Characteristics of HF Radio Waves Propagation along Subauroral and Mid-latitude Paths over Eastern Siberia during Magnetoactive Period in February 2014

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Abstract— Based on vertical and oblique-incidence sounding data, we analyzed characteristics of HF propagation during magnetoactive period in February 2014. The oblique-incidence sounding data had been obtained over subauroral and mid-latitude paths: Magadan-Irkutsk, Khabarovsk-Irkutsk, Khabarovsk-Norilsk, and Magadan-Norilsk. The period considered was characterized by a series of solar flares accompanied by intensification of proton and X-ray fluxes as well as by coronal mass ejections. These processes caused two magnetic storms of different intensity. During the main and recovery phases of the first storm, positive ionospheric disturbances were observed in the day, and negative, in the night. During the second magnetic storm, the maximum observed frequencies (MOF) over the Magadan-Irkutsk path fell sharply by 3–5 MHz. Intervals of low MOF values alternated with intervals of absence of reflected signals in ionograms. It specifies that boundaries of the main ionospheric trough could be displaced to the latitude of this path's midpoint. A similar absence of reflected signals in the ionograms was registered over the Khabarovsk-Norilsk path. Besides, during these two storms the oblique sounding ionograms showed additional signals with large time delays over the Magadan-Irkutsk and Khabarovsk-Irkutsk paths in evening and nocturnal hours. The abnormal signals were characterized by strong diffusion and their frequencies considerably exceeded MOF of standard propagation modes. Since the ionosphere is not perfectly horizontally stratified during magnetic storms, signals associated with propagation mode may arrive at a receiving point over a wide range of azimuth angles.

1. INTRODUCTION

Extreme space weather events caused by powerful solar flares and their associated magnetic storms can significantly affect radio communication, navigation and radar facilities. Numerous studies of solar flare effects on the magnetosphere-ionosphere-thermosphere system presented in reviews and original papers, for example [1, 2, 4], have showed that solar X-ray bursts and intensification of precipitation particle fluxes cause an electron density increase in the lower ionosphere, which can produce abnormally high attenuation of received HF signals and even blackouts. Heating of the ionospheric plasma due to particle precipitation and increased magnetospheric convection changes dynamics of the neutral atmosphere. During magnetic storms, boundaries of the main ionospheric trough (MIT) and auroral particle precipitation zone are displaced; activity of traveling ionospheric disturbances increases. These processes produce multipath propagation of signals as well as radio signals propagating off the great circle. Despite many years of studies of ionosphere behavior during magnetic storms, many questions remain open. This is associated with the fact that the ionospheric response to magnetic disturbances depends on many factors, therefore analyses of ionospheric parameter variations and characteristics of decametric radio wave propagation during geomagnetic events can provide additional data for studying magnetosphere-ionosphere coupling and their effects on characteristics of the ionospheric radio channel.

In this paper, using simultaneous observations over the oblique-incidence sounding paths, we analyze variations in maximum observed frequencies (MOF) during magnetically active period of February 18–28, 2014. Data on solar flares, geomagnetic indices, solar X-ray fluxes, parameters of the interplanetary magnetic field and solar wind have been taken from the following websites: http://wdc.kugi.kyoto-u.ac.jp, http://tesis.lebedev.ru/sun_flares.html, ftp://ftp.ngdc.noaa.gov/S-TP, http://cdaweb.gsfc.nasa.gov.

During this period, there were 12 X-ray flares of different intensity. Some of them were accompanied by coronal mass ejections and enhanced solar proton fluxes. The most powerful of solar flares with X4.9/2B intensity was registered on February 25 at 0039 UT. In consequence of it the minimum observed frequencies over the Khabarovsk-Irkutsk and Magadan-Irkutsk paths increased by 4–5 MHz. The interaction of solar wind inhomogeneities with the Earth's magnetosphere generated two magnetic storms. The first storm began on February 18 (minimum SYM-H = −127 nT on February 19 at 0823-0824 UT) and had a long-term recovery phase. Against the background of this phase, there were substorms accompanied by a decrease in the Dst index (February 20, 22 and 23). The second storm began on February 27. Its minimum (SYM-H = -101 nT) was recorded on February 27 at 2324–2326 UT. Variations in the interplanetary magnetic field vertical component (IMFBz), geomagnetic indices Dst and Kp, AE are shown in Figure 1.

