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THE EFFECTS OF MODIFICATION OF A HIGH-LATITUDE IONOSPHERE BY HIGH-POWER HF RADIO WAVES. PART 1. RESULTS OF MULTI-INSTRUMENT GROUND-BASED OBSERVATIONS

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We present the results of multi-instrument experiments related to studying the phenomena in the high-latitude ionosphere affected by high-power radio waves using the EISCAT technical facilities. It was found for the first time that strong small-scale artificial field-aligned irregularities (AFAIs) are excited when the ionospheric F region is heated by a high-power HF radio wave with X-mode polarization near the altitude at which the critical frequency f_{xF_2} of the F_2 layer is equal to the frequency f_{H} of the heating accompanied by an up to 50% increase in the electron temperature. The spatial structure of the artificially perturbed ionospheric F region is examined in detail using an incoherent scatter radar operated in the regime of scanning over elevation angles from 92° to 74° with a 2° step. It is shown that the spatial size of the heated patch strongly depends on the angle of the HF pumping relative to the Earth's magnetic field. The phenomena occurring in the artificially modified ionospheric F region heated at frequencies near the third electron gyroharmonic, i.e., at $f_{\mathrm{H}} = 3f_{\mathrm{ce}} = f_{\mathrm{UH}}$, where f_{UH} is the upper-hybrid frequency, are explored on the basis of multi-instrument observation data.

1. INTRODUCTION

The last decade witnessed a dramatic increase in interest in the problem of modification of a high-latitude ionosphere by a high-power HF radio wave in both purely scientific and applied aspects. This to a considerable degree is due to the end of construction of an ultrahigh-power HF heater in Gakona (Alaska, USA, the HAARP project). In March 2007, the HAARP facility was brought into a planned maximum effective radiated power equal to 3600 MW. In 2004, Great Britain constructed a SPEAR high-frequency heater on Spitsbergen, which is the only heating facility in the Arctic circle. Since 2008, the SPEAR heater belongs to the university and research center in Longyearbyen on Spitsbergen. In September 2009, the remanufacture of the HF heater in Arecibo (Puerto Rico) was finalized.

A wide variety of phenomena are observed when the ionospheric plasma is heated by a high-power HF radio wave [1]. Among the main phenomena, we should mention the development of parametric (striction and thermal) instabilities near the reflection level of an O-mode high-power radio wave, which causes the generation of intense plasma oscillations, an increase in the electron temperature, the excitation of small-scale artificial ionospheric irregulatrities and artificial radio emission, and the acceleration of the background-plasma electrons to suprathermal velocities, which, in turn, leads to artificial optical radiation from the perturbed ionospheric region and artificial plasma ionization. It should be mentioned that in the high-latitude ionosphere, where intense horizontal (electroject) and longitudinal currents, different-scale

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irregularites, precipitating particle fluxes, plasma instabilities, etc. are observed under natural conditions, new phenomena, in particular, the generation of a small-scale system of longitudinal currents, the modification of auroral arcs, and the initiation of local auroral disturbances, which are absolutely impossible at mid-latitudes, occur under the action of a high-power HF radio wave [2].

Scientific efficiency of the experiments on the ionosphere modification by a high-power HF radio wave is determined by the following factors: 1) technical characteristics of the heating facility (effective radiated power, heating frequency range, the possibility of automatic control of the heater and variation of the antenna-system directivity pattern, the possibility of rapid variation of heating regimes, etc.); 2) the use of various and high-efficiency diagnostic tools; 3) the variety of the properties and states of the ionospheric plasma heated by a high-power HF radio wave. The EISCAT/Heating high-frequency facility in Tromsø (Norway) fully satisfies all mentioned conditions. A significant merit of the heater in Tromsø is its location in close neighborhood with the incoherent scatter radar. This ensures diagnostics of the required ionospheric plasma parameters which are important for the interpretation of obtained results.

An agreement between the Arctic and Antarctic Research Institute (AARI) and the EISCAT (European Incoherent Scatter) was concluded at the end of 2008. Under this agreement, the Russian specialists were given the right for experiments with the use of the EISCAT facilities which are unique in our country both in technical characteristics and geographical location. Specifically, we mean the EISCAT/Heating facility in Tromsø (Norway) and the system of high-latitude incoherent scatter radars in northern Scandinavia and on Spitsbergen. Taking into account that Russia does not have such high-efficiency technical facilities at high latitudes and will hardly construct them in the near future, the studies based on the EISCAT equipment are extremely important. Regular experiments (two heating campaigns per year) have been performed since March 2009.

In this paper, we present the results of multi-instrument experiments on modification of the high-latitude ionosphere by a high-power HF radio wave with the use of the EISCAT facilities, which were obtained by the AARI specialists in the periods of a deep solar minimum (in March 5–12, 2009, October 29–November 6, 2009, and March 2–8, 2010). This paper aims at analyzing specific features of the excitation and evolution of the small-scale ionospheric irregularities accompanied by disturbances of the ionospheric plasma parameters, i.e., electron temperature and electron number density, in the F region of a high-latitude ionosphere.

Despite the significant progress achieved in the studies of small-scale artificial ionospheric irregularities, a number of important aspects remain unclear. It is widely known that the excitation of the mentioned irregularities can be explained in terms of the theory of thermal parametric (resonant) instability [3–5]. Thermal parametric instability develops when an O-mode high-power HF radio wave is reflected from the ionosphere or at heating frequencies slightly above the critical frequency f_{oF_2} when the O-mode wave of the order of the upper-hybrid frequency f_{UH} is at the maximum of the F_2 layer [3, 4]. The maximum scale of ionospheric irregularities across the magnetic field at the linear stage of thermal parametric instability is determined by the quantity $l_\perp = c/f_{\mathrm{H}}$, where f_{H} is the heating frequency and c is the speed of light. For example, for $f_{\mathrm{H}} = 4$ MHz, $l_\perp$ amounts to 75 m. The size of small-scale artificial field-aligned ionospheric irregularities is determined by the length of the electron heat conduction and can reach 30–50 km. Only the O-mode propagating in the vertical or almost vertical direction reaches the resonance region. The X mode is always reflected from the region lying below the resonance one; hence, the excitation of small-scale ionospheric irregularities due to the thermal resonant instability is not possible in this case.

In this paper, we primarily focus on studying the possibility, conditions of excitation, and behavior of small-scale ionospheric irregularities when the high-latitude ionospheric F region is affected by an X-mode high-power HF radio wave. Another aspect in this work is related to studying the spatial structure and size of the artificially perturbed ionospheric region based on the incoherent scatter radar in Tromsø when high-power HF radio waves are radiated into the magnetic zenith and in the vertical direction. Complete systematic and integrated studies of small-scale artificial ionospheric irregularities with different spatial scales $l_\perp$ and different characteristics of the plasma turbulence in the high-latitude ionosphere as functions of the heating-frequency detuning with respect to the gyroresonance frequency are absent at present. In this paper, we consider the results of integrated exploration of the behavior and properties of small-scale artificial ionospheric irregularities with different spatial scales ($l_\perp \approx 8$, 12, and 15 m) as well as of the parameters of the artificially perturbed ionospheric plasma in the F region (based on the Tromsø incoherent scatter data) when the ionosphere is heated at frequencies near the third electron gyroharmonic.

2. DESCRIPTION OF THE EXPERIMENTS AND THE METHODS AND FACILITIES EMPLOYED

During the experiments, the high-latitude ionosphere was modified using the EISCAT/Heating high-frequency facility (69.6°N, 19.2°E, McIlwain parameter $L = 6.2$, and magnetic declination $I = 78°$). Technical characteristics of this facility are presented in [6]. The relative number W of solar spots had a zero value in most days of observation. The magnetic conditions were quiet. In the period of the experiments, the effective radiated power amounted to 190–250 MW, and the heating frequency was varied from 3.9 to 5.4 MHz in different experiments depending on the background state of the ionosphere. The antenna system we used for the HF heater provided a beamwidth of about 12°–14°. The ionosphere state was controlled using a dynasonde (ionosonde) in Tromsø, which yielded vertical sounding ionograms one time in each 4 min.

When small-scale artificial ionospheric irregularities were studied, the ionosphere was heated by an X-mode HF radio wave in 10-min cycles. The duration of the pauses between heating cycles was varied from 5 to 40 min. The high-power HF radiation was directed into the magnetic zenith, i.e., the directivity pattern of the heater antenna was deflected by 12° south of the vertical line. For the diagnostics of small-scale artificial ionospheric irregularities, a system of CUTLASS high-frequency radars (SUPERDARN) in Finland and Iceland was employed [7]. The measurements were performed at three frequencies (about 10, 13, and 17 MHz) simultaneously. Both CUTLASS radars used a spot-beam antenna with a beamwidth of about 3.3°, which was oriented to the artificially perturbed ionospheric region over Tromsø. The range spatial resolution amounted to 45 km in the experiments of March and October–November 2009 and 15 km in March 2010. For the diagnostics of small-scale ionospheric turbulence, a multichannel Doppler HF reception system was also utilized for recording of diagnostic signals by the aspect scattering method. The system was mounted in the AARI observatory "Gorkovskaya" near St. Petersburg. The ionospheric plasma parameters (electron number density N_e, electron temperature T_e, ion temperature T_i, and ion velocity V_i) were explored using a 930-MHz [8] incoherent scatter radar near Tromsø, which provided measurements with a resolution of up to 5 s in time and 3 km in altitude in a frequency range of 90 to 600 km. The measurements were performed in the magnetic field direction in Tromsø, i.e., in the magnetic-zenith direction.

The fine spatial structure of the artificially perturbed ionospheric region was studied when the O-mode high-power HF wave was propagated in the vertical (elevation angle 90°) direction and in the magnetic zenith direction (elevation angle 78°) in 10-min heating — 5-min pause cycles. The propagation direction of the high-power HF wave was varied in each heating cycle. In those experiments, the incoherent scatter radar was operated in the regime of successive scanning of the artificially perturbed ionospheric region in the elevation-angle range from 92° to 74° with a 2° step. Thus, the incoherent scatter radar scanned the heated patch in the elevation-angle range from 92° to 74° in each 10-min period. The measurements were performed for 1 min for each value of the elevation angle.

