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Dynamics of the auroral oval during geomagnetic disturbances observed by oblique sounding of the ionosphere in the Eurasian longitudinal sector

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[1] Results of the experimental studies of features of HF signals propagation during the period of geomagnetic disturbances at oblique sounding paths in the Eurasian longitudinal sector from England to Magadan are presented. Joint analysis of the vertical and oblique sounding of the ionosphere and satellite data showed that appearance of additional signals during magnetic disturbances can be due to the refraction of radio waves in the region of the auroral oval and the main ionosphere trough and also to the scatter on small-scale field-aligned irregularities in the vicinity of the equatorial boundary of the auroral oval. On the basis of calculations and comparison to the experimental data of the oblique sounding of the midlatitude ionosphere, the side spread signals recorded at Inskip (England) to Rostov on Don path are identified as signals scattered at small-scale field-aligned irregularities, their location positioning to the southern boundary of the auroral oval. The perspective of use of the Russian and global network of linearly frequency modulated ionosondes for studying the dynamics of the midlatitude ionospheric trough and auroral oval in the Eurasian longitudinal sector poorly equipped by observational means during magnetic disturbances is described. *INDEX TERMS:* 2407 Ionosphere: Auroral ionosphere; 2487 Ionosphere: Wave propagation; 2494 Ionosphere: Instruments and techniques; *KEYWORDS:* Electron collision frequency; Attenuation of HF radiowaves; Physics of the lower ionosphere.

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1. Introduction

[2] Effects of space weather provide different and considerable impact on various sides of human activity and environment. First, these effects are manifested at high latitudes as a result of magnetosphere–ionosphere interaction of electric and magnetic fields at conditions of intensification of the solar wind and changes in the configuration of the interplanetary magnetic field. Geomagnetic disturbances being a determining factor for HF propagation at polar latitudes [*Blagoveshchensky and Zherebtsov*, 1987; *Goodman and Aarons*, 1990; *Hunsucker and Bates*, 1969; *Zhulina*, 1978] exert considerably influence on signal characteristics at midlatitude and subpolar paths [*Blagoveshchensky and Borisova*, 2000; *Kurkin et al.*, 2004; *Lockwood,* 1981; *Siddle et al.*, 2004; *Stocker et al.*, 2003; *Uryadov and Ponyatov,* 2001; *Uryadov et al.*, 2002; *Zaalov et al.*, 2003].

[3] Speaking on the structure of the high-latitude iono-

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sphere, its significant features are the main ionospheric trough and the auroral oval. The interest to them is due to the fact that the trough borders on the midlatitude ionosphere where the main channels of the decameter wave (DCMW) communication pass and trough shift to lower latitudes during magnetic storms can lead to undesirable effects of decreasing the maximum observed frequency (MOF) and variation of the signal mode structure. The midlatitude ionospheric trough (MIT) shape and dynamics depend on many factors including longitude, local time, season, and solar and geomagnetic activity levels. Various parts of the trough are different by the electron concentration, ionization gradient, and presence of irregularities [*Deminov et al.*, 1996; *Karpachev*, 2003; *Karpachev and Afonin*, 2004; *Karpachev et al.*, 1996; *Rodger et al.*, 1992].

[4] The ionosphere irregularities of various scales generated in the vicinity of the southern boundary of the auroral oval lead to an increase of the signal spread of standard modes of propagation and to appearance of anomalous signals with delays increasing considerably the delays of the main modes propagating along the arc of a large circle. The level of such signals is rather high and they influence the work of radioelectronic systems of various application. On the other hand, the presence of additional signals on ionograms of the oblique sounding in the period of disturbances may be used for determination of the boundaries of the main ionosphere trough and diagnostic of small-scale ionosphere irregularities located in the vicinity of the southern boundary of the auroral oval.

[5] Many papers are dedicated to studies of the auroral oval [see, e.g., *Yokoyama et al.*, 1998, and references therein]. Currently, studies of the subpolar and midlatitude ionosphere (including the auroral oval) are intensely developed using the data of vertical sounding, incoherent scatter radars, and meteorological and navigation satellite systems DMSP and GPS [*Afraimovich et al.*, 2004; *Potekhin et al.*, 1999; *Vo and Foster*, 2001; *Zherebtsov et al.*, 1997]. The data obtained convincingly manifest dynamic of the auroral oval during a magnetic storm and its shift toward middle latitudes when the midlatitude ionosphere demonstrates the properties typical for the high-latitude ionosphere. Therefore taking into account the effects of space weather becomes very important for provision of reliable functioning of radioelectronic systems not only at high but at middle latitudes as well.

[6] Among the complex of means aimed at studying the ionosphere and its influence on radio wave propagation the technical means of the oblique sounding (OS) occupy a special place. First, if there exists and functions a developed network of the OS stations, simultaneous sounding at the paths in a different way oriented relative the auroral oval makes it possible to perform the diagnosis of the propagation environment and control the dynamics of the oval in various longitudinal and latitudinal sectors. Second, real-time sounding makes it possible to obtain the information on the real-time state of the HF channel. The latter makes it possible to adapt the systems of HF radio communication and over-the-horizon radiolocation to the current state of the ionosphere, the latter being especially important for high-latitude regions of Arctic and North Atlantics.

[7] For study of irregularities in the high-latitude ionosphere the HF radars of the SuperDARN [*Greenwald et al.*, 1995] and CUTLASS [*Yeoman and Luhr*, 1997] are successfully used. However, it is known that a motion from high to middle latitudes of the southern boundary of the region with irregularities responsible for the scatter is observed during geomagnetic storms. In this situation due to the conditions of propagation and geometry of the scatter the irregularities are found outside the "visibility" zone of the high-latitude HF radars. The latter fact makes difficult a detailed study by these radars of the dynamics of small-scale irregularities localized at the southern boundary of the auroral oval at all stages of a magnetic storm. So to obtain a complete picture of the ionospheric irregularity dynamics during a magnetic storm it is of a considerable interest to use together with high-latitude radars also radars located at middle latitudes. For this task the Russian and global network of the LFM ionosondes [*Ivanov et al.*, 2003] located at middle latitudes may be used as HF radars in a bistatic configuration. The experiments carried out during the recent years on the basis of the LFM ionosondes network demonstrated a perspective of such approach for studying the dynamics of ionospheric irregularities and wave processes in the ionosphere and magnetosphere during magnetic storms [*Kurkin et al.*, 2004; *Uryadov et al.*, 2002, 2004a, 2004b; *Zherebtsov et al.*, 1997].

[8] There are two goals of this paper. The first one is to present the results of experimental studies and modeling of the peculiarities of HF signal propagation during geomagnetic disturbances obtained on the basis of the network of midlatitude circuits of oblique LFM sounding. The second goal is to demonstrate that the use of oblique sounding makes it possible to complete considerably the picture of midlatitude ionosphere behavior including the periods of magnetic storms in the Eurasian longitudinal sector poorly equipped by observational means and characterized by the maximum excess of geographical latitudes over geomagnetic latitudes.

