

COMPUTATIONAL STUDY OF THE HIGH-LATITUDE F-LAYER MODIFICATION BY POWERFUL HF WAVES WITH DIFFERENT FREQUENCIES IN THE DAYTIME

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Abstract. The mathematical model of the high-latitude F region, developed earlier, which takes into account the convection of the ionospheric plasma, is applied to simulate the F-layer response at auroral latitudes to powerful HF radio waves. The model enables us to calculate the time variations of the electron concentration, positive ion velocity, and ion and electron temperature profiles within a part of the magnetic field tube carried over an ionospheric heater by the convection electric field. The simulations are performed for the part of the magnetic field tube which intersects the F-layer volume illuminated by the ionospheric heater near Tromso, Norway, when it is located near the noon magnetic meridian. Simulations are performed for distinct cases in which high power waves have different frequencies. The results indicate that the frequency of HF wave can influence considerably the F-layer response to high power radio waves in the daytime high-latitude ionosphere.

Introduction

It is known that there exist some specific features characteristic of the high-latitude F-layer ionosphere which obstruct the observation of the F-region modification by powerful HF waves at night. For the ionospheric heater near Tromso, Norway, these specific features were investigated during recent years by numerical simulations [Mingaleva and Mingalev, 1997; Mingalev and Mingaleva, 1999; Mingalev et al., 2000]. The results of simulations indicated that the main fraction of the energy of the HF wave is to absorb 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. As a consequence, the upward and downward ionospheric plasma fluxes arise from the level where the electron temperature peak is located. These fluxes can produce visible changes of the electron concentration profile. The electron concentration decreases not only near the level where the electron temperature peak is located, but also at more considerable heights than the height of maximum energy absorption from the powerful HF wave, including the level of the F-region peak. However, the minimal values of the electron concentration at the level of the F-region peak are not found straight over an ionospheric heater but are displaced for rather a long distance from it under nocturnal conditions. This displacement is due to the convection of the ionospheric plasma and is the main specific feature that obstructs the observation of the F-layer modification by HF heating in the high-latitude ionosphere at night.

The purpose of this paper is to examine how the convection of the ionospheric plasma influences the possibility of the observation of the F-layer disturbances caused by the HF heating facility near Tromso, Norway, for distinct cases, in which HF radio waves have different frequencies, in the daytime.

Numerical model

The mathematical model of the high-latitude F-region ionosphere, which can be affected by a powerful HF wave, developed earlier by Mingaleva and Mingalev [1997], is utilized in the present study. In the model calculations, the effect of HF heating is taken into account by analogy with the study by Blaunshstein et al. [1992]. The utilized model has been applied for simulations of the high-latitude F-layer modification by HF waves with different frequencies under nocturnal conditions [Mingalev et al., 2000]. The model takes into account the geomagnetic field declination, magnetization of the plasma at F-layer altitudes, and convection of the ionospheric plasma. 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. For a steady convection pattern, the convection trajectories, around which the magnetic field tubes are carried over the polar region, are closed. In the present study, we use the pattern B of the empirical convection models of Heppner [1977] which is the steady nonsubstorm convection pattern. From this plasma convection pattern, we choose the convection trajectory and calculate the plasma drift velocity along it. The chosen convection trajectory intersects the F-layer volume illuminated by the HF heating facility near Tromso, Norway, when it is located near the noon magnetic meridian. The parallel (to the magnetic field) 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 profiles of ionospheric quantities versus distance from the earth along the geomagnetic field line are obtained by solving this system of transport equations. The natural spatial inhomogeneity of the ionosphere, which can take place in the high-latitude F layer, is taken into account by the utilized numerical model.

Presentation and discussion of results

The part of the convection trajectory, intersecting the F-layer volume illuminated by the HF heater, is shown in Fig.1. The moment of the entrance of the considered part of the magnetic field tube in the illuminated region is the initial moment of our examination. We suppose that the HF heater is turned on and operates during a time longer than the period required for the part of the magnetic field tube to intersect the illuminated region at F2-layer altitudes. This period is to be approximately 10 min under noon conditions. During this period, the considered part of the magnetic field tube enters the illuminated region, intersects it, abandons it, and moves farther along the convection trajectory. We consider the temporal history of the ionospheric plasma in the part of the magnetic field tube during the period of about 80 min. Since the time may be connected with the distance along the trajectory using the plasma drift velocity, we can establish that the consideration period (≈ 80 min) is sufficient for the magnetic field tube to be displaced for a distance of more than 600 km from the HF heater. This displacement is shown in Fig.1 by the solid line. At the initial moment, the considered part of the magnetic field tube is assumed to be near the magnetic meridian of 12.00 MLT. The considered convection trajectory is assumed to lie across the center of the illuminated region. The calculations of the present study are performed for autumn (5 November) and middle solar activity ($F_{10.7} = 130$) conditions under low geomagnetic activity ($K_p = 0$).