To study the ionospheric heating phenomena at frequencies near the third electron gyroharmonic, the O-mode high-power HF radio wave was directed into the magnetic zenith in 2-min heating — 2-min pause cycles. The heating frequency was varied in each heating cycle by 5–10 KHz in a range of 3900 to 4200 KHz. For the diagnostics of small-scale artificial ionospheric irregularities and ionospheric plasma parameters, the CUTLASS high-frequency radars in Finland and Iceland and the incoherent scatter radar in Tromsø were employed. For recording of artificial ionospheric radiation, a receiver and a spectrum analyzer located in close neighborhood of the HF heater were utilized.

Figure 1 shows a schematic map showing the location geometry of EISCAT/Heating and the diagnostic observation tools used in the experiments.

3. OBSERVATION RESULTS AND THEIR DISCUSSION

3.1. Excitation of small-scale irregularities during heating of the ionospheric plasma by an X-mode high-power HF radio wave

Intense small-scale stratification of the ionospheric plasma into strongly stretched magnetic-field aligned electron-density irregularities were detected even in the first experiments on the ionosphere modification by a high-power HF wave [9]. The excitation of small-scale irregularities in all the earlier experiments based on HF heating facilities such as Sura, Arecibo, EISCAT/Heating, HAARP, and SPEAR located at the mid and high latitides (see, e.g., [10–19]), was observed in the upper-hybrid resonance region during reflection of an O-mode high-power HF from the ionosphere or at heating frequencies slightly above the critical frequency f_{oF_2} when the O-mode wave is approximately equal to the upper-hybrid frequency at the F_2-layer maximum, i.e., $f_{\rm H} = (f_{oF_2}^2 + f_{\rm ce}^2)^{1/2}$, where $f_{\rm ce}$ is the electron gyrofrequency. As was mentioned, the excitation of small-scale artificial ionospheric irregularities due to the thermal (resonant) instability during the ionosphere heating by a an X-mode high-power HF radio wave is not possible since the X-mode is always reflected from the region located below the resonant one. In the experiments performed at the AARI with EISCAT/Heating in November 2009 and in March 2010, the excitation of strong small-scale irregularities during heating of the ionospheric F region by an X-mode high-power HF radio wave was detected for the first time. The excitation of irregularities was observed in the experiments in November 3, 4, 5, and 6, 2009 and also in March 5, 6, and 8, 2010 based on observations both with the help of the CUTLASS radar in Finland and by the aspect-scattering method on the London–Tromsø–St. Petersburg route.

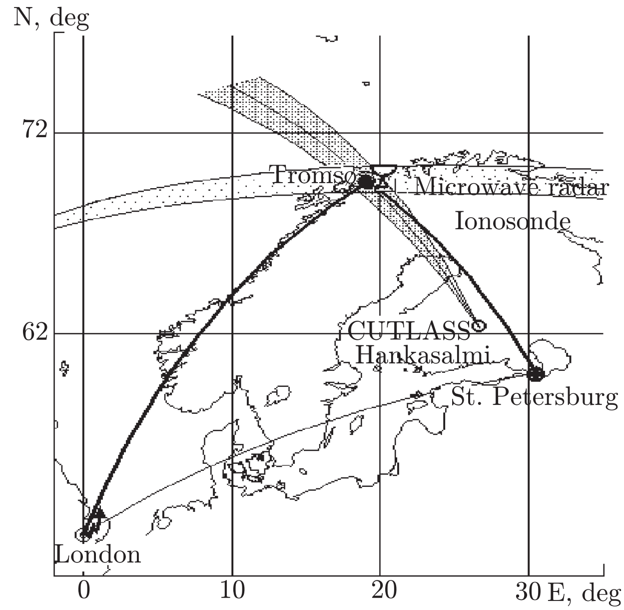

Fig. 1. A schematic map showing the location geometry of EISCAT/Heating and the diagnostic observation tools used in the experiments.

Figures 2 and 3 present the results of observations using the CUTLASS radar in Hankasalmi (Finland) at a frequency of about 10 MHz in the period of the heating experiments in Tromsø in November 5, 2009 between 14:00 and 15:30 UT and in November 6, 2009 between 14:00 and 15:20 UT, respectively. This made it possible to examine the behavior of the artificial ionospheric irregularities with spatial scales $l_\perp \approx 15$ m ($l_\perp = \lambda/2$, where λ is the radar wavelength). In the November experiments, the distance resolution (i.e., the gate) amounted to 45 km, and the first gate started with the distance 180 km. The signals scattered by artificial ionospheric irregularies were recorded in the distance range from 765 to 1215 km, which corresponds to gate Nos. 13 to 23.

Figures 2a and 3a show the temporal dependence of the scattered-signal power for a fixed distance of 945 km from Hankasalmi to the central part of the artificially perturbed ionospheric region over Tromsø (see Fig. 1), which corresponds to gate No. 17. Figures 2b and 3b show the distribution of the scattered-signal power as a function of the gate number and the universal time. The ionosphere was heated at a frequency of 4040 KHz in 10-min heating — 5-min pause cycles. In the first three heating cycles, the O-mode high-power HF radio wave was magnetic-zenith directed. It is seen in Fig. 2 that fairly intense signals scattered by small-scale artificial ionospheric irregularities were observed in the first two heating cycles when the critical frequencies f_{oF_2} of the F_2 layer for the O mode decreased from 4.0 to 3.7 MHz. Then the critical frequencies further decrease, and small-scale artificial ionospheric irregularities disappear when f_{oF_2} reaches 3.5 MHz (see Fig. 2, the last cycle of heating by an O-mode wave in the period between 14:35 and 14:45 UT). In the next heating cycle (14:50–15:00 UT), when f_{oF_2} amounted to 3.3–3.4 MHz already, the polarization of the

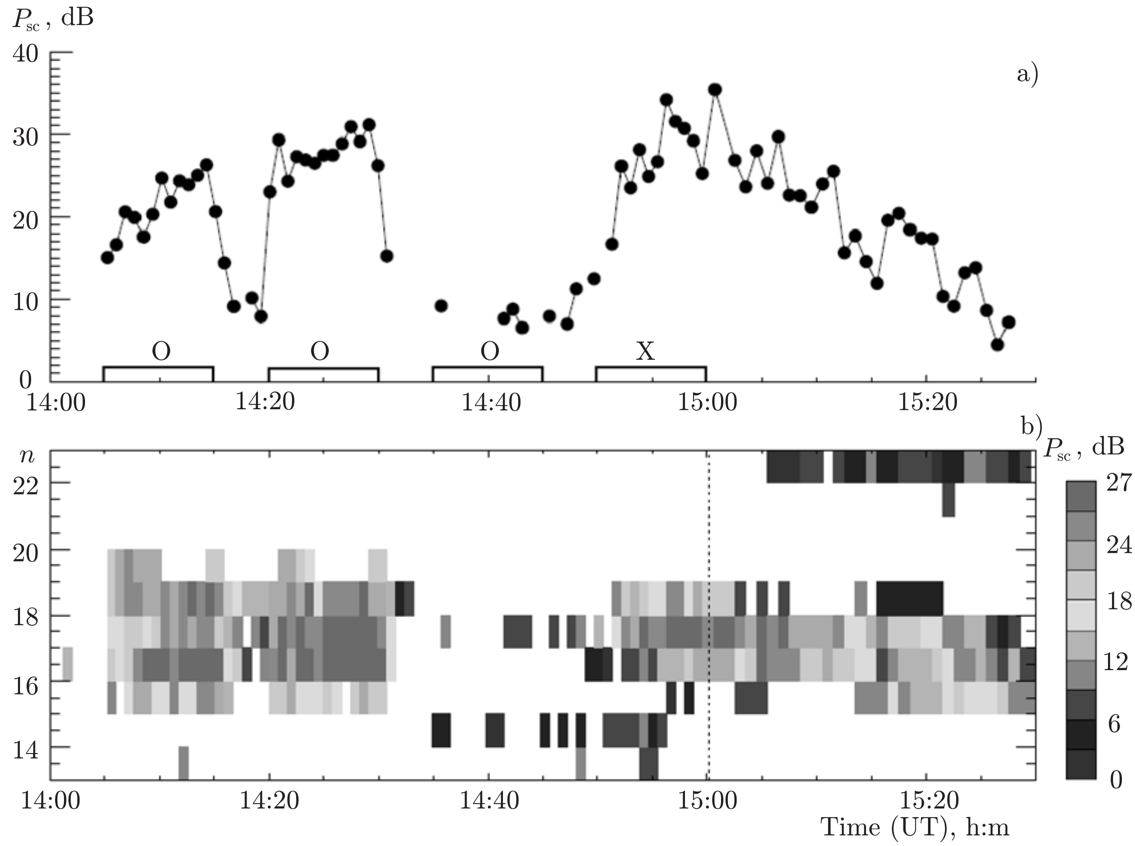

Fig. 2. Observation data based on the CUTLASS coherent HF Doppler radar in Hankasalmi, Finland (beam 5 oriented to the artificially perturbed ionospheric region over Tromsø) at a frequency of about 10 MHz in the period of the EISCAT/Heating experiment in November 5, 2009 between 14:00 and 15:30 UT. Figure 2*a* shows the temporal dependence of the scattered-signal power $P_{\rm sc}$ for a fixed distance of 945 km from Hankasalmi to the central part of the artificially perturbed ionospheric region over Tromsø, which corresponds to gate No. 17. Figure 2*b* presents the distribution of the scattered-signal power as a function of the gate number and the time. The scattered signals were recorded in the distance range from 765 to 1215 km, which corresponded to gate Nos. 13 to 23. The heating cycles and the polarization of the high-power HF radio wave are marked in Fig. 2*a* on the time axis.

high-power HF radio wave was switched from the O to the X mode. The change of polarization led to the occurrence of intense signals scattered by small-scale artificial ionospheric irregularities. The case was similar in the experiment of November 6, 2009 (see Fig. 3). However, in that experiment, the critical frequencies started to decrease earlier. The 13:46–13:56 UT cycle was the last O-mode heating cycle, in which the signals scattered by small-scale artificial ionospheric irregularities were observed. In two subsequent cycles (14:01–14:11 and 14:16–14:26 UT), when f_{oF_2} dropped below 3.5 MHz, the mentioned irregularities were not recorded at all. The change for the X-mode polarization (the 14:31–14:41 UT cycle), as in the event of November 5, led to the appearance of intense signals scattered by small-scale artificial irregularities. It should be mentioned that in November 6, 2009 a stepwise power variation scheme such as 20%, 50%, 70%, 85%, 100%, 100%, 85%, 70%, 50%, and 20% (1 min for each power level) was employed in the heating cycles. It is seen in Fig. 3 that the scattered signals appeared not immediately after the start of heating, but in 1.5–2 min, i.e., at a 50% power level. Nevertheless, a power decrease in the second half of the heating time interval did not affect the intensity of the signals scattered by small-scale artificial ionospheric irregularities.

