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Annales Geophysicae

Geophysical phenomena during an ionospheric modification experiment at Tromsø, Norway

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Abstract. We present an analysis of phenomena observed by HF distance-diagnostic tools located in St. Petersburg combined with multi-instrument observation at Tromsø in the HF modified ionosphere during a magnetospheric substorm. The observed phenomena that occurred during the Tromsø heating experiment in the nightside auroral E_s region of the ionosphere depend on the phase of substorm. The heating excited small-scale field-aligned irregularities in the E region responsible for field-aligned scattering of diagnostic HF waves. The equipment used in the experiment was sensitive to electron density irregularities with wavelengths 12–15 m across the geomagnetic field lines. Analysis of the Doppler measurement data shows the appearance of quasiperiodic variations with a Doppler frequency shift, f_d and periods about 100–120 s during the heating cycle coinciding in time with the first substorm activation and initiation of the upward field-aligned currents. A relationship between wave variations in f_d and magnetic pulsations in the Y-component of the geomagnetic field at Tromsø was detected. The analysis of the magnetic field variations from the IMAGE magnetometer stations shows that ULF waves occurred, not only at Tromsø, but in the adjacent area bounded by geographical latitudes from 70.5° to 68° and longitudes from 16° to 27°. It is suggested that the ULF observed can result from superposition of the natural and heater-induced ULF waves. During the substorm expansion a strong stimulated electromagnetic emission (SEE) at the third harmonic of the downshifted maximum frequency was found. It is believed that SEE is accompanied by excitation of the VLF waves penetrating into magnetosphere and stimulating the precipitation of the energetic electrons (10–40 keV) of about 1-min duration. This is due to a cyclotron resonant interaction of natural precipitating electrons (1–10 keV) with heater-induced whistler waves in the magnetosphere. It is reasonable to suppose that a new substorm activation, exactly above Tromsø, was closely connected with the heater-induced precipitation of energetic electrons.

Key words. Ionosphere (active experiments; ionosphere – magnetosphere interactions). Radio science (nonlinear phenomena).

1 Introduction

Between 1980–1997 a large number of ionospheric modification experiments have been performed using the HF heating facility located at Ramfjørdmoen near Tromsø, Norway (Rietveld *et al.*, 1993; Stubbe, 1996). Many efforts have been made to study experimentally and theoretically the ionospheric modification produced by powerful HF radio waves. These studies were concerned with different topics such as large- and small-scale field-aligned ionospheric irregularities (Djuth *et al.*, 1985; Noble *et al.*, 1987), stimulated electromagnetic emissions (Thide *et al.*, 1982; Stubbe *et al.*, 1984; Leyser *et al.*, 1989; Leyser *et al.*, 1990; Stubbe and Kopka, 1990), HF wave anomalous absorption particularly for heater frequencies near harmonics of the electron gyrofrequency (Stocker *et al.*, 1993; Robinson *et al.*, 1996), and secondary electromagnetic waves at very, extremely and ultra low frequencies by amplitude-modulated heating (Rietveld *et al.*, 1993; Stubbe, 1996).

It should be noted that in the heating experiments performed at Tromsø to date the plasma physics aspect has clearly dominated. The geophysical aspect has not been adequately explored. In this connection the study of Yeoman *et al.* (1997) should be noted. It shows that the combination of the latest ionospheric radars and the Tromsø HF heater provide a powerful new tool for active geophysical researches.

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Nonetheless, taking into account the distinctive behavior and features of the auroral ionosphere such as the ionospheric convection, field-aligned currents, intense electrojets, precipitating particles one would expect that the heating of this medium can lead to the generation of modification effects not encountered in dayside undisturbed ionosphere.

Here we report on the geophysical phenomena observed in the Tromsø heating experiment in the nightside auroral ionosphere during a magnetospheric substorm on 17 February 1996. We used HF long-distance diagnostic tools located near St. Petersburg combined with multi-instrument observations at Tromsø.

2 Experimental techniques and observations

The experiment was conducted at the Tromsø heating facility (69.6°N, 19.2°E, $L = 6.2$) from 20.00 UT on 17 February, 1996 in the nightside auroral ionosphere. The main technical parameters of the Tromsø heater during the experiment were the following: heater frequency $f = 4040$ kHz, O-mode polarization, effective radiated power ERP = 150 MW, transmission scheme 4 min on / 6 min off. The ionospheric modification was produced in the near field-aligned direction, as the antenna beam was tilted 6° to the south with respect to the zenith. The magnetic field inclination angle at Tromsø is close to 78°.

To study phenomena initiated by the action of powerful HF radio waves in the nightside auroral ionosphere during substorm we used the distance-diagnostic HF tools located in St. Petersburg at a distance about 1200 km from the Tromsø heater. Doppler measurements of HF diagnostic signals were carried out on the London – Tromsø – St. Petersburg path using fixed operational frequency of 12095 kHz. The diagnostic transmitter was located in London. The reception of HF diagnostic waves scattered of field-aligned artificial irregularities produced by the Tromsø heater was made by Doppler spectrum method at St. Petersburg. Spectral processing was carried out by the use of the fast Fourier transform (FFT) method. The analysis bandwidth used was 33 Hz, a specified number of 1024 FFT coefficients allowed a frequency resolution of 0.032 Hz. The receiving antenna was directed toward Tromsø.

Doppler measurements were supplemented by data from the Tromsø dynasonde (Sedgemore *et al.*, 1998 and references therein), IMAGE magnetometer network (Lühr, 1994) and airglow at Skibotn.

Figure 1 shows the general view of the experiment geometry (Fig. 1a) and locations of the IMAGE magnetometers (Fig. 1b).

Figure 2 presents the dynamic Doppler spectra (sonogram) of the HF diagnostic signals at 12095 kHz on the London – Tromsø – St. Petersburg path in the course of the heating experiment on 17 February, 1996. The field-aligned scattered signals appear after the heater is turned on and disappear after it is turned off. They are registered as additional tracks on the negative part of Doppler sonogram shifted by about −2.5 Hz from that of the direct signal propagating from the transmitter to the receiver along a great-circle path and corresponding to the 0 Hz Doppler frequency. From Fig. 2 it is clear that scattered signals are observed during all heating cycles from 20.00 to 20.46 UT.

Analysis of the Tromsø dynasonde ionograms, as well as EISCAT UHF radar data, during the heating experiment on 17 February, 1996 shows the presence of sporadic Es – layer at altitudes between 100 and 130 km sometimes with 0- and X-mode traces on the dynasonde ionograms and maximal observed frequencies from 4.1 to 4.5 MHz. We may conclude that the Es region of the auroral ionosphere was actually the region which was heated. The heating leads to the generation of intense

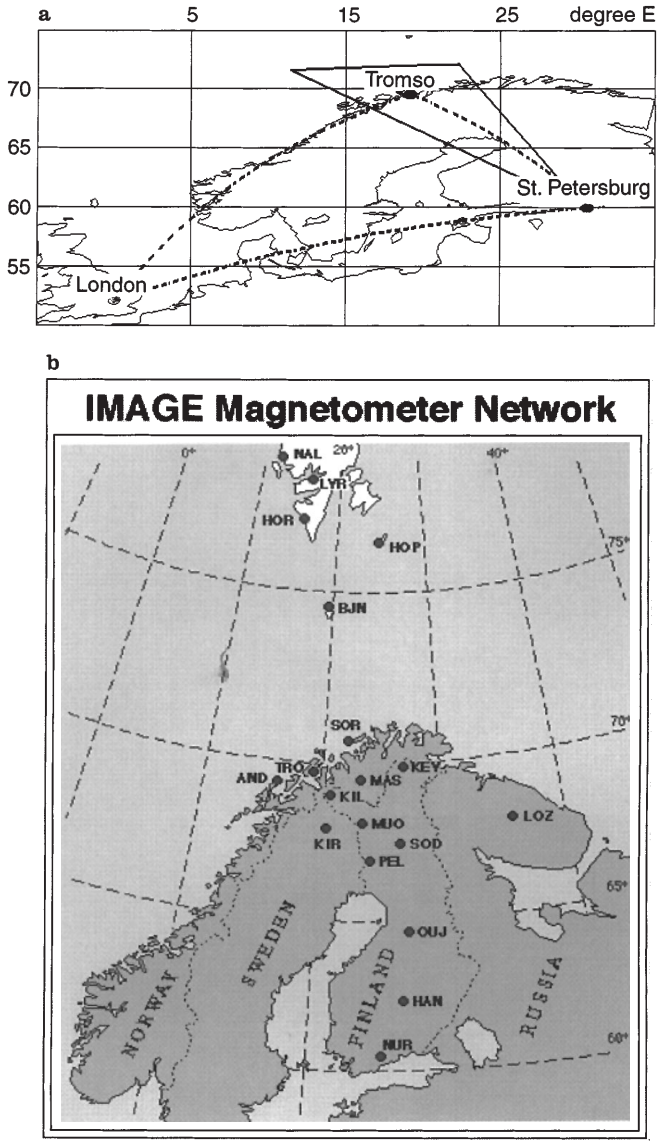


Fig. 1a, b. General view of the experiment geometry: **a** the radio path where the experimental observations of HF distance diagnostic signals scattered from artificial field-aligned irregularities were made; **b** locations of the IMAGE magnetometer stations used in this study

artificial field-aligned irregularities (striations) in the E-region of ionosphere responsible for field-aligned scattering of diagnostic HF signals on the London – Tromsø – St. Petersburg path.

