Solar-Terrestrial Physics. 2025, vol. 11, iss. 3, pp. 80–90. DOI: 10.12737/stp-113202510. © 2025
N.V. Bakhmetieva, G.I. Grigoriev, I.N. Zhemyakov, E.E. Kalinina, A.A. Lisov. Published by INFRA-M Academic Publishing House

DOI: 10.12737/stp-113202510

Received March 21, 2025
Accepted June 18, 2025

IONOSPHERE RESPONSE TO THE IMPACT OF AN EXTRAORDINARY RADIO WAVE WHEN LOCATED AT A FREQUENCY CLOSE TO THE HEATING FREQUENCY

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Abstract. The paper presents the results of experiments on the impact of powerful high-frequency radio emission from the SURA mid-latitude heating facility (56.1° N, 46.1° E) on Earth's ionosphere. The disturbance in the ionosphere was created by a radio wave of extraordinary polarization under conditions when the ordinary component of the powerful wave was not reflected by the ionosphere. The probing of the disturbed region was carried out with a probe radio wave of the same polarization at a frequency higher than the heating frequency by 228–400 kHz. During the impact on the ionosphere, a weak scattered signal with an amplitude 40–60 dB lower than the amplitude of the specular reflection signal from the F-region was received from the height of reflection of the powerful radio wave. This means that the artificial disturbance of the plasma density occurred in the region of reflection of the powerful radio wave of extraordinary polarization. Possible causes of the disturbance are discussed.

Keywords: ionosphere, plasma, high-frequency heating, sounding with a probe radio wave, artificial periodic irregularities, SURA heating facility.

INTRODUCTION

Studies of the ionosphere exposed to powerful HF radio emission from heating facilities, which began in the 1960s, have revealed many phenomena both theoretically predicted and justified, and somewhat unexpected. Extensive literature is devoted to the results of these studies, including monographs and tens of hundreds of scientific publications. Among them are monographs [Gurevich, Schwarzburg, 1973; Mityakov et al., 1989; Blagoveshchenskaya, 2001; Frolov, 2017; Kelley, 2009], reviews [Ginzburg, Gurevich, 1960; Utlaut, Cohen, 1971; Stubbe, Hagfors, 1997; Leyser, 2001; Gurevich, 2007; Gurevich, 1999; Grach et al., 2016; Streltsov et al., 2018; Belikovich et al., 2007; Frolov et al., 2007; Blagoveshchenskaya, 2010, 2020; Blagoveshchenskaya et al., 2020, 2022; Kuo, 2021], which provide extensive references to theoretical and experimental studies on artificial ionospheric disturbance by powerful radio emission. A wide range of phenomena was investigated in experiments with the heating facilities Arecibo, HAARP, EISCAT, Zimenki, and SURA on the impact of powerful radio waves of ordinary polarization on the ionosphere. One of them was the occurrence of artificial turbulence in ionospheric plasma due to the development of plasma instabilities of various types near the upper hybrid resonance, i.e. the height of the resonant interaction between the high-power wave field and ionospheric electrons [Gurevich, 2007; Vas'kov, Gurevich, 1973, 1975a, b, 1979]. A detailed review of the results of numerous experiments on the impact of powerful radio emission on the ionosphere is given in the monograph [Frolov, 2017], in [Streltsov et al., 2018; Rietveld et al., 1993, 2016; Blagoveshchenskaya, 2020; Kuo, 2021]. An important condition for enhancing the heating effects was emission of a powerful radio wave by transmitters of the facility toward the magnetic zenith [Gurevich et al., 2002; Pedersen et al., 2003].

For a long time, ionospheric disturbances during radio heating were associated with a complex of nonlinear processes developing in the field of a powerful ordinary wave and causing the formation of a developed structure of plasma inhomogeneities strongly elongated along the geomagnetic field. Radio waves of extraordinary polarization were emitted to study the ionosphere and the neutral atmosphere by the method of creating artificial periodic inhomogeneities (APIs) of ionospheric plasma, first implemented at the Zimenki heating facility and subsequently developed at the SURA facility [Belikovich et al., 1975, 1999; Belikovich et al., 2002; Bakhmetieva, Grigoriev, 2022]. The monograph [Frolov, 2017] describes in detail and discusses the results of experiments on ionospheric disturbance by an extraordinary radio wave, during which it was found that small-scale inhomogeneities with a scale transverse to the geomagnetic field $l_{\perp}\approx$10–20 m were not excited; decameter small-scale inhomogeneities with 50–200 m transverse scale and medium-scale ones with $l_{\perp}\approx$3 km were excited only in the evening and at night, whereas large-scale inhomogeneities with $l_{\perp}\approx$10–20 km or larger were excited during the same hours, provided that the heating frequency was close to the F-layer critical frequency for the extraordinary wave [Frolov et al., 2014; Frolov, 2015]. The best result was achieved by emitting a powerful radio wave in the direction of the magnetic zenith.

A large amount of research on nonlinear phenomena in plasma disturbed by a powerful radio wave of extraordinary polarization has been carried out by an international team at the EISCAT high-latitude heating facility [Blagoveshchenskaya et al., 2018; Blagoveshchenskaya et al., 2020; Blagoveshchenskaya et al., 2019, 2020, 2022; Kalishin et al., 2021; Borisova et al., 2023]. These experiments have shown that in the quiet high-latitude ionosphere the powerful radio wave of extraordinary polarization, emitted in the direction of the magnetic zenith, can affect the F-region of the ionosphere more effectively and cause a stronger disturbance of ionospheric plasma than the radio wave of ordinary polarization.

Based on the experience we have gained due to many years of research of the ionosphere by the method of resonant scattering of radio waves by APIs, a new cycle of experiments was launched at the SURA mid-latitude facility in 2006 to explore the disturbed region of the ionosphere formed during the impact of powerful radio waves of extraordinary polarization on the ionosphere. Sounding of the disturbed region with probe radio waves of the same polarization at a frequency close to the heating frequency was carried out at a partial reflection facility. Probe radio waves from the region disturbed by the radio wave of extraordinary polarization were scattered irregularly, under certain conditions. The purpose of this paper is to discuss the results of these experiments.

