Modification of the high latitude ionosphere F region by X-mode powerful HF radio waves: Experimental results from multi-instrument diagnostics

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Abstract. We present experimental results concentrating on a variety of phenomena in the high latitude ionosphere F2 layer induced by an extraordinary (X-mode) HF pump wave at high heater frequencies (f_H = 6.2 - 8.0 MHz), depending on the pump frequency proximity to the ordinary and extraordinary mode critical frequencies, foF2 and fxF2. The experiments were carried out at the EISCAT HF heating facility with an effective radiated power of 450 – 650 MW in October 2012 and October – November 2013. Their distinctive feature is a wide diapason of critical frequency changes, when the f_H /foF2 ratio was varied through a wide range from 0.9 to 1.35. It provides both a proper comparison of X-mode HF-induced phenomena excited under different ratios of f_H /foF2 and an estimation of the frequency range above foF2 in which such X-mode phenomena are still possible. It was shown that the HF-enhanced ion and plasma lines are excited above foF2 when the HF pump frequency is lying in a range between the foF2 and fxF2, foF2 ≤ f_H ≤ fxF2, whereas small-scale field-aligned irregularities continued to be generated even when f_H exceeded fxF2 by up to 1 MHz and an X-polarized pump wave cannot be reflected from the ionosphere. Another parameter of importance is the magnetic zenith effect (HF beam/radar angle direction) which is typical for X-mode phenomena under f_H /foF2 >1 as well as f_H / foF2≤ 1. We have shown for the first time that an X-mode HF pump wave is able to generate strong narrow band spectral components in the SEE spectra (within 1 kHz of pump frequency) in the ionosphere F region, which were recorded far away from the HF heating facility. The observed spectral lines can be associated with the ion acoustic, electrostatic ion cyclotron, and electrostatic ion cyclotron harmonic waves (otherwise known as neutralized ion Bernstein waves). It is suggested that these spectral components can be attributed to the stimulated Brillion scatter (SBS) process. The comparison between the O- and X-mode narrow band spectra clearly demonstrated that only an X-polarized pump wave scattered by SBS can propagate more than one thousand km without significant deterioration.

Keywords. Ionosphere (Active experiments), Radio Science (Nonlinear phenomena)

1. Introduction

HF pumping experiments in the ionospheric F-region are most commonly conducted with the use of high-power HF radio waves with ordinary polarization (O-mode). An O-polarized HF pump wave effectively interacts with the background ionosphere plasma in the F2 layer in the region between the HF reflection height and upper hybrid resonance altitude leading to the excitation of thermal parametric (resonance) and parametric decay instabilities, which produce a wide variety of phenomena (see, for example, Erukhimov et al., 1987; Robinson, 1989; Stubbe, 1996; Gurevich, 2007 and references therein). As for an X-mode HF pump wave, it does not match the resonance altitudes and, therefore, should not excite the thermal parametric (resonance) instability (TPI) as well as the parametric decay instability (PDI). However, an X-polarized HF pump wave can produce the differential ohmic heating on electrons (Gurevich, 1978; Lofas et al., 2009; Kuo et al., 2010). The electron thermal pressure force leads to the generation of artificial large-scale irregularities because of the growth of a self-focusing instability of an electromagnetic HF wave beam (Dunkan and Behnke, 1978; Gurevich, 1978; Farley et al., 1983; Kuo et al., 2010; Frolov et al., 2014).

An X-polarized HF pump wave cannot match the resonance altitude thus only an O-mode wave is able to generate small-scale field-aligned artificial irregularities (FAIs). Indeed, EISCAT HF heating experiments have demonstrated that at a heater frequency of $f_H = 4.544$ MHz, which was below the maximum plasma frequency foF2, the change of polarization to X-mode led to the disappearance of FAIs, observed under O-mode heating (Robinson et al., 1997). The opposite behavior of FAIs was found at heater frequencies lying above the foF2 (f_H /foF2 $\geq$ 1). Blagoveshchenskaya et al. (2011a; 2011b) have shown for the first time that at heater frequencies lying in the range of 4.0 – 5.4 MHz, an X-polarized HF pump wave, injected parallel to the magnetic field line at frequencies $f_H \geq$ foF2, can excite strong small-scale field-aligned artificial irregularities responsible for backscatter measured by the CUTLASS radars. Detailed studies of the X-mode FAI properties, with the spatial size across the geomagnetic field of $l_{\perp} \approx 11 - 15$ m, from a large number of EISCAT experiments at different heater frequencies of 4.040, 4.544, 4.9128 and 5.423 MHz have demonstrated that such FAIs were observed in a frequency band of about 1.2 MHz above the maximum plasma frequency foF2 (Blagoveshchenskaya et al., 2013). The experiments reported by Blagoveshchenskaya et al. (2011a; 2013) were carried out in the afternoon and evening hours in quiet magnetic conditions under an effective radiated power of 75-180 MW with the HF array having a beam width of 12° at the -3 dB point. Further investigations of X-mode HF-induced phenomena at EISCAT were carried out at high heater frequencies ($f_H > 6.0$ MHz) with an effective radiated power of about 450 – 650 MW and a heater beam width of 5°. They have shown evidence for strong plasma modifications even when the heater frequency was below foF2. It was found that at high heater frequencies the artificial optical emissions at red and green lines accompanied with HF-enhanced ion and plasma lines and strong FAIs can be excited in the F-region of the high latitude ionosphere under X-mode HF pumping towards the magnetic zenith at heater frequencies lying mainly below the foF2 (Blagoveshchenskaya et al., 2014). When $f_H \leq$ foF2, O-mode leakage effects cannot be completely excluded. The only heater pulse under f_H lying above foF2 considered by Blagoveshchenskaya et al. (2014), differed in pulse duration and background conditions. Because of that the X-mode phenomena excited above foF2 require further clarification. Moreover, this heater pulse gave no opportunity for the determination of the frequency range above the foF2 in which various X-mode HF-induced phenomena are generated.

This paper provides further insight into unresolved issues associated with X-mode pumping the high latitude ionospheric F-region by the EISCAT HF heating facility at high heater frequencies ($f_H = 6.2 - 8.0$ MHz). The key parameter considered during the observations is the ratio of the heater frequency to the O- and X-mode critical frequencies. The main attention is paid to the detailed investigation of the X-mode phenomena excited at high heater frequencies lying above the maximum plasma frequency, when the "pure" X-mode phenomena can be generated and the O-mode leakage effects are impossible. We analyze the behavior of HF enhanced ion and plasma lines (HFIL, HFPL), electron density modification, and artificial field-aligned irregularity production depending on the pump frequency proximity to the critical frequencies.

In order to investigate the magnetic zenith effect observed under X-mode pumping, we discuss experimental data obtained under different HF incidence angle of the Tromsø HF heating facility accompanied by elevation angle stepping the EISCAT UHF radar between 72° and 90° (HF beam/radar angle direction).

Finally, we demonstrate the first evidence of the generation of distinct narrow band spectral components in the stimulated electromagnetic emission (SEE) spectra within 1 kHz of the pump frequency induced by an X-mode HF pumping. These spectral components, which can be associated with the ion acoustic (IA), electrostatic ion cyclotron (EIC), and ion Bernstein (IB) waves, were recorded at a distance of about 1200 km away from the EISCAT HF Heating facility.

2. Experimental description and instrumentation

HF pumping experiments have been carried out during Russian EISCAT campaigns during October -November 2013 and October 2012 in quiet magnetic conditions and high solar activity in the afternoon and evening hours between 14 and 18 UT. Artificial perturbations in the high latitude ionosphere F2-layer were created by the EISCAT HF Heating facility (69.6° N, 19.2° E; magnetic dip angle I=77°). We will consider in detail the observational results obtained in the course of experiments on 27 and 28 October, 2 and 3 November 2013 and 21 October 2012. Much of the EISCAT heating campaign from 18 October to 3 November 2013 was described by Blagoveshchenskaya et al. (2014).

Multi-instrument diagnostics were used for the investigation of the X-mode HF-induced phenomena at high pump frequencies (f_H = 6.2 – 7.953 MHz) depending on the ratio of heater frequency to the maximum plasma frequency when the f_H /foF2 ratio was varied through a range from 0.9 to 1.35. The EISCAT UHF incoherent scatter radar at 930 MHz, spatially co-located with the HF heating facility at Tromsø, has been applied in the evaluation the ionospheric plasma parameters and HF-enhanced ion and plasma lines (HFILs and HFPLs) from the backscattered radar spectra. Small-scale field-aligned artificial irregularities (FAIs) were recognized from the backscattered signals received at Hankasalmi, Finland (62.3° N; 26.6° E) by the CUTLASS (Co-operative UK Twin Located Auroral Sounding System) HF coherent radar. The operation modes of the UHF and CUTLASS radars and parameters estimated from their measurements are the same as were used in Blagoveshchenskaya et al. (2014).

The observations of narrow band spectral components in the stimulated electromagnetic emission (SEE) spectra were conducted on 21 October 2012 and 27 and 28 October 2013 in the vicinity of St. Petersburg (60° N, 30° E) at a distance from Tromsø of about 1200 km. On 21 October 2012 the reception of HF heater signals was made with a Doppler spectral method in the 102 Hz band with a frequency resolution of 0.15 Hz. On 27 and 28 October 2013 the HF receiving system, having a large dynamic range allowed the recording of signals in the frequency band of ± 3kHz around the HF pump frequency with a resolution of about 1 Hz. The double rombic HF antenna system oriented to Tromsø was utilized in all experiments for the narrow band SEE observations. In the course of experiment on 21 October 2012 the high power HF radio wave with alternating O/X-mode polarization was injected into the ionosphere at frequency of 7.953 MHz by cycles of 10 min on, 5 min off at three positions of HF beam, 90° (vertical), 84° and 78° (magnetic field-aligned). Only for this experiment were the narrow band SEE measurements near St. Petersburg accompanied by the “classic” stimulated electromagnetic emission (SEE) observations at Tromsø in the frequency band of 200 kHz with a resolution of 200 Hz for searching the spectral component in the SEE spectra commonly observed under the radiation of the O-polarized powerful HF radio waves. On 27 and 28 October 2013 HF pumping was produced in the magnetic field - aligned direction at HF pump frequencies of 7.953 and 6.96 MHz respectively. The O/X-mode HF pumping was performed on 27 October 2013, when the ratio of f_H / foF2 ≤ 1, whereas only X-mode heating well above the critical frequency (f_H /foF2 >1) was used on 28 October 2013.

3. Observational results and discussion

3.1. HF-induced disturbances in the ionospheric plasma and small-scale field-aligned irregularities

Below we present experimental results related to the behavior of plasma parameters, HF-induced turbulence and small-scale field-aligned artificial irregularities in the high latitude ionospheric F2 layer induced by extraordinary polarized powerful HF radio waves injected into the magnetic zenith at high heater frequencies (f_H > 6.0 MHz) depending on the ratio of the HF pump frequency to O- and X-mode critical frequencies of the F2 layer. The distinctive feature of the experiments discussed below is a wide range of critical frequency changes with the unchanged pump frequency. It provides both a proper comparison of X-mode HF-induced phenomena excited under different ratio of f_H /foF2 and an estimation of the frequency band above the foF2 in which such X-mode phenomena are still possible.

3.1.1. Experiment on 3 November 2013

The HF pump wave was radiated at a heater frequency of 6.2 MHz parallel to the magnetic field with an effective radiated power of about 450 MW, from 15.30 – 18 UT. In the course of the experiment the critical frequencies foF2 gradually dropped from 6.7 MHz at 15.30 UT to 5.2 MHz at 18 UT. This makes possible the investigation of the X-mode HF-induced effects depending on the ratio of heater frequency to the maximum plasma frequency from f_H /foF2 = 0.92 to f_H / foF2 = 1.2 in the same experiment for the same background geophysical situation. Figure 1 presents the EISCAT UHF radar observations from 15.30 – 18 UT. It shows the altitude-temporal behavior of the electron density (Ne), electron temperature (Te) and ion velocities (Vi) as well as the Ne and Te variations at fixed altitudes. From 15.30 to 17 UT the heater frequencies were below or near critical frequency foF2 (f_H /foF2 = 0.92 – 1.05). In such ionospheric conditions the O-mode effects can be excited and we have conducted the alternating O/X pumping. From 17 UT, when the foF2 dropped to 5.8 MHz, only X-mode HF pumping was performed.

O-mode heating produced strong electron temperature enhancements up to 2500 – 3000 K (see Fig. 1b and e). The electron heating was accompanied by the generation of upward ion flows from the ionosphere above ~ 350 km (see Fig.1c), which has been observed in a large number of previous EISCAT heating experiments from the UHF radar measurements (see, for a example, Rietveld et al., 2003; Blagoveshchenskaya et al., 2005; Kosch et al., 2010; 2014). The thermal electron heating produces the plasma pressure gradient leading the ions to move upward along the magnetic field line (Kosch et al., 2010).

