# Features of behavior of ionospheric F-layer parameters in Irkutsk during the magnetic storm on October 29–31, 2003

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The powerful magnetic storm of October 29–31, 2003 was a superposition of two strong magnetic storms from solar flashes dated to October 28 (Õ17.02) and 29 (Õ10.00). The ionospheric response to the magnetic storm in Irkutsk was investigated by a DPS-4 digisonde, a FMCW sounder, and an incoherent scatter radar. In this paper, the main attention is paid to the analysis of distinctions in the data obtained with these three different instruments. The general features of the ionospheric response coincide for all the instruments. Appreciable distinctions are observed in the main phases of the both storms and in the recovery phase of the first storm. Distinctions in recovery phase are explained by different geographic locations of the instruments: the central point of FMCW sounder path was located 100 km west from the Irkutsk DPS-4 and almost coincided with the position of the major lobe of the incoherent scatter radar. The discrepancy in the data of the FMCW sounder and the radar is essentially less in comparison with the discrepancy from the digisonde data. Such a character of distinction indicates the existence of very strong gradients of electron concentration in the east-western direction during the recovery phase of the magnetic storm.

## 1. Description of instruments

By the end of 2002, the ionospheric observatories of the Institute of Solar–Terrestrial Physics SB RAS (in Irkutsk and Norilsk) were equipped with DPS-4 digisondes, manufactured by the Center for Atmospheric Research (University of Massachusetts Lowell, USA). The main purpose of DPS-4 is to retrieve the profile of the electron concentration from vertical sounding ionograms and to measure the drift velocity of ionospheric inhomogeneities based on Doppler and elevation measurements.[1]

The transmitting point of the FMCW sounder, using signals with linear frequency modulation (FM), is located near Usol'e-Sibirskoe, about 98 km to the north-west from Irkutsk (52°N, 104°E); the receiving point is located near Tory, about 95 km to the south-west from Irkutsk. The main characteristics of the FMCW sounder are described in Refs. 2 and 3. The FMCW sounder is designed for oblique and oblique-backscatter sounding of the ionosphere, as well as for detection of round-the-world signals, and can be used for slightly oblique sounding (at emission in Usol'e, detection in Tory, path length of about 120 km, the central point of the path roughly 76 km to the west from Irkutsk). Under the calm and weakly disturbed conditions, the ionograms of the slightly oblique sounding are similar to the vertical sounding ionograms obtained in Irkutsk.[4]

The Irkutsk incoherent scatter (IS) radar is a part of the global network of IS radars, consisting of 9 radars, each being a unique research instrument. The main purpose of the radar is to measure the electron concentration, as well as electron and ion temperatures. The detailed description of the radar can be found in Ref. 5. A distinctive feature of the Irkutsk radar is its capability of measuring the Faraday rotation of the polarization plane, which allows, unlike most IS radars, absolute measurements of the electron concentration.

The mutual arrangement of the instruments is shown in Fig. 1 (the transmitter of the FMCW sounder is located at the same point as the IS radar).

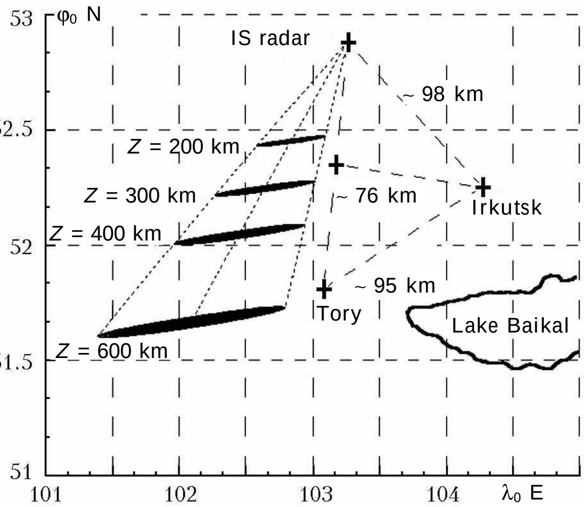


Fig. 1. Geographic arrangement of the instruments.