1. CREATING AN ARTIFICIAL DISTURBANCE IN THE IONOSPHERE AND ITS DETECTION BY PROBE RADIO WAVES

The measurements were made on October 10–11, 2006, September 1–2 and October 8, 2014, May 18, 2016, and September 24–25, 2024 in the evening hours, sometimes under conditions of strong F-layer diffusivity. In the text, we use Moscow Time (MSK) at which the SURA heating facility and the diagnostic complex operate, indicating Universal Time Coordinated (UTC) in parentheses.

October 10–11, 2006

The experiment was conducted from 19:00 to 22:00 MSK (UTC+4). The ionosphere was affected in phase by three transmitters with radiated power P_1=210 kW, P_2=220 kW, and P_3=190 kW at a frequency of 4.3 MHz. A powerful radio wave of extraordinary polarization was emitted to the zenith.

The disturbed region was also detected by an extraordinary radio wave at a frequency f_{probe}=4.7 MHz (i.e. higher than the heating frequency by 400 kHz) with the transmitter Poisk of the partial reflection facility. In the ionospheric heating mode, SURA continuously emitted powerful radio waves for 30 s with a 60-s pause. The experiment was carried out under conditions when the F2-layer critical frequency f_oF2 was lower than the heating frequency and ordinary waves were not reflected by the ionosphere. Ionospheric conditions were monitored by the ionosonde Basis. During the experiment, natural F-spread occurred in which specular wave reflection from the F layer became blurred [Brunelli, Namgaladze, 1988]. During heating and the pause in operation of the facility, impulse sounding of the perturbed region of the ionosphere was performed. To record characteristics of amplitudes and phases of signals reflected and scattered by the ionosphere, we employed dedicated equipment designed for studying the ionosphere by the partial reflection technique, which is also used to explore the ionosphere and the neutral atmosphere by the API method [Belikovich et al., 2003]. The transmitter of the partial reflection facility radiated linearly polarized radio waves to the zenith in a pulsed mode with a pulse length of 25 (50) μs and a repetition frequency of 25 (50) Hz. The transceiver antenna system of the facility has 12 vibrators for each of the two mutually orthogonal polarizations. When received, a wave corresponding to the extraordinary component was generally identified. The received signals were amplified by a receiver with a 40 (80) kHz band, and their quadrature components were recorded digitally in increments 0.7–1.4 km in the virtual altitude range 0–700 km. The experiment has shown that, when an extraordinary radio wave had an impact on the ionosphere, a weak scattered signal appeared in the virtual altitude range 30–40 km below the specularly reflected signal, which disappeared after the end of heating.

September 1–2, 2014

The experiment took place from 21:25 to 07:10 MSK (UTC+4). The ionosphere was heated by two transmitters with P_1=150 kW and P_2=160 kW at a frequency f_{heat}=4.3 MHz. Probe waves were emitted, as in 2006, at a frequency f_{probe}=4.7 MHz. After 00:16 MSK, the ordinary component of a probe wave stopped reflecting from the ionosphere. In general, the conditions of the 2006 experiment were met, yet without F-spread. Scattered signals during the impact on the ionosphere were not recorded. After 02:45 MSK, the heating wave stopped reflecting from the ionosphere.

October 8, 2014

The experiment was carried out from 22:30 to 24:00 MSK (UTC+4). Three transmitters with P_1=170 kW, P_2=150 kW, and P_3=150 kW at f_{heat}=4.3 MHz were used for heating. The probe wave diagnostic transmitter and the frequency of probe radio waves were the same as in September 2014. Scattered signals during the impact on the ionosphere were not recorded.

May 18, 2016

The experiment was conducted from 18:25 to 20:00 MSK (UTC+3). Heating was performed at a frequency of 5.750 MHz by two transmitters with P_1=200 kW and P_2=120 kW, the frequency of probe waves was changed from 5.600 to 5.900 MHz. By the end of the work, the F-layer critical frequency (x component) had decreased to 5.5 MHz, i.e. during this experiment, ionospheric sounding with the partial reflection facility was sometimes performed at a frequency lower than the heating frequency. Scattered signals during the impact on the ionosphere were not recorded.

September 24–25, 2024

The experiment was performed from 21:30 to 23:15 MSK (UTC+3) on September 24 and from 05:30 to 07:15 MSK (UTC+3) on September 25. The ionosphere was continuously heated by two SURA transmitters with P_1=220 kW and P_2=200 kW at a frequency of 5.227 MHz. Probe radio waves at a frequency of 5.455 MHz, i.e. higher than the heating frequency by 228 kHz, were emitted by the third transmitter with P_3=170 kW with a pulse length of 50 µs and a repetition frequency of 50 Hz.

To receive and record all the reflected and scattered ionospheric signals, an antenna system of the partial reflection facility and a receiving complex based on a 14-bit board (National Instruments) were exploited. The reception bandwidth was 850 kHz.

2. IONOSPHERE RESPONSE TO THE IMPACT OF A POWERFUL RADIO WAVE

Here are the main results of each measurement cycle.

2.1. Scattered signal characteristics on October 10–11, 2006

As mentioned above, during the impact of an extraordinary wave on the ionosphere, a weak scattered signal appeared at virtual altitudes, mainly 30–40 km below the height of the specular reflection of the signal from the F-region. The scattered signal was recorded from 19:40 to 21:00 MSK on October 10, 2006 and from 20:45 to 21:57 MSK on October 11, 2006. The effect was so pronounced that the appearance and development of the scattered signal during heating of the ionosphere were observed in real time without additional processing. Figure 1 gives a fragment of real-time recording of the amplitude of the signal, which appeared during the impact on the ionosphere, in virtual altitude —time coordinates. The amplitude of the scattered signal was by 40–50 dB lower than the amplitude of the specular reflection of the probe radio wave from the ionospheric F layer and changed rapidly with altitude and time. The signal developed for ~1 s, and the relaxation time was about a fraction of a second. The signal was noise-like: the correlation time interval did not exceed 0.2 s.