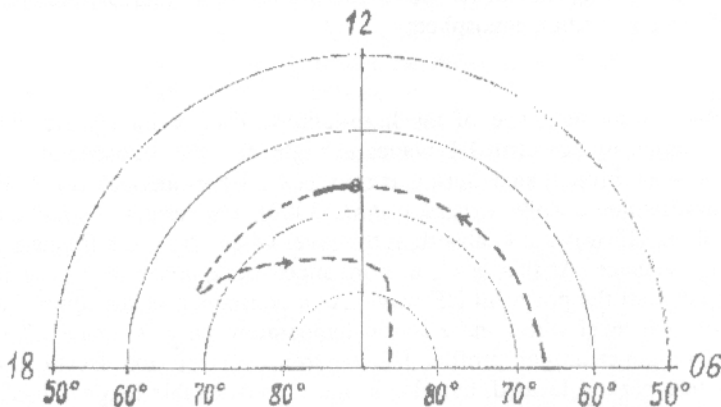


Fig.1. The part of the convection trajectory around which the magnetic field tube of plasma is carried in the numerical simulation (dashed line). Arrows on the trajectory indicate the direction of the convection flow. The solid line marks the displacement of the plasma tube corresponding to the period of 80 min after the turning-on of the HF heater.

started from obtaining the variations of calculated ionospheric parameters along the considered part of the convection trajectory under natural conditions without a powerful HF wave effect. The obtained variations turned out to be much less than those obtained by Mingalev et al. [2000] under nocturnal conditions. However, the electron concentration at the F-region levels turned out to be much more than the one obtained under nocturnal conditions. As a consequence, the F-layer critical frequency obtained in the daytime turned out to be much more than that obtained at night.

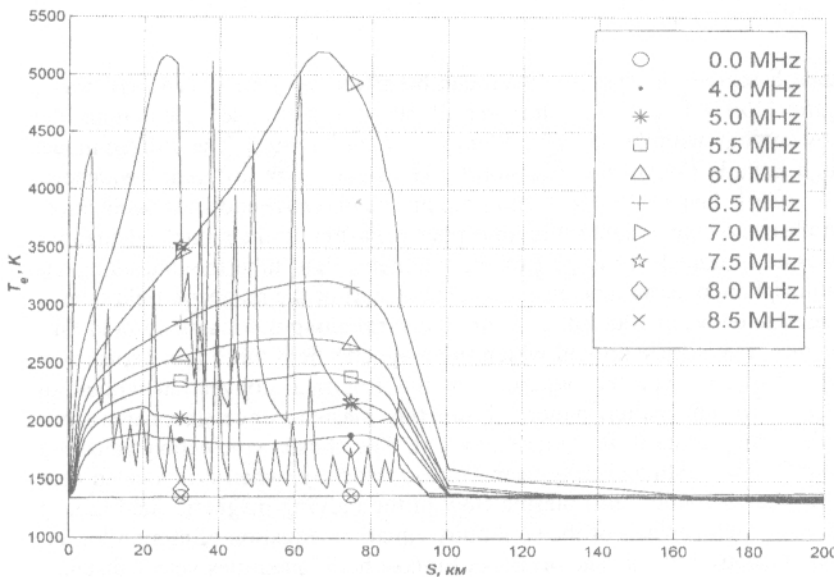


Fig.2. The variations of the electron temperature (in absolute degrees) along the considered part of the convection trajectory at the level of 260 km. The results are given for different HF wave frequencies: 4.0, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, and 8.5 MHz. The results, obtained under natural conditions 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 reaches the maximal value, is located at $S \approx 44$ km.