2. Results of Observations

[9] The experimental OS data obtained in two campaign are analyzed. The first campaign took place in the period 24 February to 11 March 1999 and the second campaign was carried out on 20–25 October and 28–31 October 2003. The OS path Magadan (59.7°N, 150.5°E) to Irkutsk (51.8°N, 104°E) was used in the first campaign. Coordinated observations at the Russian network of LFM ionosondes [*Ivanov et al.,* 2003] were carried out in the second campaign from 20 to 25 of October 2003. The following paths were used: Khabarovsk (47.5°N, 134.5°E) to Rostov on Don (47.3°N, 39.7°E), Magadan–Rostov on Don, Irkutsk–Rostov on Don, Khabarovsk–Irkutsk, Magadan–Irkutsk, Noril'sk (69.4°N, 88.1°E) to Irkutsk, Noril'sk–Rostov on Don, Khabarovsk–Nizhny Novgorod (56.1°N, 44.1°E), Magadan–Nizhny Novgorod, Irkutsk–Nizhny Novgorod, and Noril'sk–Nizhny Novgorod. In the period from 28 to 31 October the Inskip (England, 53.8°N, 2.8°W) to Rostov on Don path was

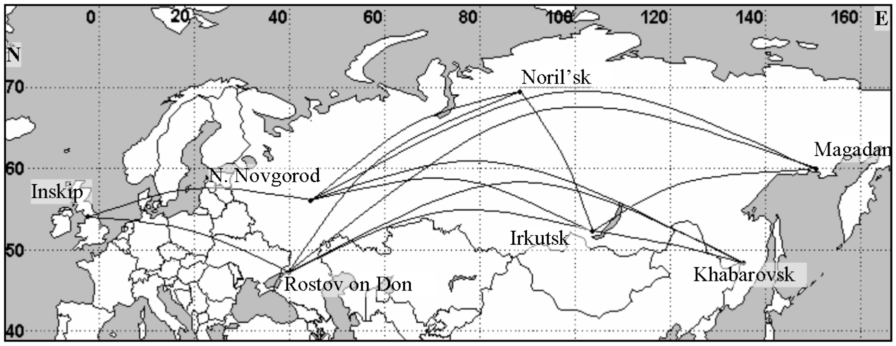

Figure 1. Geometry of the path network in the period of conduction of the experiments on oblique sounding of the ionosphere.

also used. The round the clock observations were conducted. The LFM ionosondes at Magadan, Khabarovsk, Irkutsk, and Noril'sk operated every 15 min in the frequency range 4–30 MHz and the ionosonde in Inskip radiated every 5 min in the frequency range 4.2–30 MHz. The rate of the frequency variations for all ionosondes was about 100 kHz s^{-1}. The geometry of the paths is shown in Figure 1. Some results obtained in this experiment are presented below.

2.1. First Campaign

[10] An important feature of the Magadan–Irkutsk path is that the arc of the great circle forms a small angle to the auroral oval boundary when the latter shifts into the midlatitude region. It is worth noting that the main lobe of the transmitting antenna in Magadan was oriented to Moscow. Therefore the standard propagation modes at the Magadan–Irkutsk path correspond to the radiation of side lobes of the transmitting antenna ($\Delta\varphi = 45°$). The location of the main ionospheric trough was estimated using the equatorial boundary of the auroral oval [*Basler et al.*, 1988; *Brunelli and Namgaladze*, 1988], empirical dependence of the trough on the longitude, season, local time and solar and magnetic activity [*Karpachev*, 2003; *Karpachev and Afonin*, 2004], and also the vertical sounding data at Zhigansk (66.8°N, 123.2°E), Yakutsk (61.8°N, 130°E) and Magadan. The dynamics of the auroral oval was determined using the real data of the DMSP satellites obtained on the Web (http://sd-www.jhuapl.edu/Aurora/ovation/ovation_display.html). The observation period was characterized by the moderate level of solar activity. The monthly mean index $F_{10.7}$ varied form 125 to 137 (in the units of the solar radioemission flux 10^{-22} W m^{-2} Hz^{-1} at a wavelength of 10.7 cm). Geomagnetic disturbances of various intensity were registered during the experiment except on quiet days 26 and 27 February. Moderated magnetic storms were registered from 28 February to 2 March (the minimum value of the Dst index was −94 nT) and 9–10 March (the minimum value of the Dst index was −80 nT). Small magnetic storms were observed on 3–4 March and 6–8 March. In other days substorm disturbances were registered.

[11] A typical feature of the OS ionograms at the considered path during geomagnetic disturbances was registration of the signals propagating outside the great circle arc. Additional signals with anomalously long delay began to be observed since 1200–1400 UT when the path was in the dusk-night sector. The time interval of registration of these signals reached 11 hours from the moment of their appearance. In quiet conditions on 26 and 27 February the anomalous signals were registered during a short interval of time from 1245 to 1545 UT. Their delay relative to the standard modes was 3 ms and more. The anomalous signals was characterized by a strong spread and the frequencies exceeded MOF of the standard propagation modes. In the substorm conditions on 24–25 February the anomalous signals were registered in the more broad time interval from 1200 to 2000 UT. In the beginning of this interval "quasi-multiple" signals relative to the 2F mode (relatively weakly spread) and then the "quasi-multiple" signals relative to the 1F mode appeared. The distance-frequency characteristics (DFC) of the "quasi-multiple" signals were repeating the shape of DFC of the standard mode in the range of higher frequencies. The delay of the anomalous signals relative to the standard propagation modes exceeded 3 ms. In the process of the disturbance development this delay was decreasing down to 1–2 ms. The anomalous signals were becoming more spread conserving the DFC shape. This shows that the main mechanism of anomalous signal formation is the refraction in the three-dimensional inhomogeneous ionosphere. The scatter at irregularities of various scales intensifies only a signal spread.

[12] A typical feature of the small magnetic storms on 3–4 March and 6–8 March is a significant increase of the auroral index of magnetic activity after 1800 UT (in the night hours of the local time). The auroral oval shifts in this time down to the Magadan latitudes and the great circle arc of the path is located completely within the main ionospheric trough. The MOF and amplitude of the standard signal are sharply decreasing. The anomalous signals at these hours are formed due to the scatter at irregularities of different scales located within the auroral zone.