Above 340–350 km, there are diffuse specular reflections of the probe wave from the F-region. At ~105 km, the sporadic E (E_s) layer is observed with f_oE_s=2.5–3.1 MHz. The corresponding ionograms obtained by the ionosonde Basis are presented in Figure 2. Under these conditions, an ordinary radio wave with a frequency of 4.3 MHz was not reflected from the ionosphere.

Figure 3 displays amplitudes of scattered and specularly reflected signals for a series of heatings after 21:30 MSK in the same coordinates. Above 310 km, there is a diffuse specular signal at the probe wave frequency. In Figure 3, above 270 km under the altitude of the specular reflection of the probe wave (~310–320 km), there is a 4.7 MHz scattered signal, whose development correlates with the moments when the heating is switched on. In the middle of the fifth heating session after 21.71 MSK (the time is given in fractions of an hour), the power emitted by transmitters of the heating facility decreased. The amplitude of the scattered signal is seen to noticeably decrease as well, which means that it directly depends on the heating power. By the end of the seventh heating session after 21.75 MSK, the receiving voltage was turned down (20 dB attenuation was manually turned on in the receiver), which caused the amplitude of the received signal to decrease. The sporadic E layer was observed at an altitude 100–105 km during the entire measurement period.

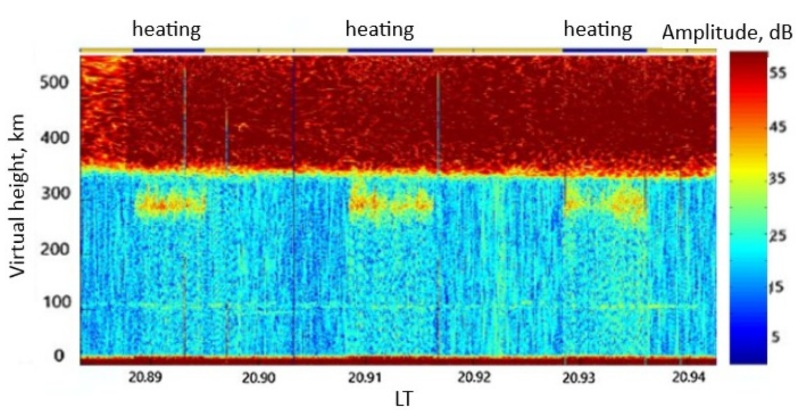

Figure 1. Fragment of real-time recording of the amplitude of a signal that appeared during the impact on the ionosphere in three heating sessions. Separate white or black vertical lines indicate incorrect scans due to failures in receiving equipment. Heating intervals are marked with dark stripes at the top. Time is given in fractions of an hour

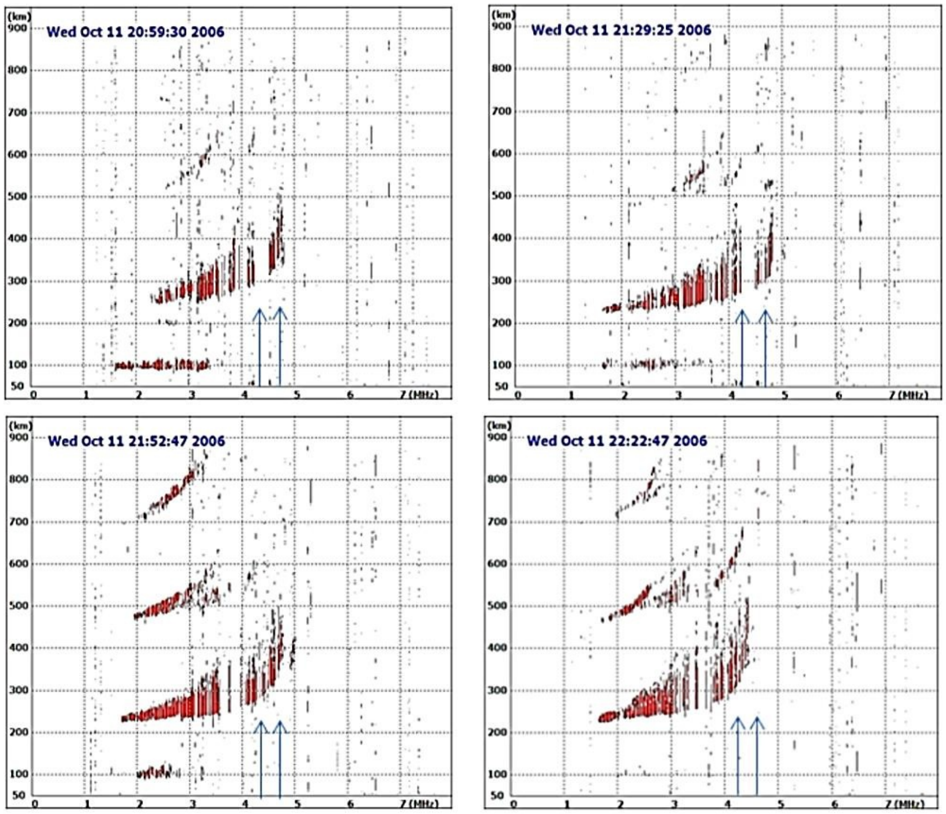

Figure 2. Ionograms obtained by the ionosonde Basis on October 11, 2006 during the experiment. Time on the ionograms is in MSK (UTC+4). Arrows indicate frequencies of heating and probe radio waves. Intense F-spread is seen to occur during the experiment