Next, we obtained the variations of ionospheric parameters along the considered part of the convection trajectory (with time) following the entrance of the magnetic field tube in the illuminated region for distinct cases in which HF radio waves have different frequencies: 4.0, 5.0, 5.5, 6.0, 6.5, 7.0,

7.5, 8.0, and 8.5 MHz. It should be noted that the F-layer critical frequency has the value of 8.2 MHz at the initial moment of our examination. The important input parameter of the numerical model is the effective absorbed power (EAP) which is a part of power radiated by the HF heater, which is deposited in the ambient electron gas and is lost for its heating. In the model calculations, the EAP varies on condition that the magnetic field tube moves along the considered part of the convection trajectory. The EAP arises, when the magnetic field tube enters the illuminated region, reaches the maximal value, when the plasma tube reaches the center of the illuminated region, decreases, when the plasma tube moves farther along the convection trajectory, and vanishes, when the plasma tube abandons the illuminated region. The maximal value of the EAP is assumed to be 30 MW that is the same as in the study by *Mingalev et al.* [2000].

It turned out that essential variations of the electron temperature, positive ion velocity, and electron concentration profiles with time (along the chosen convection trajectory) can be produced by the HF heating in the high-latitude F region in the daytime. These variations obtained for such HF wave frequencies that are with confidence less than the F-layer critical frequency, are qualitatively very similar. A pronounced peak arises in the electron temperature profile at the level where the wave frequency is equal to the frequency of the electron hybrid resonance. As a consequence, the upward and downward ionospheric plasma fluxes arise from this level. Visible changes of the electron concentration profile are ultimately produced by the energy input from the powerful HF wave. These changes arise not only near the level of maximum energy absorption from the powerful HF wave, but also above this level including the height of the F-region peak, with the electron concentration decreasing in the F layer. The mechanisms responsible for the variations of ionospheric parameters in the daytime are identical with the mechanisms, operating at night and established earlier [*Mingalev et al.*, 2000].

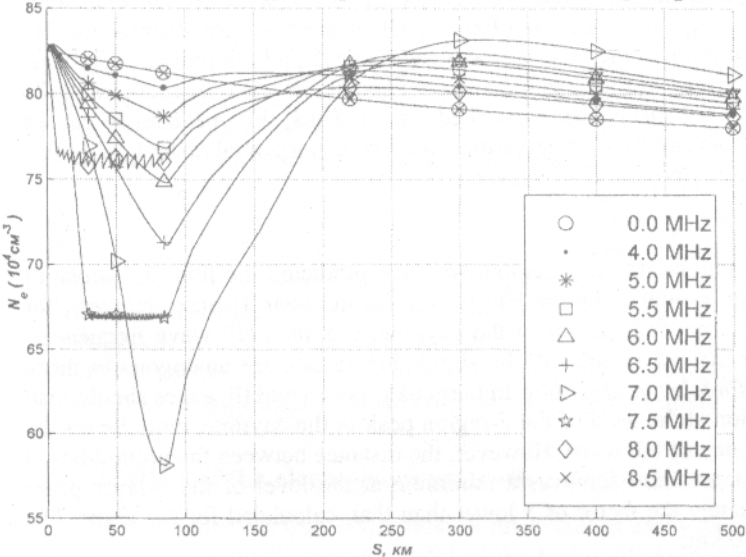


Fig.3. The variations of the electron concentration (in units of 10^4 cm^{-3}) along the considered part of the convection trajectory at the level of 350 km. The captions are the same as in Fig.2.

The variations of the electron temperature and concentration along the considered part of the convection trajectory at the level near to the F-layer peak are shown in Figs.2 and 3, respectively. It can be seen that, for the cases in which HF wave frequencies are with confidence less than the F-layer critical frequency, the variation behaviours are analogous to those obtained under nocturnal conditions [*Mingalev et al.*, 2000]. However, conspicuous distinctions between the locations of the points, where the electron concentration reaches the minimum at the level of the F-layer peak, calculated for day and night conditions, take place. In the daytime, such point is located at the distance from the ground-based HF heater of about 50 km whereas this distance was about 160 km at night [*Mingalev et al.*, 2000]. This is the consequence of the distinction between the plasma drift velocities obtained for day and night conditions. The profiles of the electron concentration, obtained 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, are shown in Fig.4. It is seen that the differences between heated and unheated electron concentrations at the level near the F-region peak depend significantly on the value of the frequency of the HF wave.