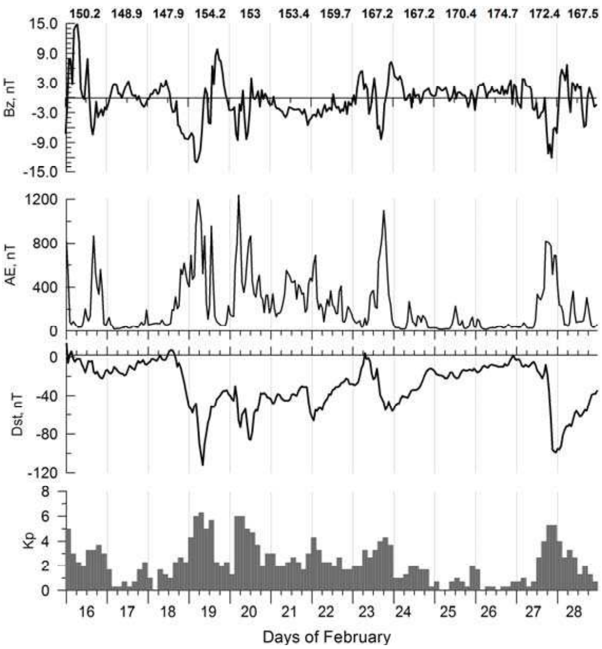


Figure 1: Variations in the IMF Bz, AE, Dst, and Kp indices on February 16–28, 2014. Numbers at the top of the figure indicate variations in the solar activity index $F_{10.7}$.

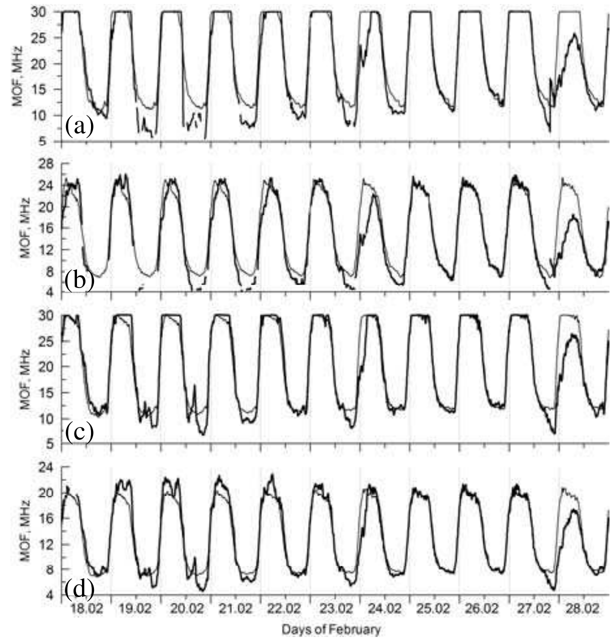


Figure 2: Variations in the MOF over the Magadan-Irkutsk ((a) MOF1F, (b) MOF2F) and Khabarovsk-Irkutsk ((c) MOF1F, (d) MOF2F) paths on February 18–28, 2014. The solid line shows current values; the dotted line, background MOF.

2. EXPERIMENTAL DATA

This study relies on oblique-incidence sounding data obtained over a network of radio paths located in the northeast region of Russia: Magadan-Irkutsk (the path length is 3034 km), Khabarovsk-Irkutsk (2297 km), Magadan-Norilsk (3000 km), Khabarovsk-Norilsk (3407 km). Sounding over the Magadan-Irkutsk and Khabarovsk-Irkutsk paths was conducted with an interval of 5 min; over the Khabarovsk-Norilsk and Magadan-Norilsk paths, with an interval of 15 min. Figure 2 shows time variations in MOF of one-hop (MOF1F) and two hop (MOF2F) modes of propagation over the Magadan-Irkutsk (a), (b) and Khabarovsk-Irkutsk (c), (d) paths. As can be seen from figure, daytime MOF1F of one-hop modes over both paths exceed the upper threshold of registration (30 MHz). According to the variations in the MOF2F mode over the Magadan-Irkutsk path, the first magnetic storm was followed by a decrease in MOF2F to 2–4 MHz in the morning, by an increase to 3.5–4.8 MHz, in the afternoon. The greatest morning decrease in MOF was recorded on February 24. It was observed during the substorm on February 23–24. The night MOF1F and MOF2F were below the background level calculated from two magnetically quiet days of February 13 and 14. The second magnetic storm caused an abrupt decrease in both MOF1F and MOF2F during the main and recovery phases of the storm. The decrease in daytime MOF2F was as much as 55%.

