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The lower ionosphere response to its disturbances by powerful radio waves

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Abstract

The paper presents data from some campaigns at Sura heating facility in 2011–1016. The experiments on probing of the artificial disturbed region of the lower ionosphere were carried out at two observation sites. One of them was located near Vasil'sursk 1 km from Sura facility (56.1°N; 46.1°E) and the other site was located at the Observatory (55.85°N; 48.8°E) of Kazan State University, 170 km to the East. Investigation of the features of the disturbed region of the lower ionosphere based on its diagnostics by the methods of the vertical sounding and oblique backscattering is the main goal of this paper. Ionosphere disturbance was fulfilled by the effect of the powerful radio wave of the ordinary or extraordinary polarization emitted by transmitters of the Sura facility with effective radiated power ERP = 50–120 MW at the frequency of 4.3, 4.7 and 5.6 MHz. Pumping waves were emitted with period from 30 s to 15 min. The disturbed region of the ionosphere in Vasil'sursk was probed by the vertical sounding technique using the partial reflexion radar at the frequency of 2.95 and 4.7 MHz. For the oblique sounding of the disturbed region the modified ionosonde Cyclon-M, operating at ten frequencies from 2.01 to 6.51 MHz was used at the Observatory site. On many heating sessions simultaneous variations of the probing partial reflection signals in Vasil'sursk and backscattered signals in Observatory were observed at the height at 40–100 km below the reflection height of the pumping wave. These observations were correlated with the pumping periods of the Sura facility. Possible mechanisms of the appearance of the disturbance in the lower ionosphere and its effect on the probing radio waves are discussed.

Keywords: Ionosphere modification; Lower ionosphere disturbances; Artificial irregularities; Ionospheric sounding; Oblique back scattering; Sura facility

1. Introduction

It is known that ionosphere modification using powerful radiowaves leads to generation of artificial irregularities of the plasma density with scales from centimeters to kilometers and more. The results of experimental and theoretical studies of artificial inhomogeneities are contained in a large number of publications (Allen et al.,1974; Minkoff et al., 1974; Belenov et al., 1977; Gurevich, 1978; Stubbe et al., 1982; Hedberg et al., 1983; Coster et al., 1985; Stubbe, 1996; Hysell et al., 1996, 2008; Bakhmetieva et al., 1997; Robinson et al., 1997; Bond et al., 1997; Franz et al., 1999; Rietveld et al., 2003; Blagoveshchenskaya et al., 2006; Kagan et al., 2006; Gurevich, 2007, 2012; Belikovich et al., 2007; Frolov et al., 2007; Crisham et al., 2008; Yeoman et al., 2008; and in many others).

For many years methods of vertical and oblique sounding of the ionosphere are applied to study the artificial disturbances in the ionosphere and to measure their

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parameters. In recent years, the enhanced interest has again been shown in experimental studies of the issues related to the formation of artificial ionospheric disturbances, including their diagnostics, study of the structure and dynamics of the disturbed region, and determination of the parameters of artificial irregularities with various spatial scales, which appear in this region (Kagan et al., 2006; Bakhmetieva et al., 2010, 2012; Blagoveshchenskaya et al., 2011, 2015; Bolotin et al., 2012; Sergeev et al., 2012; Mishin et al., 2016; Grach et al., 2016). In many respects, this interest is stipulated by starting the wide application of methods of chirp-signal probing, using ionosondes and radio direction finders, developing new Doppler techniques related in particular to phase measurements, and employing digital signal recording and modern signal processing methods. Currently, the research of scattering signals continues on paths of different lengths by linear frequency modulation (LFM) technique. New compelling evidences of the existence of the "patch" structure of the disturbed region were obtained, that was capable to scatter radio waves effectively over a wide frequency range (Uryadov et al.,2008; Vertogradov et al., 2012). Application and development of new diagnostic methods of artificially created ionospheric disturbances have provided some new information about the disturbed region and its inhomogeneous structure. Methods of the radio tomography show that the horizontal size of the region perturbed by the radiation of the heating facility far exceeds the size defined by the radiation pattern of the antenna system (Frolov et al., 2010). In the experiments we have used the vertical sounding and oblique backscattering methods of the disturbed ionospheric region. It allowed us to study its dynamics in different ionospheric conditions, and to determine the extent of the disturbed region and the electron density of artificial irregularities (Bakhmetieva et al., 1989). Nevertheless, many questions of these studies are still relevant. One of them is the mechanism of occurrence of disturbances in the lower ionosphere when a powerful wave reflects in the F-region. The study of the lower ionosphere response on its artificial disturbance was the task of the experiments, including the vertical sounding of the perturbed region and its oblique sounding from a point located at the latitude close to the heating facility simultaneously. In the paper, we present the results of the recent experiments on the diagnosis of the inhomogeneous structure of the artificially disturbed ionosphere on short mid-latitude paths by the method of vertical sounding and oblique backscattering.

2. Experiment description

The data presented in this paper was obtained during the June and September 2011, October 2014, October 2015 and May 2016 campaigns at Sura facility (56.1°N; 46.1°E) located in Vasilsursk near Niznhi Novgorod, Russia. Experiments were carried in the morning, afternoon and evening hours LT. The ionosphere was disturbed using Sura heating facility. Sura transmitters were operated in O-mode or X-mode polarization. Pumping waves were radiated at frequencies of 4.3, 4.7 or 5.6 MHz, depending on the ionosphere critical frequencies with the effective radiation power (ERP) of 50–120 MW. The heating cycle varied usually from 30 s to 15 min including 5 s (5 min) heating and 25 s (10 min) period off (called pause). The use of different time diagram allows one to study the region of the artificial perturbation of the ionosphere both on long and short time scales. The time diagram of the heater is shown in Fig. 1. Pumping radio waves always reflected in the *F*-region of the ionosphere. The antenna of the Sura heating facility was pointed at zenith, or was inclined at 12° to the south in the magnetic zenith direction.

The campaign on June 19, 2011 was carried out from 9:00 to 15:00. The pump frequency (O-mode) was set to 4.7 MHz. The heater beam was pointed to zenith. In campaign on September 2011 the pump frequency (X-mode) was set to 5.6 MHz. The heater beam was pointed to a zenith angle of 12°. ERP amounted to about 80 MW in June 2011 and 50 MW in September 2011.