By contrast, an X-mode heating caused the strong apparent electron density enhancements by 50-70% above the background Ne values, observed up to 600 km (see Fig.1a and d). Such apparent Ne increases are a typical feature of X-mode heating at different heater frequencies from EISCAT UHF radar observations (Blagoveshchenskaya et al., 2011a; 2013). They can be accompanied by HF-enhanced ion and plasma lines (HFILs and HFPLs) in the UHF radar spectra but not in all experiments. In the course of the experiment on 3 November 2013 not too strong enhanced ion and plasma lines were observed in the first three X-mode pulses in the altitude range of 220 -250 km, which did not allow the use of the standard analysis of the radar spectra to get accurate Ne estimations. The Ne behavior at fixed heights (Fig. 1d) is given from the altitude of 390 km, which is well above the altitude region occupied by HF-enhanced ion and plasma lines. In the last three heater pulses HFILs and HFPLs were not excited at all and therefore accurate estimations of the electron densities and temperatures can be performed in a wide altitude range. However, the same Ne enhancements occurred even when the pump frequency exceeded the fxF2 from 17.30 UT (f_H > fxF2). As was shown by Kuo et al. (2010), an X-mode HF pump wave moves the ionospheric F-region upward. The origin of apparent strong Ne enhancements observed under X-mode HF pumping at different heater frequencies is not yet understood. In principle, the accelerated electrons could produce the enhanced ionization Apparent Ne enhancements are typical for X-mode pumping and observed as often as the Te enhancements from UHF radar measurements under the action of O-polarized powerful HF radio waves. Hence, an efficient mechanism of the electron acceleration in a wide altitude range induced by an X-polarized pump wave should be found.

In the course of the X-mode pumping the apparent Ne enhancements were accompanied by some Te increases, which were weak (about 20 % above the background values) in two heater pulses from 15.46 – 15.56 and 16.01 – 16.11 UT, when the heater frequency was below the critical frequency foF2. The Te values, produced by ohmic heating, increased up to 50% after 17 UT, when f_H exceeded foF2.

Small-scale field-aligned artificial irregularities (FAIs) with the spatial size across the geomagnetic field of $l_\perp \approx 8$ - 11.5 m were observed throughout the experiment. This is seen in Figure 2, in which CUTLASS (SuperDARN) Hankasalmi radar observations on 3 November 2013 are presented. Alternating O/X-mode heating was produced from 15.30 – 17 UT, when the heater frequency was below and then near foF2. Here the FAIs with scales of $l_\perp \approx 8$ - 11.5 m were excited both for O- and X-mode HF pumping, but the intensity of the X-mode FAIs was about 4 – 6 dB below that of the O-mode FAIs. This differs from effects observed at lower heater frequencies ($f_H \leq 5.4$ MHz), when X-mode FAIs were not generated at all at heater frequencies below foF2 (Robinson et al., 1997).

From 17 – 18 UT the critical frequency foF2 dropped from 5.9 to 5.2 MHz (f_H / foF2 = 1.05 – 1.19). In such conditions the O-mode effects are impossible and only X-mode HF pumping was produced. As the foF2 values decreased, at first FAIs with $l_\perp \approx 8$ m, and thereafter with $l_\perp \approx 9$ m disappeared (see Fig. 2). Small-scale irregularities with a transverse size of 11.5 m were excited to 18 UT even when the f_H became above the fxF2 and an X-mode pump wave cannot be longer reflected from the ionosphere. Moreover, their intensity, when f_H / foF2 = 1.05 – 1.19 was higher when compared with the case before 17 UT under f_H / foF2 = 0.92 – 1.05.

3.1.2. Experiment on 28 October 2013

The experiment was carried out from 15.30 – 18 UT when the critical frequency foF2 decreased over a wide range from 7.6 to 5.3 MHz. An X-polarized HF pump wave was radiated at a heater frequency of 6.96 MHz along the magnetic field line with an effective radiated power of about 550 MW. The distinctive feature of this X-mode experiment, as compared with the 3 November 2013 event, was the appearance of intense HF-enhanced ion and plasma lines in the UHF radar spectra. Incoherent scatter radars are able to make direct measurements of longitudinal plasma waves. The observed spectra under X-mode heating are typical signatures of electrostatic plasma waves such as Langmuir and ion-acoustic waves. The conversion of powerful electromagnetic HF wave to Langmuir and ion-acoustic waves is direct evidence for the excitation of the parametric decay instability in the vicinity of the reflection height of the pump wave (Fejer, 1979; Hagfors et al., 1983; DuBois et al., 1990; Stubbe et. al., 1992; Stubbe, 1996; Rietveld et al., 2000; Gurevich et al., 2004). The gradual decrease of foF2 over a wide frequency range (7.6 – 5.3 MHz) with the use the a fixed heater frequency of f_H = 6.96 MHz makes the detailed investigation of HF-enhanced ion and plasma lines (HFILs and HFPLs) under different ratios of f_H / foF2 from 0.91 to 1.31 possible, permitting a clarification of the nature of the observed phenomena and an estimation of the frequency band above foF2 in which such X-mode phenomena are generated. The behavior of the undecoded downshifted plasma line power, the altitude distribution of the plasma line intensity, the raw electron density, and the critical frequency foF2 in the course of the experiment of 28 October 2013 are depicted in Figure 3. The raw electron density is defined as the backscattered power of radar signal which points to the generation of the ion lines in the radar spectra. As is evident from Fig.3, the intense HF-enhanced plasma and ion lines were excited through the whole heater cycle on the interval between 15.30 – 16.45 UT. At first the heater frequency was below or near foF2 ($f_H \leq$ foF2) and then lay in the frequency range between the ordinary and extraordinary mode critical frequency, foF2 (foF2 < $f_H \leq$ fxF2). An important point is that HF-induced plasma lines disappeared in the first part of heater-on cycle from 16.46 – 16.56 UT where the heater frequency exceeded the fxF2, f_H > fxF2 (see Fig.3 a, b). Remember, that fxF2 = foF2 + $f_{ce}/2 \approx$ (foF2 + 0.7) MHz, where f_{ce} is the electron gyrofrequency. The disappearance of HFPLs was accompanied by a change in the behavior of the backscattered power and therefore HF-enhanced ion lines (Fig. 3c), which became much weaker and had a random character.

We also compared the behavior of ion and plasma line spectra for X-mode pumping under different ratios of the heater frequency to the critical frequency of the F2 layer (f_H / foF2 < 1 and f_H / foF2 > 1). The procedure for obtaining the spectra is the same as described by Blagoveshchenskaya et al. (2014). Figure 4 presents the maximum power of the HF-enhanced downshifted plasma lines, upshifted and downshifted ion lines against altitude for HF pulses, when f_H / foF2 < 1 (15.31 – 15.41 UT) and f_H / foF2 > 1 (16.31 – 16.41 UT) in the course of the X-mode experiment on 28 October 2013. By and large they confirm the result presented by Blagoveshchenskaya et al. (2014) for other EISCAT HF pumping experiments, when it was only possible to make such a comparison between two heater pulses of different durations obtained from two different experiments under different background conditions. As is obvious from Fig. 4, the altitude distribution of the downshifted ion line power exhibits two power maxima observed both under f_H / foF2 < 1 (Fig. 4a) and f_H / foF2 > 1 (Fig. 4b). The HF-enhanced ion and plasma lines were generated over a wider range of heights when f_H / foF2 > 1 as compared with the event under f_H / foF2 < 1.

The CUTLASS Hankasalmi radar observations in the course of the X-mode experiment on 28 October 2013 from 15.30 – 18 UT are presented in Figure 5. The CUTLASS radar ran at operational frequencies of about 16, 18, and 20 MHz. Due to the Bragg condition ($l_\perp = c/2f_R$, where f_R is the radar operational frequency, and c is a speed of light) the size of FAIs perpendicular to the magnetic field $l_\perp$ responsible for the backscatter was about $l_\perp \approx 9$, 8, and 7.5 m respectively. As is seen from Fig. 5, the artificial field-aligned irregularities were generated throughout the experiment both when f_H / foF2 < 1 and f_H / foF2 > 1.

The artificial small-scale field-aligned irregularities were observed together with HF-enhanced ion and plasma lines. However, FAIs with $l_\perp \approx 9$ and 8 m persisted to the present even when HF-induced plasma lines disappeared. This occurred when f_H exceeded fxF2 and an X-polarized pump wave can no longer be reflected from the ionosphere, whereas the larger scale of FAIs in this experiment with $l_\perp \approx 9$, accompanied by apparent electron density enhancements, were generated up to the end of experiment (18 UT), when the values of foF2 dropped to 5.3 MHz, showing that the heater frequency was above the foF2 by 1.7 MHz.

CUTLASS Hankasalmi radar measurements have demonstrated that at high heater frequencies (f_H > 6.0 MHz) in the afternoon and evening hours the X-mode FAIs with size of $l_\perp \approx$ 7.5 – 11.5 m were excited when the f_H / foF2 < 1 as well as f_H / foF2 > 1. Moreover, they can even be excited under f_H > fxF2 up to 1 MHz. This differs from the X-mode FAIs at low heater frequencies ($f_H \leq 5.4$ MHz), which cannot be generated, when heater frequencies lie below foF2. However, such FAIs with $l_\perp \approx$ 11.5 – 15 m were excited above the foF2 by 0.1 – 1.2 MHz (Blagoveshchenskaya et al. 2013). There is also a significant difference in the decay times for X-mode FAIs excited at high and low heater frequencies. The FAI decay time at f_H > 6.0 MHz (see Figs. 2 and 5) did not exceed 3 min in the evening hours whereas it can reach the unusually long values of 15 -20 min at low heater frequencies between 3.95 – 5.423 MHz (Blagoveshchenskaya et al. 2011; 2013). In spite of the fact that the generation of FAIs induced by an X-polarized high power HF radio wave is a repeatable and easily reproducible feature from EISCAT heating experiments, the mechanism of their excitation is still remains poorly studied. Mention may be made of the process of stimulated scattering of an X-mode powerful radio wave by ions with the upper-hybrid or electron-cyclotron oscillations excited in the plasma (Vas'kov and Ryabova, 1998). Intense Langmuir waves can also generate FAI with a broad spectrum due to the filamentation instability (Kuo and Schmidt, 1983). However, for the small-scale FAIs excited, when high-power X-mode HF radio wave did not reflect from the ionosphere (f_H > fxF2), the most plausible mechanism for their generation could be closely related to and driven by the HF-induced large-scale artificial irregularities. An X-polarized HF pump wave heats the F-region of the ionosphere through collision processes more effectively as compared with the O-mode HF pumping (Kuo et al., 2010). The artificial large-scale irregularities are formed at the heater frequencies above and below the foF2 by the growth of a self-focusing instability of an HF pump wave beam (Gurevich, 1978; Vas'kov and Gurevich, 1979).

3.2. Magnetic zenith effect

The magnetic zenith effect is a typical phenomenon observed in the high latitude ionospheric plasma under the impact of high-power electromagnetic waves with ordinary polarization (O-mode). The magnetic zenith effect comes from a nonlinear process of the structuring HF waves along the magnetic field (Gurevich et al., 2002; 2005). Modification experiments carried out at the EISCAT HF heater at Tromsø and HAARP at Gakona, Alaska, have shown that the most intense HF-induced electron heating, optical emissions, and FAIs were excited when the O-mode HF pump wave was transmitted in the magnetic field-aligned direction (Kosch et al., 2002; Rietveld et al., 2003; Pedersen et al., 2003; Mishin et al., 2005). As was shown by Isham et al. (1999), Langmuir wave intensities also maximized under HF pumping parallel the magnetic field.

We have considered the EISCAT UHF radar observations in the course of the experiment on 21 October 2012. The experiment was carried out from 14 -16 UT under quiet magnetic conditions, when the critical frequency of the F2 layer gradually dropped from 8.9 MHz at 14 UT to 7.6 MHz at 16 UT. High power HF radio waves were injected into the ionosphere at a frequency of 7.953 MHz in cycles of 10 min on, 5 min off at three positions of the HF beam, 90° (vertical), 84° and 78° (magnetic field-aligned). From cycle to cycle the polarization of HF pump wave was changed between O- and X-mode. The effective radiated power was about ERP = 650 MW. In the course of each HF pulse the elevation angle of the UHF radar was changed every minute from 74 to 90°. The X-mode pulses have demonstrated that the most intense HF-enhanced ion and plasma lines (HFILs and HFPLs) from the incoherent scatter radar observations, which are direct evidence of the parametric decay instability, were observed when the high-power HF electromagnetic wave was injected towards the magnetic zenith (77°). For X-mode injections in the vertical direction (90°), the HFILs and HFPLs were not excited. When the HF pump wave was radiated in the 84°direction, HF-enhanced ion and plasma lines were much weaker as compared with the 77° pointing direction. The same is true for the apparent electron density and temperature enhancements observed from the EISCAT UHF radar observations. An O-mode HF pumping shows the appearance of HFILs and HFPLs under any incidence angle of the HF pump wave (90, 84 and 77°). The intensities of the HFILs and HFPLs for O- mode pumping maximized for HF pumping towards the magnetic zenith, that is in agreement with previous O-mode observations (Isham et al., 1999). However, their intensity was much weaker as compared with the X-mode HFILs and HFPLs.