It is seen that the central point of the FMCW sounder path is closer to the coverage sector of the IS radar than to Irkutsk. Thus, based on the geographic arrangement, the difference between the FMCW sounder and the IS radar is expected to be smaller than that with the Irkutsk DPS-4 digisonde.

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When comparing the results, one should take into account not only the mutual arrangement, but also the information capabilities of the instruments in measurements during a magnetic storm.

The main disadvantage of sounders is lacking data during strong absorption in the D-region, which usually accompanies the main phase of a strong magnetic storm. The appearance of an intense sporadic layer also leads to a loss of data about the F layer. The IS radar is of little sensitivity to absorption in the D-region and appearance of a sporadic layer, but has some disadvantages as well. Because of reflection from local objects, the minimal altitude for obtaining information is 150 km. At a low electron concentration during the main phase of a storm, the signal-to-noise ratio worsens significantly. Coherent echoes, often observed at the same time,[6] introduce additional errors into measurements.

## 2. Measurement results

Figure 2 shows the variations of the *D*st-index (associated with development of the ring current in the magnetosphere) from http://swdcdb.kugi.kyoto-u.ac.jp/dstdir. It can be seen that the storm of October 29–31 is a superposition of two storms: on 12 UT Oct 29–06 UT Oct 30 and on 18 UT Oct 30–06 UT Oct 31.

Figure 3 depicts the 4-day behavior of the critical frequency $f_0$F2 and the altitude $h_m$F2 of the maximum electron concentration (the maximum electron concentration obtained with the IS radar is recalculated into the critical frequency).

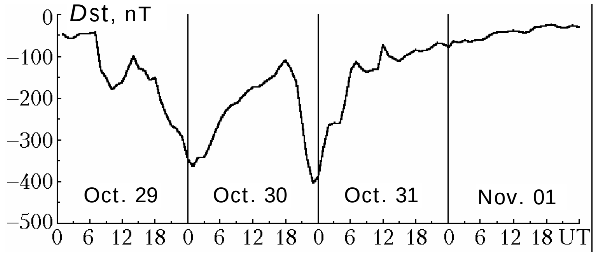



Fig. 2. Variations of *D*st index.

As can be seen from Fig. 3, all the instruments have some ranges, where data are lacking. The digisonde data are absent due to absorption, the FMCW sounder data are lacking because of the late switching-on (October 29, 20:45 UT), absorption, and some technical causes, the IS radar data are lacking because of the late switching-on (October 29, 10:45 UT), technical causes, and strong coherent echoes, leading to large errors in measuring the electron concentration profile. As a result, the complete set of data was obtained for October 30 (01–02 and 05–18 UT), October 31 (07–09 UT), and November 01. The data are most similar in the calm day of November 01 and the period between storms on October 30 (09–15 UT). The widest differences can be seen during the recovery phase of the first storm on October 30 (05–06 UT); this case will be further considered in detail.

