. Profiles of the electron concentration versus distance from the earth along the geomagnetic field line, calculated for the point of the considered part of the convection trajectory which is located at S = 212.6 km. The results are given for different HF wave frequencies: 2, 2.5, 2.8, 3, 3.2,3.35, 3.5, and 3.65 MHz, with symbol 0 MHz indicating the results obtained under natural conditions without a powerful HF wave effect.

Conclusions

Applying the numerical model of the convecting high-latitude ionosphere, we have predicted the behaviour of ionospheric quantities in the nocturnal high-latitude F region illuminated by the HF heating facility near Tromso, Norway for distinct cases in which HF radio waves have different frequencies. The simulation results indicate that the frequency of HF wave influences significantly the F-region response to high power radio waves in the nocturnal high-latitude ionosphere. The closer the incident wave frequency is to the F-layer critical frequency, the higher the values of maximal amplitudes of variations of ionospheric quantities, produced by the HF heating, ought to be. The amplitude of the increase of the electron temperature at the F-layer altitudes, produced by powerful HF waves, achieves its maximum inside the illuminated region. On the contrary, the amplitude of the decrease of the electron concentration at the F2-layer altitudes, produced by powerful HF waves, achieves its maximum at the distance of about 160 km from the ground-based HF heater. A powerful HF wave should lead to a decrease of more than 27% in electron concentration at the level of the F-region peak when the incident wave frequency is slightly less than the F-layer critical frequency. The obtained results of modeling may be useful for performing artificial modification experiments by HF radio waves in the nocturnal high-latitude F-region ionosphere and for planning the operation of the diagnostic facility.

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