Further to this, we consider the behavior of HF-enhanced ion and plasma lines depending on the elevation angle of the EISCAT UHF radar, when the heater frequency is above the critical frequency of the F2 layer. The experiment was carried out on 2 November 2013 in the evening hours. The HF pump wave with X-polarization was transmitted at a frequency of 6.96 MHz towards the magnetic zenith. The effective radiated power was about 550 MW. During each 20 min heater pulse the elevation angle of the EISCAT UHF radar was changed between 72 and 86°. As an example, Figure 6 depicts the intensities of the undecoded downshifted plasma lines and raw electron density (backscattered power) from 14.30 – 15 UT. During this pulse the heater frequency of f_H = 6.96 MHz exceeded the critical frequency of foF2 = 6.4 MHz (f_H / foF2 = 1.09). It is seen that HF-enhanced ion and plasma lines were excited for radar elevation angles between 76 - 79°, being the most intense in the field-aligned pointing the UHF radar (77°).

The ion line spectra obtained from the EISCAT UHF radar measurements for different radar elevation angles of 76, 77, 78, and 79° are shown in Figure 7. The following features of the ion line spectra in the magnetic field-aligned direction, when the heater frequency exceeded the foF2, can be seen from Fig. 7: (1) intensities of the upshifted and downshifted ion lines are maximized; (2) the appearance of two power maxima at different altitudes is observed both for downshifted and upshifted ion lines; (3) the appearance of a nonshifted (zero frequency) spectral component.

As is evident from the EISCAT UHF radar spectra, an X-mode HF heater wave transmitted parallel to the magnetic field at heater frequencies above the critical frequency foF2 is able to excite intense HF-enhanced ion lines (upshifted, downshifted and nonshifted) and plasma lines. The most intense HF-enhanced ion and plasma lines were generated when the position of the HF heater beam and UHF radar were field-aligned, therefore, they exhibit a strong magnetic zenith effect similar to the O-mode heating at frequencies below the foF2, as was shown by Isham et al. (1999). Such HF-enhanced ion and plasma lines are indicative of the parametric decay instability (PDI) and oscillating two stream instability (OTSI) (Fejer, 1979; Dysthe et al., 1983; Stubbe, 1996, Kuo et al., 1997). PDI and OTSI give the most effective channels to convert electromagnetic HF radio waves to electrostatic plasma waves, including Langmuir waves of high frequency and ion acoustic waves of low frequency. In spite of HF-enhanced ion and plasma lines (HFPLs and HFILs) in the incoherent radar spectra being indicative of the parametric decay instability, it is still not clear in what way an X-mode pump wave can excite the PDI and even OTSI, especially taking into account that the X-mode HFPLs and HFILs were much higher intensity, as compared with the O-mode effects, and were observed through the whole HF heater cycle together with artificial small-scale field-aligned irregularities (Blagoveshchenskaya et al., 2014).

3.3 Stimulated electromagnetic emissions

The stimulated electromagnetic emission (SEE) was discovered by Thidé et al. (1982) at the HF heating facility near Tromsø (Norway). During the last three decades the classical SEE spectral components with an offset of 1 kHz up to 200 kHz from the HF heater frequency have been extensively studied at different HF heating facilities located at mid- and high latitudes (see, for example, Leyser, 2001 and references therein). The most common SEE spectral feature, observed when the O-polarized HF pump wave is radiated in the vicinity of the vertical direction at a frequency below the critical frequency foF2 and away from the electron gyro harmonic frequency, is the downshifted maximum (DM). The DM is a strong emission with a pronounced peak downshifted by 8 - 12 kHz below the heater frequency f_H (Thidé et al., 1982).

Recent experiments at the HAARP facility in Gakona, Alaska, have demonstrated the generation of narrow band SEE spectral components within 1 kHz of the HF pump frequency, produced by the stimulated Brillouin scatter (SBS) (Norin et al., 2009; Bernhardt, et al., 2009; 2010; Fu et al., 2013). Such strong components are shifted only by tens of Hz from the HF pump frequency. Their origin is explained by the parametric decay of an ordinary (O-mode) polarized powerful HF electromagnetic wave to the electrostatic (ion acoustic or ion cyclotron) wave with the secondary electromagnetic wave scattered by SBS (Dysthe et al., 1977; Fejer, 1977; Norin et al., 2009; Bernhardt, et al., 2010; Fu et al., 2013; Mahmoudian et al., 2013). The ion acoustic

(IA) spectral component appears with a frequency offset of 10 - 30 Hz (Bernhardt et al., 2009) and the electrostatic ion cyclotron (EIC) line with frequency offset about of 50 Hz (for O+ ions) from the HF pump frequency (Bernhardt et al., 2010; Mahmoudian et al., 2013). Observations of the narrow band spectral components at the second harmonic of the electron cyclotron frequency showed the excitation of harmonic sidebands near multiples of the ion cyclotron frequency produced by the stimulated ion Bernstein emissions (Bernhardt et al., 2011). It is important to mention that the variety of the narrow band spectral components in the SEE spectra, such as the ion acoustic, electrostatic ion cyclotron and ion Bernstein waves, were observed in the vicinity of the HAARP facility only for O-mode pumping of the ionosphere.

Below we present the first experimental evidence of the generation of the various narrow band spectral components in the SEE spectra in the F region of the high latitude ionosphere induced by an extraodinary (X-mode) powerful HF radio wave and recorded far away from the HF heating facility. The first observations of the narrow band spectral component within 100 Hz band frequency under X-mode pumping, was made on 21 October 2012 near St. Petersburg at a distance of 1200 km away from the HF heater. These observations were accompanied by EISCAT UHF radar measurements and “classic” SEE measurements in the 200 kHz band at Tromsø. Observational results showing the spectrogram of the heater signal within a 100 Hz frequency band are depicted in Figure 8 (top panel). For comparison, the “classic” SEE dynamic spectra (spectrograms) recorded at Tromsø are presented in Fig. 8 (bottom panel). Details of the experiment on 21 October 2012 and the behaviors of the HF-enhanced ion and plasma lines (HFILs and HFPLs) from UHF radar observations are given in Section 3.2.

An unexpected feature was found in the spectra within 100 Hz of the HF heater frequency received near St. Petersburg at a distance of 1200 km from the EISCAT HF heater facility (Fig. 8, top panel). During X-mode pulses with the HF beam pointing in the magnetic field-aligned direction (14.46 -14.56 and 15.46 – 15.56 UT), a defined spectral component downshifted by 26 - 37 Hz below the heater frequency can be seen. Such a spectral component was not recognized under vertical pointing the HF beam and was very weak, when X-mode HF pumping was produced at an elevation angle of 84° (15.16 – 15.26 UT). It is an indication of the magnetic zenith effect in the X-mode narrow band spectral component behavior. There is a close correlation between the narrow band spectral lines and the HF-enhanced ion lines (HFILs) from the EISCAT UHF radar observations. As was mentioned in Section 2.2, the strongest HFILs were observed under X-mode pumping towards the magnetic zenith. They were much weaker in the 84°direction and were not excited at all for X-mode injections in vertical direction (90°). We suggest that the spectral component with the frequency offset 26 - 37 Hz observed under X-mode HF pumping towards the magnetic zenith can be attributed to the stimulated Brillion scatter process in which the excited electrostatic wave could be an ion acoustic wave. The O-mode pumping cycles at any position of HF heater beam did not show the presence of defined spectral components within 100 Hz at a distance far away from the HF heater, in spite of the generation of HFILs under any incidence angle of the HF pump wave.

Unfortunately, we were not able to carry out the narrow band SEE measurements at Tromsø in the vicinity of the HF heating facility. The frequency resolution of the SEE equipment used (200 Hz) was not sufficient to observe the narrow band SEE. As a consequence only the "classic" SEE measurements at the frequency band of 200 kHz were conducted. As is seen, SEE observations near Tromsø (Fig. 8, bottom panel) show the appearance of a well-defined DM component in the SEE spectra downshifted by about 12 kHz from the heater frequency and observed only during O-mode heater pulses in any position of the HF heater beam (90, 84, 78°). The X-mode pulses did not exhibit any defined spectral components offset from one to tens kHz from the heater frequency, but the X-mode SEE spectra were very noisy as compared with the O-mode spectra. The generation of a DM component for O-mode pumping was accompanied by strong small-scale artificial field-aligned irregularities (FAIs). In such conditions X-mode FAIs were also excited but their intensity was weaker as compared with O-mode FAIs.

In subsequent experiments on 27 and 28 October 2013, the HF receiving system, which allowed the recording of the heater signals in the frequency band of ± 3kHz around the HF pump frequency with a resolution of about 1 Hz, was used for observations near St. Petersburg. On 27 October 2013 narrow band SEE observations were conducted from 12 to 13.30 UT under quiet magnetic conditions, when the critical frequency of the F2 layer slightly dropped from 10.4 to 9.4 MHz. An HF pump wave with O/X polarization was radiated at frequency of 7.953 MHz towards the magnetic zenith by cycles of 20 min on, 10 min off. The effective radiated power was about ERP = 650 MW. The spectrogram of the heater signal within 600 Hz recorded near St. Petersburg on 27 October 2013 is shown in Figure 9a. As is seen, the O-mode pulse from 12.01 – 12.21 UT, similarly to the O-mode cycles on 21 October 2012, did not exhibit any narrow band spectral components at distance far away from HF heater. By contrast, the subsequent two X-mode cycles (12.31 – 12.51 and 13.01 – 13.21 UT) under the same background conditions have demonstrated a variety of well defined narrow band spectral lines below and above the pump frequency. Figure 9b depicts the power spectra obtained at different times in the course of the X-mode pulse from 12.31 – 12.51UT. The spectra show the well-defined narrow band spectral lines downshifted and upshifted by about 55 Hz from the pump frequency, which can be attributed to the electrostatic ion cyclotron (EIC) waves, and their multiple harmonics (up to four discrete spectral lines). The downshifted emissions were paired with upshifted spectral components. The intensity of the main downshifted emission was below the HF pump wave by – (20-30) dB during the pump pulse from 12.31 – 12.51 UT. It is important, that for the conditions of this experiment the HF pump frequency was near the sixth electron gyro harmonic frequency (below by about 200 kHz). The observed multiple spectral lines are similar to structures ordered by harmonics of the ion gyro frequency observed in the vicinity of the HAARP heating facility in the course of O-mode HF pumping experiment near the second electron gyro harmonic frequency, and are caused by stimulated ion Bernstein emissions (Bernhardt et al., 2011).

Coincident with the electrostatic ion cyclotron harmonic waves, the spectral lines downshifted by 28 and 84 Hz can be recognized in Fig. 9b. They can be attributed to the first and third harmonic of an ion acoustic wave. The second harmonic (56 Hz) cannot be resolved due to the strong EIC wave downshifted by about 55 Hz from the pump frequency with a width of the order of 10 Hz. In the course of the HF pump pulses the HF-enhanced ion lines and FAIs were excited. Their behavior for O- and X-mode pulses is very similar to those previously described for the experiment on 21 October 2012.

On 28 October 2013 narrow band SEE observations near St. Petersburg were carried out from 17 – 18 UT. The distinctive feature of the experiment is that the measurements were made when the heater frequency exceeded foF2 as well as fxF2. The critical frequency foF2 dropped from 5.8 MHz at 17 UT to 5.3 at 18 UT, while the X-polarized HF pump wave was at 6.96 MHz. The details of HF pumping and experimental results from EISCAT UHF radar and CUTLSS observations on 28 October 2013 from 15.30 – 18 UT are given in Section 3.1.2. SEE observations were conducted only in the last hour of this experiment.

Figure 10a demonstrates the spectrogram of the heater signal within 400 Hz recorded near St. Petersburg on 28 October 2013 from 17 to 18 UT. As is seen, the only very intense spectral line downshifted by about 55 Hz from the HF pump frequency was recorded in all X-mode heater pulses. As an example, Figure 10b shows the power spectra of the pump wave obtained at different times of the heating cycle from 17.01 – 17.11 UT. The observed emission line can be attributed to the electrostatic ion cyclotron wave. The intensity of this spectral emission was only 5 -15 dB less than the HF pump wave intensity. As was shown in Section 3.1.2, at pump frequencies lying above the extraordinary critical frequency fxF2, HF-enhanced ion and plasma lines are not excited. However, even when f_H > fxF2, some sporadic burst-like HFILs can be seen from UHF radar observations (see Fig. 3). The X-mode FAIs were generated up to 18 UT (see Fig. 5).

The observations of the narrow band SEE spectral components under X-mode HF pumping demonstrate evidence of the excitation of various narrow band spectral components in the SEE spectra (within 1 kHz of the pump frequency), which can be associated with the ion acoustic (IA), electrostatic ion cyclotron (EIC), and electrostatic ion cyclotron harmonic waves (otherwise known as neutralized ion Bernstein waves). It has been suggested that these spectral components can be attributed to the stimulated Brillion scatter (SBS) process. The results obtained have shown that an X-polarized electromagnetic wave scattered by SBS can propagate more than one thousand km without significant deterioration. It is important to note that O-mode narrow band spectral lines were not observed at a large distance from the EISCAT HF heating facility.