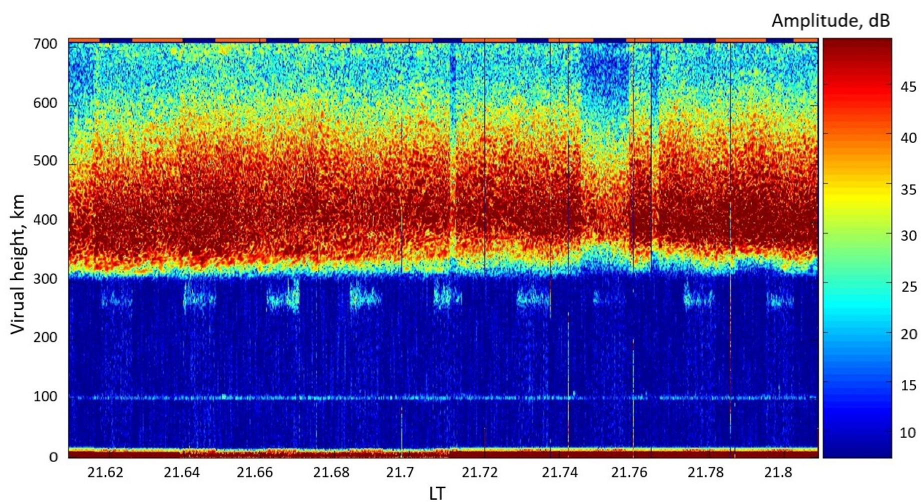

Figure 3. Fragment of real-time recording of the amplitude of a signal, which appeared during the impact on the ionosphere, for nine heating sessions after 21:30 MSK. Heating intervals are indicated by dark stripes at the top

From the analysis of the altitude electron density profiles recovered from vertical sounding ionograms it follows that the 4.7 MHz probe radio wave was reflected at altitudes close to that of reflection of the 4.3 MHz heating wave. Recall that here we are dealing with extraordinary components of heating and probe radio waves.

During heating, the F-layer diffusivity changed and hence the specular signal reflected from the F layer acquired a finer height and time structure. This is clearly seen in Figure 4, which illustrates the development of a scattered signal in the session starting at 20:55:03 MSK (h:min:s). It follows from Figures 3 and 4 that the amplitude of the scattered signal changed irregularly with height and time. Within each individual heating session, scattered signals occupied a virtual altitude range from 20 to 100 km. There are 5–10 s quasiperiodic amplitude changes.

The receiving part of the partial reflection facility was designed in such a way that the ordinary and extraordinary probe wave modes could be received alternately (every other sounding pulse). Note that there was no scattered signal in the ordinary component. This is illustrated in Figure 5 which presents the result of alternating (every other sounding pulse) reception of both probe wave components during the session at 21:21:54 MSK.

The scattered signal is clearly seen to appear during heating only in the extraordinary probe wave (Figure 5, *a*), and it was absent in the ordinary one (Figure 5, *b*). Since at that time the 4.7 MHz ordinary wave was not reflected by the ionosphere (the F-layer critical frequency was lower than the probe wave frequency), the signal above 320 km in Figure 5, *b* is a probe wave signal of extraordinary polarization, attenuated due to insufficient decoupling of the magnetoionic components in the reception path of the partial reflection facility.

Notice that the results of the October 10–11, 2006 experiment were not published or reported at conferences in due course. The authors were faced with the problem of repeating the experiment, re-obtaining the observed effect, and uncovering the reason for the appearance of a scattered signal when the ionosphere is heated by a radio wave of extraordinary polarization and the disturbed region is sounded with a probe radio wave of the same polarization, but at a frequency several hundred kilohertz higher than the heating frequency. Several such experiments were carried out later, and their results are presented below. As far as we know, such experiments have not been conducted before.

2.2. Results of the 2014 and 2016 experiments

September 1–2, 2014 (evening, night, morning)

After 0:16 MSK, the ordinary component of the probe wave stopped reflecting from the ionosphere and the conditions of the 2006 experiment were met, but no F-spread was observed. Scattered signals similar to those recorded in 2006 were not observed either. Probably, the transmitter power (two transmitters of 150 and 160 kW worked) turned out to be insufficient. After 02:45 MSK, the heating wave stopped reflecting from the ionosphere.

October 8, 2014

Under seemingly suitable experimental conditions, there were no scattered signals during heating. The heating was performed by three transmitters of 170, 150, and 150 kW with natural diffusivity of the F layer without intense F-spread. Figure 6 shows the amplitude of the specular reflection of the extraordinary component of the 4.7 MHz probe wave. The wave of ordinary polarization was not reflected by the ionosphere.

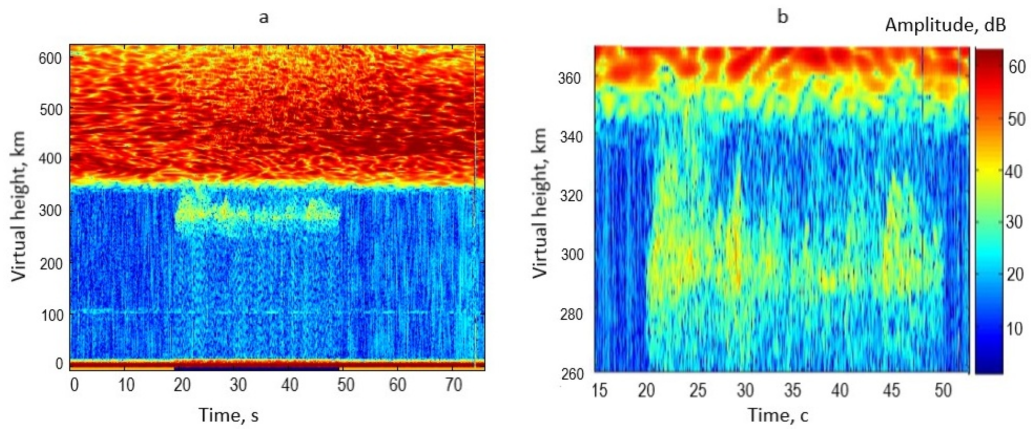

Figure 4. Development of a scattered signal in the heating session starting at 20:55:03 MSK: in a virtual altitude range 0–700 km (*a*); in a narrower altitude range 260–360 km (*b*)