The most complex mode composition of reflected radio signals was observed in nighttime. Along with the basic modes, we recorded additional diffuse signals with large time delays, which propagated off the great circle. We suppose that they were caused by reflection from the polar wall of MIT. These signals were being observed on February 19 at 1000–1800 UT, on February 20 at 1030–1925 UT, on February 23 at 1445–2230 UT.

MOF variations over the Khabarovsk-Irkutsk path (Figs. 2(c)–(d)) are generally similar to variations over the Magadan-Irkutsk path. The difference is that positive disturbances occurred during all daylight hours on February 18–23. The MOF2F increase relative to background values reached

4–5 MHz (on February 19–20). In the morning on February 24, MOF1F and MOF2F variations exhibited an abrupt decrease relative to the background values. During the second magnetic storm, MOF2F decreased to 40% on February 28 in the afternoon. While the midpoint of the Khabarovsk-Irkutsk path is $\sim 7^{\circ}$ further south than the midpoint of the Magadan-Irkutsk path, the additional diffused signals with large delays were also recorded over this path. They were being observed on February 23 from 1800 UT to 2151 UT and on February 27 (at 1921–2236 UT as one-hop mode and 2156–2326 UT as two-hop mode).

Another remarkable feature of the MOF variations over this path is a pronounced increase in MOF observed on February 20 between 1601 and 1651 UT. This might have been caused by the passage of a large-scale ionospheric disturbance since maximum values of frequency were registered

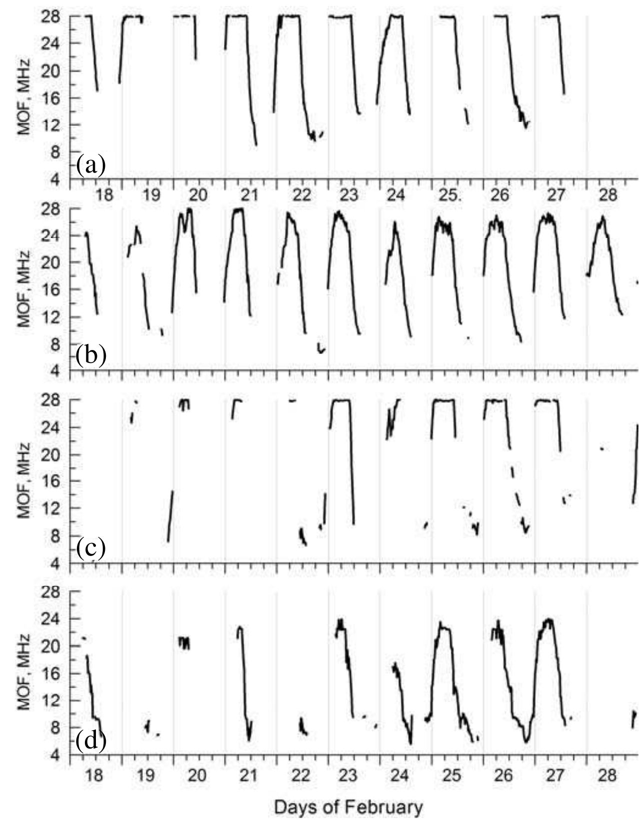
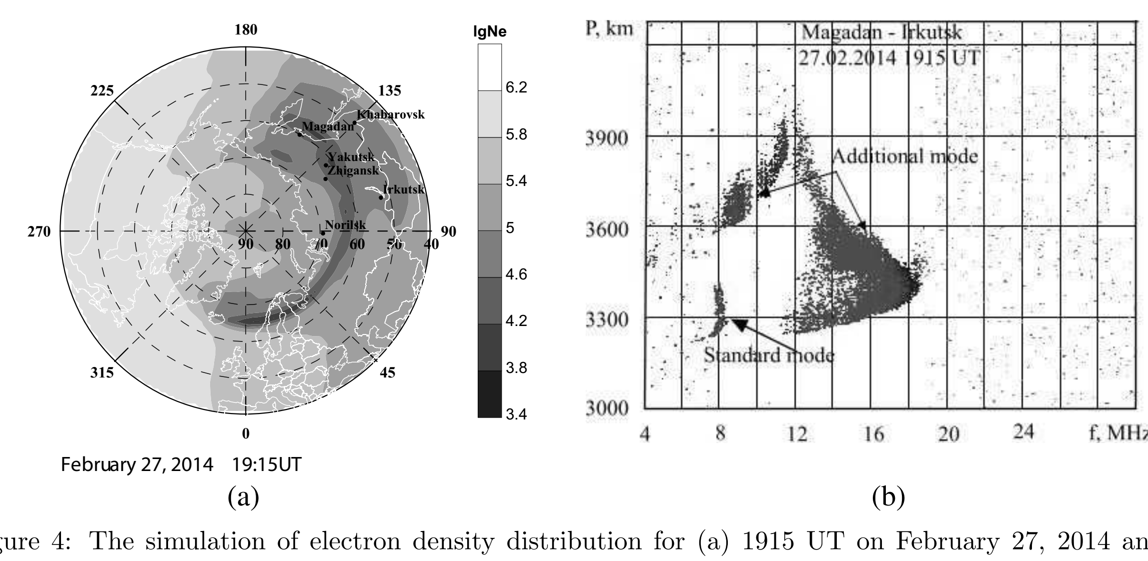