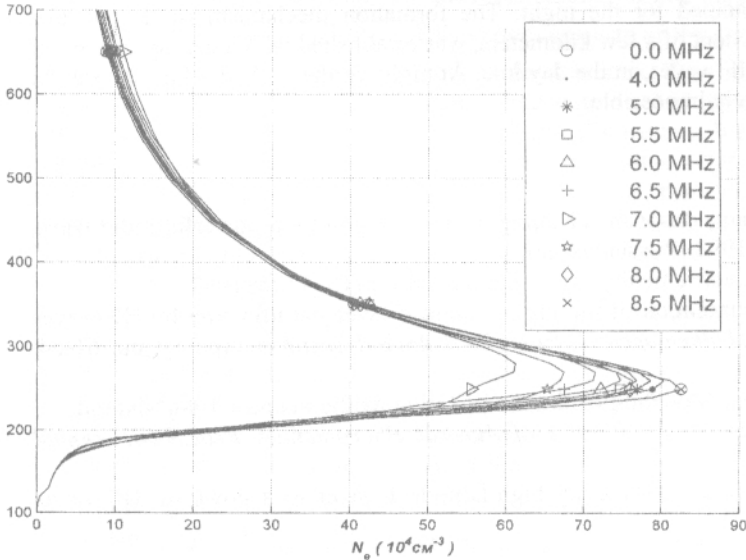


Fig.4. Profiles of the electron concentration versus distance from the earth along the geomagnetic field line, obtained for the point of the considered part of the

convection trajectory which is located at $S=85.39\text{km}$. The results are given for different HF wave frequencies: 4.0, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, and 8.5 MHz, with symbol 0 MHz indicating the results obtained under natural conditions without a powerful HF wave effect.

It can be noticed that the electron heating is possible when the transmitter operates at frequencies which slightly exceed the F-layer critical frequency. The maximal frequency of HF waves, at which the electron heating is possible, is called the "threshold of incident wave frequency" or the TIWF and it depends on the F-layer critical frequency being slightly more than the latter. It is seen from results presented (Figs.3 and 4) that HF heating leads to a decrease of the electron concentration at the level of the F-region peak. As a consequence, the F-layer critical frequency ought to decrease. Consequently, the TIWF is to decrease, too. Therefore, the effect of HF heating on the ionospheric plasma in the part of the magnetic field tube can be broken off due not only to its abandonment of the illuminated region, but also to the decrease of the TIWF below the HF wave frequency even though the plasma tube keeps staying in the illuminated region. Precisely such events take place during the period of the HF heater operation in the cases when HF wave frequencies are close to the F-layer critical frequency (Figs.2 and 3). Such events have taken place under nocturnal conditions [Mingalev et al., 2000]. However, the results of the present study differ in principle from the results obtained for nocturnal conditions. At night, the electron concentration continues to decrease smoothly after the moment of the TIWF decrease below the HF wave frequency. In the daytime, on the contrary, the electron concentration begins to increase after the moment of the TIWF decrease below the HF wave frequency when the effect of HF heating is broken off. The increase of the electron concentration, which is due to photoionization, leads to the increase of the F-layer critical frequency as well the TIWF. As a consequence, in some period of time, the TIWF reaches the HF wave frequency, and the effect of HF heating is turned on again. HF heating leads to a decrease of the electron concentration at the level of the F-region peak and the process will begin to repeat. The very irregular, like saw curves, presented in Figs.2 and 3 and obtained at HF wave frequencies of 7.5 and 8.0 MHz, are interpreted as being caused by the mechanism described above. Thus, this mechanism can be responsible for the formation of the electron concentration irregularities having a horizontal extent of a few kilometers in the high-latitude F region illuminated by powerful HF waves.

Conclusions

Using the mathematical model of the convecting high-latitude F region, we have predicted the time variations of ionospheric parameters in the high-latitude F layer produced by the HF heating facility near Tromsø, Norway, for distinct cases in which HF radio waves have different frequencies in the daytime. For such HF wave frequencies which are with confidence less than the F-layer critical frequency, the simulation results are analogous to those obtained earlier for the nocturnal conditions by Mingalev et al.[2000]. In particular, powerful HF waves should lead to a decrease of up to 30% in electron concentration at the level of the F-region peak in the daytime, with the results depending significantly on the value of the frequency of HF wave. However, the distance between the ground-based HF heater and the point, where the electron concentration achieves a minimum at the level of the F-layer peak, calculated for the daytime, ought to be approximately the factor of 3 lower than that, calculated for the night. The daytime value of this distance ought to be about 50 km.

For such HF wave frequencies which are close to the F-layer critical frequency, the simulation results, obtained for the daytime, differ in principle from those, obtained for the night. The formation mechanism of the electron concentration irregularities, having a horizontal extent of a few kilometers, was established which can operate in the high-latitude F region, illuminated by powerful HF waves, in the daytime. At night, in the darkness ionosphere, the operation of the established mechanism is absolutely impossible.

References

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