In March 5 and 6, 2010, the ionospheric F region was heated by the X mode at a frequency of 4912.8 KHz, and in March 8, 2010, at a frequency of 5423 KHz. In these experiments, the measurements by the CUTLASS radars were performed simultaneously at three frequencies, which made it possible to

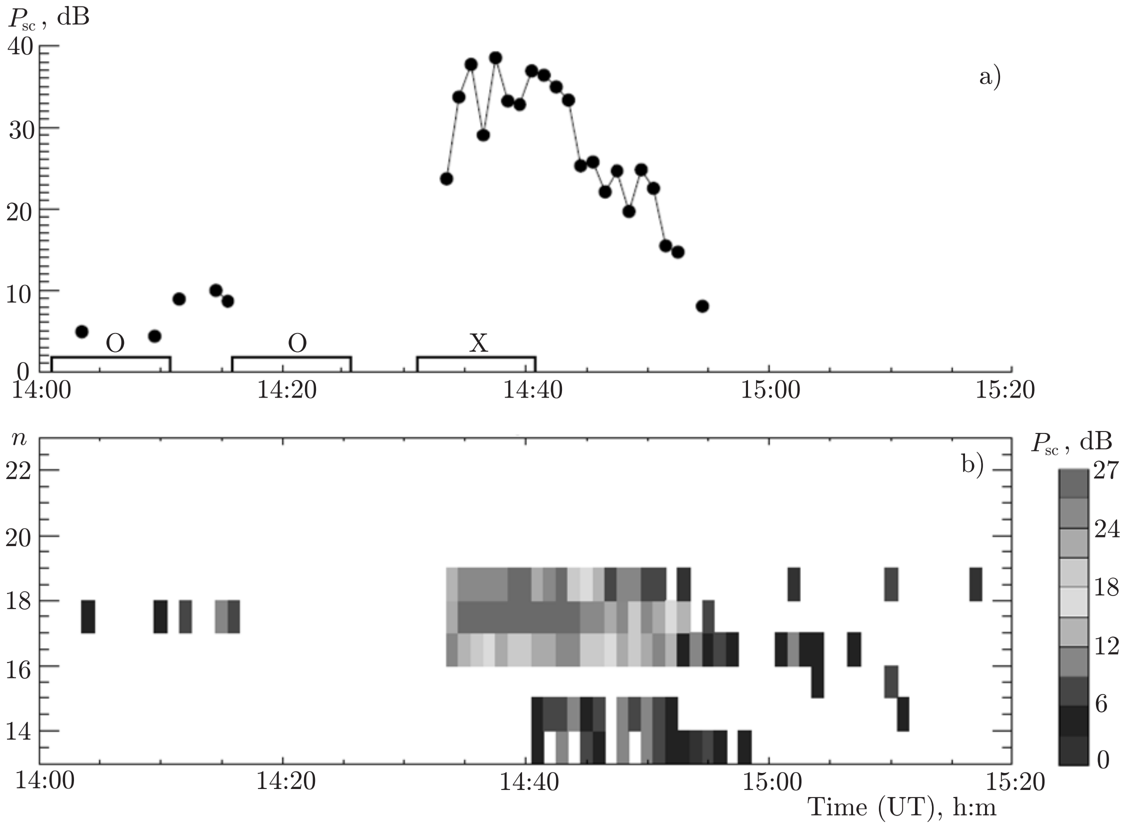

Fig. 3. Observation data based on the CUTLASS coherent HF Doppler radar in Hankasalmi, Finland (beam 5 oriented to the artificially perturbed ionospheric region over Tromsø) at a frequency of about 10 MHz in the period of the EISCAT/Heating experiments in November 6, 2009 between 14:00 and 15:20 UT. Figure 3*a* shows the behavior of the scattered-signal power as a function of time for a fixed distance of 945 km from Hankasalmi to the central part of the artificially perturbed ionospheric region over Tromsø, which corresponds to gate No. 17. Figure 3*b* shows the behavior of the scattered-signal power in the range — UT (universal time) coordinates. The scattered signals were recorded in the distance range from 765 to 1215 km, which corresponds to gate Nos. 13 to 23. The heating cycles and the polarization of the high-power HF radio wave are marked in Fig. 3*a* on the time axis. A stepwise power variation scheme such as 20%, 50%, 70%, 85%, 100%, 100%, 85%, 70%, 50%, and 20% (1 min for each power level) was used in the heating cycles.

study the behavior of small-scale artificial ionospheric irregularities with different spatial scales. In the March experiments, the distance resolution amounted to 15 km (instead of 45 km in November 2009), and the first gate started with the distance 480 km. The signals scattered by small-scale artificial ionospheric irregularities were recorded in the distance range from 780 to 1230 km, which corresponds to gate Nos. 20 to 50. Figure 4 presents the results of observations by the CUTLASS radar in Hankasalmi (Finland) at frequencies of about 10 and 13 MHz during the experiment in Tromsø in March 5, 2010 between 14:30 and 17:00 UT. This permitted us to study the behavior of the mentioned irregularities with spatial scales $l_\perp \approx 15$ and 12 m. In the first four heating cycles, the O-mode high-power HF radio wave was magnetic-zenith directed. It is seen in Fig. 4 that the signals scattered by small-scale artificial ionospheric irregularities were observed in the first three heating cycles when the critical frequencies of the F_2 layer began to decrease from 5.0 to 4.6 MHz. Then the critical frequencies further decrease, and the small-scale artificial ionospheric irregularities disappear when f_{oF_2} reaches 4.4 MHz (see the last cycle of heating by the O mode from 15:16 to 15:26 UT). In the next heating cycle from 15:31 to 15:41 UT, when f_{oF_2} amounted to about 4.2 MHz already, the polarization of the high-power HF radiation was switched from the O to the X mode. The change of polarization led to the occurrence of signals scattered by small-scale artificial ionospheric irregularities.

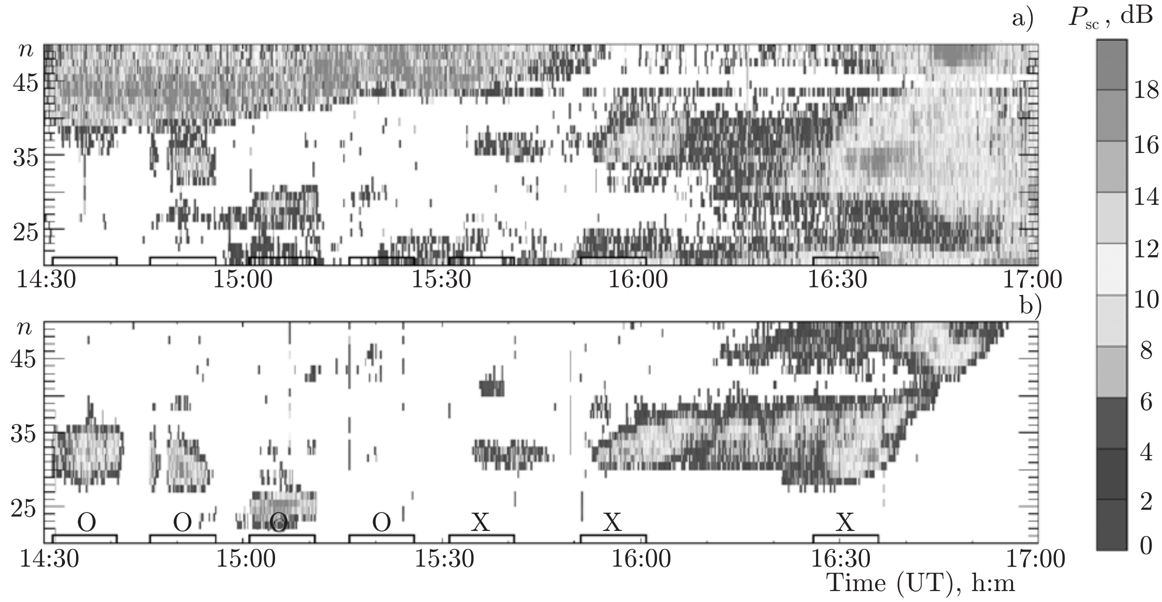

Fig. 4. Observation data based on the CUTLASS coherent HF Doppler radar in Hankasalmi, Finland (beam 5 oriented to the artificially perturbed ionospheric region over Tromsø) at frequencies of about 10 MHz (*a*) and 13 MHz (*b*) during the EISCAT/Heating experiment in November 5, 2010 between 14:30 and 17:00 UT. The behavior of the scattered-signal power in the distance — UT coordinates is presented. The scattered signals were recorded in the distance range from 780 to 1230 km, which corresponds to gate Nos. 20 to 50. The heating cycles and the polarization of the high-power HF radio wave are marked on the time axis.

In the next cycle of heating by the X mode (15:51–16:01 UT), the scattered-signal intensity increased compared with the previous heating cycle by both 10 and 13 MHz. The scattred signals were recorded until the next heating cycle (16:26–16:36 UT), in which their further amplification occurred. A similar behavior of the signals scattered by small-scale artificial ionospheric irregularities during the X-mode polarization was observed in March 6 and 8, 2010, but in those experiments, the irregularities of three spatial scales ($l_\perp \approx 8$, 12, and 15 m) were excited.

Analysis of the entire volume of experimental data shows that the excitation of strong small-scale artifical ionospheric irregularities during the X-mode heating occurred when according to the Tromsø ionosonde data, the critical frequencies of the O mode were by 0.6–0.8 MHz lower than the heating frequencies, i.e., $f_{\rm H} - f_{oF_2} \approx 0.6$–0.8 MHz. At the same time, the critical frequency f_{xF_2} of the X mode had values close to the heating frequency, i.e., the heating was performed near the critical frequency of the X mode, so that $f_{\rm H}$ was approximately equal to f_{xF_2}. The reflection height of the X-mode high-power HF radio wave was about 220 km.