[13] In the conditions of a moderate magnetic storm, starting from 1100 to 1200 UT the anomalous signals appear with a delay of more 3 ms relative to the standard modes propa-

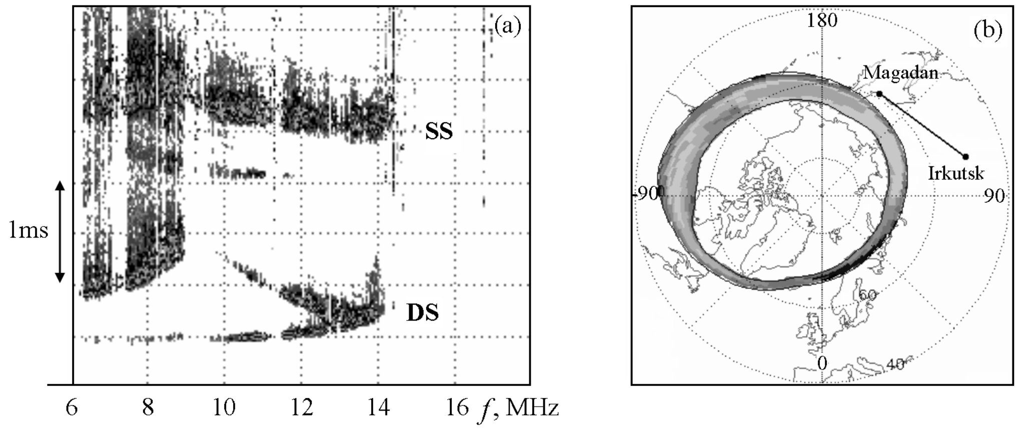

Figure 2. (a) Ionogram at the Magadan–Irkutsk path and (b) the geographical position of the auroral oval at 1202 UT on 1 March 1999. DS and SS are the direct and side signals.

gating along the great circle arc. The analysis of the DMSP satellites data showed that in these hours the equatorial wall of the auroral oval approaches the Magadan–Irkutsk propagation path. In this situation transverse gradients of ionospheric parameters begin to influence the propagation conditions. Figure 2 shows the oblique sounding ionogram and the geometrical position of the auroral oval for the moment 1202 UT on 1 March 1999. Together with the propagation modes 1F2 and 2F2 there presents in the ionogram an additional signal with the delay exceeding the delays of the main propagation modes. The appearance of such signals may be due to the refraction in the region of the polar wall of the main ionospheric trough, because the main direction of the antenna pattern of the transmitting station Magadan is oriented to Moscow.

[14] As far as the location of the main through relative to the propagation path changes, the structure and delay of the additional signals change considerably. Figure 3 shows the oblique sounding ionogram for 1432 UT on 1 March 1999 and the data on the geographical location of the auroral oval. Quasi-multiple propagation modes with the frequency dependence typical for the main modes at night are observed. As far as the ionospheric trough approaches the propagation path, the MOF of anomalous signals begins to exceed MOF of the standard propagation modes. The latter fact may be considered as an indirect confirmation of the assumption that these signals are reflected in the regions of the polar wall of the main ionospheric trough. The analysis of the vertical sounding (VS) data during the magnetic storm showed that the middle points of the propagation path of the main modes were located within the ionospheric trough.

[15] In the vicinity of the equatorial edge of the auroral oval at the boundary with the northern wall of the trough there exist structural regions of the ionosphere with dimensions of about 100 km with a sharp horizontal gradient (so called globules) which present a source of a wide spectrum of irregularities. The strong spread of the signal in Figure 4 may be due to the radio wave scatter at intense irregularities existing within such structures [*Basler et al.*, 1988; *Uryadov et al.*, 2004a]. In the morning hours at a shift of the auroral

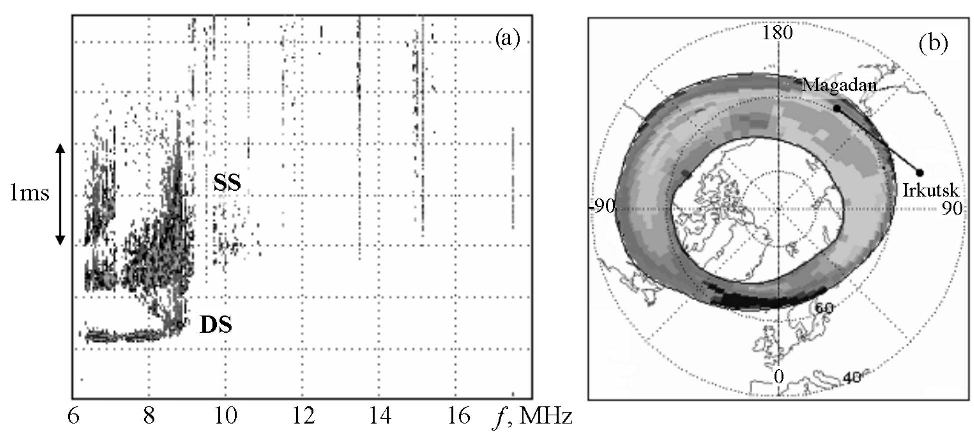

Figure 3. (a) Ionogram at the Irkutsk–Magadan path and (b) the geographical position of the auroral oval at 1432 UT on 1 March 1999. DS and SS are the direct and side signals.

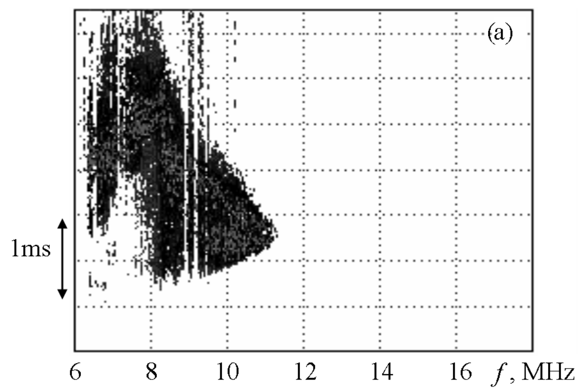

Figure 4. (a) Ionogram at the Magadan–Irkutsk path and (b) the geographical position of the auroral oval at 2047 UT on 1 March 1999.

oval into the region of higher latitudes, the delay of spread anomalous signals again increases up to 2–3 ms relative to the standard modes. Figure 5 shows the oblique sounding ionogram for 2232 UT on 1 March 1999 and the data on the geographic position of the auroral oval.

[16] Thus the joint analysis of the ionospheric VS and OS data and satellite data shows that the appearance of the additional signals may be caused by the refraction of the ray beam of the main lobe of the transmitting antenna at the transverse gradients of the electron concentration in the vicinity of the northern wall of the ionospheric trough as well as to the scatter at irregularities existing in the vicinity of the equatorial boundary of the auroral oval and the trough northern wall. The performed numerical evaluations of the localization of the scattering region confirm possibility of such mechanism of side signals formation.

2.2. Second Campaign

[17] In the second campaign the monitoring observations at the Russian LFM ionosondes network were carried out. The signals of the LFM ionosonde located in Inskip (England) were also received. Thus a vast longitudinal sector from England to Magadan was controlled by the oblique ionospheric sounding. The observations began in the moderately disturbed period. On 24 October 2003 at 1500 UT a moderate substorm disturbance was detected (see Figure 6). The disturbance was caused by the sharp jump of the solar wind velocity from 400 km s^{-1} to 600 km s^{-1} and the increase of the interplanetary magnetic field (IMF) from 10 nT to 25 nT after a series of flares of M and X classes what occurred on 22–23 October. Especially strong disturbance of the magnetic field took place on 29–31 October and was caused by a series of prominent flares. The flare of the X17.2/4B class, which began on 28 October at 0951 UT, should be specially mentioned. A dense and quick eruption of the substance with a velocity exceeding 2100 km s^{-1} was observed during this flare. In the evening of 29 October one more proton flare X10.0/2B S15W02 occurred [*Panasyuk et al.*, 2004]. As a result a series of extremely strong magnetic storms began. According to the data by *Panasyuk et al.* [2004], at 0612 UT on 29 October 2003 there was a sharp increase in the IMF magnitude from 10 to 35 nT and a sharp change of the B_z component orientation to southward with