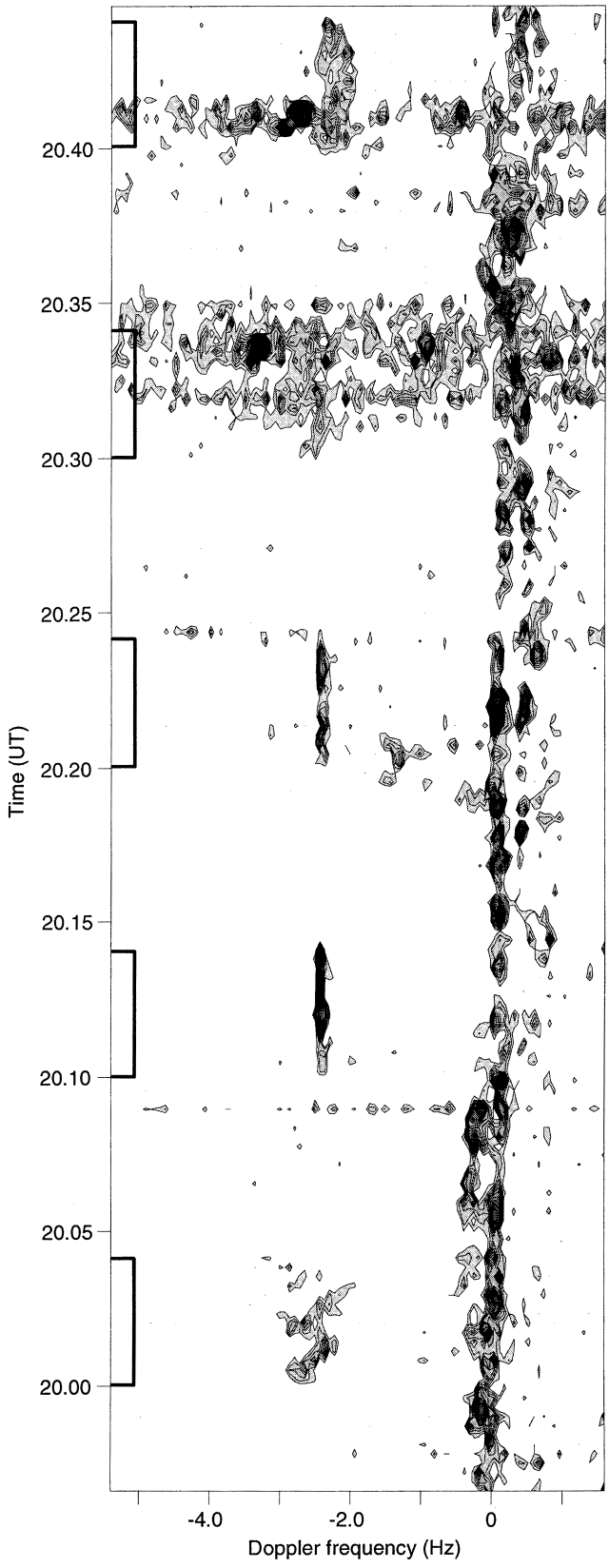


Figure 3a–c shows the behavior of the magnetic field variations from IMAGE magnetic stations in the X, Y and Z components, respectively, on 17 February, 1996. The first substorm activation started at 20.00 UT with an increase of negative magnetic perturbations (Fig. 3a) accompanied by large positive bays in the Y-components (Fig. 3b). The IMAGE X and Z component features (Fig. 3a, c) show that a maximum westward electrojet appeared poleward from Tromsø between SOR and BJN magnetic stations. It is well known (Rostoker, 1996; Kamide and Baumjohan, 1993) that positive Y component bays are detected near the western edge of the surge form produced by ionospheric Hall currents surrounding the region of the upward field-aligned currents (FACs) in the head of the surge. Note that FACs were turned on (or greatly intensified) at 20.00 UT and turned off at 20.33 UT as can be seen from the appearance and disappearance of the positive Y component bays at the IMAGE magnetic stations (Fig. 3b).

The second substorm activation started at 20.33 UT as a large negative spike in the X component and peaked at 20.34 UT from SOR to PEL magnetic stations (Fig. 3a). An inspection of peculiarities in the X and Z components at the IMAGE network (Fig. 3a, c) indicates that a new westward electrojet appeared exactly above Tromsø (maximum amplitude of negative spike in the X component and $\delta Z = 0$). Thereafter a much larger substorm occurred north of Tromsø at about 20.36 UT and peaked at 20.38 UT in the HOR magnetic station (Fig. 3a).

3 Results and discussion

An examination of dynamic Doppler spectra (Fig. 2) in course of the heating experiment on 17 February shows the following distinctive heating signatures during the auroral substorm.

Firstly, the occurrence of wave variations in the Doppler frequency shift, f_d, with periods about 100–120 s was observed during the first heating cycle (20.00–20.04 UT), coinciding in time with the onset of the substorm and initiation of the field-aligned currents.

Secondly, the occurrence of the electromagnetic emissions observed everywhere over the analyzed spectral bandwidth in the two heating cycles from 20.30 to 20.34 UT and 20.40–20.44 UT can be clearly seen.

Thirdly, the appearance of additional very intense short-lived tracks with a lifetime of order 60 s (apart from the main Doppler heating track on sonogram)

Fig. 2. The dynamic Doppler spectra (sonogram) of the HF distance diagnostic signals at operational frequency 12095 kHz on the London – Tromsø – St. Petersburg path in the course of the heating experiment on 17 February, 1996. The direct signals propagating from the transmitter to the receiver along a great circle path correspond to the 0 Hz Doppler frequency. Additional tracks on the negative part of Doppler sonogram shifted by about −2.5 Hz from that of the direct signals correspond to the field-aligned scattered signals. The intervals, when the Tromsø heating facility was turned on, are marked on the time axis