In the campaign on October 8–9, 2014 observations were carried out from 09:00 to 15:00 LT. The pump frequency (O-mode) was set to 5.6 MHz. The heater beam was pointed to a zenith angle of 12°. ERP amounted to about 120 MW. According to the ionosonde data, the observations were characterized by relatively quiet state of the ionosphere with critical frequencies of the ionospheric layers $f_0E = 2.5$–3.1 MHz, $f_0F_1 = 4.0$–4 MHz and f_0F_2=8.8–9.5 MHz.

In the campaign on October 7, 2015 from 10:00 to 12:30 LT Sura facility emitted X-mode of pumping wave at the frequency of 4.3 MHz with ERP 80 MW. The heater beam was pointed to zenith.

In the campaign on May 19, 2016 the pump frequency (O-mode) was set to 4.785 MHz with ERP = 70 MW. The heater beam was pointed to a zenith angle of 12°. The observations were conducted from 13:30 to17:10 LT.

The partial reflection radar (PRR) was located about 1 km from the Sura antenna. It was used to probe vertically the ionospheric plasma at the frequency of 2.95 MHz Sometimes the probing wave frequency was 4.7 MHz In the observation on October 7, 2015 PRR emitted probing frequencies at 2.95 and 4.7 MHz by rotation. This radar was used for vertical sounding of the ionosphere. It detected signals reflected and scattered from the all ionospheric regions. PRR emitted a linear polarized pulsed

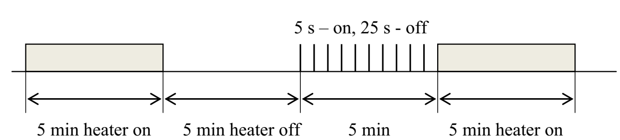

Fig. 1. The time diagram of the Sura heating of the ionosphere. The total heating cycle was 15 min including 5 min heating and 5 min off period. In the following 5 min, heating was carried out with a period of 30 s that included 5 s of heating mode and 25 s off period.

signal with a duration 30 μs and repetition rate of 25 or 50 Hz. Signals of both O- and X-polarizations, reflected and scattered from the ionosphere, were received. Their quadratures were digitally recorded with height step of 1.4 km and served as basis for determination of the probe wave amplitude and phase. CADI and other ionosondes monitored the ionosphere condition each 5–15 min.

Oblique sounding of the disturbed ionosphere was performed by modified ionosonde Cyclon-M in the Observatory of Kazan University (55.85°N; 48.8°E). It is located near Kazan at distance from the Sura heating facility of about 170 km. To probe the ionosphere disturbed region in the oblique sounding mode the Cyclon-M ionosonde operated at ten frequencies from 2.01 to 6.51 MHz with a frequency step of 500 kHz and a repetition rate of 50 Hz. Cyclon-M facility is presented in detail by Ackhyurin et al. (1995), Bolotin et al. (2012) and Sergeev et al. (2012). One ionosonde channel always operated at the Sura frequency. Note, that Sura–Observatory path is almost latitudinal. The path is situated in the plane which is practically perpendicular to the plane of the magnetic meridian passing through the Vasilsursk. This arrangement is very convenient for receiving signals back scattered by artificial ionospheric field aligned irregularities. The Cyclon-M ionosonde was switched over periodically to the routine ionogram mode. The electron density profile was retrieved from them according to the standard procedure.

Simultaneous observation using PRR and Cyclon-M ionosonde were conducted on June 19, 2011 from 07:00 to 10:00 LT and on September 13–15, 2011 in the morning and evening hours (from 08:00 to 12:00 and from 14:00 to 21:00, respectively), on October 8–9, 2014 from 9:00 to13:30 LT and on May 19, 2016 from 13:30 to 17:00 LT.

The ionosphere condition in the experimental campaigns in 2011, 2014 and 2016 was generally quiet. Effects of the Spread-F and Sudden Ionospheric Disturbances were not observed. Fifteen-minute ionograms for the measurement periods were similar to those in Fig. 2. The periods were geomagnetically quiet and Kp-index did not exceed 1–2. The reflection heights of probing waves changed little with time. A slightly different ionospheric condition was on October 7, 2015. On the previous day a weak magnetic storm with Kp = 3–4 began. Variations of the reflection height of the pumping and probing radio waves and the critical frequency of the layer were observed. Fig. 5a) shows variations of the reflection height of the O-mode of the probing wave at 2.95 MHz on October 7, 2015.

3. Experimental results

3.1. *Vertical sounding of the disturbed ionosphere. Vasil'sursk observations*

The results of the experiments presented in this article supplement the information on the perturbation of the lower ionosphere discussed in Bakhmetieva et al. (2010, 2012). During the pumping sessions signals of both polarizations, similar to the diffuse reflection probing waves appeared after heating off for 3–20 s at altitudes both below and above the height of the specular reflection of the probing wave. These signals, called by us additional, correlated with the Sura pumping periods as depicted in Fig. 2. Additional signals were detected during both 5 min (top panel) as well as with 5 s (bottom panel) heater period. Fig. 2 shows two intervals of the virtual height-time-amplitude plot for the probing wave frequency at 2.95 MHz It illustrates an appearance of echoes called additional signals from 09:29 to 10:00 – top panel and from 11:31 to 12:00 – bottom panel on October 8, 2014. The pump frequency (O-mode) was set to 5.6 MHz. The heater beam was pointed to a zenith angle of 12°. Rectangles on the top horizontal axis show heating periods.

In Fig. 2 (top panel), in the heating sessions one can see a new reflection appears at the virtual height 180 km that is below the height of the specular reflection of the O-mode probing signal. This height refers to the true altitude 120 km. This additional "sublayer" signal is noticeably separated from the specular mode. This signal appeared 20–25 s after the heating on, and it disappeared 5 s after heating off. Similar "sublayer" signals or reflections were observed in June 19, 2011.

Fig. 2 illustrates a development of the additional signals during the 5 s heating sessions (see the bottom panel). These signals showed two features. One of them is an aftereffect, when the amplitude of the signal has reached the maximum value 5–10 s after the end of the heating session, and the second is the cumulative effect, when an increase of the signal amplitude was observed in each subsequent heating session. Similar features of the additional signals in time of short heater on periods were discussed (Bakhmetieva et al., 2010, 2012).