Figure 3: The same as Fig. 2 but for (a), (b) Khabarovsk-Norilsk path and (c), (d) Magadan-Norilsk.



(a) (b)

Figure 4: The simulation of electron density distribution for (a) 1915 UT on February 27, 2014 and the oblique incidence ionogram, obtained over Magadan-Irkutsk path corresponding to (b) this time.

at 1611 UT in MOF1F variations and at 1626 UT in MOF2F ones. This disturbance might have produced a slight increase in MOF1F against the extremely low values over the Magadan-Irkutsk path, which was being seen from 1536 to 1551 UT. Vertical sounding ionograms also show an increase in critical frequencies: in Khabarovsk at 1600–1615 UT, in Irkutsk at 1545–1600 UT.

Figure 3 illustrates MOF variations over the Khabarovsk-Norilsk (a), (b) and Magadan-Norilsk (c), (d) paths. It is obvious that MOF1F over both paths was registered only during the day, and its value exceeded the upper threshold of registration (28 MHz). The two-hop mode MOF was recorded more often, especially over the Khabarovsk-Norilsk path. The daytime MOF2F variations over this path are similar to variations of this mode registered over the Magadan-Irkutsk and Khabarovsk-Norilsk paths. It can be seen that the daytime MOF2F values on February 20–23 (the first storm recovery phase) are higher than those recorded on February 25–26 under quiet geomagnetic conditions. Over the Magadan-Norilsk path, most regular two-hop mode took place only under quiet geomagnetic conditions (February 25–26).

3. DISCUSSION AND CONCLUSIONS

The data have been interpreted using a theoretical model developed at ISTP SB RAS [3]. The model accounts for ionization processes, driven by UV radiation and precipitating electron fluxes, recombination, ionospheric plasma drift under the action of the magnetospheric convection electric field. By way of illustration, Figure 4(a) shows distribution of the electron density calculated for 1915 UT of February 27, 2014. The figure clearly depicts a narrow MIT near 60°N in a longitudinal sector from −10°E to 170°E. The MIT width is maximum (about 6°) in the 130°E meridian. The station Magadan was in the MIT minimum; the station Yakutsk, near the polar wall (near the MIT minimum). The same MIT shift to the geographical latitude of 55–57° are shown by calculations made using empirical model [4] for other time intervals during which additional reflections with large time delays were being registered. A significant part of the Magadan-Norilsk path was located in MIT in evening and night hours. The middle part of the Khabarovsk-Norilsk path was located in a region of the lowest electron density. This explains the absence of reflections in oblique-incidence ionograms. The appearance of additional reflections over the Magadan-Irkutsk and Irkutsk-Khabarovsk paths and the decrease in their time delays are attributed to the approach of MIT boundaries to midpoints of the paths.

Similar additional signals with delays exceeding those of standard reflections were recorded at the vertical sounding stations Irkutsk.

Thus, the experimental oblique-incidence sounding data obtained during the geomagnetic period of February 18–28, 2014 revealed a complex picture of the influence of electron density distribution on characteristics of the ionospheric radio channel. Simulation of electron density allowed us to qualitatively explain the observed phenomena. The results we obtained demonstrate the importance of a precise definition of major morphological structures boundaries in the polar ionosphere, which determine characteristics of radio wave propagation.

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