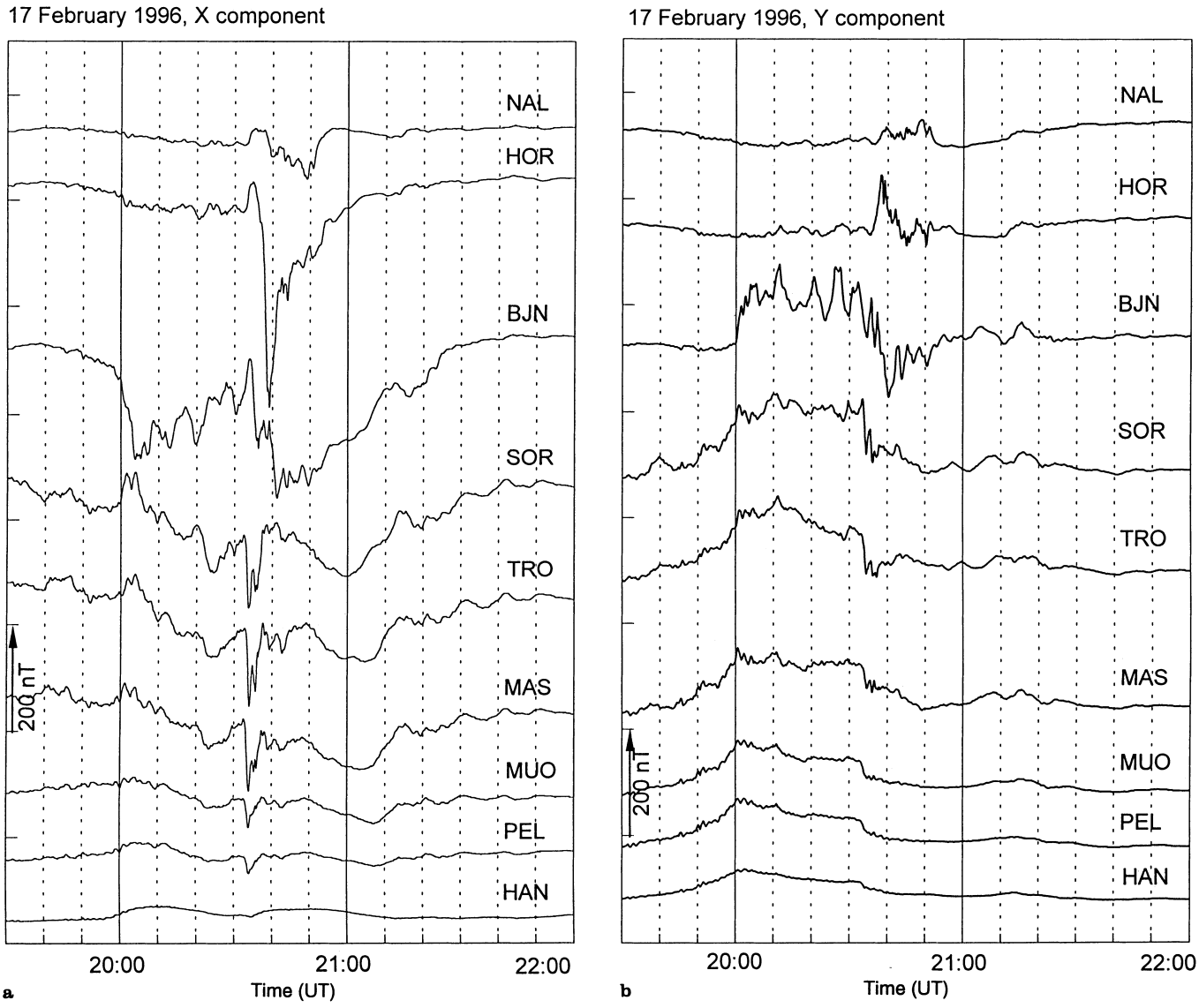


Fig. 3a–c. The behavior of the magnetic field variations from the IMAGE magnetometer stations: **a** X component; **b** Y component; **c** Z component

associated with the second substorm activation were detected in the same heating cycles where emissions were observed.

To study the geophysical phenomena during a heating experiment it is advantageous to use the variations of X and Y magnetic components from the quiet level. Figure 4 presents these variations obtained from IMAGE magnetometers located along the latitude from AND to KEV (Fig. 4a) as well as along the longitude from BJN to OUJ (Fig. 4b).

3.1 Wave processes in the onset of the substorm

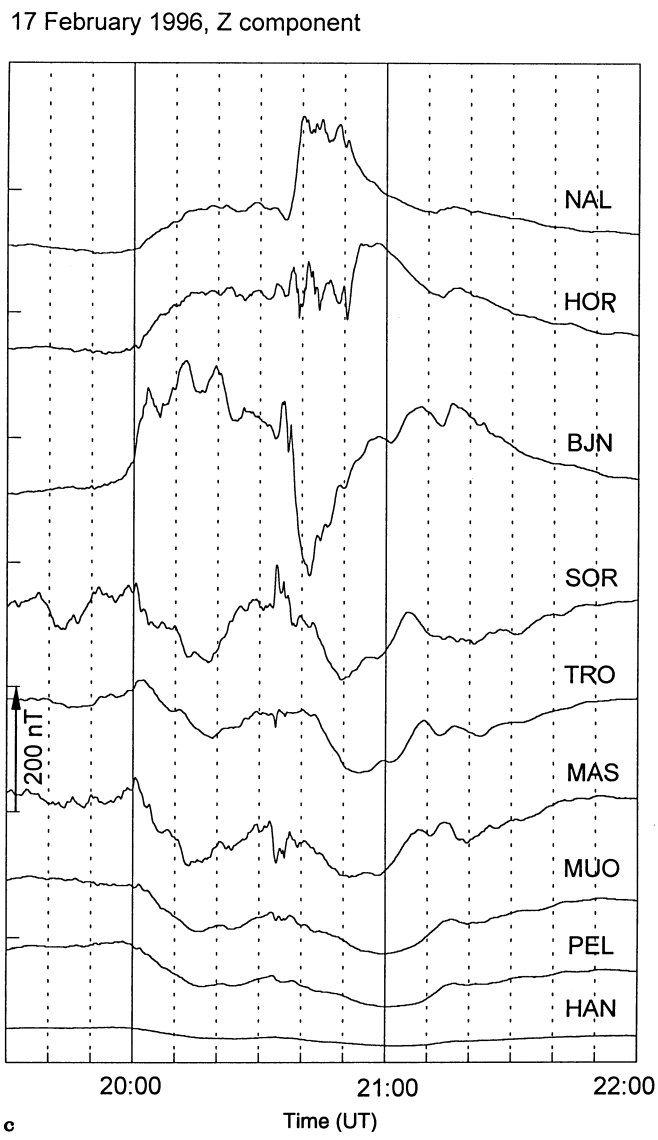
The interesting peculiarity of the field-aligned scattered HF signals on London – Tromsø – St. Petersburg path is the appearance of the wave variations in Doppler shift, f_d, with periods about 100–120 s during the first heating cycle from 20.00 to 20.04 UT (Fig. 2). The amplitude of this ULF wave determined as the maximum fluctuation of f_d during the heating cycle ($f_{dmax} - f_{dmin}$) was about 0.8 Hz. In the next heating cycles the variations of f_d on the scattered signal are absent. The direct HF signal from London to St. Petersburg does not contain such variations during the whole interval analyzed.

It is of interest to compare the observed ionospheric small-scale wave process and magnetic variation data in Tromsø. There is evidence of the appearance of well-defined magnetic pulsations in the Y component of the geomagnetic field (Fig. 4a) during the first heating cycle (20.00–20.04 UT). They have periods about 100–120 s and a large amplitude, of order 15–20 nT. Detailed comparison of the wave variations in Doppler shift, f_d, and magnetic (in the Y component) pulsations at Tromsø during the first heating cycle is shown in Fig. 5 where close correlation between ionospheric and magnetic pulsations can be seen.

It is appropriate to estimate the parameters of a ULF wave from Doppler measurement data. The relationship of ionospheric (f_d) and magnetic field (Y component) fluctuations corresponds to correlation between variations in the meridional, north-south component of the electric field (E_x) and zonal, east-west component of the magnetic field (B_y) in the artificially modified ionospheric E_s region produced by Tromsø heating facility during substorm onset. In this case on the assumption that electron drift in the E region is a pure $\mathbf{E} \times \mathrm{B}$ drift, from Doppler measurement data the vertical component of the Doppler velocity, the values of the vertical displacements of the artificially disturbed region of the ionosphere, and electric field of a ULF wave can be estimated.

The Doppler velocity V_d is given by

$$V_d = -\frac{f_{d\max} \cdot c}{2f \cdot \cos\theta} \ ,$$



c

Fig. 3c.

where f_{dmax} is the maximum Doppler frequency shift, f is the operational frequency, θ is the incidence angle of the diagnostic wave on the artificially disturbed region, and c is the velocity of light.

Knowing the vertical component of the Doppler velocity V_d and periods T of oscillations of the Doppler frequency shift, one can estimate the values of the vertical displacement M of the heated region of the ionosphere as

$$M = T \cdot V_d \ .$$

The electric field (north-south component) would be expressible as

$$E_x = \frac{V_d \cdot B_0}{\cos I} \ ,$$

where I is the angle of the magnetic declination and B_0 is the Earth's magnetic field.

Rough estimations using the values $f_{dmax} = \pm 0.4$ Hz, $f = 12095$ kHz, $\cos\theta = 1$, $T = 115$ s, $B_0 = 50$ μT, $I = 78°$ give $V_d = \pm 5.2$ m/s, $M = \pm 600$ m and $E_x = \pm 1.3$ mV/m.

It should be pointed out that the distinctive feature of the experiment is the use of continuous heating instead of amplitude-modulated heating of the ionosphere. This means that the duration of the heating cycle was significantly larger than the periods of the ionospheric (in f_d) and magnetic pulsations observed in the described experiment. Consequently, the origin of the ionospheric and magnetic pulsations could not be explained by modulation of the conductivity and, therefore, the current distribution flowing due to amplitude-modulated heating of the E-region. Thus, one can conclude that ionospheric and magnetic pulsations are possibly the result of modification of the specific nightside auroral ionosphere, by action of powerful HF radio waves on the Es region or they are natural pulsations during auroral substorm onset.