Fig. 3 shows the height-time-amplitude plot for the probing wave frequency at 2.95 MHz illustrating the appearance of additional signals from 09:58:00 to 10:00:34 on October 9, 2014. The pump frequency (O-mode) was set to 5.6 MHz. The heater beam was pointed to a zenith angle of 12°. Rectangles on the top horizontal axis show heating periods. Fig. 3 shows the appearance of strongly-enhanced additional signals correlating with the pumping wave period at the heights of 200–450 km. Note, that according to the $N(h)$ profile calculated from the ionogram the virtual height $h = 200$ km corresponds to the true height 120–130 km. That is signals come from the E region and bottom part of the F_1 region. Intensive additional signals were detected at 5 min heater period as rule. Note, the signals appeared at beginning at the altitude immediately adjacent to the height of reflection of the probing wave and then propagated to the higher altitudes. On the whole, rise and decay times of the additional signal corresponded to those obtained in other observations and to results of the experiments performed at the same path and reported with allowance for the ionospheric states in (Bakhmetieva et al., 2010, 2012; Sergeev et al., 2012;

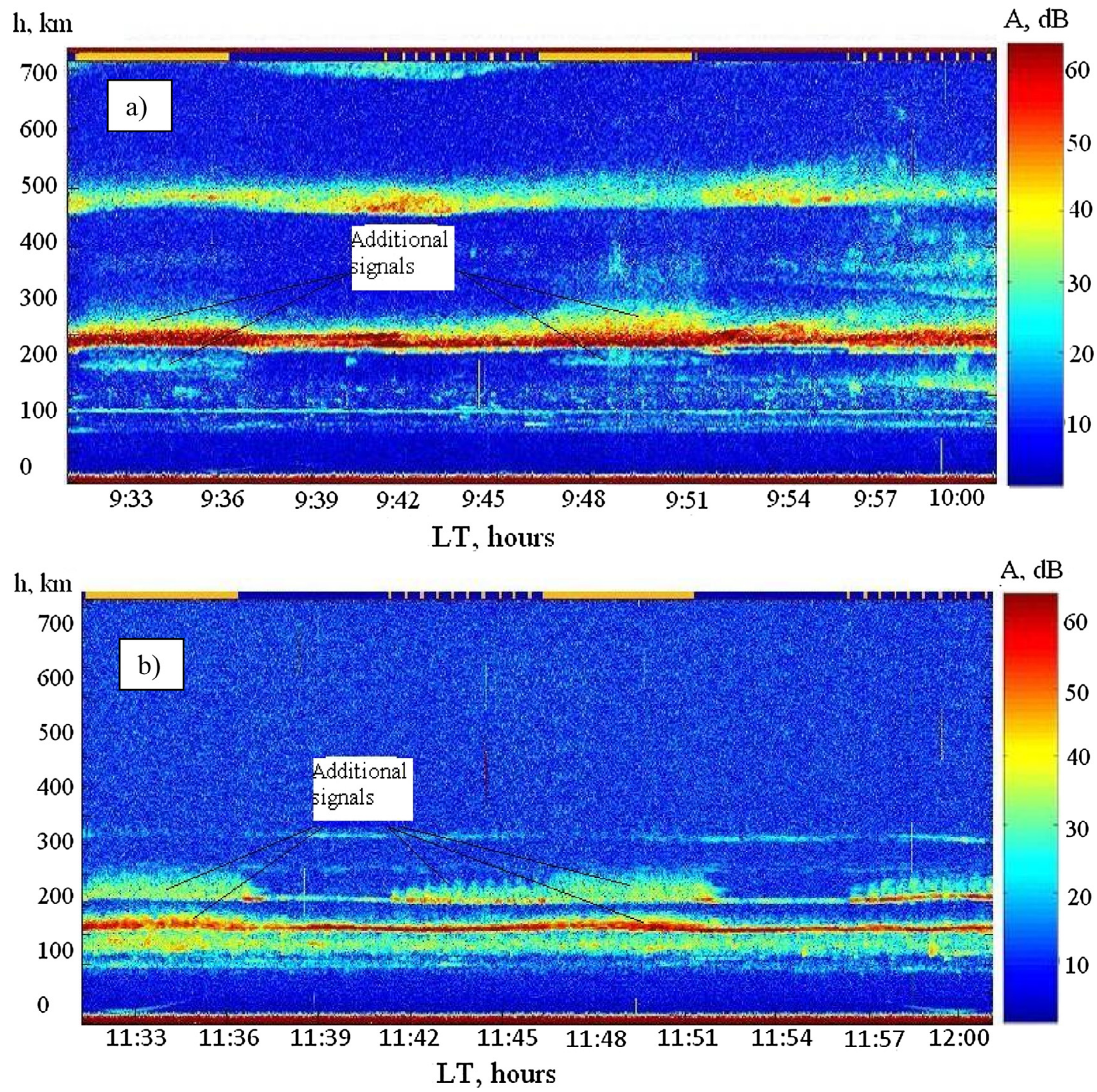

Fig. 2. Two intervals of the height-time-signal amplitude plot for the probing wave frequency at 2.95 MHz illustrating the appearance of echoes called additional signals from 09:29 to 10:00 – (a) and from 11:31 to 12:00 – (b) on October 8, 2014. The pump frequency (O-mode) was set to 5.6 MHz The heater beam was pointed to a zenith angle of 12°. Rectangles on the top horizontal axis show heating periods. Note, that X-mode of the probing wave was reflected at the bottom part of the E-region near virtual height $h \sim 100$ km. Partial reflection signals scattered by natural irregularities of the D region are depicted below 100 km. O-mode of the probing wave reflected in the E region at the height at 150 km and in the F_1 near $h = 200$–250 km. Additional signals were detected during both 5 min (a,b) as well as 5 s (b) heater period. After that "sublayer" additional signals were observed at the virtual height $h \sim 180$ km (b).

Bolotin et al., 2012). Usually the additional signal developed to stationary level in 20–80 s and relaxed in 30–80 s. Sometimes two time decay constants were observed. Note, that two-stage feature of the scattered signal decay was observed in many experiments on oblique sounding of the artificially disturbed ionosphere (Belenov et al., 1977; Hysell et al.,1996; Robinson et al., 1997).

Fig. 4 presents two ionograms measured by ionosonde DPS-4 (left) at 07:31:00 UT or 10:31:00 LT on October 8, 2014 and by Cyclon-M ionosonde at 09:57:00 LT on October 9, 2014. It is seen that the critical frequency of the F_2 layer was 10.2 MHz (left ionogram) and 7.8 MHz (right ionogram), so the O-mode of the pumping wave reflected at the virtual height $h \sim 250$ km (true height $z = 180$–200 km) on October 8, 2014. The O-mode of the probing wave at the frequency 2.95 MHz reflected at the height $h = 150$–200 km (true height $z = 120$ km). On October 9, 2014 the pumping wave reflected at the virtual height $h \sim 280$ km. The probing wave reflected at the same true heights as on October 8, 2014. We present these ionograms to point out that the additional signals are caused by heating effects in the lower ionosphere.