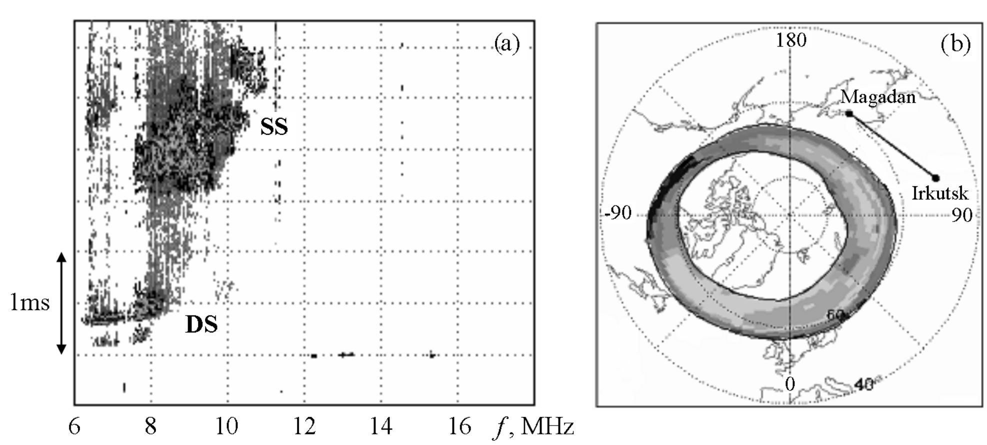

Figure 5. (a) Ionograms at the Magadan-Irkutsk path and (b) the geographical position of the auroral oval at 2232 UT on 1 March 1999. DS and SS are the direct and side signals.

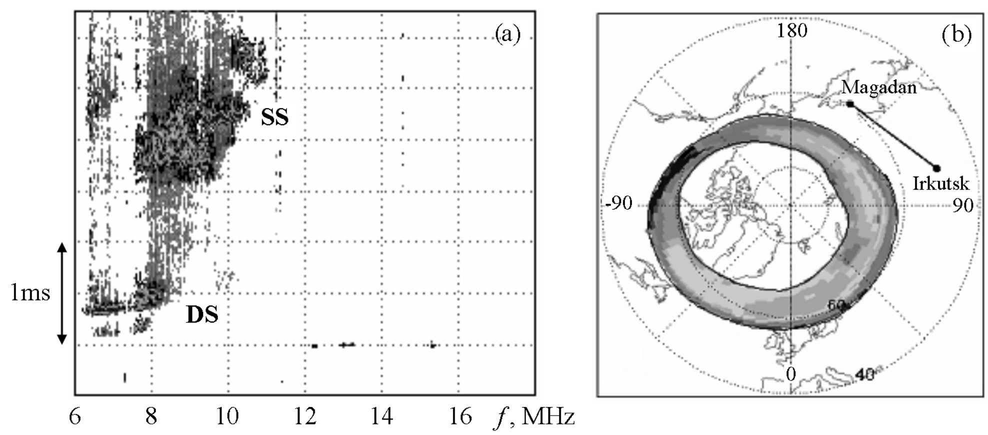

Figure 6. Behavior of the geomagnetic indices during the carrying out of the second experimental campaign on 20–31 October 2003.

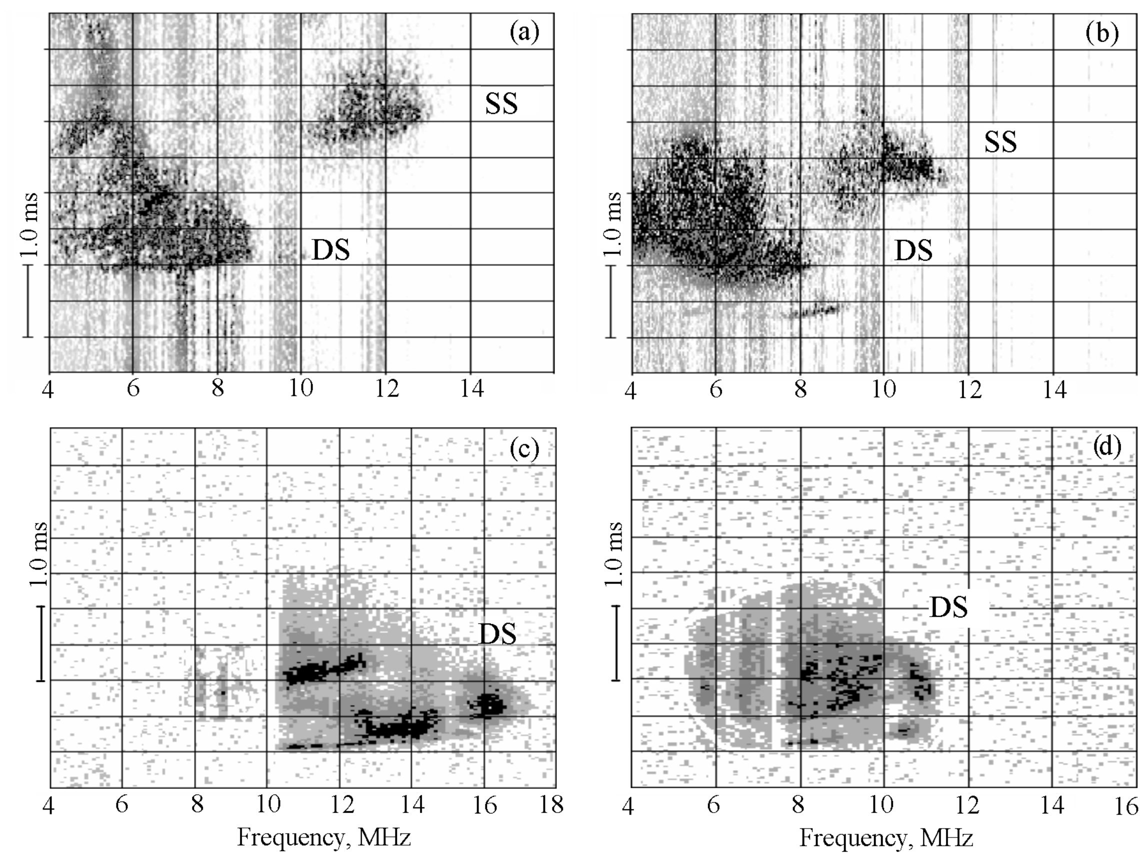

Figure 7. Oblique sounding (OS) ionograms at the (a) Irkutsk–Rostov on Don path at 1800 UT on 24 October 2003, (b) Khabarovsk–Rostov on Don at 2225 UT on 24 October 2003, (c) Irkutsk–Nizhny Novgorod at 1800 UT on 24 October 2003, and (d) Khabarovsk–Nizhny Novgorod at 2225 UT on 24 October 2003 during geomagnetic disturbances. DS and SS are direct and side signals, respectively.