4. Summary and concluding remarks

We have presented experimental results related to the variety of phenomena in the high latitude ionospheric F2 layer induced by an extraordinary (X-mode) HF pump wave at high heater frequencies (f_H = 6.2 - 8.0 MHz) depending on the pump proximity to the critical frequencies foF2 and fxF2. Results come from a large body of X-mode HF pumping experiments at the EISCAT HF heating facility in October 2012 and October – November 2013 with the use of multi-instrument diagnostics. X-mode HF pumping experiments have been carried out at high heater frequencies of 6.2, 6.96, and 7.953 MHz in quiet magnetic conditions under effective radiated powers of 450 – 650 MW. The distinctive feature of the experiments is a wide diapason of critical frequency changes, when the f_H /foF2 ratio was varied through a range from 0.9 to 1.35. It provides both a proper comparison of X-mode HF-induced phenomena excited under different ratio of f_H /foF2 and an estimation of the frequency band above the foF2 in which such X-mode phenomena are still possible.

Intense HF-enhanced ion and plasma lines (HFILs and HFPLs) in the UHF radar spectra, which are the typical signatures of ion-acoustic and Langmuir waves, were excited through the HF pump pulse under different ratios of heater frequency to the maximum plasma frequency (f_H / foF2≤ 1 and f_H /foF2 >1). The generation of the HFILs and HFPLs above foF2 occurred in the frequency range between the ordinary and extraordinary mode critical frequencies, foF2 ≤ f_H ≤ fxF2. An important point is that HF-induced plasma and ion lines disappeared when the heater frequency exceeded the fxF2 and an X-polarized pump wave can no longer be reflected from the ionosphere.

HF-enhanced ion and plasma lines were accompanied by the generation of small-scale artificial field-aligned irregularities (FAIs) with a spatial size across the geomagnetic field of $l_\perp \approx$ 7.5 – 9 m. An unexpected feature in the FAI behavior is their generation under conditions when the X-mode wave cannot be reflected from the ionosphere (f_H exceeded fxF2) and HF-enhanced plasma and ion lines were not excited. Under such conditions FAIs were accompanied by apparent electron density enhancements and the electron heating increased by 50% from the background values. In spite of the fact that the generation of X-mode FAIs is a repeatable feature from EISCAT heating experiments, the mechanism of their excitation remains poorly studied. Mention may be made of the process of stimulated scattering an X-mode powerful radio wave by ions (Vas'kov and Ryabova, 1998) and intense Langmuir waves which can also generate FAI with a broad spectrum due to the filamentation instability (Kuo and Schmidt, 1983). However, for the FAIs excited under f_H > fxF2, the most plausible mechanism of their generation could be closely related to and driven by HF-induced large-scale artificial irregularities.

The magnetic zenith effect was found in the behavior of the X-mode HF-enhanced ion and plasma lines. X-mode pumping experiments under different pointing directions of the HF antenna beam (90, 84 and 77°) have demonstrated that the most intense HF-enhanced ion and plasma lines were observed when the high-power HF electromagnetic wave was transmitted towards the magnetic zenith (77°). Experimental results from an elevation angle stepping of the

EISCAT UHF radar between 72 and 90° have also shown that at heater frequencies above the critical frequency foF2 the most intense HF-enhanced ion (upshifted, downshifted and nonshifted) and plasma lines were generated when the UHF radar was pointing field-aligned. Such HF-enhanced ion and plasma lines are indicative of the parametric decay instability (PDI) and oscillating two stream instability (OTSI) excited above foF2. The same is true for the apparent electron density enhancements observed from the EISCAT UHF radar observations.

We have presented the first experimental evidence showing that an extraodinary (X-mode) powerful HF radio wave is able to generate different narrow band spectral components in the SEE spectra (within 1 kHz of pump frequency) in the F region of the high latitude ionosphere, which were recorded far away from the HF heating facility. The observed X-mode spectral lines can be associated with the ion acoustic (IA), electrostatic ion cyclotron (EIC), and electrostatic ion cyclotron harmonic waves (otherwise known as neutralized ion Bernstein waves). It has been suggested that these spectral components can be attributed to the stimulated Brillion scatter (SBS) process in which the excited electrostatic wave could be an ion acoustic or electrostatic ion cyclotron waves. Similar narrow band SEE spectral lines, induced by the ordinary (O-mode) polarized HF pump wave, were observed in the HAARP experiments in the immediate vicinity (by 20 km) of the HF heating facility (Bernhardt, et al., 2009; 2010; 2011; Fu et al., 2013). However, the comparison between the O- and X-mode narrow band spectra within 1 kHz from the pump frequency clearly demonstrated that only an X-polarized electromagnetic wave scattered by SBS can propagate more than one thousand km without significant deterioration. O-mode narrow band spectral lines were not observed at a large distance from the EISCAT HF heating facility.

In spite of the fact that excitation of intense X-mode HF-induced phenomena in the F-region of the high latitude ionosphere is a repeatable and easily reproducible feature from EISCAT heating experiments, many aspects of the nonlinear interaction between an X-polarized HF pump wave and the ionosphere plasma are still remain poorly understood and require further theoretical as well as experimental research. Among the theoretical aspects we would like to point out the following.

HF-enhanced ion and plasma lines in the incoherent radar spectra are indicative of the parametric decay instability, but it is not clear through what mechanism an X-mode pump wave can excite the PDI and even OTSI, especially taking into account that the X-mode HF-induced ion and plasma lines are much higher intensity, as compared with the O-mode effects, are observed through the whole HF pump pulse and coexist with strong artificial small-scale field-aligned irregularities.

The generation mechanisms of small-scale artificial field-aligned irregularities needs validation, particularly for FAIs excited when the heater frequency exceeds the fxF2 and an X-polarized pump wave cannot be reflected from the ionosphere.

Strong apparent Ne enhancements from EISCAT UHF radar measurements are typical for X-mode pumping and are observed as often as the Te enhancements under the action of O-polarized HF pump waves. They occurred along the magnetic field line in a wide altitude range whether the HF-enhanced ion and plasma lines were excited or not. The origin of such apparent Ne enhancements under X-mode HF pumping at different heater frequencies is not yet understood and needs the clarification. In principle, the accelerated electrons can produce the enhanced ionization. Hence, an efficient mechanism of the electron acceleration induced by an X-polarized pump wave should be found.

In closing, we list desirable experiments to be carried out in future for better understanding the unusually strong phenomena in the F-region of the ionosphere induced by an X-polarized HF pump wave. It is known that significant changes of phenomena, excited near the upper hybrid resonance altitude and the reflection height of the ordinary (O-mode) HF pump wave, occur when the HF pump frequency is lying in the vicinity of the electron gyro harmonic frequency. HF-induced effects in the vicinity of the electron gyro harmonics have been extensively studied at different HF heating facilities. It will be interesting to investigate the electron gyro harmonic effects under an X-mode HF pumping into the F-region of the ionosphere for different numbers of electron gyroharmonics. There is also a need to find out the influence of the HF heater beam width and effective radiated power on characteristics of the plasma turbulence and other phenomena associated with the X-mode plasma modification. It is important to determine the threshold values of effective radiated power (ERP) needed to generate various X-mode HF-induced phenomena at heater frequencies f_H lying above and below the critical frequency foF2 as well as to compare the ERP thresholds of alternating O/X-mode effects at heater frequencies $f_H \leq$ foF2. It is of interest also to compare the simultaneous observations of the narrow band spectral emissions in the immediate vicinity of HF heating facility and far away from it for O- and X-mode HF pumping of the high latitude ionospheric F region. Such narrow band SEE observations should be accompanied by UHF incoherent scatter radar and HF coherent scatter radar measurements.

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References

Bernhardt, P.A., Selcher, C.A., Lehmberg, R.H., Rodriguez, S.P., Thomason, J.F., McCarrick, M.J., Frazer, G.J., 2009. Determination of the electron temperature in the modified ionosphere over HAARP using the HF pumped Stimulated Brillouin Scatter (SBS) emission lines. Annales Geophysicae 27, 4409-4427.

Bernhardt, P. A., Selcher, C.A., Lehmberg, R.H., Rodriguez, S.P., Thomason, J.F., Groves, K.M., McCarrick, M.J., Frazer, G.J., 2010. Stimulated Brillouin Scatter in a magnetized ionospheric plasma. Physics Review Letters 104, 165004, doi:10.1103/PhysRevLett.104.165004.

Bernhardt, P.A., Selcher, C. A., Kowtha, S., 2011. Electron and ion Bernstein waves excited in the ionosphere by high power EM waves at the second harmonic of the electron cyclotron frequency, 2011. Geophysical Research Letters, 38, doi:10.1029/2011GL049390.

Blagoveshchenskaya, N. F., Kornienko, V.A., Borisova, T.D., Rietveld, M.T., Bösinger, T., Thidé, B., Leyser, T.B., Brekke, A., 2005. Heater-induced phenomena in a coupled ionosphere-magnetosphere system. Advances in Space Research 38, 2495–2502.

Blagoveshchenskaya, N. F., Borisova, T. D., Yeoman, T., Rietveld, M. T., Ivanova, I.M., Baddeley, L.J., 2011a. Artificial field-aligned irregularities in the high-latitude F region of the ionosphere induced by an X-mode HF heater wave. Geophysical Research Letters 38, doi: 10.1029/2011GL046724.

Blagoveshchenskaya, N. F., Borisova, T.D., Yeoman, T. K., Rietveld, M. T., 2011b. The effests of modification of a high-latitude ionosphere by high-power HF radio waves. Part 1. Results of multi-instrument ground-based observations. Radiophysics and Quantum Electronics (Engl. Transl.) 53, (9–10), 512 – 531.

Blagoveshchenskaya, N. F., Borisova, T. D., Yeoman, T. K., Rietveld, M. T., Häggström, I., Ivanova, I. M., 2013. Plasma modifications induced by an X-mode HF heater wave in the high latitude F region of the ionosphere. Journal of Atmospheric and Solar-Terrestrial Physics 105-106, 231 – 244.

Blagoveshchenskaya, N. F., Borisova, T. D., Kosch, M., Sergienko , T., Brändström, U., Yeoman, T. K., Häggström I., 2014. Optical and Ionospheric Phenomena at EISCAT under Continuous X-mode HF Pumping. Journal of Geophysical Research: Space Physics 119, 10,483–10,498, doi:10.1002/ 2014JA020658.

DuBois, D. F., Rose, H. A., Russell, D., 1990. Excitation of strong Langmuir turbulence in plasmas near critical density: Application to HF heating of the ionosphere. Journal of Geophysical Research 95, 21221–21272.

Dunkan, L.M., Behnke, R.A., 1978. Observations of self-focusing electromagnetic waves in the ionosphere. Physics Review Letters 41, 998 – 1001.

Dysthe, K.B., Leer, E., Trulsen, J., Stenflo, L., 1977. Stimulated Brillouin scattering in the ionosphere. Journal of Geophysical Research 82, 717 – 718.

Dysthe, K.B., Mjølhus, E., Pécseli, H.L., Rypdal, K., 1983. A thermal oscillating two-stream instability. Physics Fluids 26, 146 – 157.

Erukhimov, L.M., Metelev, S.A., Myasnikov, E.N., Mityakov, N.A., Frolov, V.L., 1987. Artificial ionospheric turbulence (review). Radiophysics and Quantum Electronics (Engl. Transl.) 31, 156 – 171.

Farley, D.T., LaHoz, C., Fejer, B.G., 1983. Studies of the self-focusing instability at Arecibo. Journal of Geophysical Research 88, 2093 – 2102.

Fejer, J.A., 1977. Stimulated Brillouin scattering and incoherent backscatter. Geophysical Research Letters 4, 289 – 290.

Fejer, J.A., 1979. Ionospheric Modification and Parametric Instabilities. Rev. Geophys. Space Phys., 17 (1), 135 - 153.