Summarizing the features of the behavior of small-scale artificial ionospheric irregularities during heating of the high-latitude ionospheric F region by an X-mode high-power HF radio wave, we note the following. The mentioned irregularities appeared in 1–3 min and reached the maximum intensity in 2–5 min after the heating was started. Their characteristic feature was the unusually long time of relaxation, which reached 20–30 min. The longest relaxation after the X-mode radiation was stopped took place in the southern part of the artificially perturbed region. It should be mentioned that the relaxation was stepwise, with a gradual decrease in the scattered-signal intensity after the end of the heating cycle. One of the features of the behavior of small-scale artificial ionospheric irregularities detected in the experiments of March 2010 is that they were removed from the artificially perturbed region both in the south and north directions. According to the CUTLASS radar in Finland, the spatial size of the region, in which the mentioned irregularities were excited, amounted to about 60–120 km in different experiments. Note that the size of the artificially perturbed ionospheric region, which is determined by the directivity pattern of the EISCAT/Heating antenna system at altitudes 200–220 km amounts to about 60 km. Taking into account the time of development and relaxation of small-scale artificial ionospheric irregularities in the high-latitude ionospheric F region during the ionosphere heating by an X-mode high-power HF radio wave, it seems expedient to conclude that they are related to superlarge-scale plasma-density disturbances with spatial scales of the order of the size of the artificially perturbed region. The performed experiments [20] showed that the superlarge-scale irregularities can be created in the ionosphere when the ionosphere is heated by both O-mode and X-mode waves.

It is interesting to consider the behavior of the electron temperature and plasma density at different altitudes during the ionosphere heating by X-mode HF waves. Figure 5 shows the behavior of the electron temperature T_e at different altitudes using the Tromsø incoherent scatter data obtained in November 6, 2009 between 14:01 and 14:45 UT (Fig. 5*a*) and in March 6, 2010 between 15:38 and 17:00 UT (Fig. 5*b*). For comparison, these figures show the T_e variations during the ionosphere heating by O-mode high-power radio waves (the heating cycle from 14:16 to 14:26 UT in November 6, 2009 and from 15:41 to 15:51 UT in March 6, 2010) when the heating frequency exceeded f_{oF_2} by about 0.7 MHz. It is seen in Fig. 5 that an elevated electron temperature, i.e., Joule heating, was observed in the heating cycles at altitudes 200–250 km. The T_e disturbances due to heating by the X-mode radiation were higher than when the O-mode polarization was employed and reached 50% of the unperturbed level of T_e immediately before the heating cycle was started. For example, an increase in T_e from 1000 to 1500 K was observed in November 6, 2009 in the cycle of ionospheric heating by an X-mode radio wave from 14:31 to 14:41 UT (see Fig. 5*a*) at an altitude of 200 km, while T_e increased only from 1200 to 1400 K when the ionosphere was heated by the O-mode radiation (the 14:01–14:11 UT cycle).

Figure 6 shows the altitude profiles of the electron temperature $T_e(h)$ and electron density $N_e(h)$ contructed on the basis of the incoherent scatter data obtained in March 6, 2010 for different temporal intervals of the heating cycle 15:56–16:06 UT, as well as for the time intervals before and after the ionosphere heating by an X-mode high-power HF radio wave. Analysis of the data given in Fig. 6 shows that the T_e disturbances were observed in the altitude range from 180 to 300 km. The maximum disturbances of T_e occurred near the reflection level of a high-power HF radio wave at an altitude of about 220 km. It was unexpected that the electron number density increased in the magnetic-field direction by about 25% in a broad range of altitudes from 230 to 400 km. It is interesting to mention that the altitude intervals in which T_e and N_e increase did not coincide. Specifically, the maximum of T_e was recorded near the reflection level of a high-power HF radio wave at an altitude of about 220 km, while the maximum increase in N_e took place at an altitude corresponding to about 270 km, i.e., by 50 km higher than the T_e disturbance maximum. Moreover, while T_e returned to the unperturbed level after the end of heating (the temporal interval 16:06–16:08 UT), the N_e disturbances remained strong enough. Two main mechanisms of the N_e rise under the action of high-power radio waves on the ionosphere [21] are known at present: violation of the ionization–recombination balance and stumulated ionization by accelerated electrons. The estimates done in [22] for the conditions of the heating experiments in Tromsø show that due to the violation of the ionization–recombination balance, N_e at altitudes 210–230 km can increase by 2.4–5.3% with respect to the unperturbed level. Thus, this mechanism cannot explain the observed rise in N_e by about 25%. The most probable mechanism of the N_e increase in the experiment of March 6, 2010 at altitudes higher than the reflection level of a high-power HF radio wave is generation of an accelerated electron flux in the field of an X-mode high-power HF radio wave. Analysis of the incoherent scattering radar shows that the so-called heat-enhanced ion and plasma lines indicating the excitation of a strong Langmuir turbulence appear near the reflection level of a high-power HF radio wave in the signal spectra. Such a turbulence causes the generation of a flux of electrons accelerated to energies capable of increasing the electron number density in the regions above the reflection level of a high-power HF radio wave [1].

To finalize this section, we note that the mechanism of excitation of strong small-scale artificial ionospheric irregularities during heating of the high-latitude ionospheric F region by an X-mode high-power HF radio wave is unclear and requires further thorough studies, both experimental and theoretical. However, it can already be mentioned that the excitation of such irregularities requires special heating conditions,

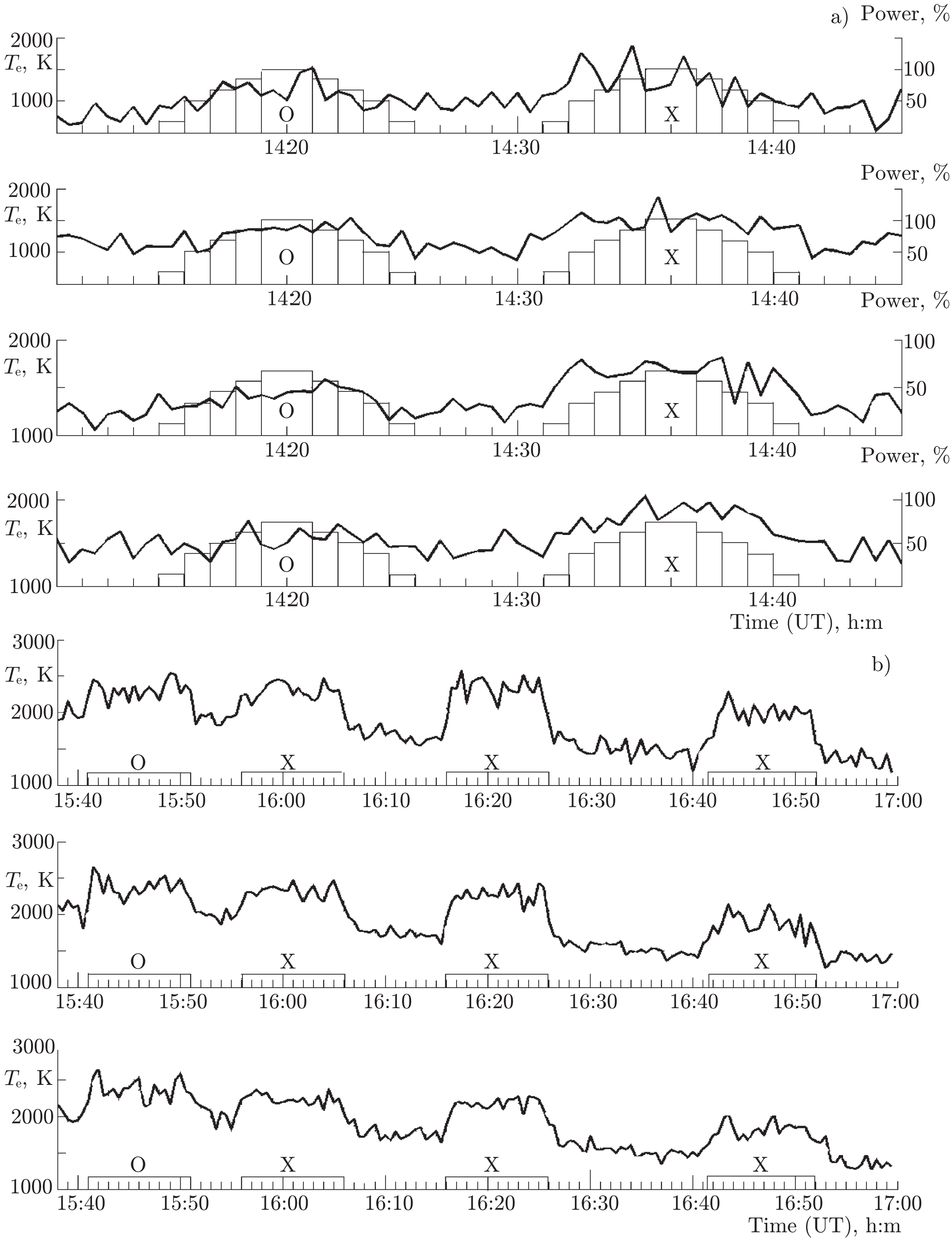

Fig. 5. Temporal variations in the electron temperature T_e at different altitudes based on the measurement data of the microwave incoherent scatter radar in Tromsø: (*a*) in November 6, 2009 between 14:01 and 14:45 UT at altitudes (from top to bottom) 186, 200, 214, and 247 km; (*b*) in March 6, 2010 between 15:38 and 17:00 UT at altitudes (from top to bottom) 214, 230, and 246 km. The heating cycles and the polarization of the HF radiation are marked on the time axis.