It would be expected that the substorm activation is accompanied by the generation of Pi2 magnetic pulsations of 40–150 s. In this case the ionospheric and magnetic pulsations observed during the first heating cycle could be signatures of natural pulsations. It should be noted that Yeoman *et al.* (1997) studied wave activity in the ULF band with CUTLASS radar and IMAGE magnetic stations, during the Tromsø experiment, of F2 region heating in the early evening hours, and attributed these to naturally occurring ULF waves.

To study this point in our heating experiment the magnetic field variations in X and Y components were considered from all IMAGE magnetometer stations during the onset of the substorm activation. The ULF waves in magnetic field measurements are shown in more detail in Fig. 6, which displays X and Y components from eight IMAGE magnetometers, covering geographical latitudes from 74.5°–64.5° and geographical longitudes from 16°–27°, bandpass filtered between 120 and 80 s. ULF waves can be seen both in the unfiltered (Fig. 4) and filtered (Fig. 6) magnetic data. An ULF wave is most pronounced in the first heating

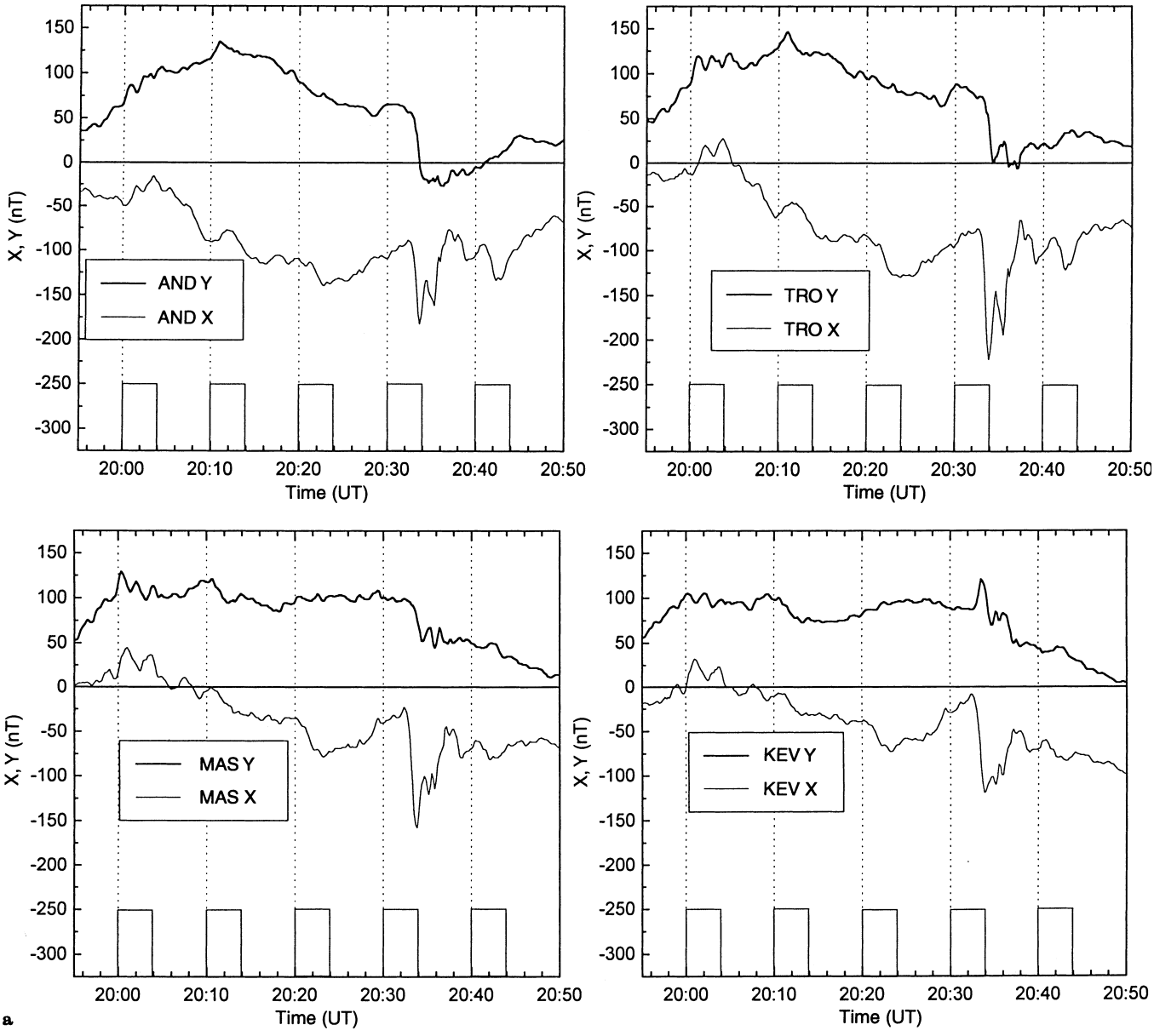


Fig. 4a, b. Perturbations of the X and Y magnetic field components from the quiet level during heating experiment on 17 February 1996 for IMAGE magnetometers, **a** along the latitude from AND to KEV and **b** along the longitude from BJN to OUJ (see Fig. 1b). The intervals when the Tromsø heater was turned on are *marked* on the time axis

cycle from 20.00–20.04 UT in the area bounded by geographical latitudes from 70.5° (SOR) to 68.02° (MUO) and geographical longitudes from 16.03° (AND) to 27.01° (KEV). This area can be identified with a region covered by the upward field-aligned currents. After the Tromsø heater was turned on at 20.00 UT the abrupt increase of the oscillation amplitude in the X as well as in the Y component started. Note that irregular pulsations in the Pi2 range appeared only slightly in filtered magnetic data (Fig. 6) over the whole time interval analyzed. During the first heating cycle the period and phase of the ULF wave are relatively constant with latitude from SOR to the south in both magnetic components, that is the characteristic signature of a cavity resonance (McDiarmid and Allan, 1990). Maximum amplitude (peak-to-peak) from unfiltered magnetic data up to 30 nT in X and 20 nT in Y components can be seen from TRO, SOR and MAS magnetic data but they were heavily attenuated with latitude, particularly in the X component. It should be noted that the ratio between X and Y component amplitudes is more than one, $X/Y > 1$, only in a narrow latitudinal region including magnetometer stations AND, TRO, SOR, MAS and KEV that does not contrast with the field-line resonance (Yeoman *et al.*, 1991). The resonance width was 1° latitude (110 km). To the south, from this narrow latitudinal region, the ratio is less than one $X/Y < 1$. It is of interest to estimate the relations between Y-component amplitudes within the width of a field-line resonance. The ratios of SOR, MAS, AND and KEV Y component amplitudes to TRO Y component amplitude for the first and second