Frolov, V.L., Bolotin, I.A., Komrakov, G.P., et al., 2014. Generation of artificial ionospheric irregularities in the midlatitude ionosphere modified by high-power high-frequency X-mode

radio waves. Radiophysics and Quantum Electronics (Engl. Transl.) 57, (6), 393 – 416.
Fu, H., Scales, W. A., Bernhardt, P. A., Samimi, A., Mahmoudian, A., Briczinski, S. J., McCarrick, M. J., 2013. Stimulated Brillouin scatter and stimulated ion Bernstein scatter during electron gyroharmonic heating experiments. Radio Science 48, 607-616, doi:10.1002/2013RS005262.
Gurevich, A. V., 1978. Nonlinear Phenomena in the Ionosphere. Springer-Verlag, New York.
Gurevich, A., Zybin, K. Carlson, H., Pedersen , T., 2002. Magnetic zenith effect in ionospheric modifications. Physics Letters A 305, (5), 264–274.
Gurevich, A.V., Carlson, H.C., Medvedev, Yu.V., Zybin, K.R., 2004. Langmuir turbulence in ionospheric plasma, Plasma Physics Reports, 30, 995–1005.
Gurevich, A., Zybin, K. Carlson, H., 2005. Magnetic zenith effect in ionospheric modifications. Radiophysics and Quantum Electronics (Engl. Transl.) 48, (9), 686 – 699.
Gurevich, A.V., 2007. Nonlinear effects in the ionosphere. Physics – Uspekhi (Engl. Transl.) 50, 1091 – 1121.
Hagfors, T., Kofman, W., Kopka, H., Stubbe, P., Ijnen, T., 1983. Observations of enhanced plasma lines by EISCAT during heating experiments. Radio Science 18, 861 – 866.
Isham, B., Rietveld, M., Hagfors, T., LaHoz, C., Mishin, E., Kofman, W., Leyser, T., van Eyken, A., 1990. Aspect angle dependence of HF enhanced incoherent backscatter. Advances in Space Research 24, (8), 1003–1006.
Kosch, M., Rietveld, M., Yeoman, T., Cierpka, K., Hagfors, T., 2002. The high-latitude artificial aurora of 21 February 1999: An analysis. Advances in Polar Upper Atmosphere Research 16, 1–12.
Kosch, M. J., Ogawa, Y., Rietveld, M.T., Nozawa, S., Fujii, R., 2010. An analysis of pump-induced artificial ionospheric ion upwelling at EISCAT. Journal of Geophysical Research 115, A12317, doi:10.1029/2010JA015854.
Kosch, M. J., Vickers, H., Ogawa, Y., Senior, A., Blagoveshchenskaya , N., 2014. First

observation of the anomalous electric field in the topside ionosphere by ionospheric modification over EISCAT. Geophysical Research Letters 41, doi:10.1002/ 2014GL061679.

Kuo, S.P., Schmidt, G, 1983. Filamentation instability in magneto plasmas. Physics Fluids 26, 2529 – 2536.

Kuo, S., Lee, M., Kossey, P.,1997. Excitation of oscillating two stream instability by upper hybrid pump in ionospheric heating experiments at Tromsø. Geophysical Research Letters 24, 2969 -2972.

Kuo, S., Cheng, W.-T., Snyder, A., Kossey, P., Battis, J., 2010. Contrasting O/X-mode heater effects on O-mode sounding echo and the generation of magnetic pulsations. Geophysical Research Letters 37, L01101, doi: 10.1029/2009GL041471.

Leyser, T. B., 2001. Stimulated electromagnetic emissions by high-frequency electromagnetic pumping of the ionospheric plasma. Space Science Review 98, 223 – 328.

Lofas, H., Ivchenko, N., Gustavsson, B., Leyser, T.B., Rietveld, M.T., 2009. F-region electron heating by X-mode radiowaves in underdense conditions. Annales Geophysicae 27, 2585 – 2592.

Mahmoudian, A., Scales, W. A., Bernhardt, P. A., Fu, H., Briczinski, S. J., McCarrick M.J., 2013. Investigation of ionospheric stimulated Brillouin scatter generated at pump frequencies near electron gyroharmonics. Radio Science 48, 685697, doi:10.1002/2013RS005189.

Mishin, E.V., Burke, W. J., Pedersen, T., 2005. HF-induced airglow at magnetic zenith: theoretical considerations. Annales Geophysicae 23, 47 – 53.

Norin, L., Leyser, T. B., Nordblad, E., Thidé, B., and McCarrick, M., 2009. Unprecedentedly strong and narrow electromagnetic emissions stimulated by high-frequency radio waves in the ionosphere. Physics Review Letters 102, 065003, doi:PhysRevLett102.065003..

Pedersen, T. R., McCarrick, M., Gerken, E., Selcher, C., Sentman, D., Carlson, H. C., Gurevich, A., 2003. Magnetic zenith enhancement of HF radio-induced airglow production at HAARP, Geophysical Research Letters 30, (A4), 1169, doi:10.1029/2002GL016096.

Rietveld, M.T., Isham, B., Kohl, H., Hoz, C.L., Hagfors, T., 2000. Measurements of HF-enhanced plasma and ion lines at EISCAT with high altitude resolution. Journal of Geophysical Research 105, 7429 – 7439.

Rietveld, M.T., Kosch, M. J., Blagoveshchenskaya, N.F., Kornienko, V.A., Leyser, T.B., Yeoman, T.K., 2003. Ionospheric electron heating, aurora and striations induced by powerful HF radio waves at high latitudes: aspect angle dependence. Journal of Geophysical Research 108(A4), 1141, doi:10.1029/2002JA009543.

Robinson, T.R., 1989. The heating of the high latitude ionosphere by high power radio waves. Physics Reports 179, 79 – 209.

Robinson, T.R., Stocker, A.J., Bond, G.E., Eglitis, P., Wright, D.M., Jones T.D., 1997. O-and X-mode heating effects observed simultaneously with the CUTLASS and EISCAT radars and low power HF diagnostic at Tromsø. Annales Geophysicae 15, 134 - 136.

Stubbe, P., Kohl, H., Rietveld, M.T., 1992. Langmuir turbulence and ionospheric modification. Journal of Geophysical Research 97, 6285 – 6297.

Stubbe P., 1996. Review of ionospheric modification experiments at Tromsø. Journal of Atmospheric and Solar-Terrestrial Physics 58, 349 – 368.

Thidé, B., Kopka, H., Stubbe, P., 1982. Observations of stimulated scattering of a strong high frequency radio wave in the ionosphere. Physics Review Letters 49, 1561 – 1564.

Vas'kov, V.V., Ryabova, N.A., 1998. Parametric excitation of high frequency plasma oscillations in the ionosphere by a powerful extraordinary radio wave. Advances in Space Research 21, 697 – 700.

Figure captions

Figure 1. EISCAT UHF radar observations in the magnetic zenith (13°S) obtained with 30 s integration time during HF modification experiment at Tromsø on 3 November 2013 from 15.30 – 18 UT. Altitude-temporal variations of the electron density (a), temperature (b), ion velocities (c), and variations in time at fixed altitudes of the electron density (d) and temperature (e). High-power HF radio waves with alternating O/X polarization were transmitted along the magnetic field line at frequency of 6.2 MHz by pulses of 10 min on, 5 min off. Effective radiated power is about of 450 MW. The heater pulses and polarization of HF pump wave are drawn on the time axis of the bottom plot.

Figure 2. CUTLASS (SuperDARN) radar observations at Hankasalmi, Finland, at frequencies of about 13, 16, and 18 MHz, by using the single beam 5 directed over Tromsø, on 3 November 2013 from 15.30 – 18 UT. Backscatter averaged over the HF-induced ionosphere patch (top panel) and backscatter at every frequency in the dependence on distance (range gate) and time (bottom panels). The features of HF heater transmission are the same as in Fig. 1

Figure 3. EISCAT UHF radar observations in the magnetic zenith (13°S) in the course of HF modification experiment at Tromsø on 28 October 2013 from 15.30 – 17.45 UT. Behavior in time of undecoded plasma line powers (a), altitude distribution of downshifted plasma line intensities (b), altitude distribution of raw electron densities, or backscattered powers (c), and critical frequencies of the F2 layer, foF2 (d). High-power HF radio waves with X polarization were transmitted along the magnetic field line at frequency of 6.96 MHz by pulses of 10 min on, 5 min off. Effective radiated power was about of 550 MW. The heater pulses are drawn on the time axis.

Figure 4. The maximum power of HF-enhanced downshifted plasma lines, upshifted and downshifted ion lines against the altitude during HF pulses from15.31 – 15.41 UT at 15.32, 15.34, 15.36, 15.38, and 15.40 UT, when f_H / foF2 < 1 (a) and from 16.31 – 16.41 UT at 16.32, 16.34, 16.36, 16.38, and 16.40 UT, when f_H / foF2 > 1 (b) in the course of the X-mode experiment on 28 October 2013. The power spectra were calculated with integration time of 30 s and height resolution of 3 km from the "raw" data obtained with the EISCAT UHF radar at Tromsø. The details of HF heater transmission are the same as in Fig. 3.

Figure 5. CUTLASS (SuperDARN) radar observations at Hankasalmi, Finland, at frequencies of about 16, 18, and 20 MHz, by using the only beam 5 directed over Tromsø, on 28 October 2013 from 15.30 – 18 UT. Backscatter averaged over the HF-induced ionosphere patch (top panel) and backscatter at every frequency in the dependence on distance (range gate) and time (bottom panels). The features of HF heater transmission are the same as in Fig. 3. The heater pulses are drawn on the time axis.

Figure 6. EISCAT UHF radar observations under elevation angle stepping between 74 and 86° in the course of HF modification experiment at Tromsø on 2 November 2013 from 14.30 – 15 UT, when the heater frequency exceeded the critical frequency of the foF2. Behavior in time of undecoded plasma line powers at the heights of 209 – 383 km (top panel) and the altitude distribution of raw electron densities, or backscattered powers (bottom panel). High-power HF radio waves with X polarization were transmitted along the magnetic field line at frequency of 6.96 MHz from 14.31 – 14.51 UT. Effective radiated power was about of 550 MW. During HF pump pulse the UHF radar elevation angle was changed every 2 min in an orderly sequence of 74, 76, 77, 78, 79, 80, 82, 84, and 86°. The UHF radar elevation angles are shown on the time axis.

Figure 7. The ion line spectra depending on the altitude from the EISCAT UHF radar measurements on 2 November 2013 for radar elevation angles of 76, 77, 78, and 79° within the HF pump pulse from 14.31 – 14.51 UT. The ion line spectra were calculated with integration time of 30 s and height resolution of 3 km from the "raw" data obtained with the EISCAT UHF radar at Tromsø. The features of HF heater transmission are the same as in Fig. 6.

Figure 8. The spectrogram of the heater signal within 100 Hz received near St. Petersburg at a distance about 1200 km away from Tromsø (top panel) and spectrogram of the "classic" SEE in the 200 kHz frequency band recorded near Tromsø (bottom panel) during the alternating O/X mode HF pumping on 21 October 2012 from 14 – 16 UT. High power HF radio wave was injected into the ionosphere at frequency of 7.953 MHz by cycles of 10 min on, 5 min off at three positions of HF beam, such as 90 (vertical), 84 and 78° (magnetic field-aligned). From cycle to cycle the polarization of HF pump wave was changed between O- and X-mode. Effective radiated power was about ERP = 650 MW. The heater pulses, HF beam position, and polarization of HF pump wave are shown on the time axis of the top panel.

Figure 9. The spectrogram of the heater signal within 600 Hz of pump frequency recorded near St. Petersburg for alternating O/X-mode HF pumping on 27 October 2013 from 12 to 13.30 UT(a) and power spectra obtained at 12.32.40, 12.35.40, 12.36.20, and 12.38.10 UT in the course of the X-mode pulse from 12.31 – 12.51 UT(b). HF pump wave was transmitted at frequency of 7.953 MHz by cycles of 20 min on, 10 min off towards the magnetic zenith. Effective radiated power was about ERP = 650 MW. The heater pulses and polarization of HF pump wave are shown on the time axis of the top panel.

Figure 10. The spectrogram of the heater signal within 400 Hz of pump frequency recorded near St. Petersburg for X-mode HF pumping on 28 October 2013 from 17 to 18 UT(a) and power

spectra obtained at 17.03.30, 17.05.40, 17.08, and 17.09.20 UT in the course of the pulse from 17.01 – 17.11 UT(b). The features of HF heater transmission are the same as in Fig. 3. The heater pulses are shown on the time axis of the top panel.