Fig. 5 presents the height-time-amplitude plot for two probing wave frequencies at 2.95 and 4.7 MHz (top and bottom panel respectively) on October 7, 2015. The figures show the absence of additional signals in the pumping period. The pump frequency (X-mode) was set to 4.3 MHz and ERP amounted to 80 MW. The heater beam was

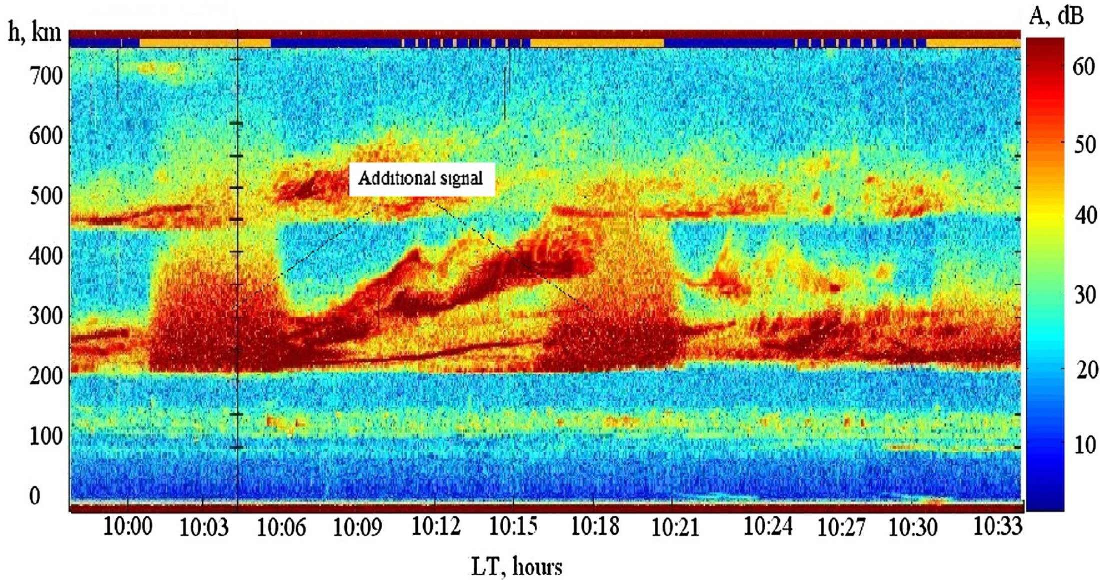

Fig. 3. The height-time-signal amplitude plot for the probing wave frequency at 2.95 MHz illustrating the appearance of additional signals from 09:58:00 to 10:00:34 on October 9, 2014. The pump frequency (O-mode) was set to 5.6 MHz. The heater beam was pointed to a zenith angle of 12°. Rectangles on the top horizontal axis show heating periods. Intensive additional signals were detected at 5 min heater period as a rule. They occupied a range of heights from 200 to 450 km. Their rise and decay times were about a minute.

pointed to zenith. Rectangles on the top horizontal axis show heating periods. On the top panel one can see significant variations in the reflection height of the probing wave without correlation with heating periods. Both O- and X-modes of the probing wave at frequency 2.95 MHz reflected in the E-region of the ionosphere (virtual height $h = 250$ km and more for O-mode and $h = 100$ km for X-mode). The probing wave at frequency 4.7 MHz reflected in the F-region and the virtual reflection height decreased over time. It was $h = 450$–330 km for O-mode (true height $z = 220$–200 km) and $h = 400$–300 km ($z = 210$–170 km) for X-mode. We note that the frequency of the second probing wave exceeded the heater frequency so that at this frequency it was difficult to expect the heating effect. I fact, it was a test experiment using capabilities of the partial reflection radar at two probing frequencies.

Fig. 6 shows the height-time-amplitude plot for probing wave frequency at 2. 95 MHz on May 19, 2016. The pump frequency (O-mode) was set to 4.3 MHz with ERP = 70 MW. The heater beam was pointed to zenith. An unexpectedly strong perturbation is observed in the probing wave reflected in the lower ionosphere virtual height at 100–150 km (E region) and at 180–220 km (bottom part of the F_1 region). The figure shows wave-like variations of the reflection height of the probing wave at $h \sim 200$ km. The reflected signal amplitude increased by 20–30 dB during the heating period. It is seen also how the range of reflection heights of the probing wave has significantly expanded in the E-region at the height near 100 km after the second heating session.

Presented results showed that perturbations of the E-layer of the ionosphere and the lower part of the layer F_1 most likely influenced the probe wave at the frequency of 2.95 MHz Growth of the electron density in the lower ionosphere during the heating period and an evolution of its inhomogeneous structure could cause the emergence of additional signals during pumping period. Estimates made on the basis of the electron density profile recovered from the vertical sounding ionograms showed that these signals could appear due to an increase of the electron density of 5–10% in this session. Such an increase of the electron density corresponds to theoretical estimations of the heating of the E-region by passing radio waves with ERP about 80–100 MW.

3.2. Oblique sounding of the disturbed ionosphere. Kazan observations

The aim of these observations was to study the back scattered signals (BSS) from the anisotropic irregularities of the ionospheric plasma excited by its pumping together with the study of perturbations in the lower ionosphere by its vertical sounding. Observation using the modified Cyclon-M ionosonde to detect the signal back scattered from artificial anisotropic irregularities were conducted in some campaigns. These experiments were carried out on June 19, 2011 from 07:00 to 10:00 LT and in September 13–15, 2011 in the morning and evening hours (from 08:00 to 12:00 and from 14:00 to 21:00, respectively), in October 8–9, 2014 from 9:00 to13:30 LT and in May 19, 2016 from 13:30 to 17:00 LT. Backscattered signals were not observed in each experiment. It was not always possible to explain their absence.