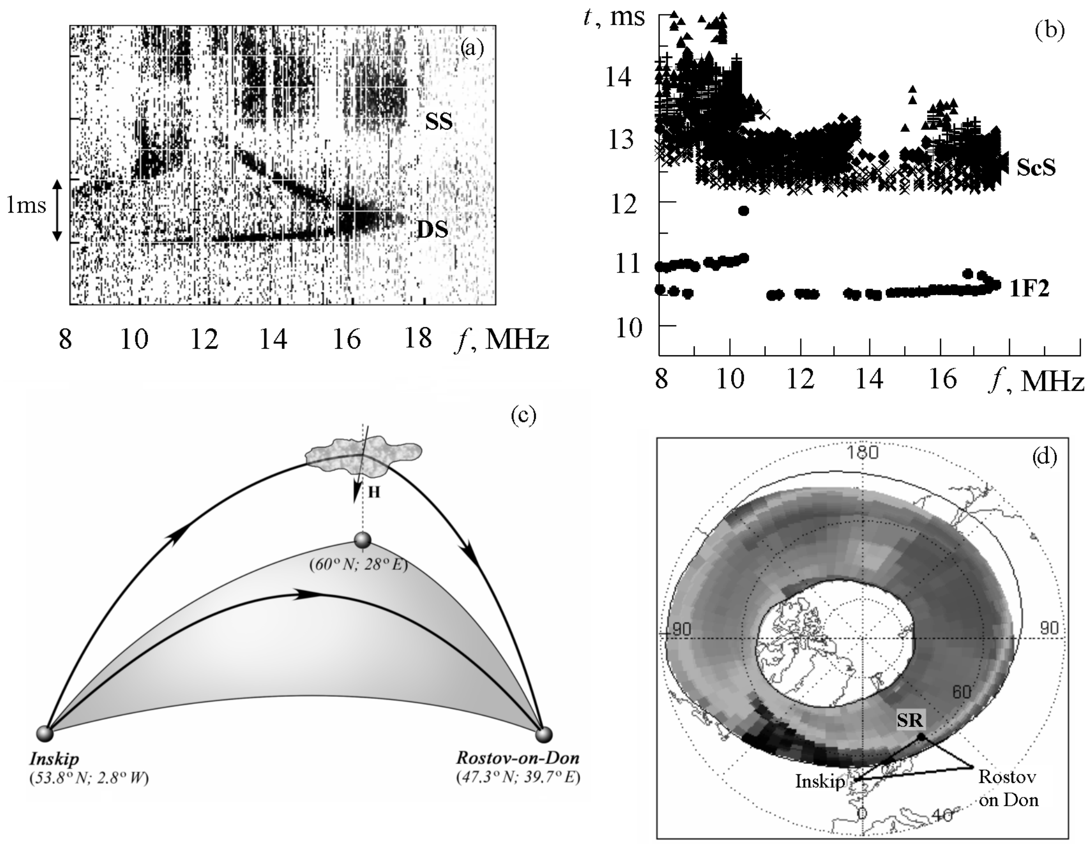

Figure 8. (a) Experimental and (b) calculated ionograms at the Inskip–Rostov on Don path during the magnetic storm 1442 UT 29 October 2003 (DS, SS, and ScS are direct, side, and scattered signals, respectively), Crosses, diamonds, triangles, and pluses are markers for scattering regions which centers have subionospheric coordinates (60°N, 28°E)(61°N, 28°E), (62°N, 28°E), and (60°N, 32°E), respectively. (c) tracing for frequency 16 MHz. (d) Position of the auroral oval with the position of the scattering region (SR).

the value of −25 nT. This effect was caused by a strong solar flare of class X17.2. Figure 6 shows the geomagnetic activity level expressed in the Kp (a) and Dst (b) indices. The observations were conducted on the background of this geomagnetic situation.

[18] Now we analyze the most prominent events characterizing propagation of HF signals at midlatitude paths during geomagnetic disturbances. They were mainly observed at Rostov on Don where the reception of the signals was conducted at an oblique V antenna with the diagram oriented to the azimuth of $A \sim 20°$. The ionograms presented in Figures 7a, 7b, and 8a illustrate appearance at the Irkutsk–Rostov on Don, Khabarovsk–Rostov on Don, and Inskip–Rostov on Don of additional signals during geomagnetic disturbances. The propagation time of the additional signal exceeds the propagation time of the main mode and on the ionogram these signals are marked by SS (side signals). The direct signals propagating along the great circle arc are marked by DS. One can see that all SS are spread signals, their intensity being comparable to the intensity of DS.

[19] The OS ionograms registered at the Irkutsk–Nizhny Novgorod and Khabarovsk–Nizhny Novgorod paths for the same moments of time as the ionograms in Figures 7a and 7b are shown in Figures 7c and 7d for comparison. One can see in Figures 7c and 7d that only direct spread signals are observed in the ionograms, whereas additional (side) signals are absent. Different appearance of the side signals in the reception points with different latitudes (in this case those are Rostov on Don and Nizhny Novgorod) may be caused by several factors including the following. We have already mentioned that the auroral oval is shifted to middle latitudes during a magnetic storm. Small-scale irregularities localized at its southern boundary and responsible for the aspect scatter may appear outside the “visibility” zone for the more northern configuration of LFM HF radars (in our case it is true for the paths Irkutsk–Nizhny Novgorod and Khabarovsk– Nizhny Novgorod in comparison with more southern paths Irkutsk–Rostov on Don and Khabarovsk–Rostov on Don). This concept is confirmed by the satellite observations of the auroral oval. According to the data of the site (http://sd-www.jhuapl.edu/Aurora/ovation/