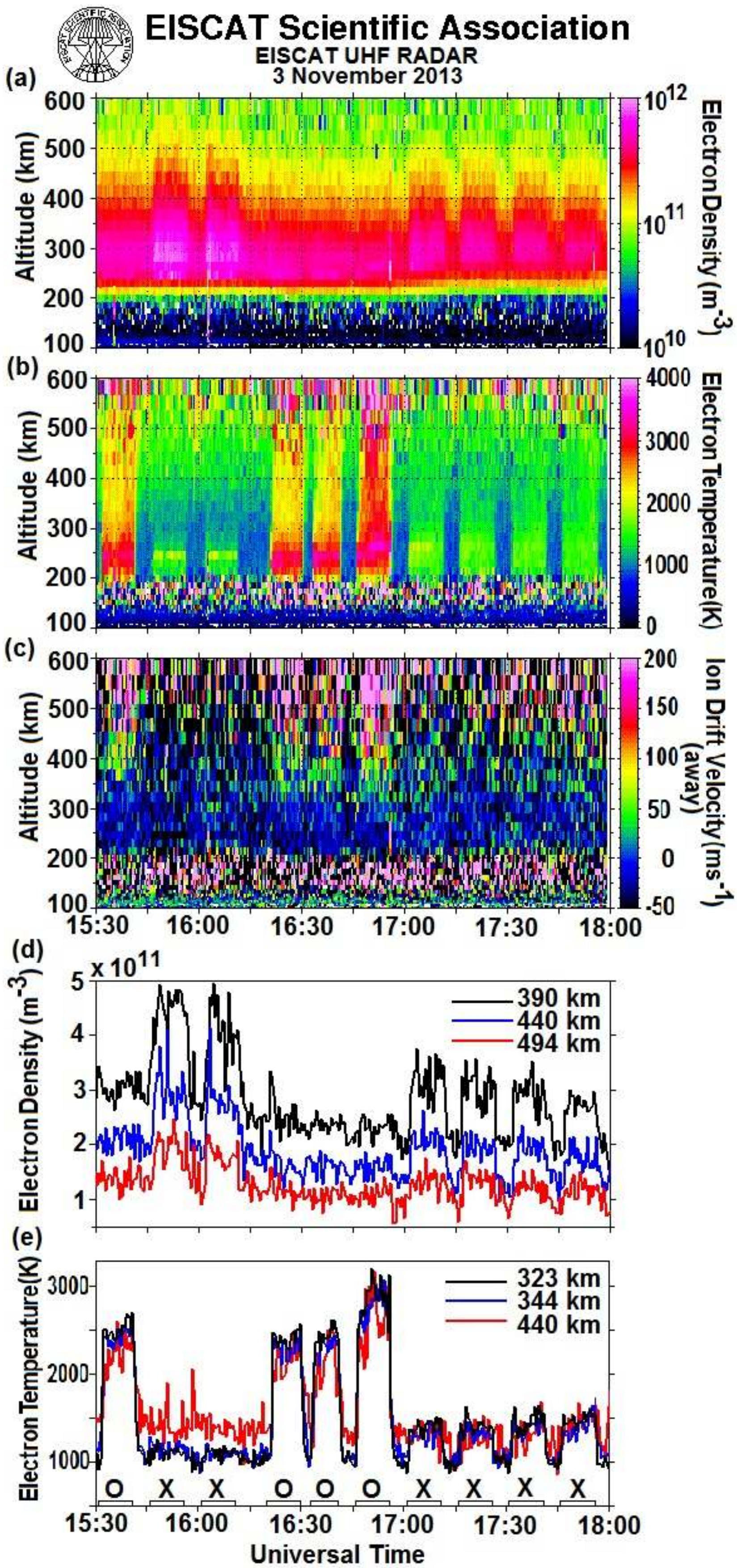
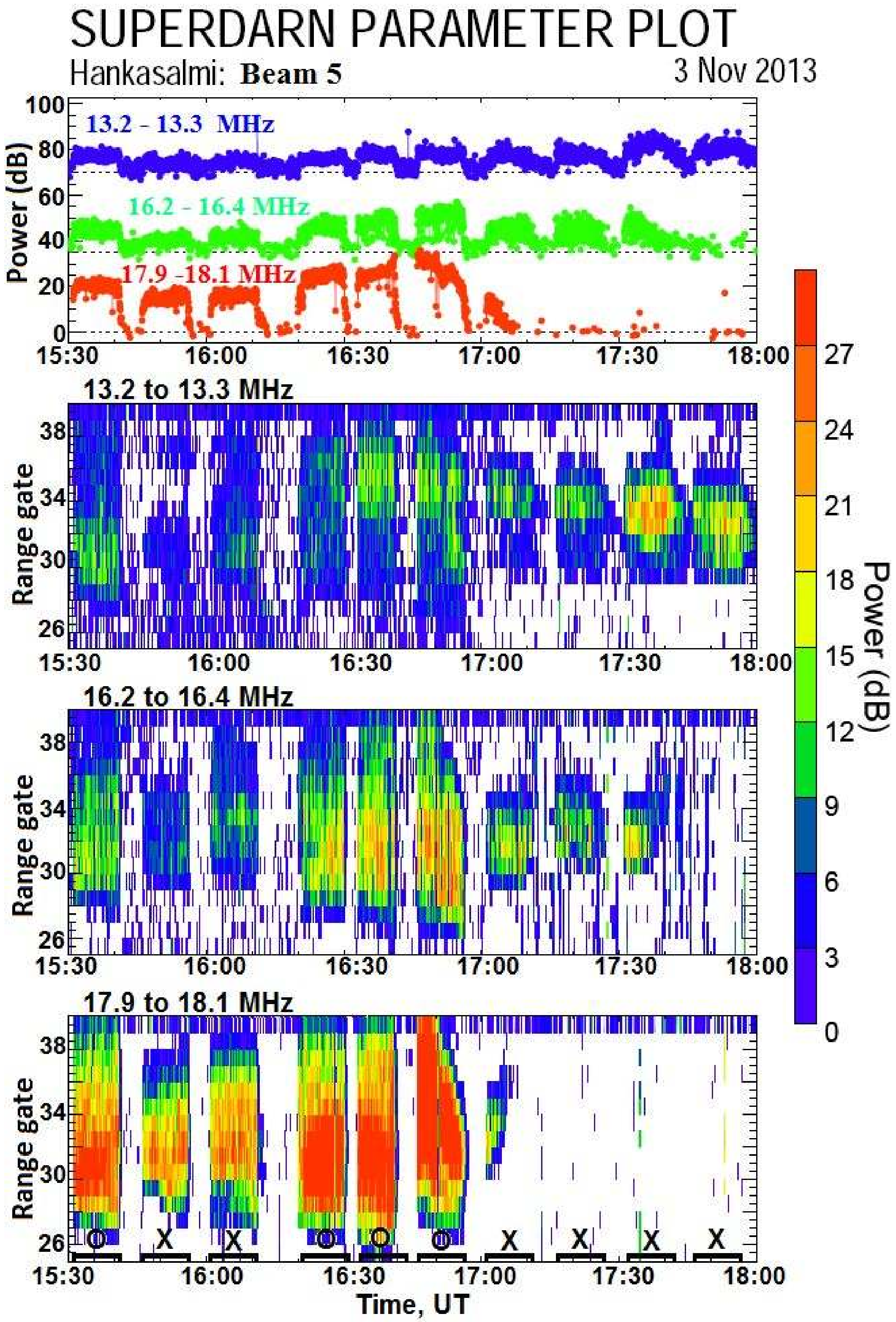

EISCAT Scientific Association
EISCAT UHF RADAR
3 November 2013
(a)
Altitude (km)
Electron Density (m-3)
(b)
Altitude (km)
Electron Temperature(K)
(c)
Altitude (km)
Ion Drift Velocity (ms-1) (away)
15:30
16:00
16:30
17:00
17:30
18:00
(d)
x 10^11
Electron Density (m-3)
390 km
440 km
494 km
(e)
Electron Temperature(K)
323 km
344 km
440 km
O X X O O O X X X X
Universal Time

Figure 1.



SUPERDARN PARAMETER PLOT
Hankasalmi: Beam 5
3 Nov 2013
Power (dB)
13.2 - 13.3 MHz
16.2 - 16.4 MHz
17.9 -18.1 MHz
13.2 to 13.3 MHz
16.2 to 16.4 MHz
17.9 to 18.1 MHz
Range gate
Time, UT
Power (dB)

Figure 2.

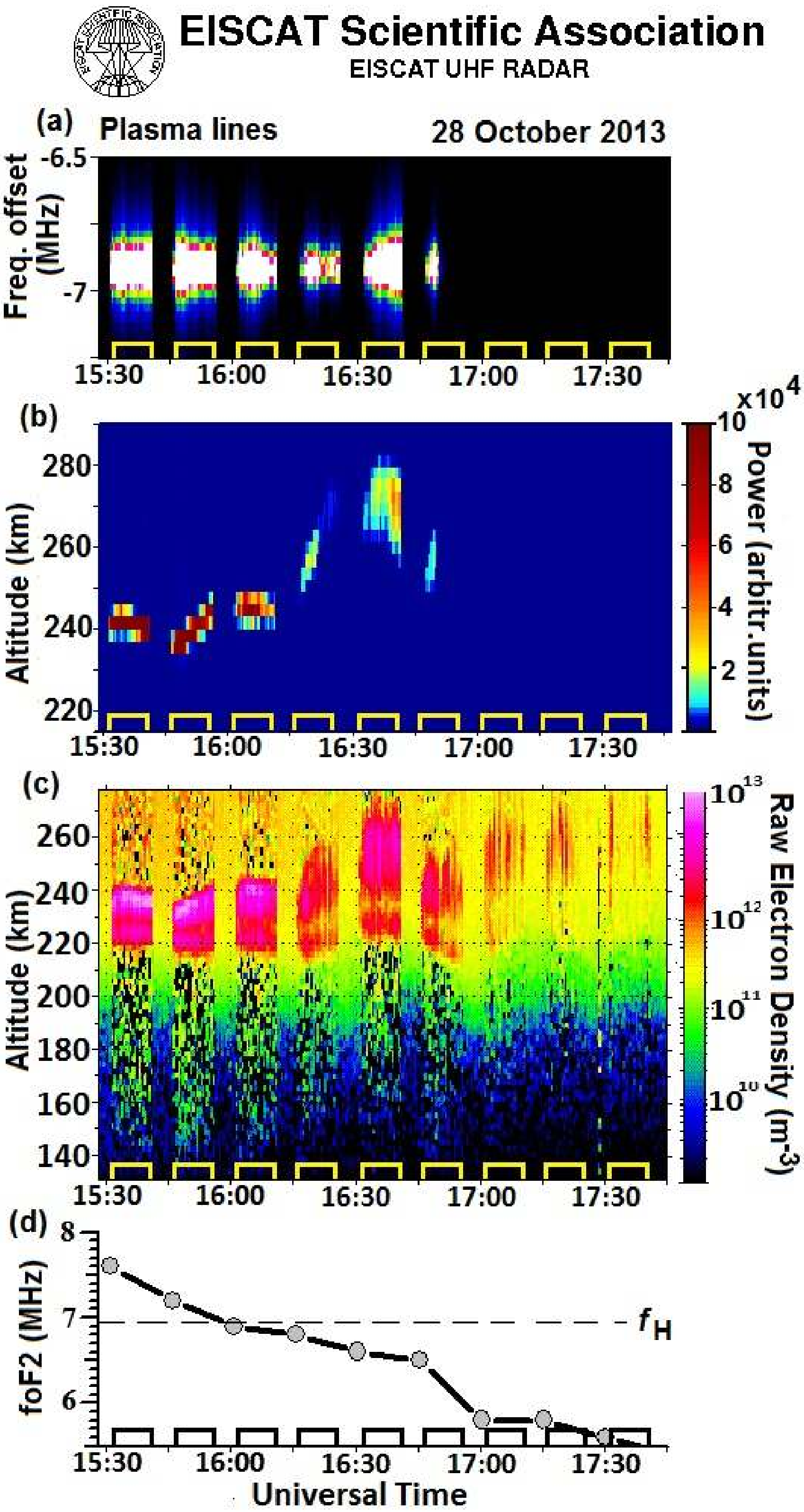
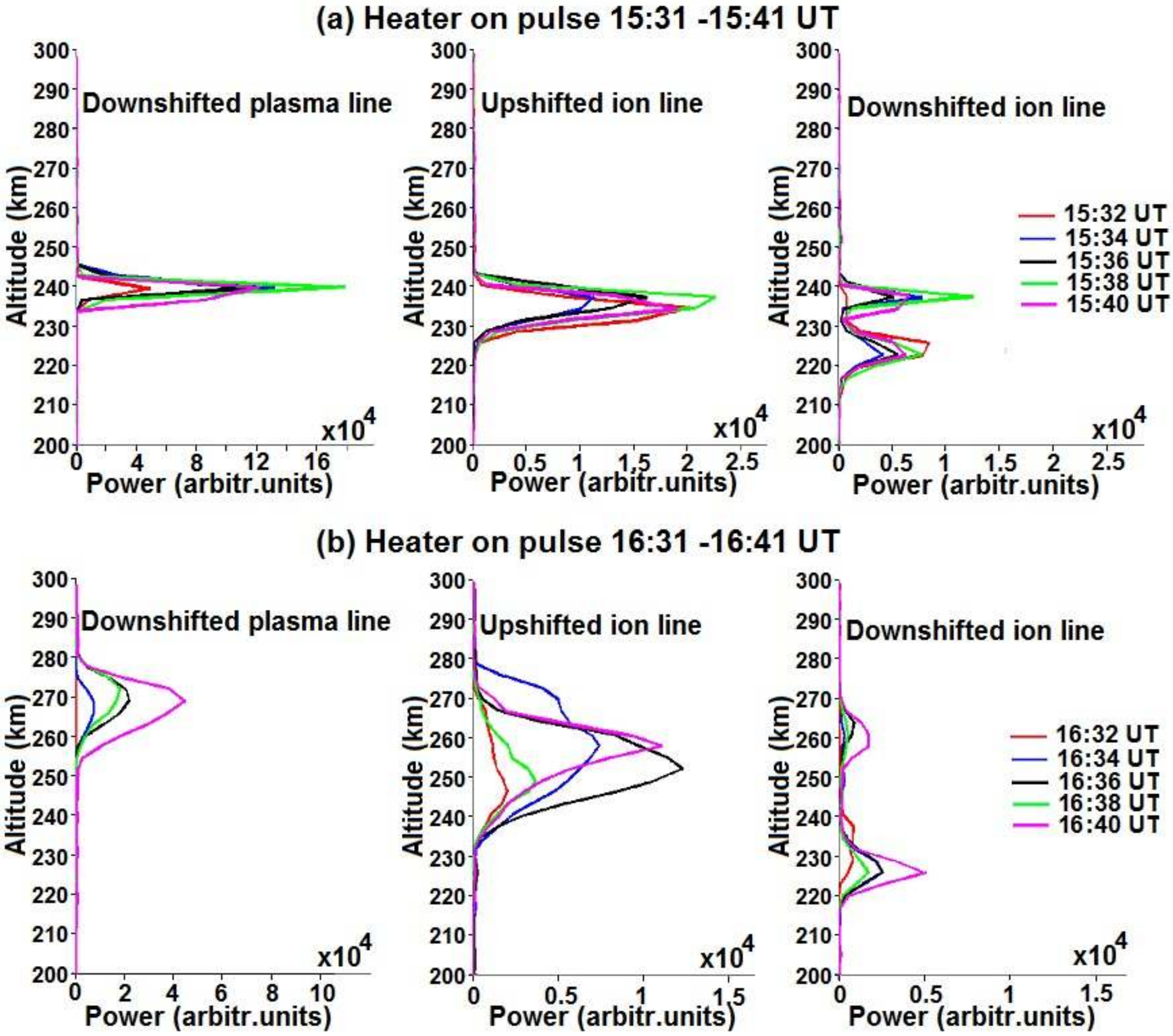
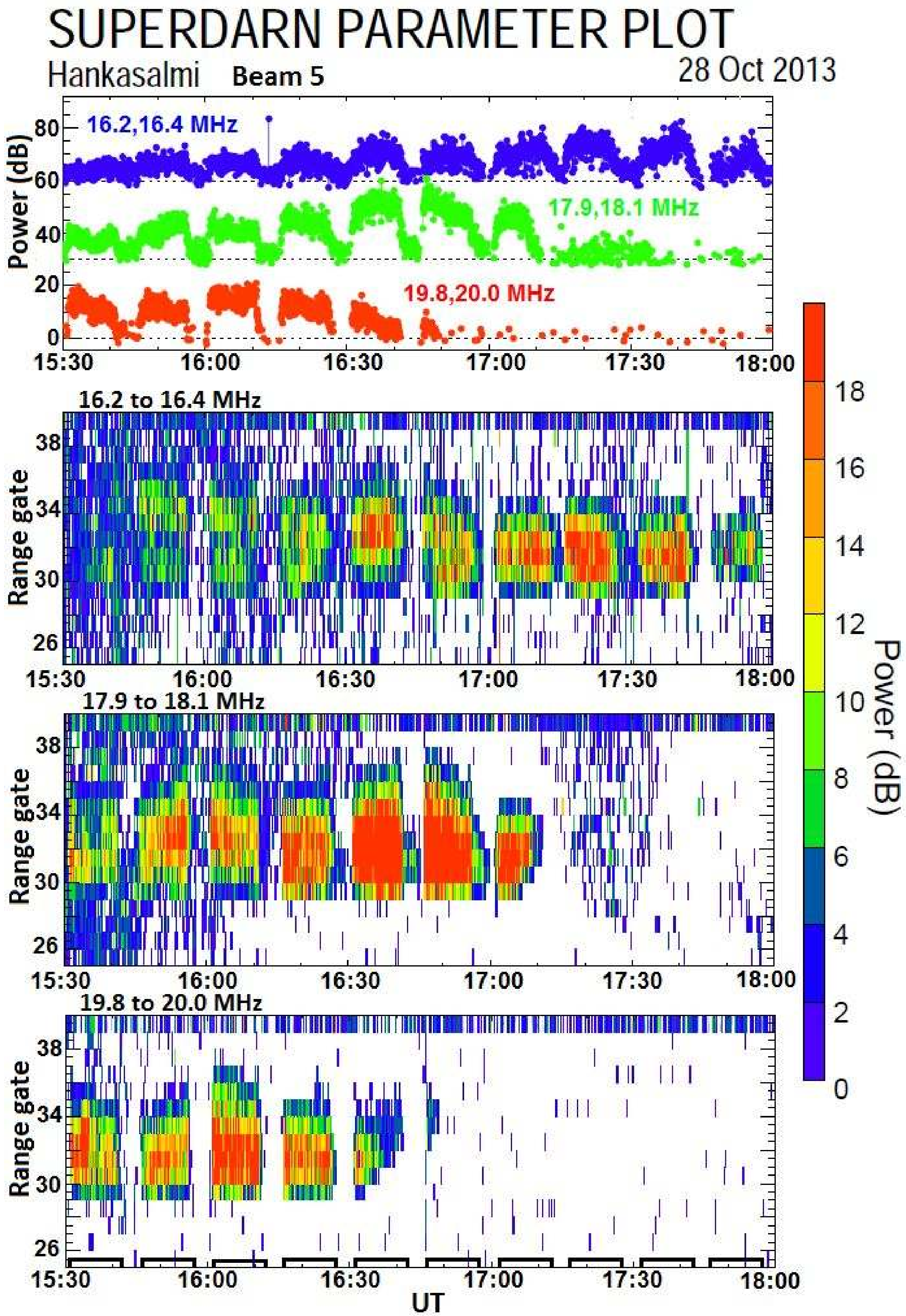