The BSS signals were almost never observed when an intensive blanketing sporadic E layer developed on the trace between the points of Vasil'sursk (site of the Sura

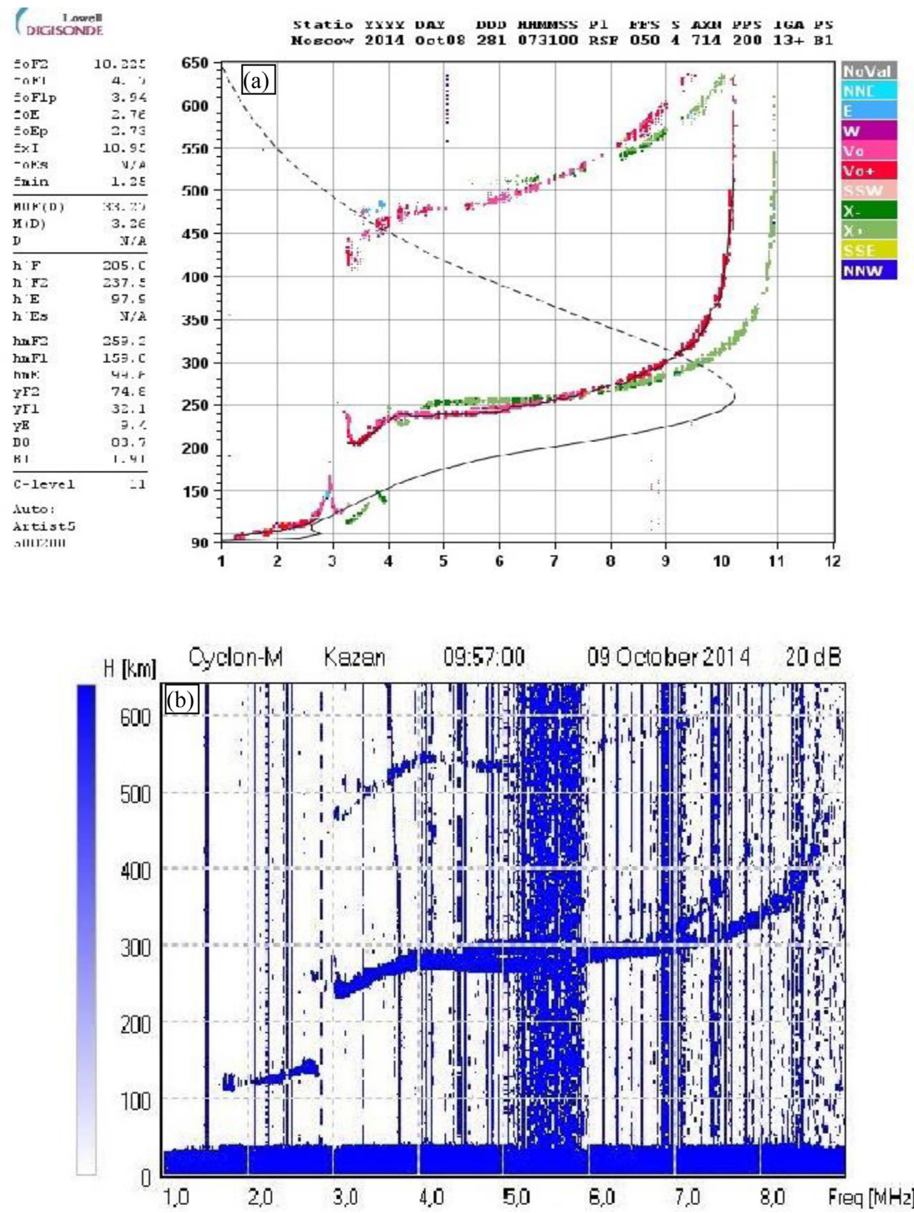

Fig. 4. Two ionograms measured by ionosonde DPS-4 (left) at 07:31:00 UT or 10:31:00 LT on 8 October 2014 and by ionosonde Cyclon-M at 09:57:00 LT on 9 October 2014. It is seen that the critical frequency of the F_2 layer was 10.2 MHz (a) left ionogram) and 7.8 MHz (b) right ionogram), so the O-mode of the pumping wave reflected at the virtual height $h \sim 250$ km (true height $z = 180$–200 km) on 8 October 2014. The O-mode of the probing wave at the frequency 2.95 MHz reflected at the height $h = 150$–200 km (true height $z = 120$ km). On 9 October 2014 the pumping wave reflected at the virtual height $h \sim 280$ km. The probing wave reflected at the same true heights as on 8 October 2014.

facility) and the Observatory (site of the Cyclon-M). In this case sporadic E-layer reflected almost all the ionosonde probing frequencies. Sometimes BSS were not observed even under favorable ionospheric state and at high ERP of the Sura facility. For example, just very weak backscattered signals were detected from time to time in October 8–9, 2014 when ERP was 120 MW. On May 19, 2016 scattered signals were not observed at all. For this reason, we present only some results of the observation of back scattered signals using Cyclon-M on June and September 2011. They have already been partially presented (Bakhmetieva et al., 2012).

During oblique sounding of the perturbed region of the ionosphere in the frequency range 2.01–6.51 MHz signals due to backscatter of radio waves on the of artificial field aligned irregularities were observed. Back scattered signals were received at almost all probing wave frequencies. Fig. 7 shows the delay-time-amplitude plot of the backscattered signals only at the probing frequencies of 2.51 MHz – (a), 4.7 MHz – (b) and 5.51 MHz – (c) observed by Cyclon-M ionosonde during the pumping period for the heating session at 18:48:00 LT on September 13, 2011. The bottom panel d) shows the ionogram concerned for this session when Cyclon-M was operated in routine ionogram mode.