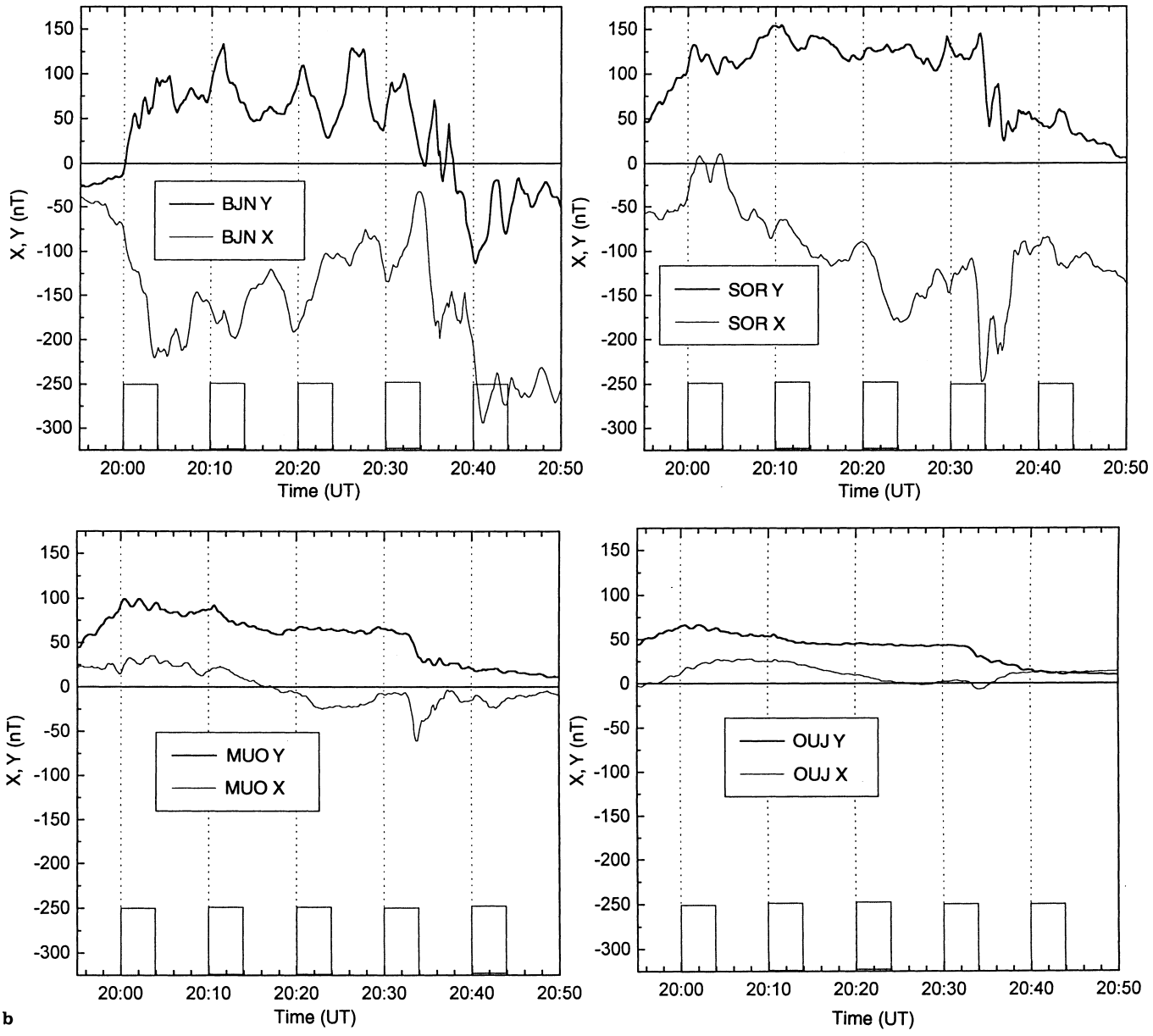


Fig. 4b.

maximums accordingly during the heater on period from 20.00–20.04 UT are the following: $Y_{SOR}/Y_{TRO} = 1.0$; 0.7, $Y_{MAS}/Y_{TRO} = 1.0$; 0.8, $Y_{AND}/Y_{TRO} = 0.4$; 0.4, $Y_{KEV}/Y_{TRO} = 0.6$; 0.6.

There is good reason to consider the polarization parameters (X-Y plane) from eight IMAGE magnetometer stations for the time interval containing the first heating cycle shown in Fig. 7. One can recognize that polarizations are clockwise (CW) to the south and anticlockwise (AW) to the north of the TRO latitude. Further examination shows the change of the polarization sense from CW to AW in the course of the first heater on period observed in the restricted longitudinal region at the TRO latitude, including TRO, MAS, SOR and KEV magnetometers. It should be noted that the nearest AND station, located to the west from TRO, did not show a change of the polarization sense. In addition, the most drastic change of polarization was first observed at TRO station and thereafter the polarization sense changes occurred at MAS, SOR and KEV magnetometer stations.

Let us consider the possible generation mechanisms of the ULF observed during substorm onset. The pulsation behavior from IMAGE magnetometer stations shows that it is not the typical signature of natural irregular Pi2 magnetic pulsations. On one hand the relation $X/Y > 1$ was observed in a narrow latitudinal region around Tromsø that is not contrary to the development of the field line resonance (Yeoman *et al.*, 1991). On the other hand the period and phase are relatively constant with latitude, as expected for a cavity resonance (McDiarmid and Allan, 1990). Moreover the

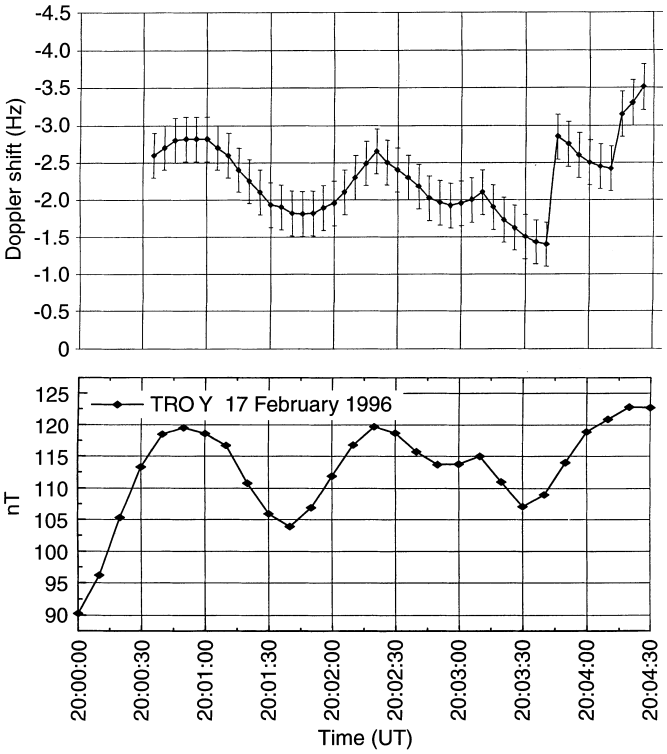


Fig. 5. The wave variations in Doppler frequency shift on the London-Tromsø-St. Petersburg path (*top*) and in Y component at Tromsø (*bottom*) during the first heating cycle (20.00–20.04 UT) on 17 February, 1996

abrupt changes of the ULF characteristics, such as amplitude and the change of the polarization sense are clearly visible during the first heater-on period. It should be noted that substorm onset and generation of the upward field-aligned currents, and, correspondingly, the establishment of the Birkeland current wedge were observed in temporal coincidence with the first heating cycle.

In our opinion the observed pulsations can result from superposition of natural and heater-induced ULF waves. The generation mechanism of the heater-induced ULF wave may be the following. The powerful HF radio wave, in the lower ionosphere, locally modifies the ionospheric conductivity. In our experiment it would be expected that the strong modification of the ionospheric conductivity resulted because the pump wave was reflected from E_s layer. The region of the enhanced ionospheric conductivity is polarized in the background electric field, and the polarization electric field propagates into the magnetosphere along the magnetic field lines as the field of the outgoing Alfvén wave (Kan and Sun, 1985; Lysak, 1990; Borisov *et al.*, 1996). The problem of the Alfvén wave generation over a circle-like inhomogeneity of the disturbed conductivity, where the background field-aligned current is upward, has been studied by Kozlovsky and Lyatsky (1997). From these results it may be deduced that an outgoing Alfvén wave is generated from a heater-induced inhomogeneity of the enhanced conductivity. The field-aligned current of this wave is directed as background upward current due to the total field-aligned current increases. The field-aligned current of the Alfvén wave, reflected from the magnetosphere, would provide the downward field-aligned current that reduces the background upward FAC. As a result the additional field-aligned currents associated with the heater-induced Alfvén wave would modulate the background upward FAC in the surge site and lead to the appearance of the magnetic and ionospheric pulsations. The period of these pulsations is determined by the Alfvén wave travel time between the ionosphere and magnetosphere. It is exactly that observed in our heating experiment for $L = 6.2$ (from 100–120 s). Note that the ULF wave was observed not only at Tromsø but at other magnetometer stations located in the area of the background upward FAC as well. The effect of the background FAC modulation falls off with distance from Tromsø. It can be clearly seen from the relations between SOR, MAS, KEV and AND Y component amplitudes and TRO Y component amplitude (peak-to-peak) during heater-on period. We emphasize that the geophysical conditions (substorm onset, field-aligned currents, the presence of E_s-layer) during the heating experiment significantly control the occurrence of magnetic and ionospheric pulsations.

Thus, we conclude that the observed ULF wave in the Pi2 range can result from modification of natural ULF wave by the heater-induced Alfvén wave during substorm onset and initiation stage of the background upward field-aligned currents.