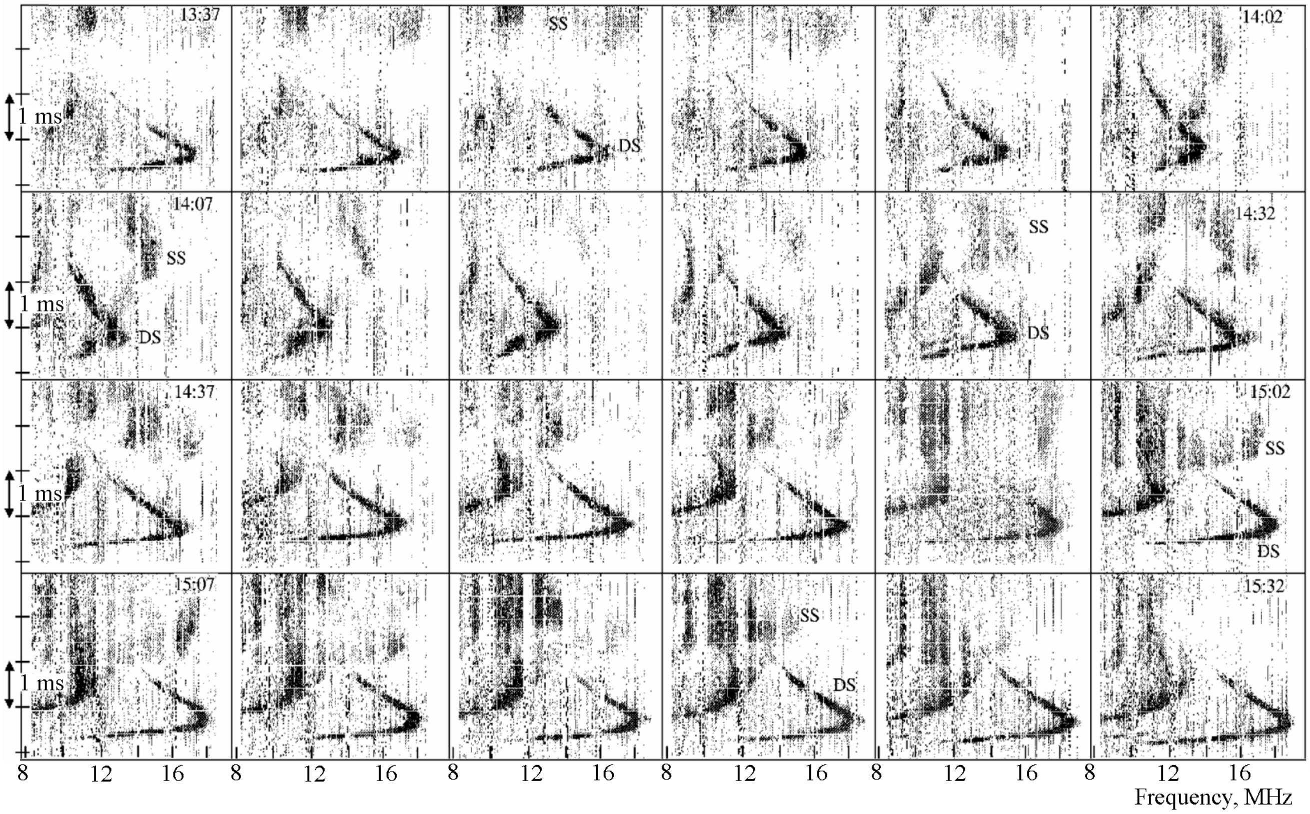

Figure 9. Ionograms at the Inskip–Rostov on Don path during the magnetic storm on 29 October 2003. Ionograms were recorded every 5 min. UT goes from left to right and from top to bottom. SS and DS are the side and direct signals, respectively.

ovation_display.html) for the above indicated moments of time the paths Khabarovsk–Nizhny Novgorod and Irkutsk–Nizhny Novgorod cross the oval. In this case the irregularities would influence the signal spread due to the radio wave forward scatter at intermediate-scaled irregularities of the auroral zone. This effect is seen in OS ionograms as a halo around of the main propagation modes (see Figures 7c and 7d). It is worth noting that similar situation is observed at the Magadan–Irkutsk path at 2047 UT on 1 March 1999 (see Figure 4).

[20] The detailed picture of the spread side signal dynamics with time during the magnetic storm on 29 October 2003 is visually seen in Figure 9 which shows a sequence of ionograms at the Inskip–Rostov on Don path. The ionograms were recorded every 5 min, time in the ionograms goes from left to right and from top to bottom. The SS signals are presented at all ionograms though not all of them are marked to avoid overloading Figure 9. One can see that SS demonstrate a strong dynamics: the distance-frequency characteristics of SS change every 5–10 min. The latter manifests a rapid variability of the position of the region responsible for the spread side signal formation. From 1337 to 1437 UT a decrease of the SS delay relative to DS from about 3 ms to 2 ms was observed. Estimates show that the rate of the motion of this region in the latitudinal direction was on the average of $\sim 2.5^{\circ}$ per hour.

[21] One should note that during the main phase of the magnetic storm from 0812 to 1002 UT DFC of the direct signal was modulated by traveling ionospheric disturbances (TID) descending in the coarse of time downward along the Pedersen mode. Figure 10 illustrates the dynamics of the DFC in the presence of TID. Moreover, from 1100 to 1300 UT deep quasiperiodic oscillations of MOF with a period of about 1 hour and amplitude of about 2 MHz were observed. They are visually seen in Figure 11 where the time behavior of MOF at the Inskip–Rostov on Don path from 0600 to 1800 UT on 29 October 2003 is shown. In Figure 11 the intervals are hatched of observations of ionospheric disturbances with the DFC modulation in the vicinity of MOF (light hatching) and spread side signals (dark hatching). It is worth noting that these time intervals correspond to the main phase of the magnetic storm development characterized by a depletion of the *Dst* index of the geomagnetic field (see Figure 6b).

3. Modeling and Discussion

[22] The midlatitude ionosphere during magnetic storms gets features of the high-latitude ionosphere. This is manifested in appearance of rather strong anomalous signals related either to side reflection of radio waves from the north-

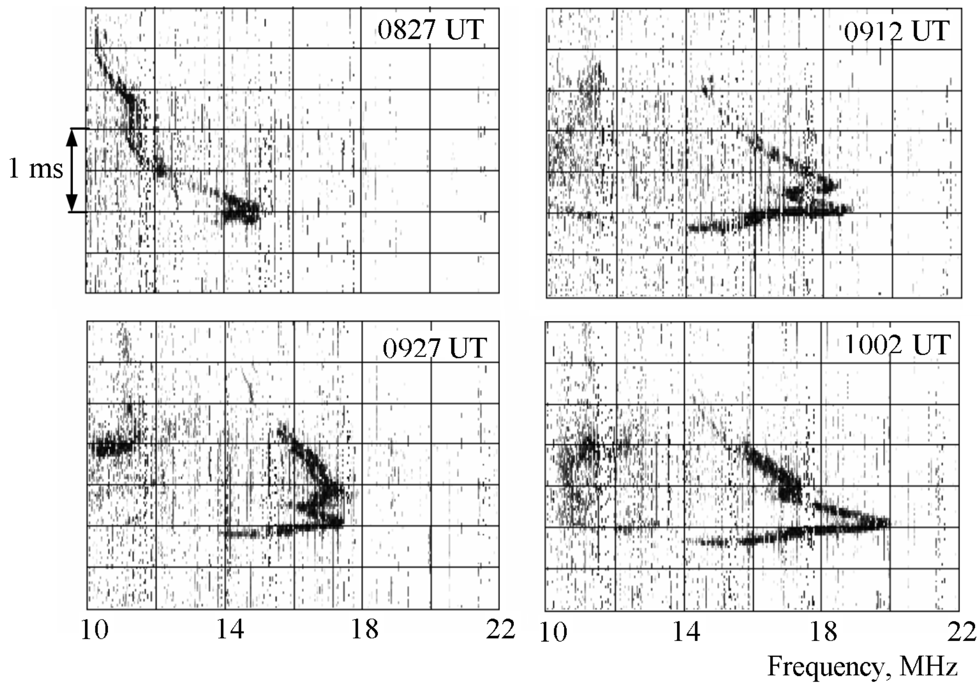

Figure 10. Oblique sounding (OS) ionograms at the Inskip–Rostov on Don path during the main phase of the magnetic storm on 29 October 2003.

ern wall of the ionospheric trough or from large-scale structures of the globules types with enhanced electron concentration or to the scatter at intense small-scale irregularities located at the southern boundary of the auroral oval, as well as to a combination of all this factors. The side signals were registered during geomagnetic disturbances at frequencies both below and above MOF of the hop propagation modes. The frequency range of SS and its position relative to the main mode depends on some factors and is determined by the geometry of the ionosonde location, ionospheric conditions at the propagation path, and geophysical situation.