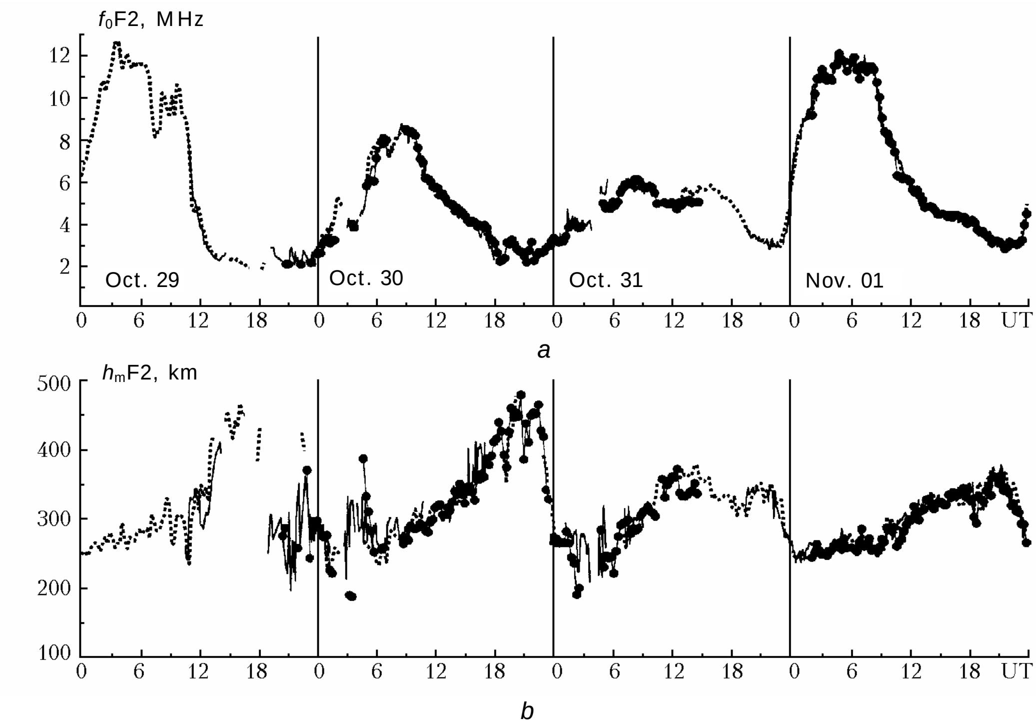
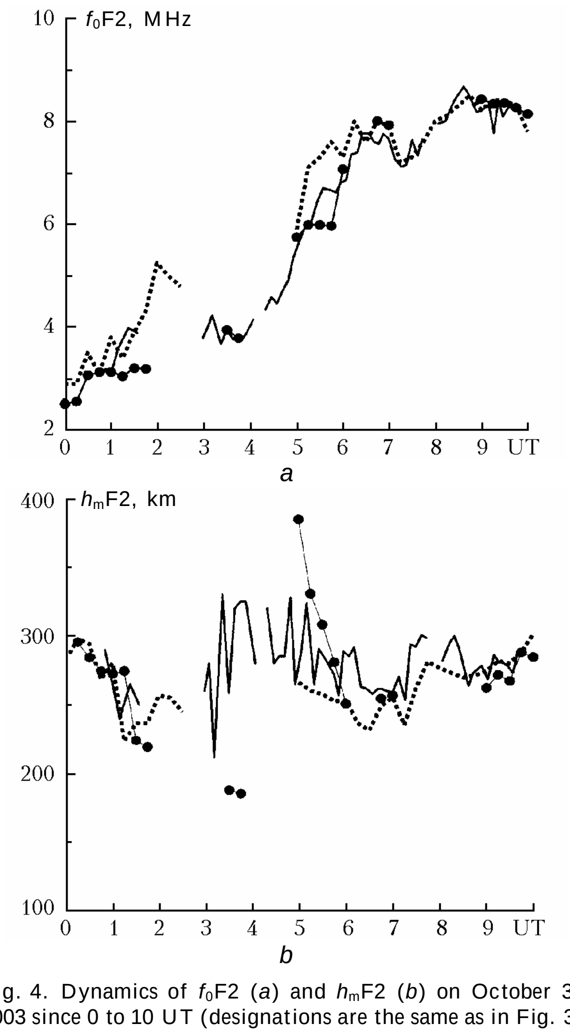



Fig. 3. Dynamics of the critical frequency $f_0$F2 (*a*) and the altitude of the maximum $h_m$F2 (*b*) during the magnetic storm on October 29–November 1, 2003: DPS-4 digisonde data (dashed line), FMCW sounder data (line with circles), and IS radar data (solid line).