3.2 Phenomena during the second activation

From Fig. 2 it can be seen that the heater switching on at 20.30 UT leads to the appearance of field-aligned scattered HF signals as seen in the previous heating cycles. They are displaced from the direct HF signals by about −2.5 Hz. Then after about 60 s very strong emissions were observed everywhere over the analyzed spectral bandwidth. Thereafter, at 20.33 UT, the additional very intense short-lived track with an average existence of order 60 s appears apart from the main heating track on the sonogram. Its Doppler frequency shift is −0.8 Hz from the main field-aligned track. The heater switching off, at 20.34 UT, is accompanied by the disappearance of the additional short-lived track but the emission was still supported for 1 min. In the next heating cycle both the emission and additional short-lived track are also observed. But, in this case, the emission existed only 1 min, and the lifetime of additional track was about 40 s, and its f_d is −0.4 Hz from the main field-aligned track. The main field-aligned Doppler track was observed throughout the heating cycle from 20.40 to 20.44 UT.

It should be remembered that the second substorm activation started at 20.33 UT. Further examination of the IMAGE magnetometer data showed that a new westward electrojet appeared exactly above Tromsø. The reversal of the Z component sign from positive (SOR) to negative (MAS) values, $\delta Z = 0$, as well as the

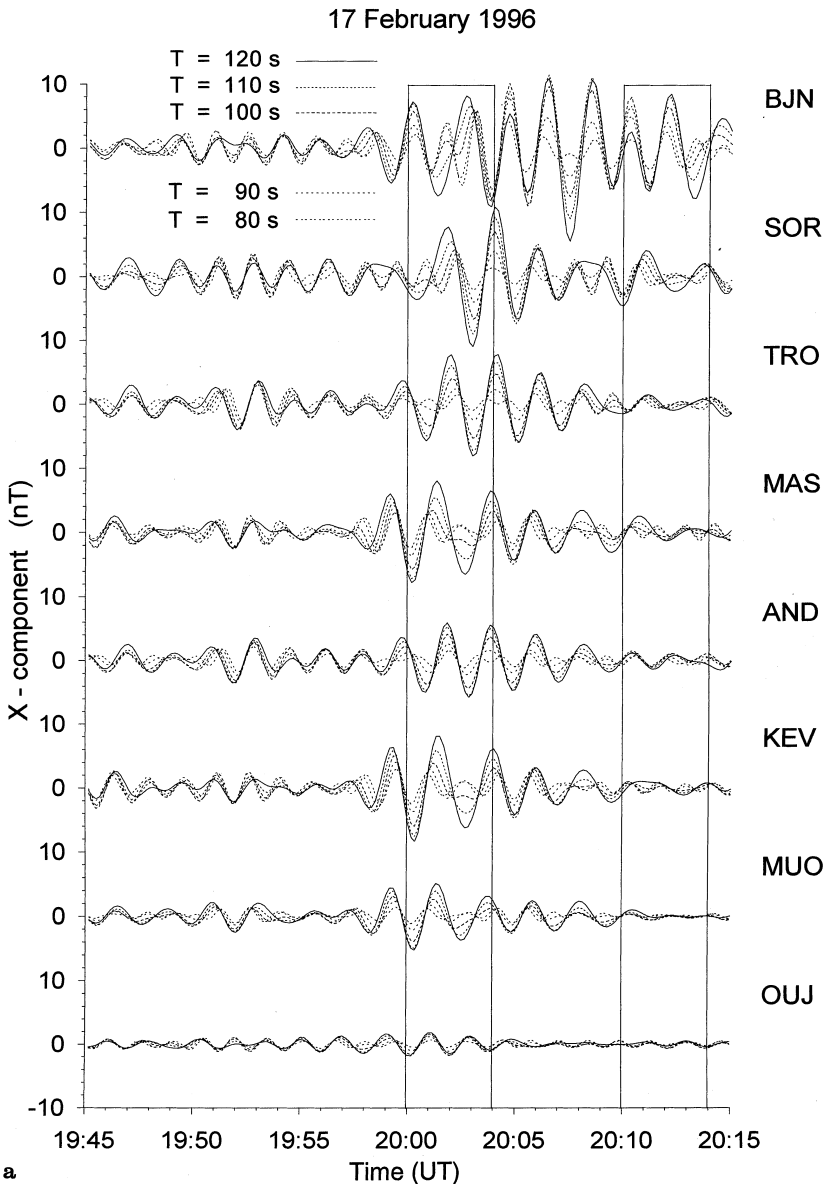


Fig. 6a, b. Magnetic field variations from eight IMAGE magnetometer stations, bandpass filtered between 120 and 80 s for **a** the X component and **b** the Y component

maximum amplitude of the negative X spike $\delta X = -150$ nT are observed in TRO magnetic data (Fig. 3a, c). Therefore, the occurrence of the additional short-lived track on the Doppler sonogram, and the onset of the second substorm activation are related to each other. In the heating cycle, from 20.40 to 20.44 UT, some intensification of the electrojet was also observed.

The heating of the auroral E_s region has excited the small-scale field-aligned irregularities (striations) in the ionospheric E region responsible for field-aligned scattering of diagnostic HF waves. The equipment used in the experiment on 17 February was sensitive to electron density irregularities with wavelengths of 12–15 m across the geomagnetic field lines. The properties of these E_s region striations can be understood within the frame of the thermal resonance instability, taking place at the upper hybrid level (Vaskov and Gurevich, 1977; Inhester, 1982). Note, that E-region striations have been previously observed only with the 1 m STARE radar (Noble *et al.*, 1987) and with a mobile 3 m radar (Djuth *et al.*, 1985; Noble *et al.*, 1987).

The other unusual phenomenon observed from HF Doppler measurements at operating frequency 12095 kHz was the generation of the well-defined stimulated electromagnetic emission (SEE) produced by the E_s region heating. It is known (Thidé, 1990), that SEE results from reemission of HF induced plasma waves as electromagnetic waves due to a wave-wave interaction, as well as from their scattering by striations. If the pump frequency f_H is not extremely close to an electron gyroharmonic, there are strong SEE signals downshifted from f_H with a strongly pronounced maximum downshifted by the lower hybrid frequency f_{LH}. Such downshifted maximum, $f_{DM} = f_H - f_{LH}$, in the SEE spectra is well known (Thidé, 1983). It is common knowledge (Leyser *et al.*, 1989) that the lower hybrid frequency is approximately 8 kHz in the ionosphere above Tromsø. Moreover, from SEE observa-

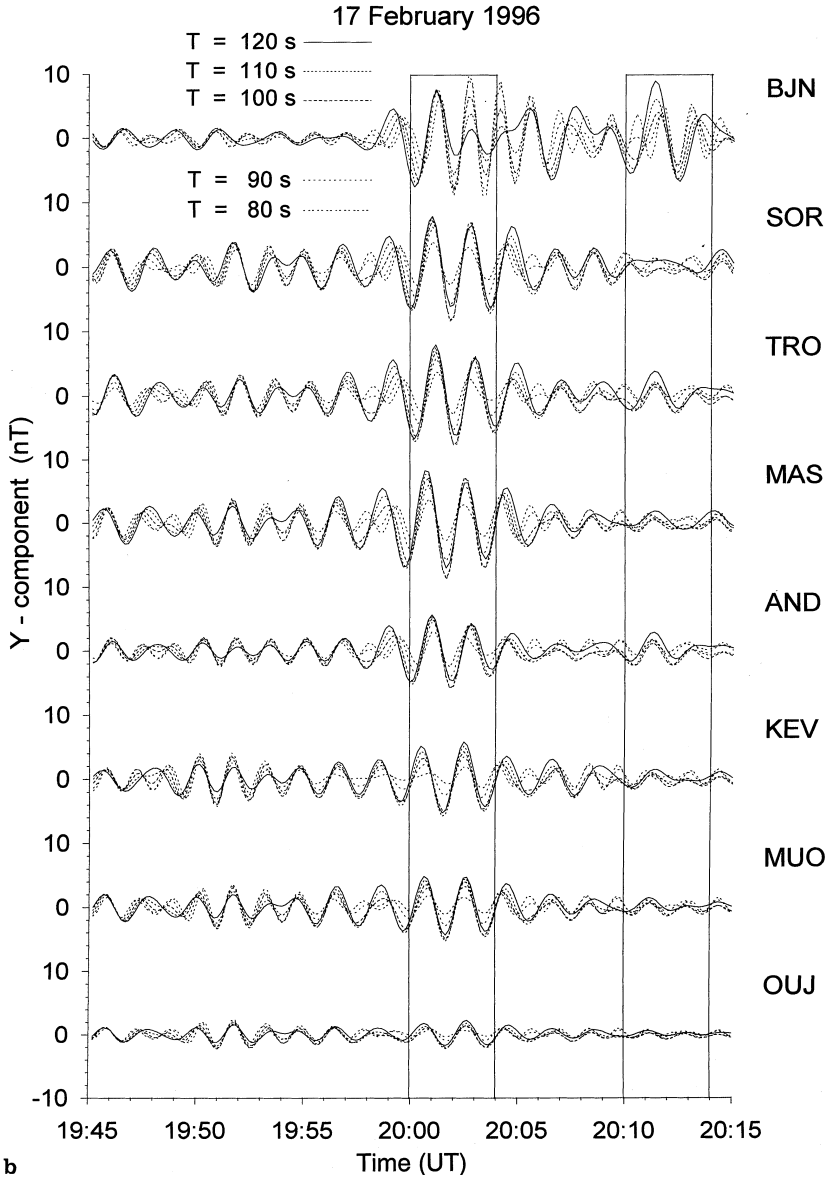


Fig. 6b.