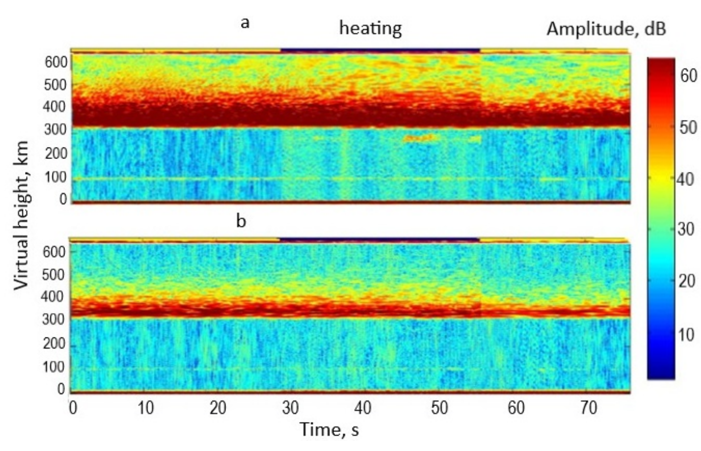

Figure 5. Example of recording of a scattered signal of extraordinary (*a*) and ordinary (*b*) polarization of a probe wave in the session at 21:21:54 MSK (h:min:s)

May 18, 2016

Two transmitters with P_1=200 kW and P_2=120 kW at a frequency of 5.750 MHz operated for heating, probe waves were transmitted in the range 5.6–5.9 MHz. At the beginning of observations, the probe wave frequency was lower than the heating wave frequency, then it was increased, and the difference between them was 150 kHz. A result similar to that presented in Figure 6 for October 8, 2014 was obtained, i.e. scattered signals were not recorded during heating.

2.3. Characteristics of the scattered signal on September 24–25, 2024

As noted above, in the next experiment in September 2024 ionospheric signals were received by the antenna system of the partial reflection facility, and a probe signal was emitted by one of the three transmitters of the SURA heating facility. The signals were recorded digitally, using a 14-bit NI board with a vertical data sampling step of 150 m. The difference between the heating frequency f_{heat}=5.227 MHz and the probe frequency f_{probe}=5.455 MHz of radio waves was 228 kHz. Due to the fact that the receiver's bandwidth was wider, during subsequent processing the received signals were filtered by a sixth-order Bessel filter with a 40 kHz bandwidth, which made it possible to almost completely eliminate the heating frequency signal from the data. The work schedule was designed to include dusk (night) hours in conditions of diffuse ionospheric F layer and early dawn hours in conditions of more regular ionosphere. Figure 7 displays fragments of recording of ionospheric signals during 30 s heating and 60 s pause in operation of the heating transmitters.

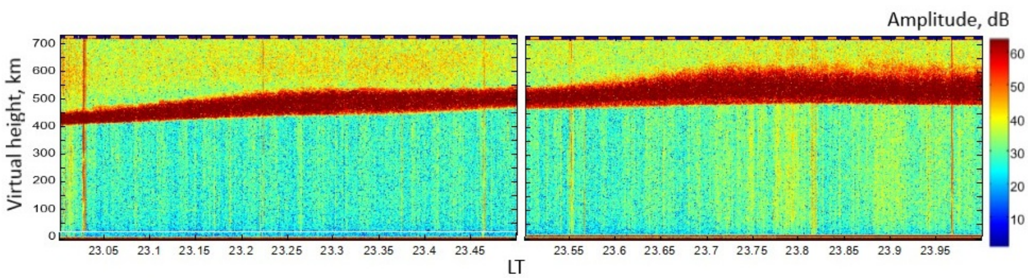

Figure 6. Specular reflection of a probe wave from the F layer on October 8, 2014, heating intervals are marked with light stripes on the top axis