[23] In this paper we do not consider the problem of interpretation of all observed anomalous signals recorded at the paths considered, in particular the anomalous signals registered at frequencies above MOF of hop propagation at long midlatitude paths Khabarovsk–Rostov on Don and Irkutsk–Rostov on Don, and also quasi-multiple signals observed at the Magadan–Irkutsk path. This problem requires additional studies with use of direction finding measurements, detailed ionospheric and geophysical information, and also calculation of radio wave propagation in three-dimensional inhomogeneous medium. The main attention will be paid to interpretation of strongly spread signals observed at the Inskip–Rostov on Don path during extremely strong magnetic storm on 29–31 October 2003. We believe that the side spread signals are due to the scattering of radio waves at small-scale field-aligned irregularities. Such irregularities exist at the southern boundary of the auroral oval [*Fejer and Kelley*, 1980; *Tsunoda*, 1988]. They may serve as an indicator for determination of the position of the auroral oval during magnetic disturbances by registration of the side (scattered) signals at oblique sounding ionograms.

[24] For the Inskip–Rostov on Don path where the spread side signals were observed during the magnetic storm, we performed calculations in order to localize the region with the irregularities responsible for the scatter. The IRI model and (superposed on it) empirical model of the main (midlatitude) ionospheric trough [*Karpachev*, 2003; *Karpachev and Afonin*, 2004] were used in the calculations. The concentration in the F-layer maximum on the trough walls coincide with the values given by the IRI model. Within the trough the interpolation was performed depending on the width,

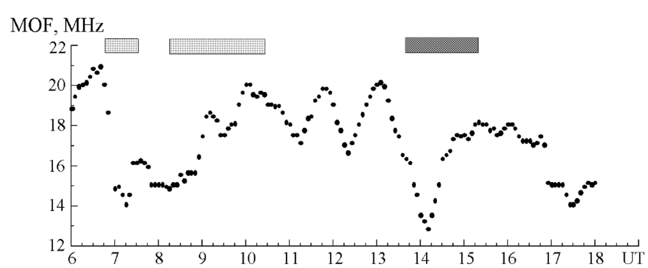

Figure 11. Time behavior of the maximum observed frequency (MOF) at the Inskip–Rostov on Don path on 29 October 2003. Gray rectangles correspond to the observation intervals with modulation of ionograms in the vicinity of MOF by traveling ionospheric disturbances. Shaded rectangles correspond to the interval of observations of the side signal.

depth, and minimum concentration position. The correction of the electron concentration values using the data of Chilton station (51.6°N, 1.3°E) (http://www.wdc.rl.ac.uk) was also performed to provide the agreement between the calculated and experimental ionograms of the direct signal.

[25] Evidently, the region with the irregularities should be located within the ellipse with the focal points in the reception and transmission stations. The position of the scattering region within the ellipse itself was fitted by calculations, comparing the model and experimental ionograms and using the aspect scatter condition at strongly stretched field-aligned irregularities [*Ponyatov and Uryadov*, 1996]. The location of such scattering regions was taken in the form of a latitude-longitude net in the vicinity of the southern boundary of the auroral oval. The position of the region containing irregularities in the form of a disk with a radius of 50 km varied within considerable limits both, in latitude (from 58°N to 62°N) and longitude (from 25°E to 40°E) in the height interval from 230 km to the F-layer maximum. The calculations showed that in principle the side signals caused by the radio wave scattering at small-scale field-aligned irregularities may come from different regions. The best coincidence of the experimental and calculated ionograms was a criterion of the choice.

[26] According to the calculations for the regions with scattering irregularities in the vicinity of 25°E (the distance from Inskip to the scattering region (SR) is of the order of 1800–1900 km) the aspect conditions at low frequencies $\sim 8 - 10$ MHz are fulfilled for the second mode: the scattering occurs from the peak of the second hop. At frequencies above 12 MHz radio waves reach SR in the peak of the first hop. However, either the reception point Rostov on Don is located in the dead zone for the scattered ray or the latter goes away to the ricocheting mode. Therefore the scattered signal from this region is not received at high frequencies. For the eastern regions in the vicinity of 40°E, the distance from Inskip to SR increases and the scattering from the peak of the first hop is observed only for high frequencies. This range is narrowing shifting to higher frequencies (above 15–16 MHz) and almost disappears for the regions with the longitude above 40°E. Frequencies below 12 MHz are scattered from the peak of the second hop. For frequencies 12–16 MHz SR falls into the dead zone between the peaks of the first and second hops, so the scattered signal from this range is absent. For the regions with scattering irregularities in the vicinity of 28–32°E an optimum case is realized under the given geometry of the position of the transmitter (Inskip) and receiver (Rostov on Don). The scattered ricocheted modes are transformed into hop modes and the reception station Rostov on Don falls into the reception zone. Therefore for these regions the maximum range of passing and reception of the scattered signal is observed.

[27] Figure 8b shows the ionogram at the Inskip–Rostov on Don path calculated for the conditions of the experiment (1442 UT, 29 October 2003) taking into account radio wave scatter at field-aligned irregularities. The diffusive signal delayed relative the direct signal is marked by ScS (scattered signal). This signal is due to the scattering at irregularities located in the topside ionosphere. The subionospheric coordinates of the centers of the regions with irregularities providing the better agreement of the experimental and calculated data on the scattering lie within the latitude and longitude intervals 60–62°N and 28–32°E, respectively. Comparing Figures 8a and 8b, one can see a quite satisfactory agreement between the calculated and experimental ionograms. Figure 8c shows the ray trajectories at a frequency of 16 MHz realized at the direct path along the arc of a great circle Inskip–Rostov on Don and along the path with the deviation from the great circle arc at the aspect scattering at field-aligned irregularities located in the upper ionosphere at heights of about 270–300 km. The calculations were performed for the region with irregularities, the center of the region having subionospheric coordinates 60°N, 28°E. Figure 8d shows the geographical position in the map of the auroral oval of the scattering region which according to the propagation conditions and scattering geometry provides the main input to the spread (scattered) side signal in the oblique sounding ionogram for the given position of the transmitting and reception points. One can see in Figure 8d that the calculated region with irregularities responsible for the scattering and appearance in the OS ionogram of anomalous spread signal is well positioned to the location of the southern boundary of the auroral oval (according to the measurements on board the DMSP satellite (http://sd-www.jhuapl.edu/Aurora/ovation/ovation_display.html), the latter fact supporting the suggested interpretation of the nature of the anomalous signal.

[28] It should be noted that during the registration of side spread signals in the OS ionograms in the period 1340–1530 UT on 29 October 2003 the B_z component of the interplanetary magnetic field (IMF) was northward ($B_z > 0$), however the value of the IMF magnitude was high. It is known that magnetic storms well correlate to the southward component of IMF ($B_z < 0$). The data on the dynamics of the auroral oval obtained on the basis of the oblique sounding of the disturbed ionosphere confirm a possibility of a substorm development and southward motion of the auroral oval also in the periods when $B_z > 0$. These data show also that with an increase of the magnitude of the interplanetary magnetic field the energy injected into the magnetosphere increases and this causes intensification of the magnetospheric and ionospheric current systems determining the dynamics of the high-latitude ionosphere and formation of irregularities. The equatorward motion of the auroral oval directly or indirectly manifests changes in the magnetospheric configuration as a result of the reconnection of field lines of the interplanetary and geomagnetic fields and intensification of the ring current. According to *Yokoyama et al.* [1998] the intensity of the ring current measured by Dst provides the main input into variation in the equatorial boundary of the auroral oval. Moreover, *Yokoyama et al.* [1998] suggested that the equatorial boundary of the oval moves southward due to the increase of the auroral electrojet activity. It is worth noting that during the extreme magnetic storm on 29–31 October 2003 an aurora was observed at the midlatitude station IZMIRAN (55°N, 37°E) [*Panasyuk et al.*, 2004].