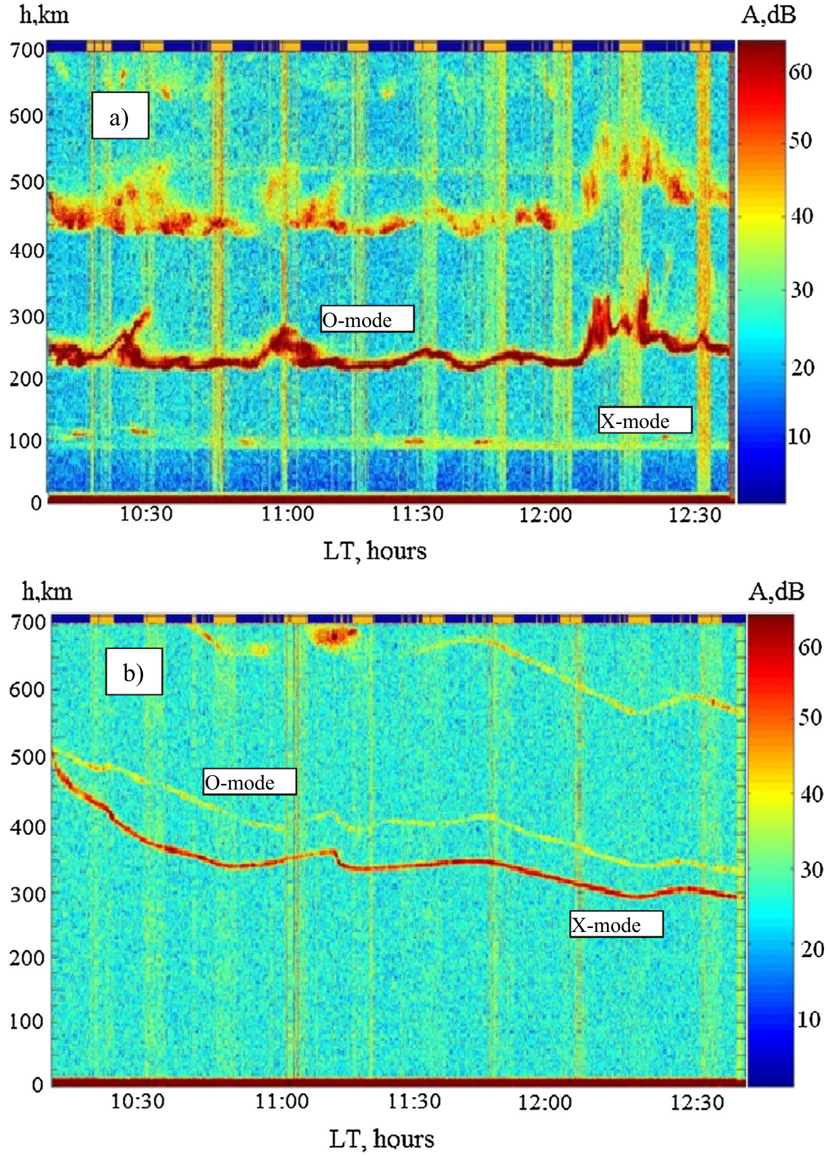

Fig. 5. The height-signal amplitude plot for two probing wave frequencies at 2.95 MHz – (a) and 4.7 MHz – (b) on October 7, 2015. The transmitter of the partial reflection facility emitted probing frequencies alternating between 2.95 and 4.7 MHz The pump frequency (X-mode) was set to 4.3 MHz The heater beam was pointed to zenith. Rectangles on the top horizontal axis show heating periods. Critical frequencies varied from 2.61 to 2.9 MHz in the E region, from 3.9 to 2.9 MHz in the F_1 region and from 4.68 to 5.33 MHz in the F region simultaneously with a decrease in the height of the region from 500 to 300 km. One can see the absence of the additional signals during the pumping period.

Back scattered signal is marked by the red oval on the ionogram. The interval of group delays corresponding to the receiving signals was equal to 1000–1400 μs. The pumping wave frequency (O-mode) was set to 4.7 MHz. It is shown as red columns on the Figure. ERP was about 50 MW.

After the end of the heating the scattered signals gradually disappeared. In the session at 18:48 LT the scattered signals at probing frequencies of 2–4 MHz appeared in the delay range from 1000 to 1100 μs, which is seen well in the ionogram shown in Fig. 7. At the probing frequency of 5.51 MHz, the scattered signal appeared in both polarizations of the probing radio wave with delay at 1100–1150 μs. X-mode of the scattered signal was adjacent to the same mode of the specular signal, whereas the O-mode was strongly diffusive and occupied the delay interval 1200–1800 μs. Without Sura heating at this frequency, the specular reflection of the O-mode component of the probing wave was almost absent since the frequency 5.51 MHz exceeded the critical frequency of the F layer.

At the probing frequency of 5.51 MHz, the backscattered signal was of the strongly diffusive type and occupied the delay interval 1200–1800 μs. Weak scattered signals at the frequency 5.51 MHz were obtained during pumping periods of 5 s.

Scattered signals appeared 5–30 s after the start of the pumping. They reached a steady state within 5–10 s as a rule. After the end of the pumping session scattered signals

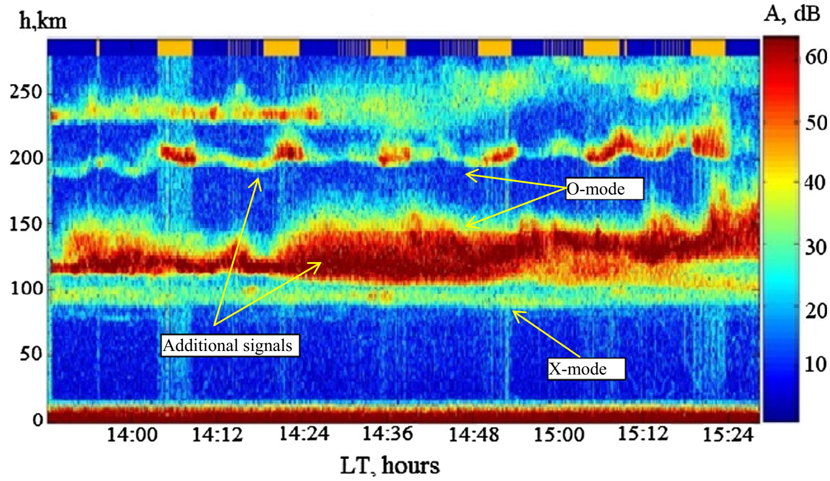

Fig. 6. The height-time-signal amplitude plot for probing wave frequencies at 2.95 MHz on May 19, 2016. The pump frequency (O-mode) was set to 4.785 MHz with ERP = 70 MW. The heater beam was pointed to a zenith angle of 12°. It is shown that strong perturbation is observed in the probing wave reflected in the lower ionosphere at the virtual height of 100–150 km (E region) and at 180–220 km (bottom part of the F_1 region). The figure shows wave-like variations of reflection height of the probing wave at $h \sim 200$ km. Both rise and decay times of these signals were about 30 s. The signal amplitude increased by 20–30 dB during the heating period. After that it is seen the range of reflection heights of the probing wave in the E-region near 100 km has significantly expanded at the height after the second heating session.

disappeared, their time decay varied from 5–10 s to 50 s. In the evening, after 19:00, the decay process, on the whole, was longer.

Fig. 8 shows the height-time-signal amplitude plot for O-mode of probing wave frequencies at 2.95 MHz on September 13, 2011. Additional and BSS signals shown on Fig. 7 were observed simultaneously.