tions around the second harmonic of the Tromsø heater frequency it was shown (Blagoveshchenskaya *et al.*, 1998), that wide-band emissions with a pronounced maximum at the second harmonic of the downshifted maximum, $2f_{DM} = 2(f_H - f_{LH})$, appeared. They were registered 1200 km from the Tromsø heater whereas most previous SEE measurements have been made within 100 km (Leyser *et al.*, 1989; 1990; Stubbe *et al.*, 1984; 1990; Thidé *et al.*, 1982; 1983). Therefore, from the result obtained it may be concluded that the SEE at the harmonics of the downshifted maximum may occur in the heating experiments. In our experiment operational frequency ($f = 12095$ Hz), used for Doppler measurements of HF diagnostic signals, was equal to the third harmonic of the downshifted maximum $3f_{DM}$ ($f = 3f_{DM}$, $3f_{DM} = 3(f_H - f_{LH})$, where $f_H = 4040$ kHz, $f_H = 8$ kHz). Because of this one can suggest that wide-band emissions on the Doppler sonogram is due to the $3DM$ component of the SEE spectra.

The next phenomenon, closely connected with stimulated electromagnetic emissions at the frequency near the third harmonic of the downshifted maximum, was the appearance of very intense short-lived tracks with durations of 40–60 s apart from the main field-aligned tracks on the Doppler sonogram. The observed phenomenon can be qualitatively interpreted by the following. Ionospheric parameters obtained by the Tromsø dynasonde and EISCAT UHF radar show the presence of a sporadic E_s layer during the second substorm activation. In the same time the auroral arc was observed from airglow data. It is a matter of general experience that these structures formed by the typical electron energies from 1 to 10 keV (Bösinger *et al.*, 1996). On the other side, the strong HF heater-induced plasma waves can accelerate thermal electrons. Moreover, the generation of the strong SEE was observed. Perhaps one can concede that SEE at the frequency $3f_{DM}$ is accompanied by the excitation of VLF waves. It is known (James *et al.*, 1990; Kimura

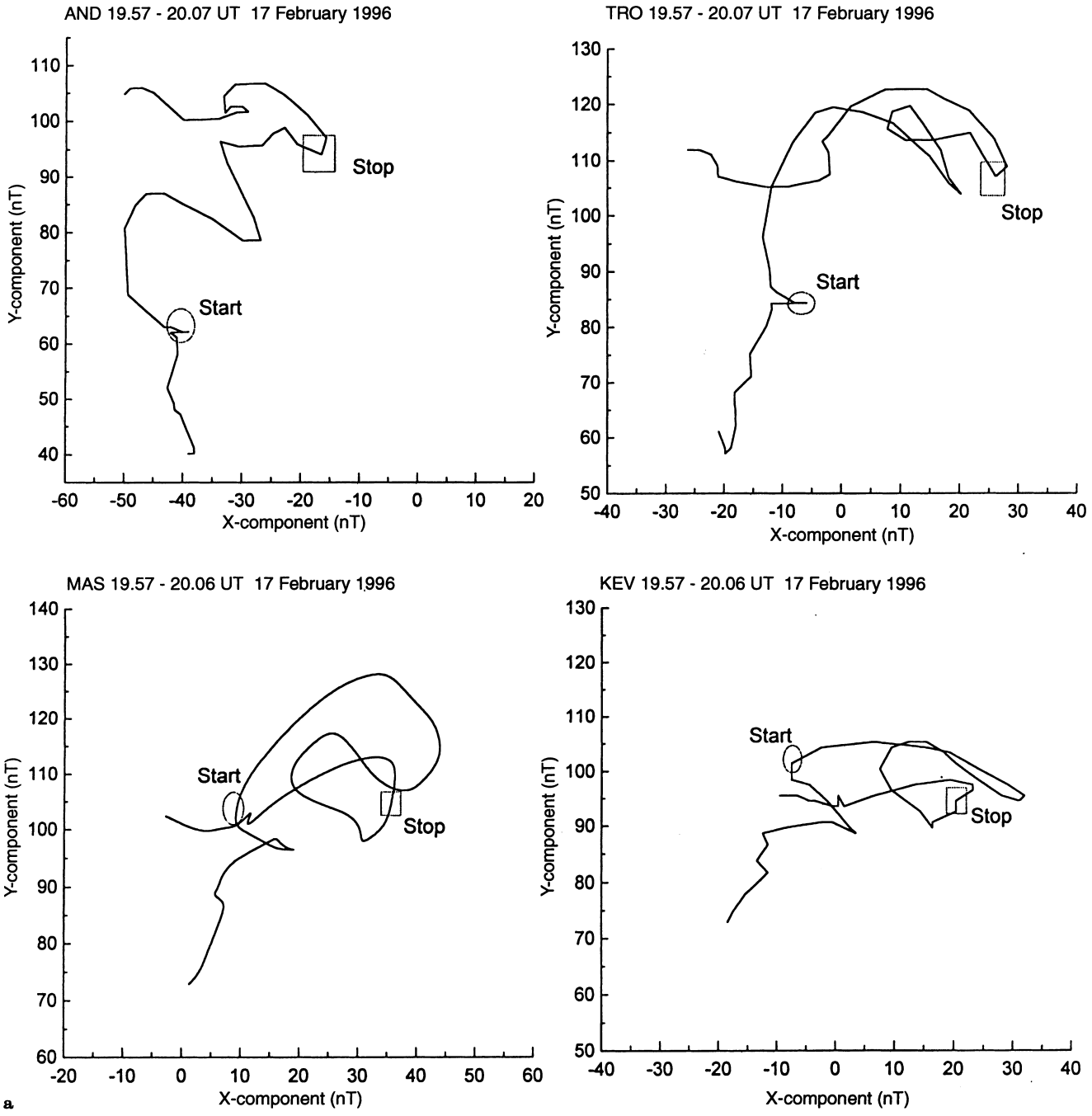
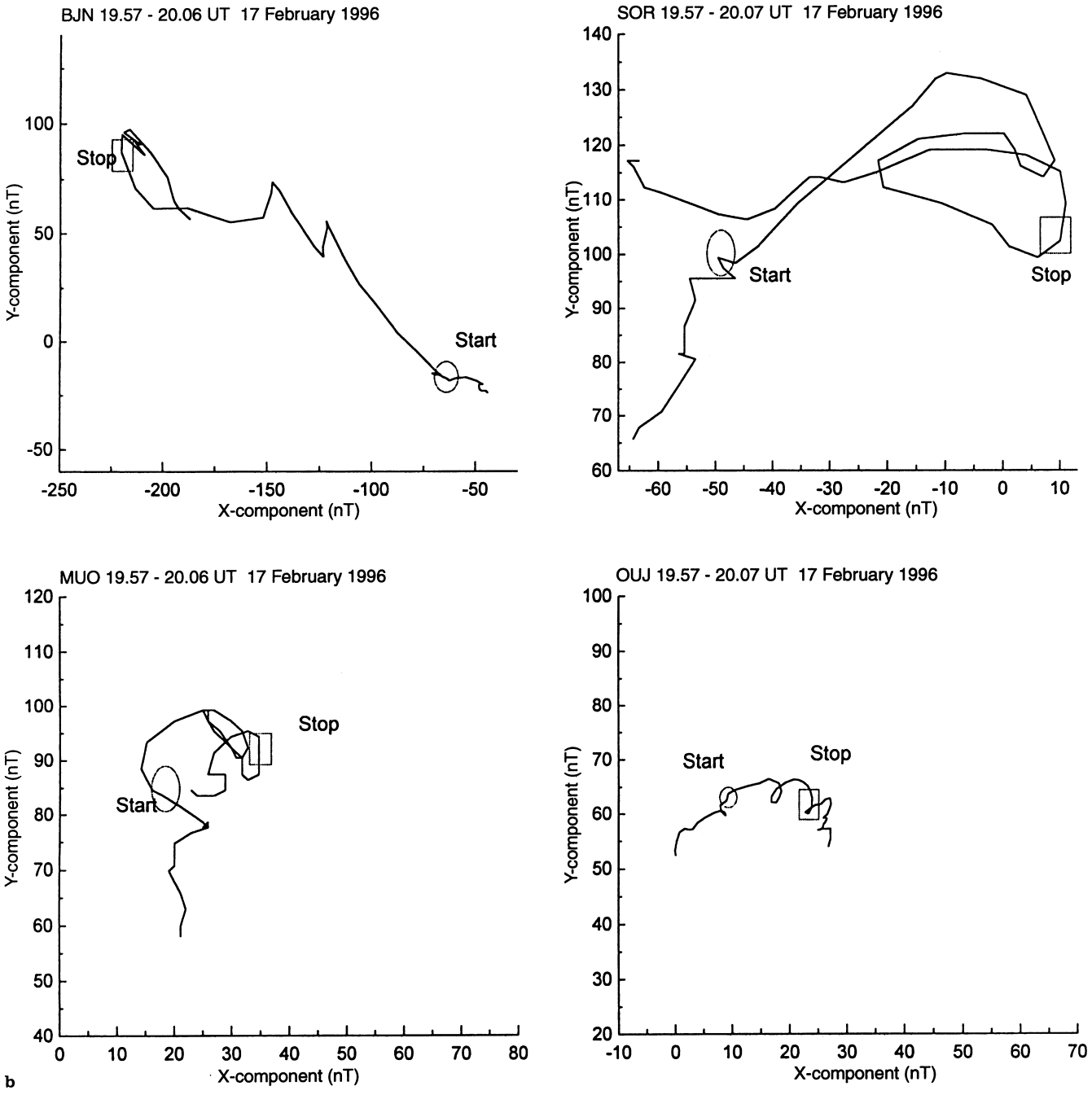