[29] As for the traveling ionospheric disturbances (TID) observed at the midlatitude path Inskip–Rostov on Don dur-

ing the magnetic storm on 29 October 2003 at 0800–1000 UT (see Figure 10), they are an ionospheric response to acoustic gravity waves (AGW). The mechanisms of generation of AGW in the auroral zone are known and related to the Joule heating, Lorenz force, and particle precipitation [*Hocke and Schlegel*, 1996; *Hunsucker*, 1982; *Williams et al.*, 1988]. At high latitudes, TID are well detected by HF radars. For example, according to the data of the observations on the network of SuperDARN radars [*Bristow et al.*, 1994; *MacDougall et al.*, 2001], at high latitudes at backscatter oblique sounding (BOS) signals a modulation of the echo signal is often observed. This modulation is interpreted as a focusing at the radio waves reflection from the ionosphere modulated by traveling wave disturbances.

[30] The traveling ionospheric disturbances registered in oblique sounding ionograms may serve as an indicator of manifestation of the magnetosphere-ionosphere relations during geomagnetic disturbances because of generation of AGW and their propagation from the high to middle latitudes. It is worth noting here that a good correlation between AGW and magnetic activity was observed also in the Worldwide Atmospheric Gravity-wave Study (WAGS) experiment [*Williams et al.,* 1988]. In this experiment various technical means took part at high and middle latitudes including the incoherent scatter radar EISCAT, networks of magnetometers and riometers, vertical sounding ionosondes, and also the system of HF radars.

[31] The comparison of the results of measurements of MOF variations during a storm and in quiet conditions shows that during a storm the amplitude of the MOF variations increases considerably, the amplitude of rapid variations (≤ 15 min) intensifies, and the behavior of MOF with time becomes of a pulsating character, the latter manifesting wave processes occurring in the ionosphere in the periods of geomagnetic disturbances. The estimates made on the basis of the modeling of ionospheric HF propagation, taking into account TID by the method described by *Erukhimov et al.* [1998], show that the observed effect of the DFC modulation in the vicinity of MOF may be expected from wave-like disturbances of the electron concentration with the amplitude of about 20–30% of the background level. The large-scale variations in MOF observed approximately from 1100 to 1400 UT are evidently due to the passing of the terminator at the propagation path. Similar effect was observed in the dusk at the midlatitude Inskip–Moscow path in April 2002 in quiet geomagnetic conditions [*Cherkashin et al.*, 2003].

[32] Thus, according to the data obtained magnetic storms are accompanied by a generation of powerful TID and southward motion of the ionospheric trough and auroral oval. The combination of these factors provides (by refraction and radio wave scatter) formation of side signals recorded in oblique sounding ionograms at midlatitude paths during geomagnetic disturbances.

4. Conclusions

[33] The main results of the paper may be formulated as follows:

[34] 1. It is demonstrated that the system of the oblique sounding paths covering a vast Eurasian longitudinal sector from England to Magadan may serve as an effective tool for monitoring of ionospheric effects of geomagnetic disturbances. The network of LFM ionosondes may be used as bistatic HF radars sensitive to both large-scale structures (the main ionospheric trough, auroral oval, traveling ionospheric disturbances, patches with increased electron concentration) and small-scale irregularities accompanying such large-scale formations. The network of LFM ionosondes for oblique sounding may serve as an addition to the existing ground-based and satellite systems of ionospheric monitoring in various geophysical conditions, the latter being especially important for the regions weakly equipped by diagnostics means.

[35] 2. The joint analysis of the VS and OS of the ionosphere and satellite data shows that the appearance of the additional signals during geomagnetic disturbances may be due to the refraction of radio waves in the region of the auroral oval and main ionospheric trough, and also by the scatter at irregularities of different scales in the vicinity of the equatorial boundary of the auroral oval and the northern wall of the trough. First of all this is confirmed by the data obtained at the Magadan–Irkutsk path in the conditions of moderate magnetic storm when the distance-frequency characteristics (DFC) of the anomalous signal repeated the shape of the DFC of the standard mode.

[36] 3. On the basis of numerical simulations and comparison to the experimental data of oblique sounding the identification is performed of the additional strongly spread signals registered during the magnetic storm at the midlatitude Inskip (England) to Rostov on Don path as signals scattered at small-scale field-aligned irregularities located at the southern boundary of the auroral oval. It is shown that during the main phase of the magnetic storm on 29 October 2003, there occurred a shift of the southern boundary of the auroral oval from high to middle latitudes with a mean velocity of about 2.5° per hour. It is worth noting that the ionospheric effects observed at the midlatitude path of oblique LFM sounding Inskip–Rostov on Don during the prominent magnetic storm on 29–31 October 2003 are more typical for the auroral zone of the Arctic. In such situation the radio wave propagation conditions at midlatitude paths become similar to the corresponding conditions in the high-latitude ionosphere. Fairly intense signals with the propagation outside a great circle arc are registered and this fact should be taken into account while organizing the operation of various radio electronic systems (HF radiocommunication, over horizon HF radiolocation, radio direction finding etc.)

[37] 4. It is shown that during the main phase of a strong magnetic storm on 29 October 2004 a modulation of DFC in the vicinity of MOF related to the generation of acoustic gravity waves and their response in the form of traveling ionospheric disturbances was observed at the midlatitude Inskip–Rostov on Don path. According to the estimates the amplitude of the wave disturbances was $\sim 20-30\%$ of the electron concentration background level.

[38] Concluding we note that the results of the performed studies of shortwave propagation manifest a complicated picture of physical processes in the magnetosphere-ionosphere

system during geomagnetic disturbances. These processes involve the structure and dynamics of both large-scale formations (ionospheric trough, auroral oval) and accompanying these formations small-scale irregularities. During strong disturbances these factors are able to impact considerably the HF signal characteristics not only in the high-latitude ionosphere, but at middle latitudes as well, where the main part of decameter radio lines passes. It is evident that for further progress in this region and obtaining of more complete data on the physics of ionospheric processes and mechanisms of HF propagation in the conditions of geomagnetic disturbances coordinated studies with use of modern radiophysical and geophysical methods of measurements are needed. The experimental study of the ionosphere by the oblique sounding method at paths of different length and orientation in the region of the subauroral ionosphere may serve as an important tool of diagnosis of the position and structure of the main ionospheric trough. We plan in the future to carry out such studies attracting both national and foreign systems of diagnostics of the ionosphere and magnetosphere, including direction finding measurements [*Vertogradov et al.*, 2004].

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