Thus, using the results of multi-frequency oblique sounding of the disturbed region of the ionosphere from the observation point located 170 km from the Sura heating facility at a nearly-latitudinal path, we can make the following conclusion. Back scattered signals from artificial field-aligned irregularities of the ionospheric plasma appear in the pumping period. The transverse scale of these irregularities, are determined by the Bragg backscattering condition as $l_{\perp}=\lambda/2n$ where n is a refractive index. Using $n\approx0.4$–0.5 calculated according to $N(z)$- profile of the electron density we find the transverse scales are about 60–190 m.

Let's pay attention to that fact that the true height of scattering of the probing wave at the lowest frequency 2.01 MHz, at which the backscattered signal was received did not exceed 100–120 km. These values were obtained according to the ray-tracing calculations performed for this path with allowance for the magnetic field. In this way the difference between the reflection heights of the pumping and probing wave was not less than 100 km. Scattered signals emitted on frequencies at 4–6 MHz were detected from heights of 40 km below the height of the reflection of the pumping wave. These differences in the heights of the reflection of the powerful wave and the scattered signal corresponds to propagation of the artificial perturbations down with an effective velocity amounted to 3 km/s.

4. Discussion

The main goal of these studies was the investigation of the features of the disturbed region of the lower ionosphere on the basis of its diagnostics by the methods of the vertical sounding and oblique backscattering methods. On the basis of these observations in two mid latitude points and with considering results [Bakhmetieva et al., 2010; 2012] one can see some key points.

In both observation points signals were not observed during heating in cases where the difference between the critical frequency of the F_2 layer and powerful wave frequency was greater than 1 MHz Modification of the ionosphere by X-mode of the pumping wave led to the appearance of additional and backscattered signals sometimes.

Backscattering signals with both polarizations were obtained at the Observatory reception point in the case of oblique sounding of the perturbed region. At the same time, in the case of vertical sounding at the Vasilsursk point, X-mode additional signals were obtained along with the O-mode only in those cases, where the difference between the scattering altitudes of the probing and pumping radio waves did not exceed 40–70 km.

The tilt of the antenna diagram of the heating facility at 12° south did not fundamentally effect on the results of the observations in these experiments. Said tilt corresponds to the propagation of powerful radio waves in the direction of the magnetic zenith, that, according to (Gurevich, 2007, 2012), should lead to increased interaction of powerful radio waves with the ionospheric plasma. A possible example of this can be found on Fig. 6 when the amplitude of the additional signal increased by 20–30 dB during the pump-

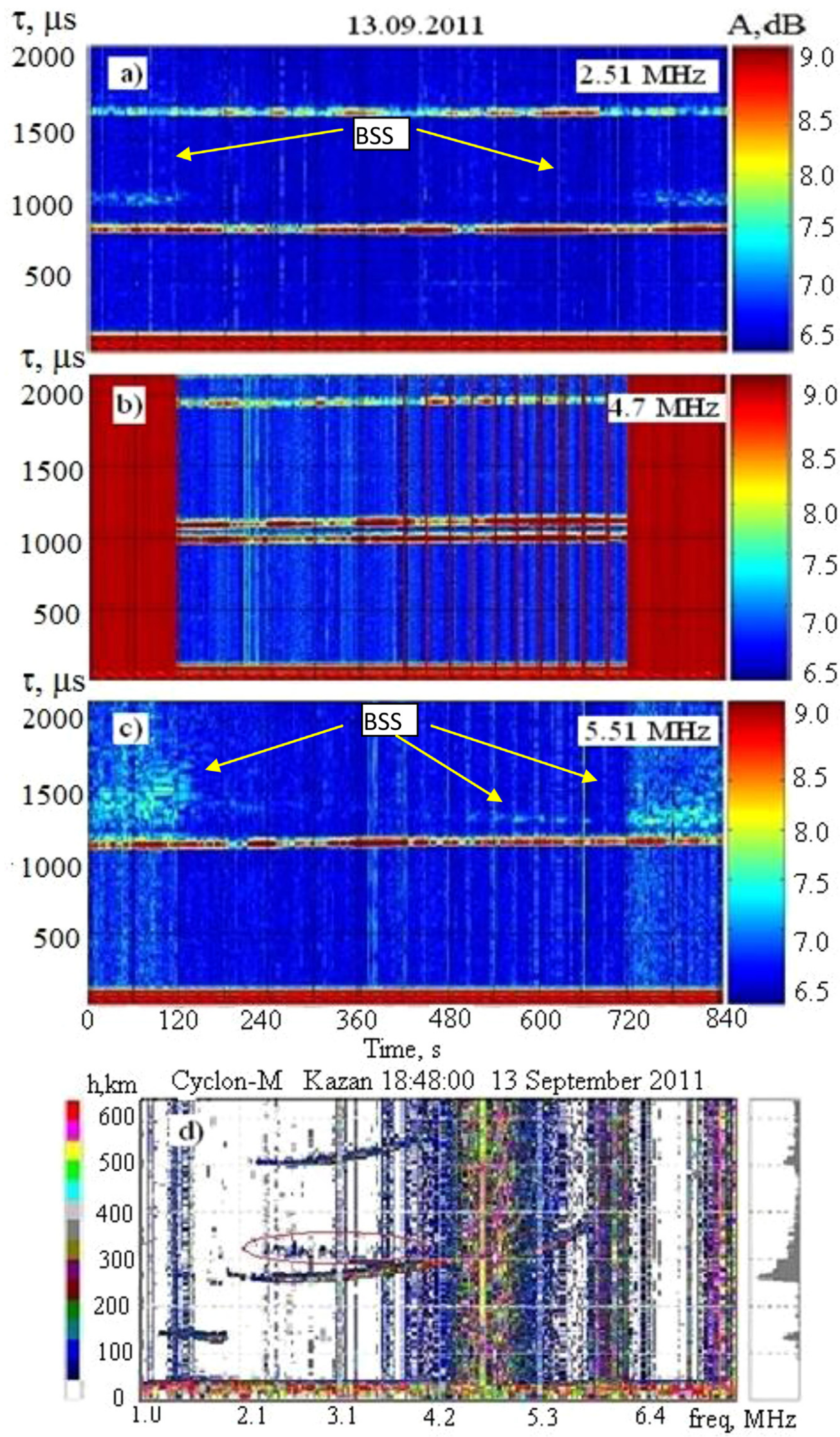

Fig. 7. Backscattered signals (BSS) at the probing frequencies of 2.51 – (a), 4,7 – (b) and 5.51 – (c) MHz observed by ionosonde Cyclon-M on Observatory site for session at 18:48:00 LT on September 13, 2011. *Y* axis is the BSS time delay. The pump frequency (O-mode) was set to 4.7 MHz ERP was about 50 MW. The bottom panel – d) shows the ionogram concerning this session. Back scattered signal is marked by the red oval. The heater beam was pointed to zenith. BSS were received at almost all probing wave frequencies from 2.01 to 6.51 MHz One can see weak BSS at the frequency 5.51 MHz were obtained during 5 s heating periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ing period. After that Fig. 6 shows wave-like variations of reflection height of the probing wave with a period about 15 min at $h \sim 200$ km. It is probable the variations are natural internal gravity waves manifestations. It is doubtful that they were excited by exposure of radiation of the Sura facility on the ionosphere. With oblique sounding of the