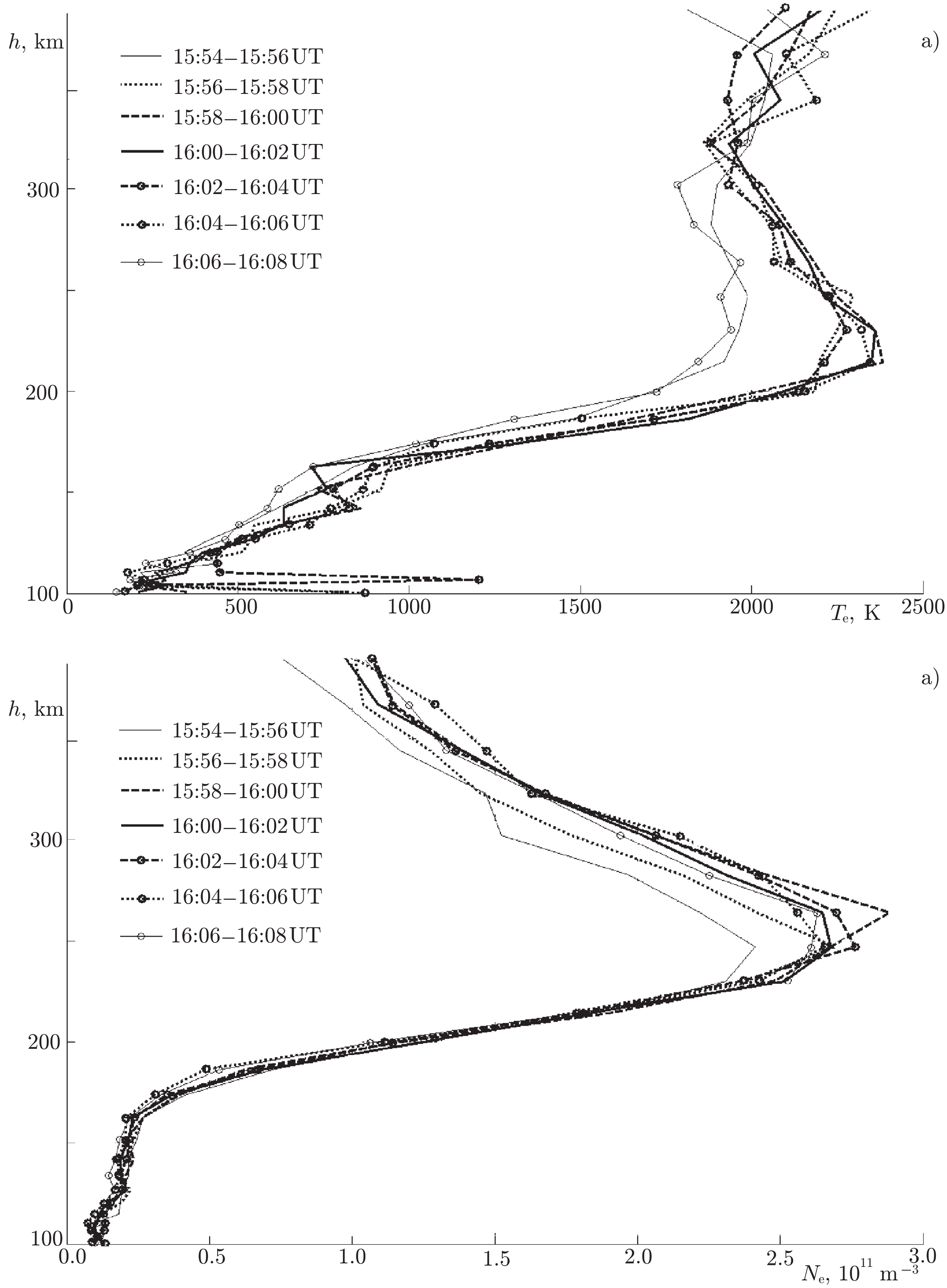

Fig. 6. Altitude profiles of the electron temperature $T_e(h)$ (*a*) and electron density $N_e(h)$ (*b*) obtained in March 6, 2010 for different temporal intervals during the heating cycle 15:56–16:06 UT, as well as 2 min before and 2 min after it, which were constructed on the basis of the Tromsø incoherent scatter data. An X-mode high-power radio wave was emitted at a frequency of 4912.8 KHz into the magnetic zenith.

namely, heating at the frequency $f_{\rm H} \approx f_{xF_2}$. Such unusually long times of rise and relaxation of small-scale artificial ionospheric irregularities probably indicate that they are closely related to superlarge-scale plasma-density disturbances having spatial scales of the order of the sizes of the artificially perturbed region.

3.2. Spatial structure of the artificially perturbed ionospheric F region

Information on the size and spatial structure of the artificially perturbed ionospheric region is extremely important and is necessary for both research and planning of heating experiments in different geophysical environments. The horizontal size of this region is roughly estimated by the main-lobe beamwidth of the antenna system of the HF heater and depends on its location height. When all 12 transmitters of the EISCAT/Heating facility are operated, an aperture of width about 12–14° is formed, depending on the frequency of the high-power HF radiation. Under the actual conditions of a high-latitude ionosphere, the size of the artificially perturbed region depends significantly on the angle of the HF pumping relative to the Earth's magnetic field. In [18, 19], according to the Tromsø incoherent scatter data, the spatial structure of the mentioned region was explored for different angles of the pump-wave radiation (in the vertical $\Theta = 90°$, magnetic-field $\Theta = 78°$, and intermediate $\Theta = 84°$ directions) in the solar maximum epoch. Successive scanning of the artificially perturbed ionospheric F region was performed in directions 84°, 90°, and 78° for each of the three angles using an incoherent scatter radar. It was found that for any direction of the pump-wave radiation, the strongest disturbances of the electron temperature $T_{\rm e}$ were observed in the magnetic-field direction in Tromsø. It is certainly of interest to study the fine structure of the artificially perturbed region by scanning it using an incoherent scatter radar not with the elevation angle 6°, as was done in [18, 19], but with a much smaller one to obtain a detailed distribution of its parameters in the horizontal direction.

In what follows we consider the results of the experiments on scanning of the artificially perturbed region by an incoherent scatter radar with a 2° elevation-angle step, which were performed in Tromsø in October–November 2009. The fine structure of the heated patch was examined both during heating of the high-latitude ionospheric F region by an O-mode high-power HF radio wave in the vertical direction ($\Theta = 90°$) and during heating in the magnetic-zenith direction when the antenna of EISCAT/Heating was inclined 12° south of the vertical line ($\Theta = 78°$). The experiments on scanning of an artificially perturbed ionospheric region were performed in October 29 and 31, as well as in November 5, 2009. The high-power HF radio wave was emitted at one of the frequencies 4912.8, 4544 or 4040-KHz in 10-min heating — 5-min pause cycles. The ratio of the heating frequency to the critical frequency of the F_2 layer $f_{\rm H}/f_{oF_2}$ was varied within the limits of 0.9–1.0. The effective radiated power amounted to 190–250 MW depending on the heating frequency. For each of the two fixed angles of propagation of a high-power HF radio wave using an incoherent scatter radar in a 10-min heating cycle, the artificially perturbed ionospheric F region was scanned successively in the directions 92° to 74° with a 2° step. The measurements were performed for each value of the elevation angle for 1 min.

As an example, Fig. 7 presents the measurement data for the ionospheric plasma parameters, namely, the electron number density $N_{\rm e}$ and the electron temperature $T_{\rm e}$, which were obtained by scanning an artificially perturbed region in the range of angles from 92° to 74° with an incoherent scatter radar in October 29 between 12:28 and 12:58 UT (Fig. 7*a*) and in October 31, 2009 between 12:12 and 12:42 UT (Fig. 7*b*). The data obtained at a fixed altitude of 200 km near the reflection height of the high-power HF radio wave at the F_2 layer are presented. In the analyzed period of time in October 29, the high-power HF radio wave had a frequency of 4912.8 KHz and was emitted between 12:30 and 12:40 UT in the vertical direction ($\Theta = 90°$) and between 12:45 and 12:55 UT in the magnetic-field direction (in magnetic zenith, $\Theta = 78°$). In October 31, the pump wave at a frequency of 4544 KHz was emitted in the vertical direction ($\Theta = 90°$) between 12:15 and 12:25 UT and then in the magnetic-zenith direction ($\Theta = 78°$) between 12:30 and 12:40 UT.

Analysis of the data presented in Fig. 7 permits one to extract the following characteristic features in the distribution of disturbances inside the artificially perturbed region when the high-power HF radio wave