EISCAT Scientific Association
EISCAT UHF RADAR
(a)
Plasma lines
28 October 2013
Freq. offset (MHz)
-6.5
-7
15:30
16:00
16:30
17:00
17:30
(b)
x10^4
10
8
6
4
2
Power (arbitr.units)
Altitude (km)
280
260
240
220
15:30
16:00
16:30
17:00
17:30
(c)
Altitude (km)
260
240
220
200
180
160
140
Raw Electron Density (m^-3)
15:30
16:00
16:30
17:00
17:30
(d)
foF2 (MHz)
8
7
6
f_H
15:30
16:00
16:30
17:00
17:30
Universal Time

Figure 3.



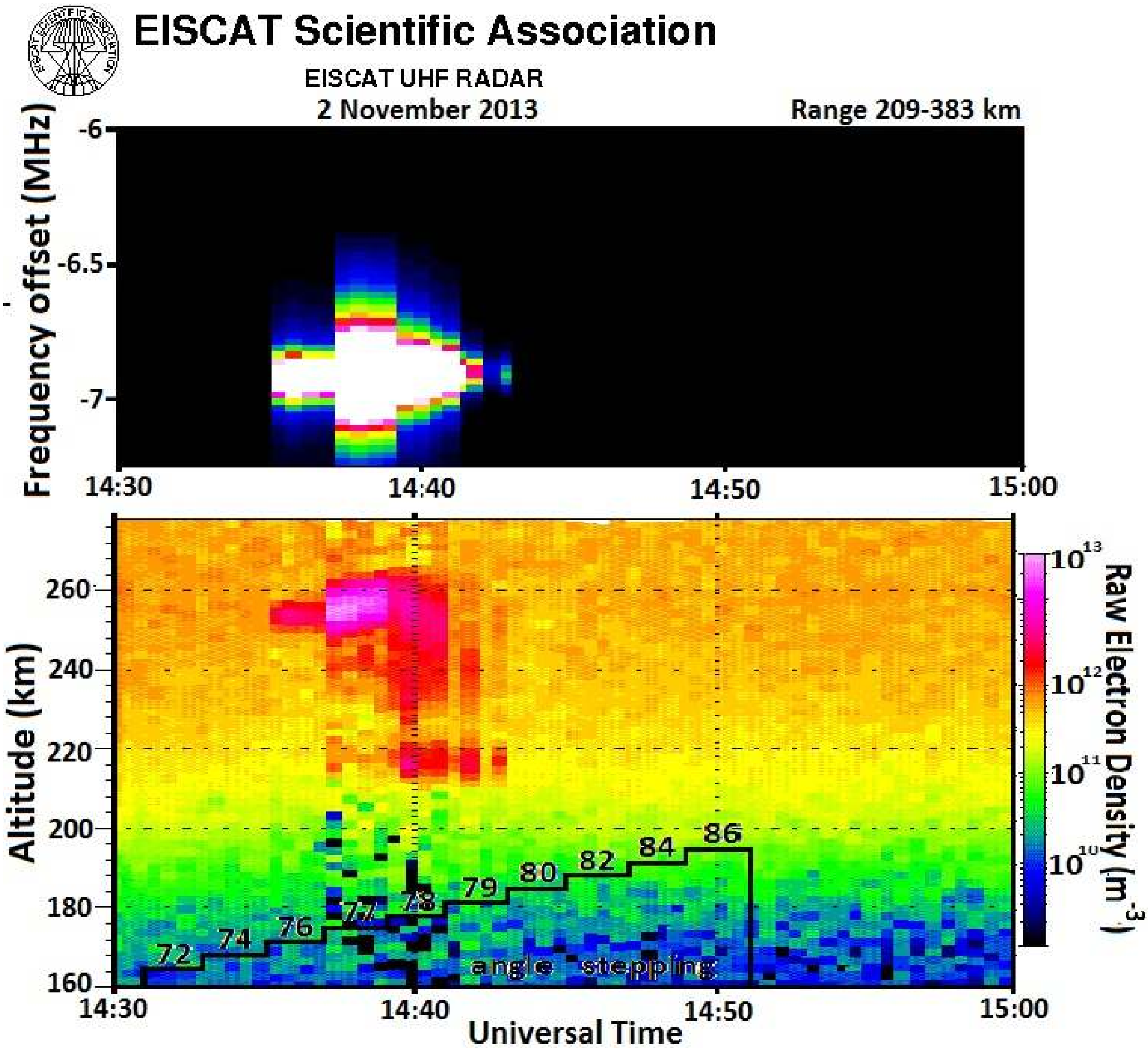
(a) Heater on pulse 15:31 -15:41 UT
Downshifted plasma line
Upshifted ion line
Downshifted ion line
Altitude (km)
Power (arbitr.units)
x10^4
15:32 UT
15:34 UT
15:36 UT
15:38 UT
15:40 UT
(b) Heater on pulse 16:31 -16:41 UT
16:32 UT
16:34 UT
16:36 UT
16:38 UT
16:40 UT

Figure 4.



SUPERDARN PARAMETER PLOT
Hankasalmi Beam 5
28 Oct 2013
16.2,16.4 MHz
17.9,18.1 MHz
19.8,20.0 MHz
Power (dB)
16.2 to 16.4 MHz
17.9 to 18.1 MHz
19.8 to 20.0 MHz
Range gate
UT
Power (dB)

Figure 5.



EISCAT Scientific Association
EISCAT UHF RADAR
2 November 2013
Range 209-383 km
Frequency offset (MHz)
-6
-6.5
-7
14:30
14:40
14:50
15:00
Altitude (km)
260
240
220
200
180
160
72
74
76
77
78
79
80
82
84
86
angle stepping
Universal Time
Raw Electron Density (m⁻³)

Figure 6.