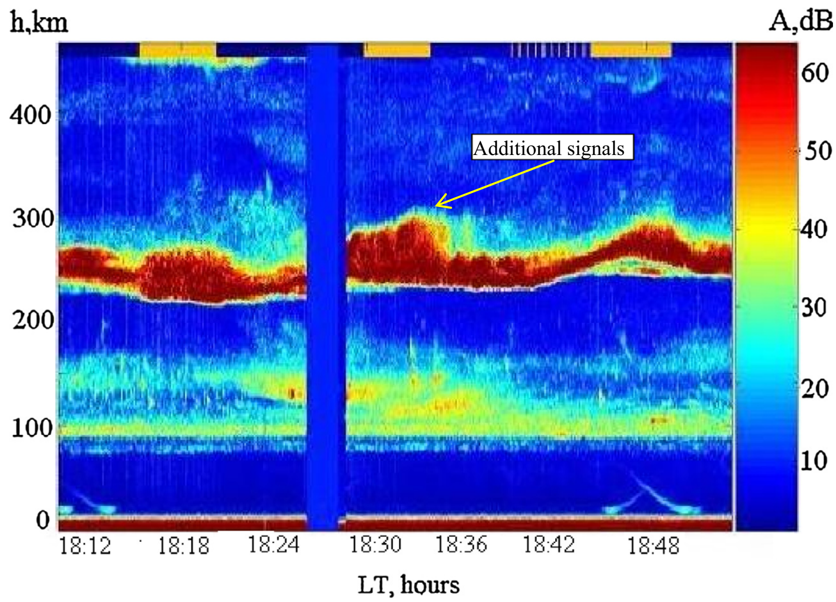

Fig. 8. The height-time-signal amplitude plot for O-mode of probing wave frequencies at 2.95 MHz on September 13, 2011. Additional and BSS signals shown in Fig. 7 were observed simultaneously. A blue vertical bar indicates that the Sura transmitters suddenly turned off. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

disturbed region at the Observatory point the amplitude of the backscattered signal was significantly smaller than the specular signal amplitude.

The amplitude of the additional signal in the vertical sounding in some cases was comparable with the amplitude of the reflection specular signal.

The height range with which backscattered signals in the Observatory and additional signals in Vasil'sursk were received, was practically the same. It can be stated that the lower limit of this range was at 40–120 km below the altitude region of the resonant interaction of a powerful wave with ionospheric plasma.

On the basis of these and other features of the evolution of signals reflected and scattered by the disturbed region of the ionosphere, it is important for us to find out the mechanism that causes the appearance of signals at altitudes well below the reflection height of the powerful wave. This mechanism is not completely understandable. There is no doubt that the signals at the Observatory point are due to the backscattering from anisotropic irregularities (Bragg scattering). It was shown theoretically in (Gurevich, 1978, 2012) and proven reliably in many experiments performed by different research teams (see detailed reviews (Frolov et al., 2007; Belikovich et al., 2007) that these irregularities are formed in the resonance region of the interaction between a high-power O-mode wave and the ionospheric plasma. Irregularities with transverse scale more than 100 m are caused by the self-focusing instability (Vas'kov and Gurevich, 1979). They can be excited by radio waves of both pumping modes including passing waves without reflection from the ionosphere with sufficient radiation power.

But *E* region heights are not located in the resonance region. Therefore, the question about how field-aligned irregularities appeared in this region remains unclear. In terms of the order of magnitude, the velocities of the downward propagation of the disturbances are close to or higher than the speed of the ionospheric heating along the geomagnetic field. This mechanism seems unlikely.

In papers (Bakhmetieva et al.,2010; Sergeev et al., 2012), where possible mechanisms of development of an artificial disturbance at the altitudes of the E region were discussed, it is concluded that the main features of the additional signals do not contradict the concept that the additional signals could be due to perturbations of the E layer of the ionosphere by the radio waves passing through the layer (with the corresponding growth of the electron density) and the lower part of the F_1 layer. When the power of the heating facility was 70–120 MW, the electron density in the E region could increase by 5–10%, which should lead to an increase in the amplitude of the scattered probing wave. The rise time of such disturbances in the E region is 30–90 s (Gurevich, 1978, 2012). It is probable that "sublayer" additional signals which were observed at the height of the E region are also due to the increase of the electron density. Enhancement of natural irregularities with dimensions over 200 m and the development of plasma instabilities during heating (Gurevich, 2012) could maintain the additional signal in short heating sessions.

For short heating periods additional signals have been observed as an aftereffect, when the amplitude of the signal have reached its maximum value 5–10 s after the end of the heating. A cumulative effect has also been observed, when there was an increase in the signal amplitude in each subsequent heating session. Probably, these features of the development in time of heating effects can be provided by the development of plasma instabilities.

This brief discussion shows that the appearance during the pumping of backscattered signals (oblique sounding) and additional signals (vertical sounding) at altitudes of the *E* region is not yet satisfactorily explained. It can be seen that additional theoretical studies in this direction are required. We plan to do it in the near future.

5. Conclusion

In this paper we gave a small overview of the experimental investigations of the artificial disturbance in the lower ionosphere using Sura heating facility. Perturbation diagnosis was carried out by vertical sounding at the frequency of 2.95 MHz and oblique sounding at the frequency of 2.01–6.51 MHz Under modification of the ionosphere by O-mode and sometimes by X-mode of the pumping wave of the Sura facility at frequencies of 4.3, 4.7 and 4.785 MHz with an effective power of 50–120 MW artificial disturbances on the probe signal were obtained. Additional (in Vasil'sursk) and backscattered (in Observatory) signals were received in two points separated by 170 km. The artificial disturbances propagated at altitudes of 40–120 km downward from the height of the reflection of the powerful waves that is significantly below the height of the resonant interaction of high-power radio waves with ionospheric plasma. They are probably related to the development of irregularities and the perturbation of the electron density in the E region.

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