Analyzing the data in general, we can note that the differences in the altitude of the maximum are much more pronounced than those in the critical frequency. These differences manifest themselves in the form of fast noise-like variations of the altitude of the maximum, obtained with the IS radar. The periods of such variations are observed in the main phase of the first storm on October 29 (19–23 UT), in the recovery phase of the first storm on October 30 (03–06 UT), in the initial stage of the second storm on October 30 (15–18 UT), and at the recovery phase of the second storm on October 31 (01–05 UT). These variations are possibly caused by the residual influence of coherent echoes. To be noted is a good agreement between the digisonde and IS radar data at the initial stage of the first storm on October 29 (11–15 UT), as well as between the digisonde and FMCW sounder data in the main phase of the second storm on October 30 (18–21 UT).

From the viewpoint of comparison of the data, of interest is the period of the recovery phase of the first storm, during which the widest differences in the critical frequency were observed between three instruments. Figure 4 depicts the variations of $f_0$F2 and $h_m$F2 in the period of 0–10 UT on October 30.




*a*

*b*

Fig. 4. Dynamics of $f_0$F2 (*a*) and $h_m$F2 (*b*) on October 30, 2003 since 0 to 10 UT (designations are the same as in Fig. 3).

The storm recovery phase is characterized by the nonmonotonic growth of the critical frequency with a local maximum near 02 UT (by the digisonde data) and a local minimum near 04 UT (by the FMCW sounder and IS radar data). The monotonic increase of the critical frequency starts at 04 UT (by the IS radar data). The data of the digisonde and the FMCW sounder are available since 05 UT, but the dynamics of $f_0$F2 increase by the digisonde data differs significantly from that by the FMCW sounder data. Since 06 UT the instruments give close readings, and after 09 UT the data are almost identical. It can be noticed that from 05 to 06 UT the smallest differences in the group of three instruments are observed between the FMCW sounder and IS radar data. This character of the difference can be explained by the different geographic locations of the instruments (see Fig. 1), assuming the presence of very strong gradients of the electron concentration in the eastern–western direction. Based on the difference ~1.5 MHz in the critical frequency, the gradient of the electron concentration should be $\sim 2 \cdot 10^5$ cm$^{-3}$ per 100 km. In the 05–06 UT period, the differences can be seen not only in the critical frequency, but also in the altitude of the maximum electron concentration. The altitude values obtained with the FMCW sounder are much higher than the digisonde data, while the IS radar data are intermediate.

Figure 5 shows the profiles of the electron concentration $N_e(z)$, drawn based on the data of three instruments. The comparison of the profiles indicates that at 05:00, 05:15, 05:30, and 05:45 UT the instruments give far different results, at 06:00 the data are quite close, and at 06:45 the profiles of the digisonde and the FMCW sounder almost coincide. At 05:15 and 05:30, the IS radar and the FMCW sounder give close values of the maximal electron concentration, but the values of $N_e$ at the altitude ~250 km differ roughly by $2 \cdot 10^5$ cm$^{-3}$, approximately the same value as the difference between the digisonde and IS radar data.

The fact that three instruments give different profiles of the electron concentration already cannot be explained by only the gradients in the eastern–western direction. Most likely, the inhomogeneous structure of the ionosphere had a cloudy character with a complex height dependence. It is not excluded that in such a complex medium no one of the instruments gives a "true" vertical profile of the electron concentration. The trajectory of the FMCW sounder signal propagation can differ significantly from an arc of a large circle; multibeaming is possible.

In the case of vertical sounding, powerful side reflections can take place along with vertical reflections. The data of the IS radar are markedly influenced by the different position of the major lobes of the directional pattern at different altitudes (see Fig. 1) and rather large width (~100 km) of the lobes in the eastern–western direction.