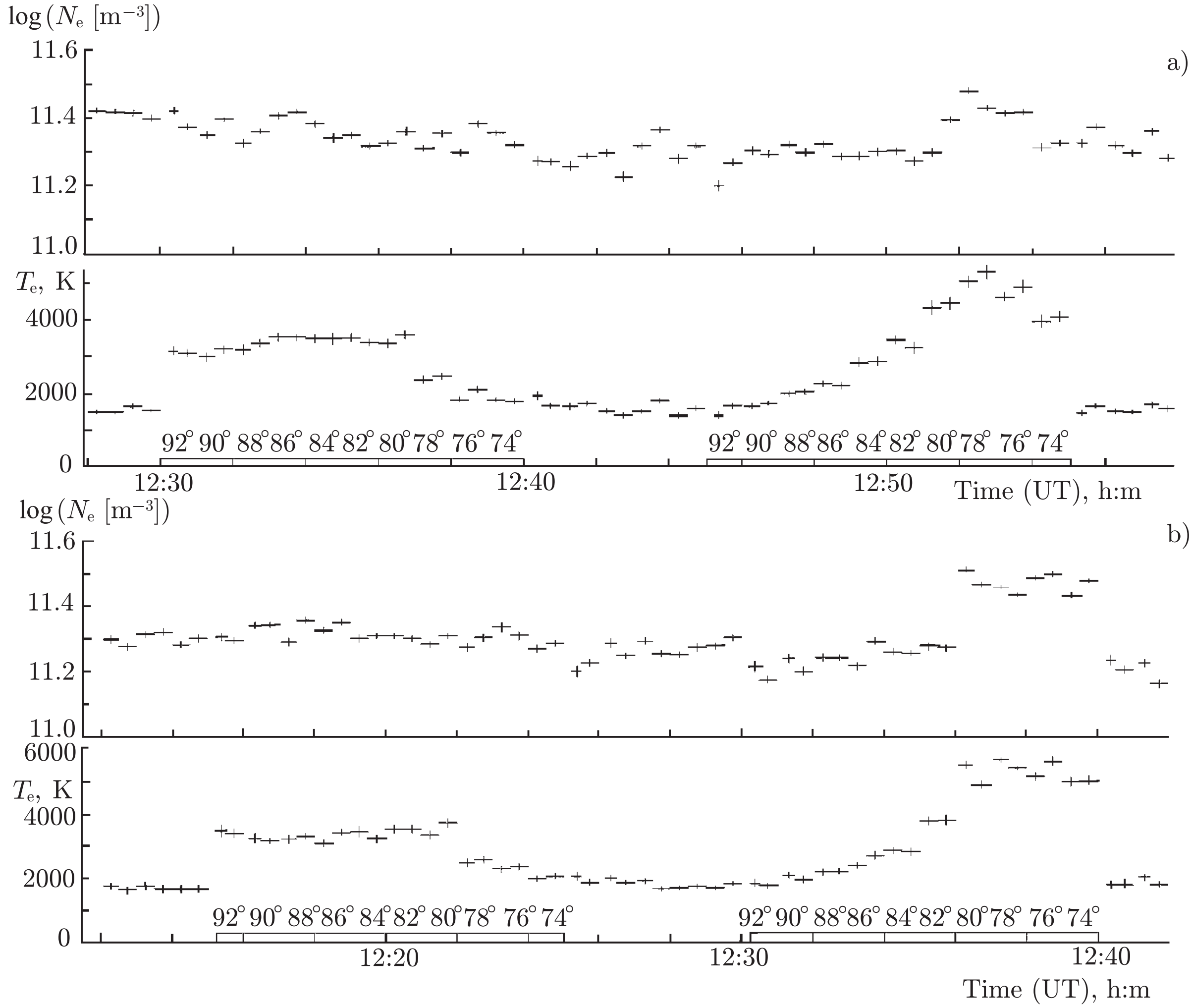

Fig. 7. Temporal variations in the electron number density N_e and electron temperature T_e at a fixed altitude of 200 km based on measurements by the microwave incoherent scatter radar in Tromsø in the regime of successive scanning of an artificially perturbed ionospheric F region in the direction from 92° to 74° with a 2° step: (*a*) in October 29, 2009 between 12:28 and 12:58 UT. The O-mode high-power HF radio wave with a frequency of 4912.8 KHz was emitted between 12:30 and 12:40 UT in the vertical direction ($\Theta = 90°$) and between 12:45 and 12:55 UT in the magnetic-field direction (in magnetic zenith, $\Theta = 78°$); (*b*) in October 31, 2009 between 12:08 and 12:38 UT. The O-mode high-power HF radio wave was emitted at a frequency of 4544 KHz in the vertical direction ($\Theta = 90°$) between 12:15 and 12:25 UT and then in the magnetic-zenith direction ($\Theta = 78°$) between 12:30 and 12:40 UT.

is emitted at angles $\Theta = 90°$ and 78°. Firstly, the maximum distrubances of T_e during the magnetic-zenith heating ($T_{e\,max} = 5400$–5700 K) are much greater compared with the vertical heating ($T_{e\,max} = 3400$–3600 K) for the same background values of T_{e0} in the pauses between the heating cycles, which are equal to about 1500–1800 K. It also follows from Fig. 7 that in the vertical heating ($\Theta = 90°$), the maximum disturbances of the electron temperature T_e (see Fig. 7*b*) are uniformly distributed over a broad range of scanning angles from 92° to 80°. When the high-power HF radio wave is magnetic-field oriented ($\Theta = 78°$), the maximum disturbances of T_e are concentrated in a sufficiently narrow range of scanning angles from 80° to 74°. Such a strong rise in T_e in a fairly narrow range of angles in the magnetic-field direction is stipulated by the magnetic-zenith effect, which is a result of the strong nonlinear process of the plasma structuring and anomalously strong electron heating. The theory of the magnetic-zenith effect was developed for a high-latitude ionosphere in [1, 23]. Analysis of the behavior of the N_e variations based on the incoherent scatter radar data (see

Fig. 7*a*) shows that when the high-power HF radio wave is magnetic-zenith oriented ($\Theta = 78°$) in a narrow range of angles from 80° to 74°, the electron number density locally increases. Under the discussed conditions, the heat-enhanced ion and plasma lines were recorded in the signal spectra obtained by the incoherent-scattering radar measurements. This indicates the excitation of a strong Langmuir turbulence. In the region of strong Langmuir turbulence, near the reflection level of a high-power HF radio wave, the electrons are accelerated to energies capable of causing an increase in the plasma ionization degree [1, 22].

Analysis of the entire volume of experimental data obtained in the solar minimum epoch under quiet magnetic conditions leads to the following conclusion on the spatial structure of the artificially perturbed ionospheric region. When the pump wave was emitted vertically upwards ($\Theta = 90°$), the maximum disturbance of the electron temperatures reached $T_{\mathrm{e\,max}} = 3200$–$4000$ K for the background values $T_{\mathrm{e}0} \approx 1200$–$1800$ K in the pauses between the heating cycles. The maximum disturbances of T_{e} are uniformly distributed inside a region of width 20°–24° (with allowance for the symmetric distribution of T_{e} with respect to the direction $\Theta = 90°$). The spatial size of the region in which the electron-temperature disturbance exceeds the background values by 50%, i.e., the region where $T_{\mathrm{e}}/T_{\mathrm{e}0} = 1.5$, reaches large values and amounts to 24°–32°. Thus, in the case of the vertical radiation of the pump wave, the actual spatial scale of the artificially perturbed region (i.e., the region where the ionospheric plasma is well heated) on the horizontal line significantly exceeds the size of the perturbed region determined by the antenna beamwidth 12°–14°.

The case is absolutely different when the high-power HF radio wave is magnetic-zenith oriented ($\Theta = 78°$). Here, the electron-temperature disturbances reached higher values of $T_{\mathrm{e\,max}} = 4100$–$5800$ K for the same background values $T_{\mathrm{e}0} = 1200$–1800 K. However, under these conditions, strong focusing of the artificially perturbed region was observed and the maximum disturbances of T_{e} were concentrated in a narrow region of width 6°–8°, which was centered with respect to the magnetic field direction. The spatial size of the artificially perturbed region, in which the electron temperature disturbance exceeds by 50% the background values, i.e., the regions where $T_{\mathrm{e}}/T_{\mathrm{e}0} = 1.5$, reached large values and was commensurable with the antenna beamwidth 12°–14° of the EISCAT/Heating facility in Tromsø.

3.3. Features of excitation of small-scale artificial ionospheric irregularities in the high-latitude ionospheric F region during heating at frequencies near the third electron gyroharmonic

It is well known that at certain frequencies f_{H} of a high-power radio wave, two resonance effects can be realized in the ionosphere simultaneously. The first one is the usual resonance between f_{H} and the upper-hybrid frequency f_{UH}. The second one is the resonance with frequency multiple of the electron gyrofrequency, $f_{\mathrm{H}} = nf_{\mathrm{ce}}$. Thus, the double resonance appears in the ionospheric regions where the condition $f_{\mathrm{H}} = nf_{\mathrm{ce}} = f_{\mathrm{UH}}$ is fulfilled. Very strong variations in characteristics of all the phenomena occurring in the upper-hybrid resonance region when the ionosphere is heated by a high-power wave take place near the double resonance, namely, the suppression of the upper-hybrid plasma turbulence generation and a decrease in the intensity of small-scale ionospheric irregularities up to their complete disappearance, total transformation of the artificial ionospheric radiation spectrum, etc. are observed [1]. The total width of the frequency range in which drastic variations in the modification effects occur amount to about 2–3% of the resonance frequency range $f_{\mathrm{H}} = nf_{\mathrm{ce}}$, i.e., 100–200 KHz [1]. It is important to mention strong dependence of the observed phenomena on the gyroharmonic number n. The studies performed to date regarding different characteristics of the plasma turbulence in a high-latitude ionosphere as functions of the frequency detuning δf with respect to the gyroresonance frequency for different harmonic numbers are incomplete. Moreover, experimental data on the behavior of small-scale artificial ionospheric irregularities of different spatial scales $l_{\perp}$ near the gyroresonance are absent.

In this section, we present the results of studying the phenomena in an artificially modified high-latitude ionospheric plasma in the double-resonance region when the heating frequency is close to the third electron gyroharmonic, i.e., $f_{\mathrm{H}} = 3f_{\mathrm{ce}} = f_{\mathrm{UH}}$. The experiments were performed in March 2009 by using a

TABLE 1. Times of passage of the heating frequency through the third gyroharmonic, the heating frequency f_{H} and the height h_{refl} of its reflection from the ionospheric F_2 layer, as well as the critical frequencies f_{oF_2} for different days of the experiments performed in March 2009.

Date	Time, UT	f_{H}, KHz	h_{refl}, km	f_{oF_2}, KHz
March 6, 2009	12:40–12:42	4100	185	4200
March 7, 2009	13:12–13:14	4100	185	4500
March 9, 2009	13:12–13:14	4100	185	4500
March 10, 2009	14:00–14:02	4100	185	4400
March 11, 2009	16:20–16:30	4040	220	4070–3900

combination of various modern diagnostic tools both located in close neighborhood of the EISCAT/Heating facility (an incoherent scatter radar, a special receiver for recording of artificial ionospheric radiation, and an ionosonde) and remote observation stations comprising a system of CUTLASS high-frequency radars and a multichannel HF Doppler facility near St. Petersburg operated in the backscattering regime. The ionospheric plasma parameters were measured by an incoherent scatter radar in the Earth's magnetic field direction. In the period of the experiments, the O-mode high-power HF radio wave was directed along the magnetic field in 2-min heating — 2-min pause cycles. The effective radiated power amounted to 190 MW. The operation regime of the HF heater ensured a stepwise variation in the heating frequency by 5–10 KHz in a frequency range of 3.9 to 4.2 MHz in each 2-min heating cycle. This yielded detailed information on the ionospheric plasma phenomena both near the gyroresonance and in the frequency range above and below the third gyroharmonic frequency where $f_{\mathrm{H}} > 3f_{\mathrm{ce}}$ and $f_{\mathrm{H}} < 3f_{\mathrm{ce}}$, respectively. Measurements using CUTLASS high-frequency radars performed simultaneously at three frequencies, 10, 13, and 17 MHz, permitted us to study the behavior of small-scale artificial ionospheric irregularities of different spatial scales $l_\perp \approx 8$, 12, and 15 m ($l_\perp = \lambda/2$, where λ is the radar wavelength).