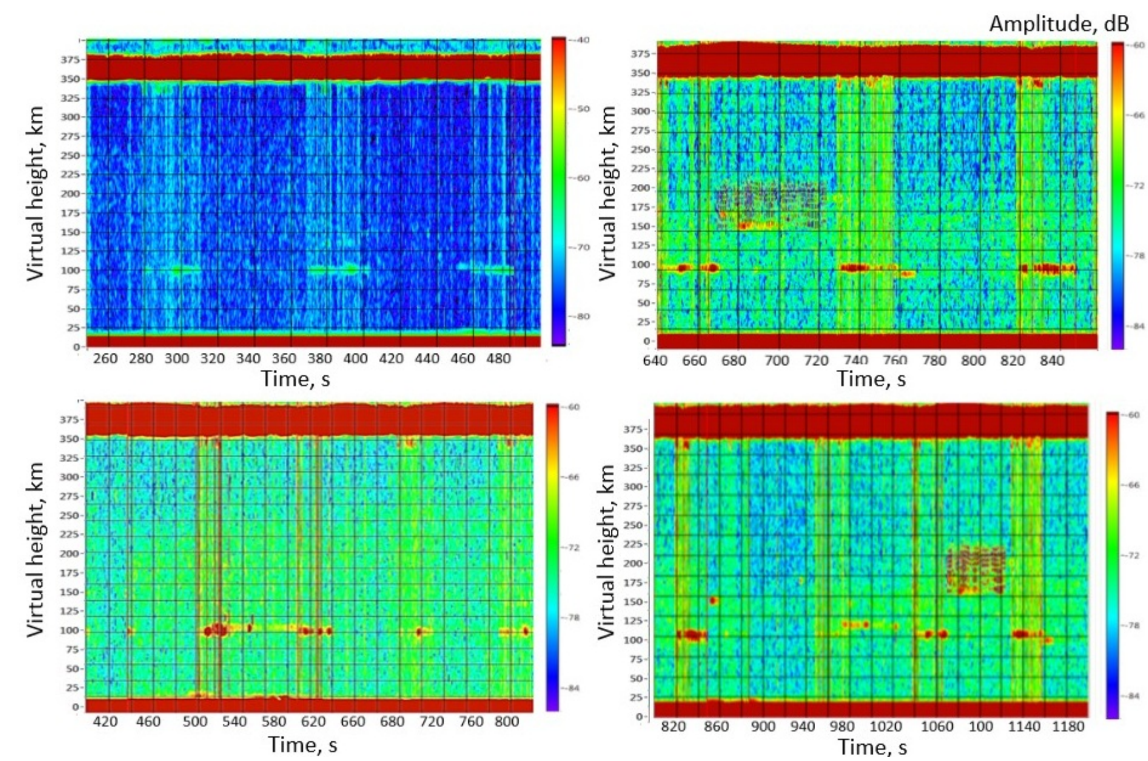

Figure 7. Appearance of scattered signals below the virtual altitude of 350 km under the altitude of the specular reflection of a probe wave and E-region signals at an altitude of 100 km during the impact on the ionosphere: in the session starting at 21:45:50 (top); in the session starting at 21:15:50 (bottom). Heating periods are well identified by vertical stripes, which indicate an incompletely filtered powerful signal at the heating frequency

Probe waves of extraordinary polarization with a frequency of 5.455 MHz were reflected above 350 km, and F-layer diffusivity was observed. During heating, scattered signals appeared below the reflection altitude of the probe radio wave. The scattered signal was by 60–70 dB weaker than the specular signal and occupied the virtual altitude range 20–25 km, being directly adjacent to the altitudes of the specular signal reflection (in contrast to the 2006 experiment). The signal developed for ~1 s and disappeared for a shorter time, as in 2006. In addition, signals from the E-region appeared (intensified) during heating. At this time, a semi-transparent sporadic E layer with 2.5–3.1 MHz critical frequency was occasionally observed on ionograms at 100–105 km. At the same time, a weakening of the scattered signal in the F layer was detected when the amplitude of the reflected signal from the E_s layer increased during ionosphere heating sessions.

During the morning hours at sunrise and after sunrise under conditions of a rapid increase in critical frequencies, a decrease in the height of the F layer, and pronounced ionospheric dynamics, there was no scattered signal at the 5.455 MHz probe wave frequency during the impact of the 5.227 MHz extraordinary wave on the ionosphere. Figure 8 exhibits a fragment of recording of ionospheric signals for 12 min in the session starting at 06:30:50. Both probe wave components are shown. Multiple off-angle reflections are seen below the virtual altitude of 200 km, oblique reflections near 150 km, and radio reflections from meteor trails near 100 km.

Thus, the scattered signal at a frequency differing by 228–400 kHz from the heating frequency was observed only in two of the five experiments we conducted during different years on the impact of a powerful radio wave of extraordinary polarization on the ionosphere and on sounding of the perturbed region by probe radio waves of the same polarization.

3. DISCUSSION

Analysis of altitude electron density profiles obtained from vertical sounding ionograms on October 10–11, 2006 has shown that the region of appearance of scattered signals practically coincided with the reflection level of the powerful wave at a true altitude of 223.4 km. This means that the artificial plasma density disturbance occurred in the region of reflection of the powerful radio wave of extraordinary polarization. There are two possible explanations for the observed effect.

3.1. Hypothesis 1 — Plasma wave excitation and induced ion scattering

The October 10–11, 2006 experiment has revealed that a powerful radio wave of extraordinary polarization causes a plasma density disturbance in the region of its reflection from the ionosphere. The question about the nature of the disturbance in the ionosphere when it is heated by a powerful radio wave of extraordinary polarization is considered in detail in [Vas'kov, Ryabova, 1997]. This disturbance can be created either directly by the electric field of a radio wave or by the field of excited plasma oscillations. In the case of large wave vectors, such oscillations can propagate below the reflection level of an extraordinary radio wave of close frequency and can be excited by a powerful radio wave due to the development of various striction instabilities. The cause for this is the excitation of high-frequency plasma oscillations as a result of induced ion scattering of an extraordinary radio wave, for which, as shown in [Vas'kov, Ryabova, 1997], the threshold field value turns out to be relatively small. Calculations based on this work have shown that under conditions of October 10–11, 2006 experiments at the frequency of the heating wave of extraordinary polarization f_{heat}=4.3 MHz and its effective radiation power ~100–120 MW, we would expect a sufficiently strong excitation of plasma waves in the order of 10^{-4} s. However, the experiment has revealed that the excitation of plasma waves by the field of the extraordinary radio wave, if it did occur, was strongly suppressed. This is evidenced by the low intensity of the scattered signal and its location near the level of reflection of the powerful wave from the ionosphere, where its electric field increases due to focusing. In the absence (or with strong suppression) of plasma waves, artificial inhomogeneities must be created directly by the field of a powerful radio wave. As a result, the amplitude

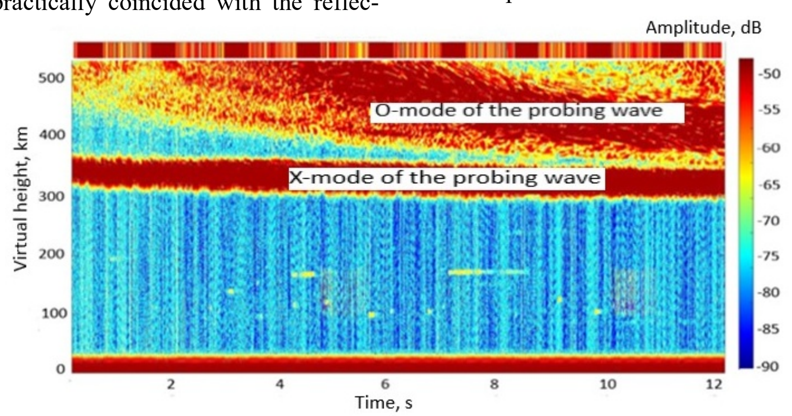

Figure 8. Fragment of recording of ionospheric signals for 12 min in the session starting at 06:30:50. The 30 s heating intervals are indicated by dark red stripes on the top axis

of a scattered signal should increase in direct proportion to the intensity of the powerful wave. The experiment with a step-by-step increase in heating power was planned, yet was not carried out for technical reasons.