To estimate the characteristics of the inhomogeneous structure of the ionosphere, it is necessary to carry out rather complicated simulation, taking into account the above factors; now our

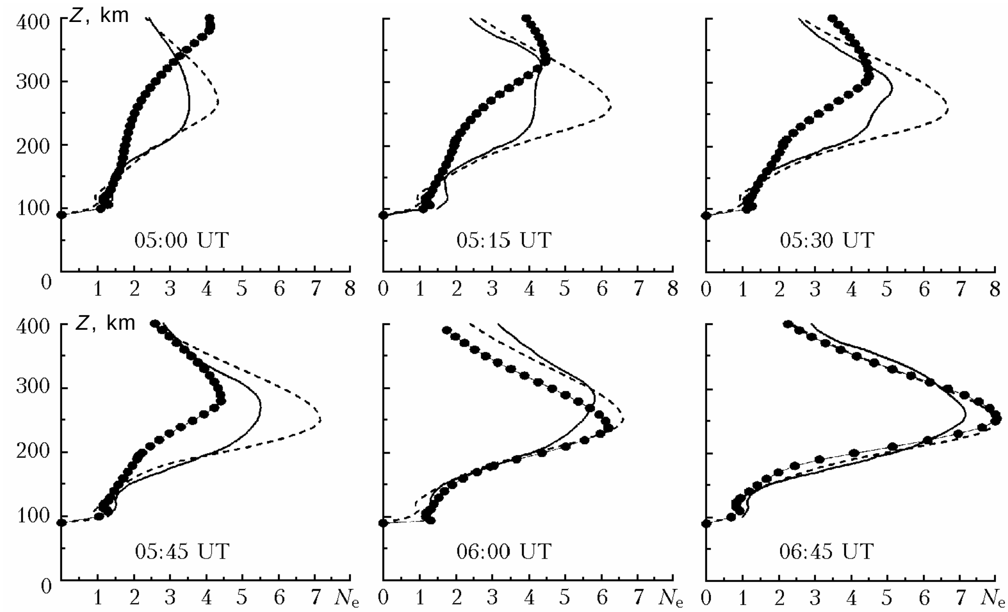



Fig. 5. Profiles of the electron concentration $N_e(z)$ $(10^{-5} \cdot \text{el}/\text{cm}^3)$ on October 29, 2003 (designations are the same as in Fig. 3).