Table 1 shows the time of passage of the heating frequency through the third harmonic of gyroresonance, the heating frequency and the heights of its reflection from the ionospheric F_2 layer, as well as the critical frequencies for different days of the experiments performed in March 2009. The times of passage of the heating frequency through the gyroresonance were identified by the disappearance of the so-called DM (down-shifted maximum) component in the spectrum of stimulated electromagnetic emission [24], following the procedure given in [25]. The characteristics of the stimulated electromagnetic emission were controlled in close neighborhood of the EISCAT/Heating facility.

As a typical example, we consider the behavior of the ionospheric-plasma parameters during heating near the third gyroharmonic frequency in March 9, 2009. Figure 8 shows variations in the heating frequency and the electron temperature T_{e} based on the incoherent scatter data for the magnetic-field oriented radio waves and the power of signals scattered by small-scale artificial ionospheric irregularities at frequencies 10, 13, and 17 MHz based on the measurement data obtained by the CUTLASS radar in Hankasalmi (FInland) during the experiment performed in March 9, 2009 between 13:02 and 14:03 UT. The times of emission of high-power HF radio waves are marked on the time axis by square brackets. The spectra of artificial ionospheric radiation and the simultaneous vertical-sounding ionograms obtained in Tromsø for the same experiment in March 9, 2009 are presented in Fig. 9.

We note that for the above-considered cases of gyroresonance at heating frequencies exceeding the third harmonic of the gyroresonance frequency where $f_{\mathrm{H}} > 3f_{\mathrm{ce}}$ at 20–40 KHz, the spectrum of artificial ionospheric radiation showed the excitation of the 2DM component, which was accompanied by the enhancement of small-scale artificial ionospheric irregularities and a rise in the disturbed electron temperature $\mathrm{T_e}$. The intensity of the mentioned irregularities and the disturbance of T_{e} reached the maximum values at frequencies by 50–70 KHz higher than $3f_{\mathrm{ce}}$, at which the spectrum of stimulated electromagnetic emis-

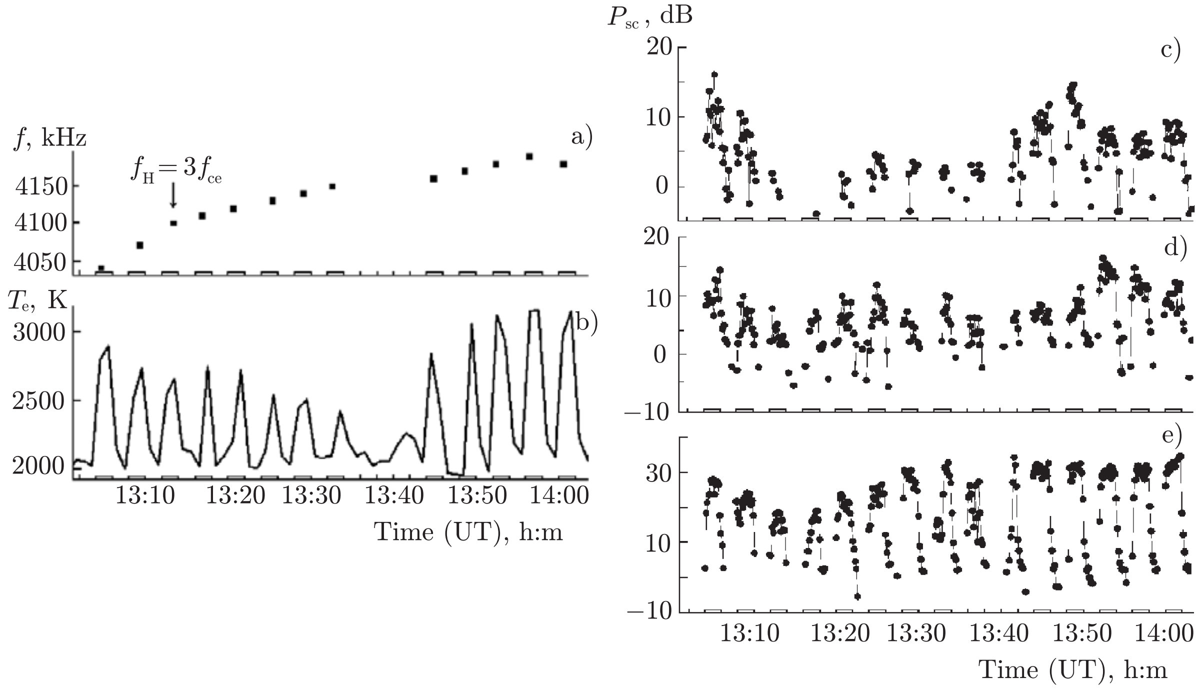

Fig. 8. Variations in the heating frequencies (*a*), the electron temperature T_e (*b*) (according to the incoherent scatter data), and the power of signals scattered by small-scale artificial ionospheric irregularities at frequencies of about 10 MHz (gate No. 18), 13 MHz (gate No. 17), and 17 MHz (gate No. 16) (*c*, *d*, and *e*) according to the measurement data obtained by the CUTLASS coherent HF radar (ray 5) in Hankasalmi (Finland) during the experiment performed in March 9, 2009 between 13:02 and 14:03 UT. The O-mode high-power HF wave was directed into the magnetic zenith in 2-min heating — 2-min pause cycles. The heating cycles are marked on the time axis by square brackets. In the 13:36–13:38 UT cycle, the heating was not performed, and in the 13:32–13:34 and 13:40–13:42 UT cycles, the tuning time did not exceed 1 min.

sion showed the excitation of the broad symmetrical structure. An interesting feature was detected in the behavior of small-scale artificial ionospheric irregularities of different scales in the gyroresonance vicinity. According to the CUTLASS radar measurements at three frequencies, it was found that the mentioned irregularities with transverse scales near 15 and 12 m are suppressed much stronger than those with smaller scales of about 8 m. Note that the disturbances of the electron temperature T_e at the gyroresonance decreased only slightly (by 200–300 K) compared with the T_e disturbances in the neighboring heating cycles. The performed multi-instrument experiments permitted us to detect and examine in detail the ionospheric plasma phenomena initiated by the high-power HF radio wave under conditions when the heating frequency is close not only to the third harmonic of the electron gyroresonance frequency, but, simultaneously, to the critical frequency of the F_2 layer, i.e., when $f_H = f_{UH} = 3f_{ce} = f_{oF_2}$. Such conditions were realized in the experiment of March 11, 2009 in the heating cycle of 16:20 to 16:30 UT.

Figure 10 shows the altitude profiles of the electron temperature $T_e(h)$ and the electron number density $N_e(h)$, which were plotted on the basis of the incoherent scatter data in March 11, 2009 for different time intervals within the limits of the 16:20–16:30 UT heating cycle, as well as for the time intervals before and after the heating. Analysis of the data presented in Fig. 10 shows that under the above-mentioned specific conditions of the experiment when $f_H = f_{UH} = 3f_{ce} = f_{oF_2}$, an extremely strong (up to 4500 K) rise in the electron temperature was observed in a broad range of altitudes throughout the entire 10-min heating cycle. The electron number density in the magnetic-field direction according to the incoherent scatter data increased drastically (up to 35%) in the first 6–7 min of the heating cycle and then it decreased gradually. This process continued after the 10-min heating cycle due to the background decrease in the electron number density in the evening hours. It is interesting to mention that according to the incoherent scatter data, the

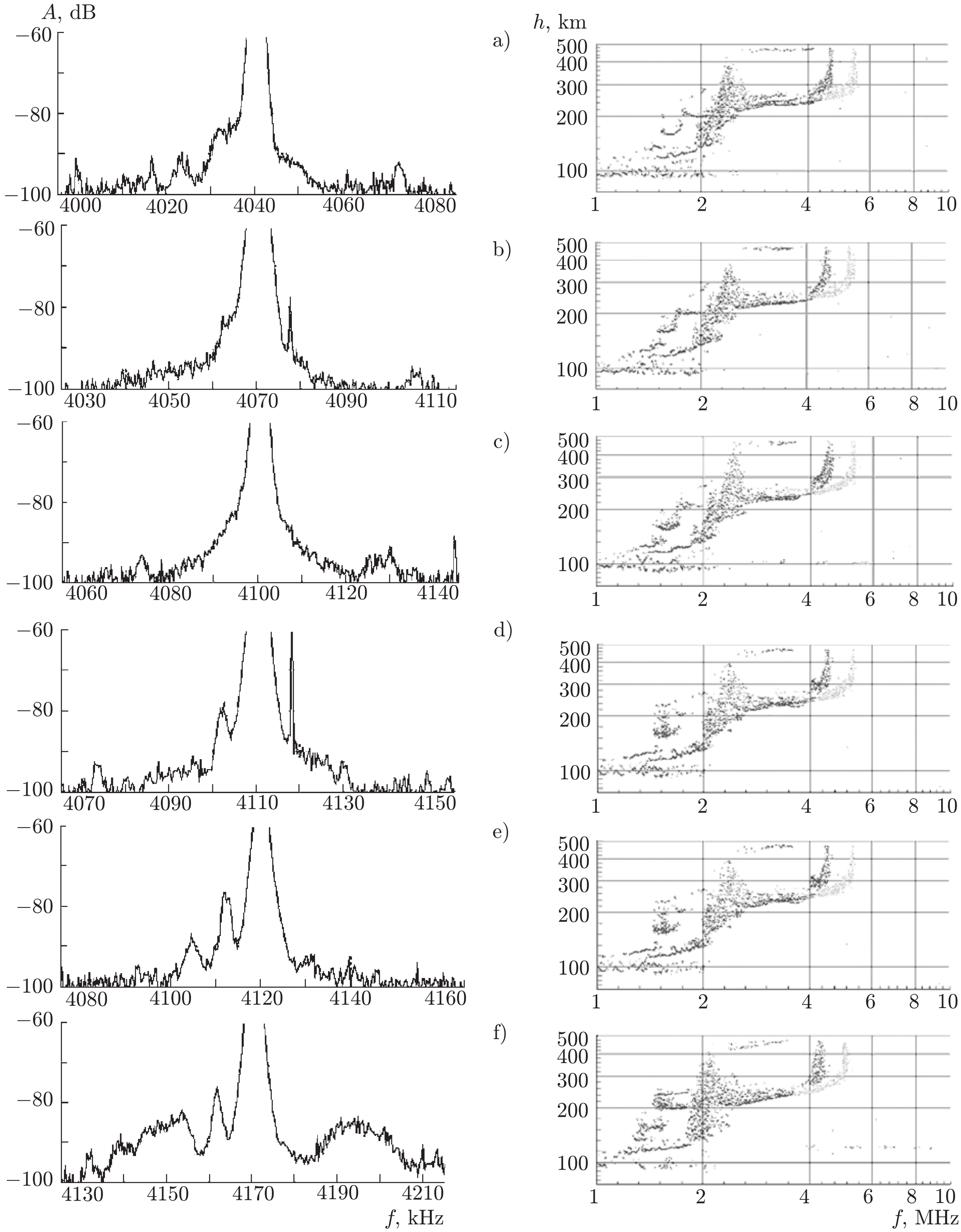

Fig. 9. Spectra of stimulated ionospheric emission and simultaneous vertical-sounding ionograms obtained in Tromsø in March 9, 2009 with a stepwise variation in the heating frequency: (*a*) heating frequency 4040 KHz, 13:04 UT, (*b*) 4070 KHz, 13:08 UT, (*c*) 4100 KHz, 13:12 UT, (*d*) 4110 KHz, 13:16 UT, (*e*) 4120 KHz, 13:20 UT, and (*f*) 4170 KHz, 13:48 UT.