3.2. Hypothesis 2 — Scattering of probe radio waves by artificial periodic inhomogeneities of ionospheric plasma

As is known, APIs in the field of a powerful wave are most effectively created by an extraordinary radio wave (X-mode) [Belikovich et al., 1999; Belikovich et al., 2002; Bakhmetieva, Grigoriev, 2022]. They exist throughout the ionosphere in the D-, E-, and F-regions, and the interlayer E–F depression. Near the specular reflection point in the F-region, APIs increase due to the "swelling" of the field of the powerful wave and an increase in its length [Ginzburg, 1967]. Under quiet conditions, APIs replicate the structure of the standing wave field described by the Airy function [Ginzburg, 1967] and scatter only probe radio waves of the same polarization as the heating wave if frequencies of heating and probe radio waves coincide, i.e. the condition of spatial synchronism is fulfilled [Belikovich et al., 1999; Belikovich et al., 2002]. We determined the synchronism frequency band during the July 16, 2006 experiment [Bakhmetyeva, Belikovich, 2007, 2008], which was aimed at studying the effect of the E_s layer on APIs. To identify the synchronism frequency band when APIs were detected for receiving scattered signals, we sequentially selected frequencies spaced away from the 4.785 MHz heating frequency by 30, 35, and 20 kHz to the 4.700 MHz frequency. It appeared that with sequential detuning from the frequency of API creation, the amplitudes of signals scattered by periodic inhomogeneities decreased; and with detuning at 85 kHz (the 4.700 MHz receiving frequency), the signals from APIs disappeared completely, only specular reflections from the F layer, E-region, and E_s layer were recorded. The synchronism frequency band, we have experimentally determined [Bakhmetyeva, Belikovich, 2007, 2008], under these conditions did not exceed 85 kHz (complete disappearance of the scattered signal from APIs) with a probe pulse duration of 30 ms and a receiver bandwidth of 40 kHz.

According to the synchronism frequency band found under quiet conditions with the 228–400 kHz frequency difference between the heating and probe radio waves, the scattered API signal should not have been observed. Nonetheless, during the October 10–11, 2006 experiment there was intense F-spread apparently caused by natural ionospheric disturbance (natural plasma inhomogeneities). This disturbance might have distorted the ordered structure of quasi-periodic inhomogeneities and led to a broadening of the angular and frequency spectrum of a signal scattered by APIs. This was probably responsible for the appearance of the scattered signal during heating in a certain altitude region near the altitude of reflection of the lower-frequency powerful wave. We believed that a test of this hypothesis could be to conduct such an experiment under quiet conditions and in the presence of F-spread, which, to a certain extent, was an objective of the October 24–25, 2024 experiment. The experiment has confirmed that the scattered signal during heating was observed in the evening under conditions of F-layer diffusivity and was not recorded in the early morning under conditions of a rapid increase in critical frequencies, a decrease in the F-layer height, and pronounced dynamics of the ionosphere.

What could cause the natural disturbance of the F layer? It is known that in the F layer there are plasma streams directed upward during the day and downward at night from the magnetosphere or the conjugate hemisphere [Brunelli, Namgaladze, 1988]. If we assume that F-spread is created by similar streams with velocities of 20 m/s or higher, the periodic structure (API), which is formed in such a moving medium, will be distorted and shifted downward in altitude in the evening. Then a vertical velocity gradient will appear, the periodic structure will be compressed, and the synchronism condition will be met at a higher frequency due to a decrease in the altitude API period [Belikovich et al., 1999; Belikovich et al., 2002]. We can assume that in this case under conditions of strong natural disturbance, the synchronism frequency band may exceed the previously found 85 kHz and APIs will scatter probe signals in a wider frequency band.

There was no E-region on the ionograms at that time, and the semi-transparent E_s layer with f_oE_s=2.5–3.1 MHz was occasionally observed at 100–105 km. As noted above, during the ionosphere heating sessions with an increase in the amplitude of the signal reflected at the altitude of 100 km, the scattered signal in the F layer generally weakened, which is clearly seen in Figure 7. This can be explained by an increase in the reflection coefficient of the probe wave from the E layer due to an increase in the electron density in it during heating. In [Gershman, Ignatiev, 1997; Ignatiev, 1975], the question about perturbation of the ionospheric E-region, including the E_s layer, when exposed to powerful radio emission, is examined in detail. When the ionosphere heats up in the E-region, the effective recombination coefficient decreases with increasing electron temperature [Gurevich, Shvartsburg, 1973], thereby causing the electron density to rise under the influence of powerful radio emission. As a result, the reflection coefficient of the powerful wave in the lower ionosphere increases, which leads to a decrease in the impact on the F layer and hence to a decrease in the intensity of probe wave scattering in the F layer. The semi-transparent E_s layer has the same effect if it is formed by the redistribution of atmospheric NO^+ and O_2^+ ions rather than metal ions, which is possible in the evening and night hours [Gershman, Ignatiev, 1997; Ignatiev, 1975]. Note also that during the night hours the electron density in the E-region decreases markedly, but does not disappear completely [Danilov, Vlasov, 1973; Brunelli, Namgaladze, 1988]. Studies of the ionosphere at sunset and sunrise, we have carried out using the method of resonant scattering of radio waves by APIs in different years, have shown that sufficient ionization in the E-region can persist all night [Belikovich et al., 2002; Bakhmetieva et al., 2005, 2024]. Measurements performed by the API method on September 23–24, 2024 have shown that at least until 23 MSK, i.e. after sunset in the ionosphere, signals scattered by APIs were reliably recorded in the altitude range 90–130 km. Note that the method based on resonant scattering of radio waves by APIs allows us to detect ionospheric regular and sporadic layers with low ionization, undetectable by ionosondes [Belikovich et al., 1999; Belikovich et al., 2002; Bakhmet'eva, Belikovich, 2007, 2008].