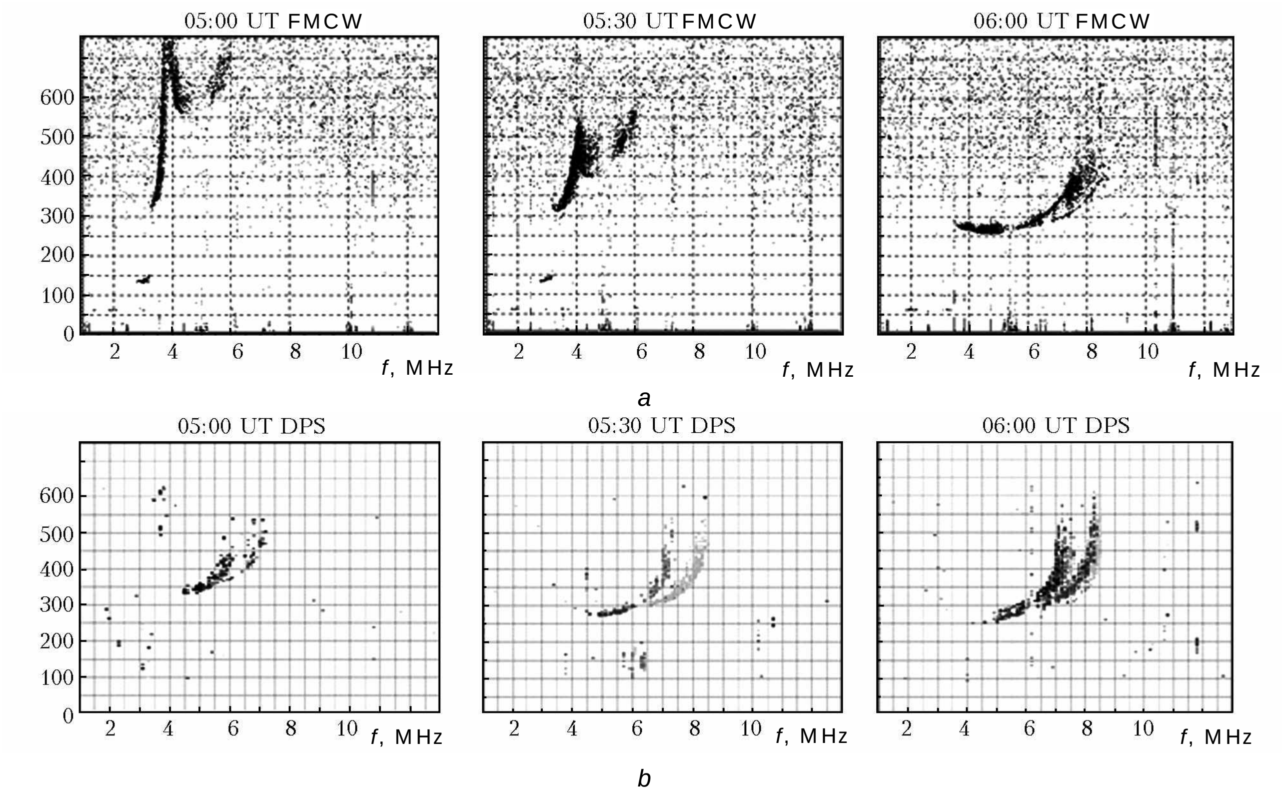



Fig. 6. Ionograms of FMCW sounder (*a*) and DPS-4 digisonde (*b*).

consideration can be restricted to only the estimation of the gradient of the maximal electron concentration, amounting to about $2 \cdot 10^5$ cm$^{-3}$ per 100 km.

Figure 6 shows the ionograms obtained with the digisonde and the FMCW sounder at 05:00, 05:30, and 06:00 UT. If at 06:00 UT the ionograms are quite similar, then at 05:00 and 05:30 UT they are absolutely different.

The traces of the F1 layer, observed in the FMCW sounder ionograms, are not seen in the digisonde ionograms, and the differences in *h*′F2 amount to 250 and 200 km for 5:00 and 5:30 UT, respectively. The more complex trace of the FMCW sounder is likely the result of the trajectories, realizable at a slightly oblique propagation and non-realizable at a vertical propagation.

It should be noted that the observation of the widest differences between three instruments from 05 to 06 UT on October 30 does not indicate that the complex inhomogeneous structure of the ionosphere was characteristic of only this period. It is quite probable that other cases of wide discrepancies were not detected because of the lack of digisonde and FMCW sounder data due to strong absorption.

## Conclusions

The results of investigation of the ionospheric response to the superposition of two magnetic storms based on the simultaneous measurements with the DPS-4 digisonde, FMCW sounder, and IS radar look as follows. Under calm conditions (calm day on November 01 and in the period between the storms on October 30), all three instruments give close results. A good agreement by pairs is observed between the digisonde and IS radar data at the initial phase of the first storm and between the digisonde and FMCW sounder data at the main stage of the second storm. The widest differences are observed at the recovery phase of the first storm. The differences observed are caused by strongly developed inhomogeneous structure of the ionosphere and the different geographic location of the instruments. The gradient of the maximal electron concentration in the eastern–western direction was estimated as about $2 \cdot 10^5$ cm$^{-3}$ per 100 km. For more detailed estimation of the characteristics of the inhomogeneous structure, it is necessary to carry out the simulation taking into account the complex character of radiowaves propagation in the inhomogeneous ionosphere.

## Acknowledgments

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