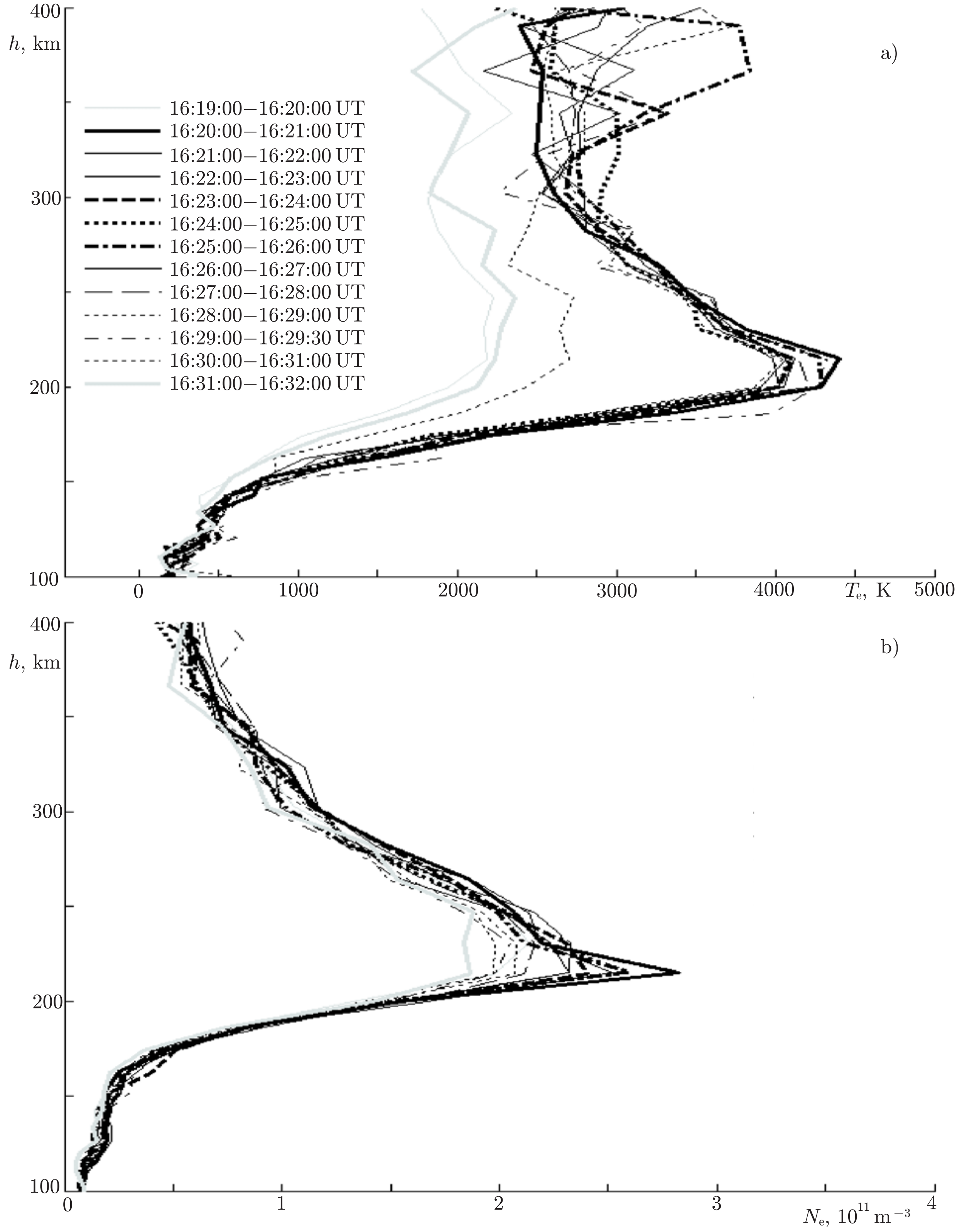

Fig. 10. Altitude profiles of the electron temperature $T_e(h)$ (*a*) and the electron number density $N_e(h)$ (*b*) obtained in March 11, 2009 for different time intervals during the 16:20–16:30 UT heating cycle, as well as 1 min before and 2 min after the heating, which were plotted on the basis of the Tromsø incoherent scatter data. The O-mode high-power HF wave was emitted at a frequency of 4040 KHz into the magnetic zenith.

heat-enhanced ion lines were recorded in the considered heating cycle in the scattered-signal spectra, which is direct evidence for the excitation of a strong Langmuir turbulence. Under these conditions, such a strong rise in the electron number density can be stipulated by the generation of a flux of accelerated electrons in the region of strong Langmuir turbulence near the reflection level of a high-power HF radio wave, as was observed in [22].

4. CONCLUSIONS

On the basis of the multi-instrument experiments on modification of the high-latitude ionosphere by a high-power HF radio wave, which were performed in March, October–November 2009, and March 2010 in the deep solar minimum epoch under quiet magnetic conditions using the EISCAT technical facilities, the following main results have been obtained.

The excitation of strong small-scale artificial field-aligned irregularities in the ionospheric F region during propagation of an X-mode high-power HF radio wave in the Earth's magnetic field direction at heating frequencies near the critical frequency of the X mode, i.e., when $f_{\rm H} \approx f_{xF_2}$, was detected for the first time. The mentioned irregularities appear in 1–3 min and reach the maximum intensity in 2–6 min after the heating is started. A characteristic feature of the small-scale artificial ionospheric irregularities excited when the ionosphere is heated by an X-mode high power HF radio wave is that the relaxation time is unusually long and amounts to 30 min. Such unusually long times of rise and relaxation of the mentioned irregularities probably indicate that they are closely related to superlarge-scale plasma-density disturbances with spatial scales of the order of the sizes of the artificially excited region. The excitation of small-scale artificial ionospheric irregularities was accompanieed by an increase in the electron temperature (Joule heating). The disturbances of $T_{\rm e}$ during the X-mode heating were higher than those in the case of the O-mode polarization and reached 50% of the unperturbed level of $T_{\rm e}$ immediately before the heating cycle was started. The mechanism of excitation of small-scale artificial ionospheric irregularities during the X-mode heating is unclear and requires thorough examination, both experimental and theoretical. However, it can already be mentioned that the excitation of such irregularities requires special conditions of heating, namely, heating at a frequency in the vicinity of f_{xF_2}.

The spatial structure of the electron-temperature disturbances in an artificially perturbed ionospheric region has been explored. It is shown that the sizes of this region significantly depend on the angle of the HF pumping relative to the Earth's magnetic field. When the pump wave is emitted vertically upwards ($\Theta = 90°$), the maximum disturbances of the electron temperature $T_{\rm e\,max} = 3200$–4000 K are uniformly distributed inside a region of width 20°–24°. The spatial size of the region with electron-density disturbances exceeding the background values by 50%, i.e., the region where $T_{\rm e}/T_{\rm e0} = 1.5$, reaches large sizes and amounts to 24°–32°, which significantly exceeds the size determined by the antenna beamwidth 12°–14°. When the high-power HF radio wave is magnetic-zenith oriented ($\Theta = 78°$), the electron-temperature disturbances reached higher values, namely, $T_{\rm e\,max} = 4100$–5800 K. However, under these conditions, the maximum disturbances of $T_{\rm e}$ concentrate in a narrow region of width 6°–8° centered with respect to the magnetic field direction in Tromsø. The spatial size of the artificially perturbed region, in which the electron-temperature disturbances exceed the background values by 50% reaches large sizes and is commensurable with the antenna beamwidth 12°–14° of the EISCAT/Heating facility in Tromsø.

The phenomena occurring in the artificially modified ionospheric F region heated at frequencies near the third harmonic of the electron gyrofrequency, i.e., where $f_{\rm H} = 3f_{\rm ce} = f_{\rm UH}$, have been considered. The multi-instrument measurements showed that 1) small-scale artificial ionospheric irregularities of larger transverse scales, $l_\perp \approx 15$ and 12 m, are suppressed in the gyroresonance much stronger than the irregularities of smaller scales, $l_\perp \approx 8$ m; 2) near the gyroresonance, the electron temperature $T_{\rm e}$ decreases slightly, by 200–300 K; 3) at heating frequencies exceeding the third harmonic of the electron gyrofrequency by 20–40 KHz, the excitation of the 2DM component, accompanied by the enhancement of small-scale artificial ionospheric irregularities and the $T_{\rm e}$ increase, was observed in the spectrum of stimulated electromagnetic emission; 4) in the range of heating frequencies exceeding the third harmonic of the electron gyrofrequency by 50–70 KHz, the generation of the BSS (broad symmetrical structure) component was recorded in the spectrum of stimulated electromagnetic emission, and the intensity of small-scale artificial ionospheric irregularities and electron-temperature disturbances reached the maximum; 5) under specific conditions when the heating is performed at frequencies close not only to the third harmonic of the electron gyrofrequency, but, simultaneouly, the critical frequency of the F_2 layer, i.e., when $f_{\rm H} = f_{\rm UH} = 3f_{\rm ce} = f_{oF_2}$, an extremely strong (up to 4500 K) rise in the electron temperature in a broad range of altitudes, accompanied by a drastic (up to 35%) local increase in the electron number density along the magnetic-field direction, was observed.

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