4. BASIC REQUIREMENTS FOR DESIGNING AN EXPERIMENT

After analyzing the conditions and results of experiments in different years, we made the following conclusions on the optimal organization of such an experiment on the impact of emission of a powerful radio wave of extraordinary polarization to the zenith on the ionosphere at the SURA heating facility.

The experiments have shown that stable, preferably maximum heating power is required. Unfortunately, the capabilities of the SURA facility are limited in this regard. The power of the diagnostic transmitter is not so important, as can be seen from the results of the experiments in 2006 and 2024 when using a low-power transmitter of the partial reflection facility as a source of probe waves; a distinct scattered signal was recorded in real time. Thus, the intensity of the scattering effect largely depends on the heating power and to a much lesser extent on the diagnostic transmitter power.

The optimal situation is when the heating frequency is higher than the F2-layer critical frequency for the ordinary component and lower than the F2-layer critical frequency for the extraordinary one; in this case, only the powerful wave of extraordinary polarization is reflected by the ionosphere. In our opinion, the 228–400 kHz frequency difference between the heating and probe waves was large, it probably should be smaller. At the same time, a narrow reception band of the probe signal is desirable in order to adjust to the heating frequency. Finally, we should take into account the strong dependence of the result on the state of the ionosphere: in our conditions, a more pronounced effect was observed during intense F-spread or diffusivity of the ionosphere and was not observed in their absence.

Unlike the experiments on the impact on the ionosphere performed at the EISCAT heating facility [Blagoveshchenskaya, 2010; Blagoveshchenskaya, 2020; Borisova et al., 2023], in the experiments from 2006 to 2024 at the SURA facility the effects of ionospheric disturbance by a powerful radio wave of extraordinary polarization when detected by probe radio waves of the same polarization, but of a different frequency, were observed irregularly and were rather weak. Obviously, the power of the heating wave was of crucial importance. The emission power comparable to that of the EISCAT high-latitude facility is unattainable at SURA. Moreover, the powerful radio wave was emitted to the zenith, rather than to the magnetic zenith, which might have enhanced the observed effect.

CONCLUSION

During the impact of a powerful radio wave of extraordinary polarization on the ionosphere and when sounding the disturbed ionosphere with probe radio waves of the same polarization at a frequency close to the heating frequency, but differing by 228–400 kHz, a scattered signal appeared at virtual altitudes below the altitude of specular probe wave reflection. In October 2006, the scattered signal amplitude was 40–50 dB lower than the specular signal amplitude, and it occupied a range of virtual altitudes 30–40 km lower than the altitude of the signal mirrored from the F layer. The development time of the scattered signal was ~1 s, and the relaxation time was by an order of magnitude shorter. The signal was noise-like, and its amplitude changed rapidly with height and time. The effect was observed in the evening under conditions of strong F-layer diffusivity (F-spread phenomenon). In September 2024, in the late evening, a scattered signal with an amplitude 50–60 lower than the amplitude of the signal mirrored from the F layer appeared directly below it and occupied a virtual altitude range 15–25 km. During 30 s heating sessions, a signal from the E-region or sporadic E layer appeared (intensified) for 1 s or less. When a scattered signal appeared in the E-region, a scattered signal in the F layer generally weakened.

Analysis of vertical electron density profiles has shown that a probe wave of extraordinary polarization with a frequency by 228–400 kHz higher than the frequency of the heating wave of the same polarization was reflected almost at the altitude of reflection of the latter and a scattered signal appeared near this altitude. This implies that the powerful radio wave of extraordinary polarization caused a disturbance in the plasma density in the region of its reflection from the ionosphere. During the morning hours after sunrise under conditions of a rapid increase in critical frequencies of the ionosphere, such a scattered signal was not observed during the impact on the ionosphere.

We have proposed two explanations of the observed phenomenon. At present, it seems preferable to suppose that probe radio waves are scattered by artificial periodic inhomogeneities of ionospheric plasma, which arise in the field of a powerful radio wave. Scattering of radio waves by APIs when the polarization of heating and probe radio waves coincide, and a scattered signal appears at a frequency other than the heating one, may be due to a change in synchronism conditions and an expansion of the band of observed frequencies during scattering by APIs under conditions of intense F-spread. This is confirmed by the absence of a scattered signal in a more regular ionosphere in the morning after sunrise. Nevertheless, it has to be stated and the experiments carried out have convincingly shown that the question about the mechanisms of formation of plasma inhomogeneities in the field of a powerful radio wave of extraordinary polarization remains theoretically open.

We gratefully remember Belikovich Vitold Vitalievich and Vas'kov Viktor Viktorovich died prematurely in 2009, who took an active part in experiments we started in 2006; the results are presented in this paper.

The work was financially supported by RSF (Grant No. 25-27-00031).

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The paper is based on material presented at the 20th Annual Conference on Plasma Physics in the Solar System, February 10–14, 2025, Space Research Institute of the Russian Academy of Sciences, Moscow, Russia.

Original Russian version: Bakhmetieva N.V., Grigoriev G.I., Zhemyakov I.N., Kalinina E.E., Lisov A.A., published in Solnechno-zemnaya fizika. 2025, vol. 11, no. 3, pp. 88–99. DOI: 10.12737/szf-113202510.

How to cite this article

Bakhmetieva N.V., Grigoriev G.I., Zhemyakov I.N., Kalinina E.E., Lisov A.A. Ionosphere response to the impact of an extraordinary radio wave when located at a frequency close to the heating frequency. *Sol.-Terr. Phys*. 2025, vol. 11, No. 3, pp. 80–90. DOI: 10.12737/stp-113202510.