Fig. 7a, b. Hodographs presenting the time evolution of the Y-X polarization surfaces on 17 February, 1996 for the time interval from 19.57 to 20.06 UT containing the first heating cycle (from 20.00–20.04 UT) from IMAGE magnetometers, **a** along the latitude from AND to KEV and **b** along the longitude from BJN to OUJ (see Fig. 4a, b). The Tromsø heater turning on and off are marked by *circles* and *rectangles* correspondingly

et al., 1994) that VLF waves in the whistler mode are able to propagate into the upper ionosphere and magnetosphere. In this case it would be expected that the appearance of the stimulated precipitation of energetic electrons with energies between 10 and 40 keV would occur due to a cyclotron resonant interaction of natural precipitating electrons (1–10 keV) with heater-induced whistler waves in the magnetosphere. It was shown by Trefall *et al.*, (1975) that a cyclotron generation mechanism is operating in a narrow region of a magnetic flux tube. Therefore, two electron populations involving natural soft electrons (1–10 keV) and HF heater-induced hard electrons (10–40 keV) could take place during the heating experiment in the substorm maximum. There are indications that only a hard electron component took part in the short period electron precipitation as observed in a study of a pulsating auroral arc by Bösinger *et al.*, (1996). Thus, the analysis of experimental data shows the possibility of the excitation of the stimulated electron precipitation



b

Fig. 7b.

in the heating modification of the auroral E_s region. From the result obtained it may be concluded that a new substorm activation exactly above Tromsø was intimately associated with the heater-induced precipitation of energetic electrons. The critical requirements of a similar stimulated precipitation (auroral trigger) are the presence of the field-aligned artificial irregularities in the E-region, stimulated electromagnetic emissions, possibly closely connected with heater-induced VLF waves and natural precipitation of the soft electrons.

4 Conclusions

We have studied phenomena initiated by the action of powerful HF radio waves at Tromsø in the nightside auroral Es region during the magnetospheric substorm on 17 February, 1996. The analysis is based on experimental data from distance-diagnostic HF tools located in St. Petersburg. Doppler measurements of HF diagnostic signals were carried out on the London – Tromsø – St. Petersburg path using a fixed operating frequency of 12095 kHz. Furthermore, multi-instrument data from Tromsø dynasonde, IMAGE magnetometer network, EISCAT incoherent scatter radar, were used.

The heating of the auroral E_S region excited the small-scale field-aligned irregularities in the ionospheric E region with wavelength of the order 12–15 m across the geomagnetic field lines. These irregularities then act as an artificially produced target for the diagnostic HF waves on the London – Tromsø – St. Petersburg path and are responsible for field-aligned scattered diagnostic signals.

Magnetic data from IMAGE network show that the first substorm activation started at 20.00 UT and coincided exactly with the Tromsø heater turning on. The substorm onset was accompanied by development of the upward field-aligned currents (FACs) at the western edge of the westward electrojet. The second substorm activation started at 20.33 UT as a large negative spike in the X component and peaked at 20.34 UT with a maximum westward electrojet exactly above Tromsø. Thereafter, a much larger substorm occurred north of Tromsø at about 20.36 UT.

The interesting peculiarity of the field-aligned scattered HF signals is the appearance of wave variations in Doppler frequency shift, f_d, with periods about 100–120 s and amplitude about 0.8 Hz during the substorm expansion onset. These ionospheric pulsations closely correlated with magnetic pulsations in the Y component of the geomagnetic field at Tromsø, falling in the Pi2 range and with a large amplitude of the order 15–20 nT. The relationship of the ionospheric (f_d) and magnetic field (Y component) fluctuations corresponds to correlation between variations in the meridional, north-south component of the electric field (E_x) and zonal, east-west component of the magnetic field (B_y) in the artificially modified ionospheric E_s region. Parameters of the observed ULF wave were estimated from Doppler measurement data. They are the following: the vertical displacements of the heated Es region $M = \pm 600$ m and the north-south component of electric field $E_x = \pm 1.3$ mV/m. The analysis of the magnetic field variations from the IMAGE stations shows that ULF waves occurred not only at Tromsø but in the adjacent area bounded by geographical latitudes from 70.5° to 68° and longitudes from 16° to 27°. This area can be identified with region covered by the upward field-aligned currents. Moreover it was found the change of the polarization sense ($X - Y$ plane) from clockwise to anticlockwise in the course of the first heater-on period observed in a narrow latitudinal region around Tromsø (110 km). It does not contrary to the development of the field line resonance. We conclude that the observed ULF wave in the Pi2 range can be result from strong modification of natural ULF wave by the heater-induced Alfvén wave. It may be deduced that Alfvén wave is generated from a heater-induced inhomogeneity of the enhanced conductivity during substorm onset and initiation stage of the background upward field-aligned currents (FACs). As a result the additional field-aligned currents of this Alfvén wave would modulate the background upward FAC in the surge site. The effect of the background FAC modulation falls off with distance from Tromsø.

During substorm expansion we found the well-defined stimulated electromagnetic emissions (SEE) at the third harmonic of the downshifted maximum frequency ($3f_{DM}$). The next phenomenon, closely connected with this SEE, was the appearance of very intense short-lived tracks (40–60 s) on Doppler sonogram apart of the main field-aligned tracks caused by the artificial field-aligned small-scale irregularities (striations) in the E_S region during heater-on periods. It was suggested, that the SEE at the frequency of $3f_{DM}$ is accompanied by the excitation of VLF waves, which in whistler mode are able to penetrate into the magnetosphere. Then, a cyclotron resonant interaction of natural precipitating electrons (1–10 keV) with heater-induced whistler waves in the magnetosphere leads to stimulated precipitation of more hard electrons with energies 10–40 keV, responsible for the appearance of additional short-lived tracks on Doppler sonogram. We conclude that the second substorm activation exactly above Tromsø was intimately associated with the heater-induced precipitation of energetic electrons.

Results of the Tromsø heating experiment in the nightside auroral E_S region clearly show the evidence on the modification of the ionosphere-magnetosphere coupling during magnetospheric substorm, produced by powerful HF radio waves. The distinctive behavior of the auroral ionosphere as well as field-aligned currents, precipitating particles, ionospheric convection, and substorm current wedge system significantly control the type and properties of observed phenomena. It must be underscored that the heating of the auroral ionosphere, essentially during magnetospheric substorms, leads to the generation of the new phenomena including trigger effects not encountered in the dayside, undisturbed ionosphere.

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