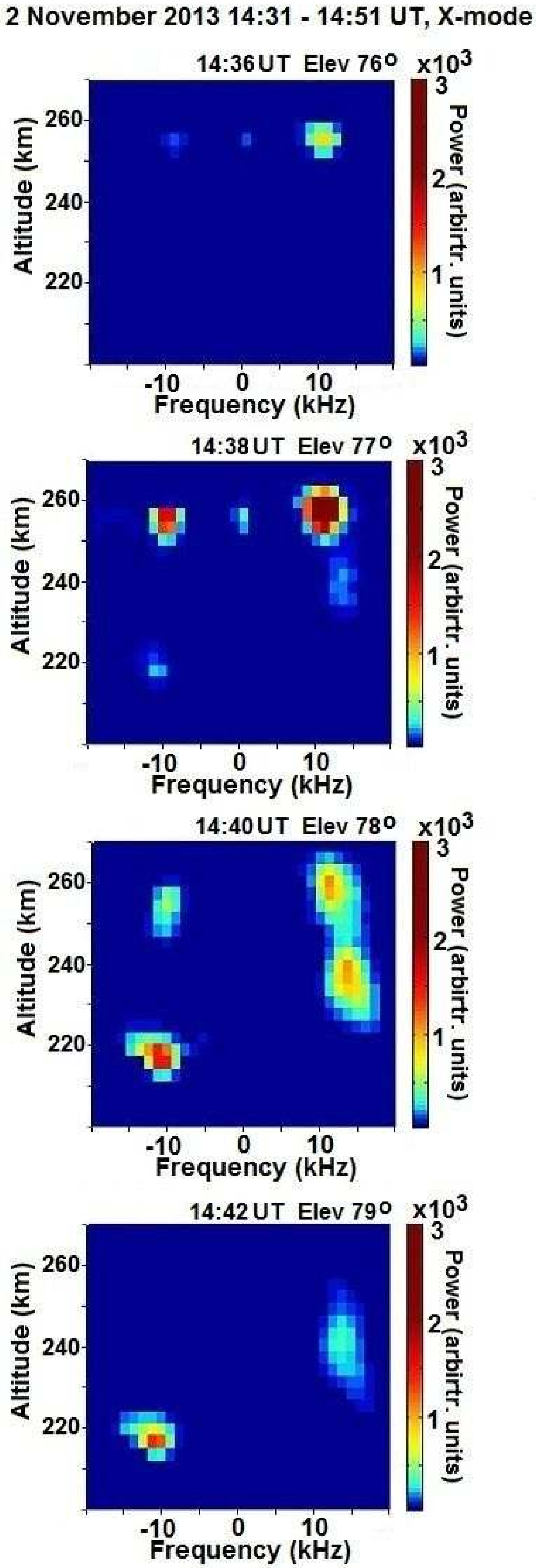
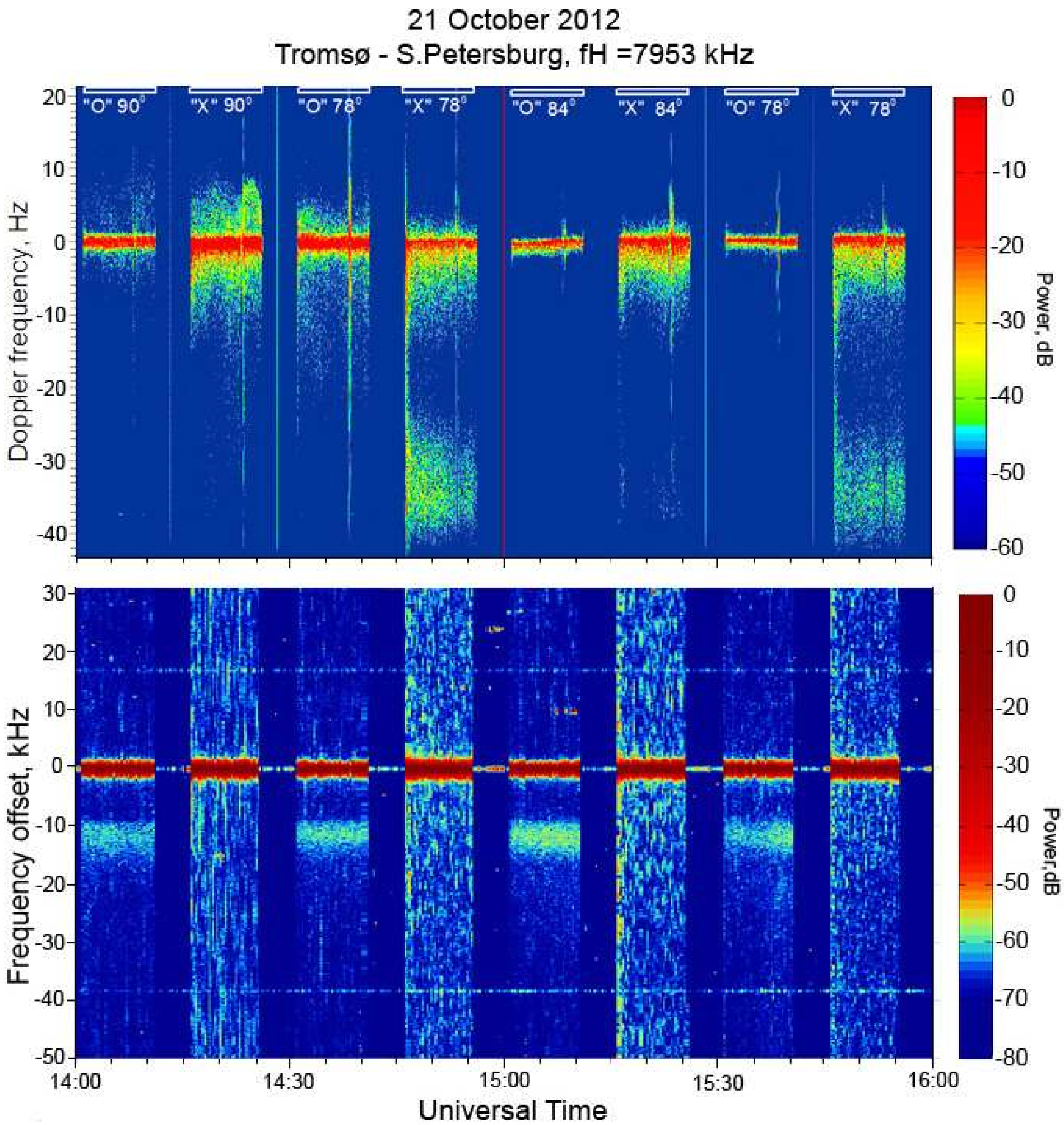

2 November 2013 14:31 - 14:51 UT, X-mode
14:36UT Elev 76°
14:38UT Elev 77°
14:40UT Elev 78°
14:42UT Elev 79°
x10^3
Power (arbirtr. units)
Altitude (km)
Frequency (kHz)

Figure 7.



21 October 2012
Tromsø - S.Petersburg, fH =7953 kHz
"O" 90°
"X" 90°
"O" 78°
"X" 78°
"O" 84°
"X" 84°
"O" 78°
"X" 78°
Doppler frequency, Hz
Power, dB
Frequency offset, kHz
Power,dB
Universal Time
14:00
14:30
15:00
15:30
16:00

Figure 8.

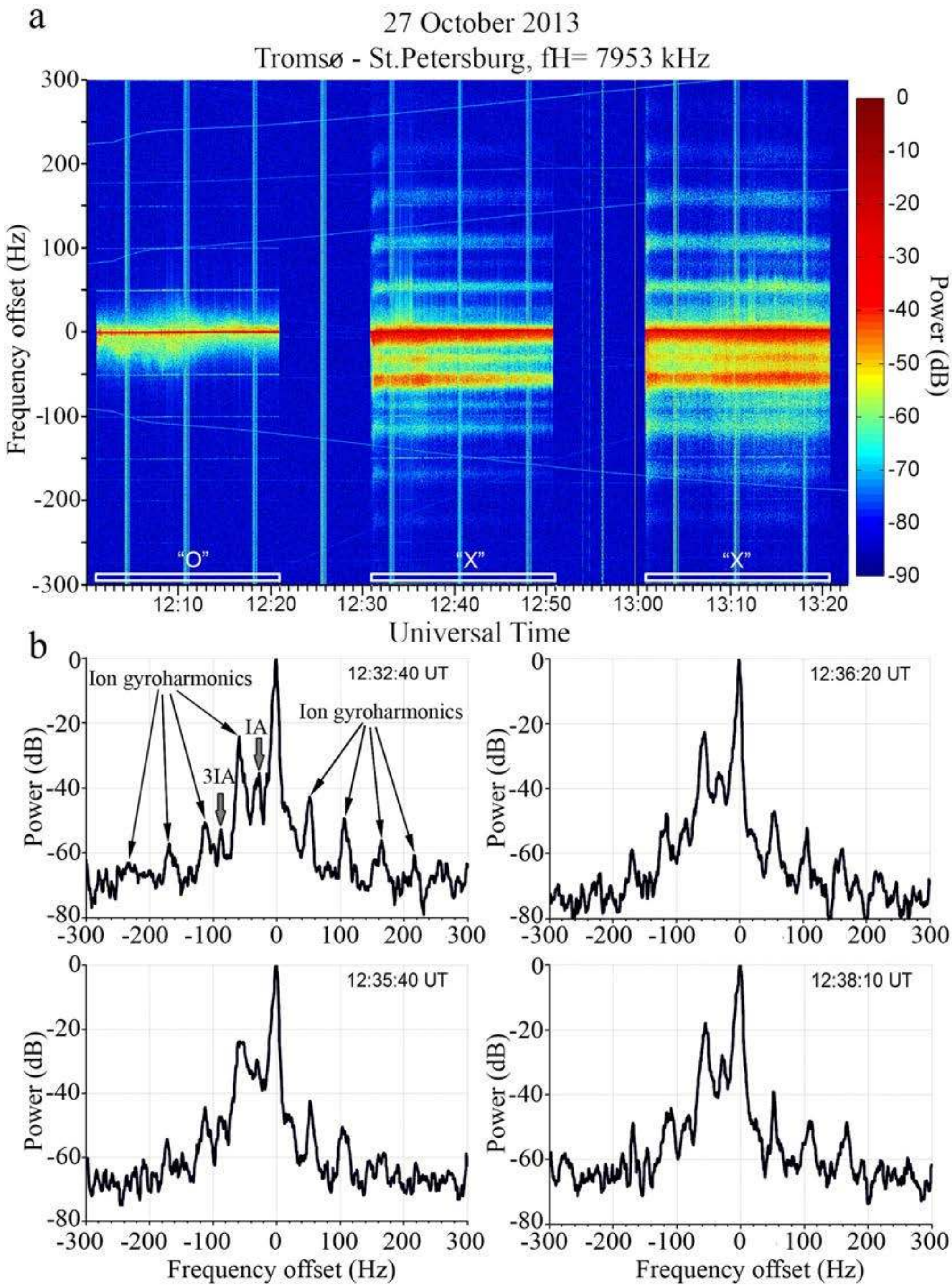

a
27 October 2013
Tromsø - St.Petersburg, fH= 7953 kHz
Frequency offset (Hz)
Power (dB)
"O"
"X"
"X"
Universal Time
b
Ion gyroharmonics
IA
3IA
Ion gyroharmonics
12:32:40 UT
12:36:20 UT
12:35:40 UT
12:38:10 UT
Power (dB)
Frequency offset (Hz)

Figure 9.

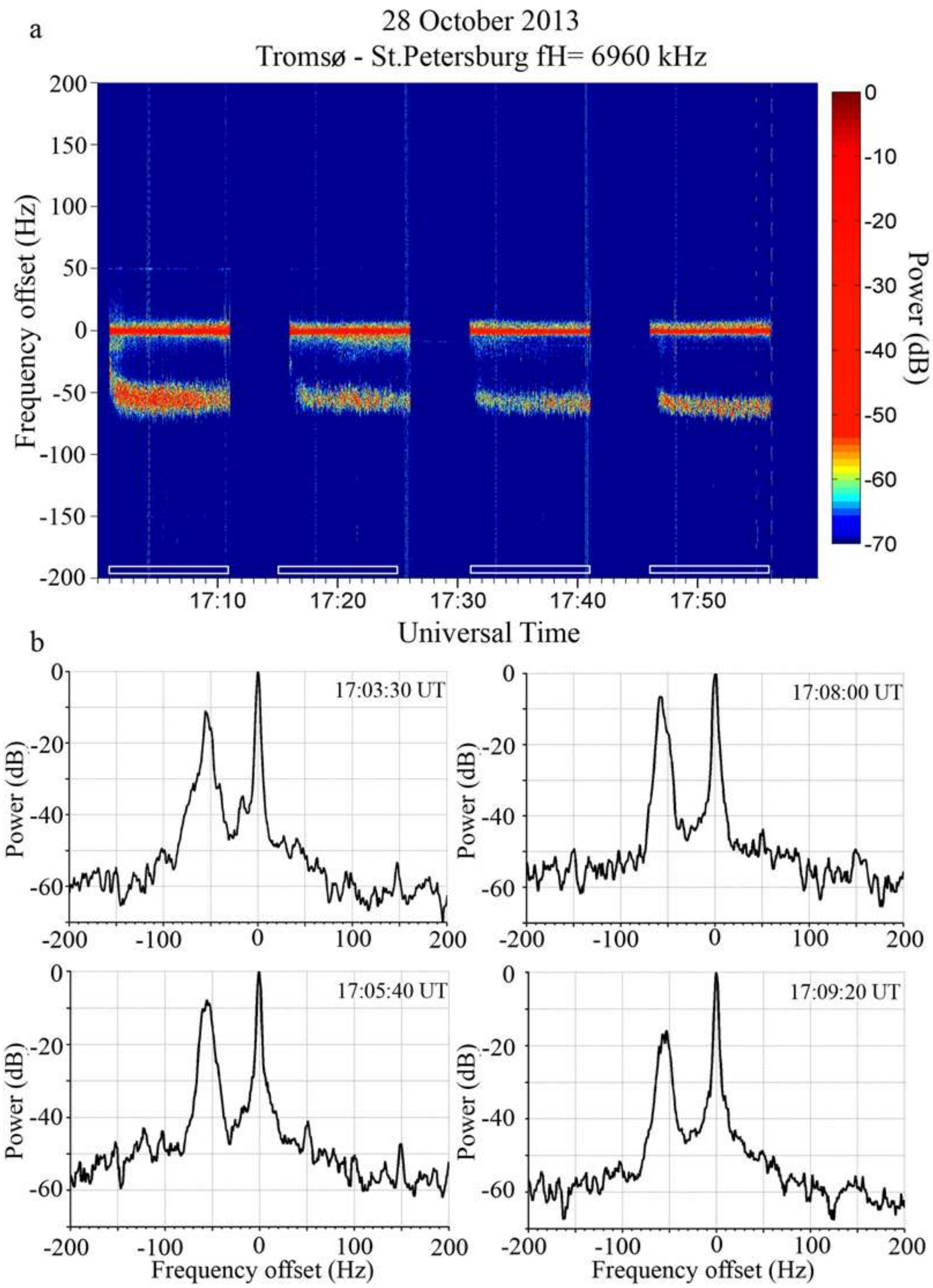

a
28 October 2013
Tromsø - St.Petersburg fH= 6960 kHz
Frequency offset (Hz)
Power (dB)
Universal Time
17:10
17:20
17:30
17:40
17:50
b
17:03:30 UT
17:08:00 UT
17:05:40 UT
17:09:20 UT
Power (dB)
Frequency offset (Hz)

Figure 10.