PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 62 (2000) 133–140

Journal of
ATMOSPHERIC AND
SOLAR-TERRESTRIAL
PHYSICS

Determining dynamic parameters of different-scale ionospheric irregularities over northern Siberia

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Received 25 May 1999; received in revised form 19 November 1999; accepted 22 November 1999

Abstract

In 1995–1996, observations were carried out at Norilsk (geomagnetic latitude and longitude 64.2°N and 160.4°E) to determine dynamic parameters of irregularities in the high-latitude ionosphere. The short-baseline spaced-receiver method that has been implemented at the ionospheric facility of the Norilsk Integrated Magnetic–Ionospheric Station, provides a means of simultaneously measuring parameters of small-scale irregularities (spatial scale of 3–5 km) by the Similar-Fading Method (SFM), as well as of medium-scale irregularities (time scale of 10–30 min, spatial scale of hundreds of kilometres) by the Statistical Angle-of-arrival and Doppler Method (SADM). About 20 h of the observational data for the F2-layer under quiet geomagnetic conditions ($K_p < 3$), 20 h under disturbed conditions ($K_p \geq 3$) and about 15 h for the sporadic E-layer ($K_p \approx 3$) were processed. It has been found that the propagation directions and velocities of different-scale irregularities do not coincide. Small-scale irregularities of the F2-layer travel predominantly eastward or westward. The velocity of the F2-layer irregularities is about 100 m/s, and under disturbed conditions it is up to 200–250 m/s. Small-scale irregularities of the sporadic E-layer travel mostly in the northward direction. It is confirmed that the E_s-layer is characterised by high velocities of the irregularities (as high as 1000 m/s). Medium-scale irregularities with periods in the range of 10–30 min travel mostly in a southward direction with velocities of 20–40 m/s. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Ionospheric irregularities; High-latitude ionosphere

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1. Introduction

Over the course of several decades now, most information about the inhomogeneous structure of the ionosphere has been obtained by two main types of ways of analysing ionospheric radio signals from spaced receivers: (a) the Similar-Fading Method (SFM) (Mirkotan and Kushnerevsky, 1964; Burke, 1970); (b) the phase (interference) methods (Afraimovich, 1982; Mercier, 1986). In particular, in the last few years the Statistical Angle-of-arrival and Doppler method (SADM) (Afraimovich, 1997) has been used. Behind the SFM is the assumption that the reflection region involves a host of small-scale irregularities, with the size typically of about 3–5 km (Al'pert, 1972; Briggs, 1968). A simple model of electron density variations in the form of the superposition of plane travelling waves in a thin ionospheric layer is used in interpreting observations obtained by SADM. This method is useful for obtaining parameters of medium-scale wave irregularities or travelling ionospheric disturbances (time scale of 10–30 min, spatial scale of

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PII: S1364-6826(99)00103-0

hundreds of kilometres) (Afraimovich, 1997; Afraimovich et al., 1999). Measurements of ionospheric irregularity parameters by these two methods simultaneously have not been made to date. We were the first to do this with the ionospheric measuring facility at Norilsk.

Earlier attempts were also made to compare parameters of different-scale ionospheric irregularities. According to research results, in some cases (Afraimovich et al., 1999) there was a good agreement of velocities and a less satisfactory agreement of travelling directions; in other cases (Mirkotan and Kushnerevsky, 1964) the propagation velocities of medium-scale irregularities exceeded those of small-scale irregularities, and the prevailing travelling directions were nearly perpendicular to each other (East-West and North-South, respectively, for small-scale and medium-scale irregularities). Mirkotan and Kushnerevsky (1964) reached the conclusion that medium- and small-scale irregularities probably are of different origin. These two types of irregularities seem to be drifting with different velocities and in different directions; however, the factors responsible for changes in the travelling direction are common to both. These investigations were carried out in mid-latitudes. As regards the high latitudes, the intensity of small-scale irregularities was found to be enhanced due to large-scale gradients of ionospheric plasma (Rino and Owen, 1980). The construction of the ionospheric measuring facility at Norilsk enabled researchers for the first time to obtain parameters of both small-scale and medium-scale ionospheric structure over that high-latitude region.

During the 1960s–1970s, regular investigations of the small-scale structure of the high-latitude ionosphere were made at Norilsk using the D1-method (Zherebtsov et al., 1974, 1988). Averaged drift patterns were obtained in the E- and F-regions of the auroral ionosphere for different seasons and levels of geomagnetic activity.

As far as small-scale irregularities of the sporadic E-layer are concerned, the following results may be pointed out (Ferberg, 1980; Zherebtsov et al., 1988). The drift direction of E_s-irregularities is predominantly South-West or North-East. The most probable velocities lie in the range 40–160 m/s. There is a small maximum at the velocity values 240–300 m/s. Furthermore, higher velocities — of up to 480–1000 m/s — were also recorded (Zherebtsov, 1971). Small-scale irregularities of high-latitude E_s stretch out along the geomagnetic field and move across it.

In the F-region, the travelling velocity of small-scale irregularities varied through the range of 20–260 m/s (Ferberg, 1980; Zherebtsov et al., 1988). The most probable velocity values lie in the range 50–150 m/s, with a pronounced maximum of the velocity distribution at 60–70 m/s. In addition, there is a maximum in the velocity range 140–180 m/s. The drift velocity does not remain constant, but the prevailing direction is westward or eastward. As for high-latitude layers, there is a tendency for the drift velocity to increase with increasing magnetic activity.

Investigations of medium-scale wave irregularities have not been carried out at Norilsk to date. A review by Hunsucker (1982) presents observational results on medium-scale wave irregularities at high latitudes for a number of stations in other countries. For almost all irregularities in the northern hemisphere, the travelling direction is southward, with the disturbance source lying in the auroral zone. Furthermore, velocities obtained by different investigators and with different instruments differ quite dramatically (from 30 m/s to 400–700 m/s) (Hunsucker, 1982). Ma et al. (1998) also obtained southward travelling directions of medium-scale irregularities for the high-latitude zone. With the advent of more sophisticated and informative techniques of ionospheric research, the small-baseline spaced-receiver method has lost its significance in many respects. However, while investigations in West Europe, Canada and in some other countries are pursued with incoherent scatter radars (EISCAT, Sonderstrom, etc.), the GPS system, and HF radars (SuperDARN) (Stone, 1996), at high latitudes in Russia there are neither powerful instruments of this kind nor such a dense network of stations. The Norilsk Integrated Magnetic-Ionospheric Station (geomagnetic latitude and longitude 64.2°N and 160.4°E) operated by the Institute of Solar-Terrestrial Physics SD RAS is the Siberian region's unique high-latitude station admirably equipped with an appropriate facility for investigating the fine structure of the ionosphere. Therefore, experimental data obtained there are significant as they provide virtually the only available information about ionospheric motions over the region.

The objective of this study was:

- to obtain parameters of different-scale irregularities simultaneously;
- to obtain space–time parameters of the propagation of small-scale irregularities, and to compare with results obtained at Norilsk during the 1960s–1970s; and
- to investigate parameters of medium-scale wave irregularities under different geophysical conditions.

2. Equipment and methods of measurement

The measuring facility includes a digital vertical-incidence sounding pulsed ionosonde. Some characteristics of the measuring facility:

- working frequency range 1–20 MHz,
- transmitter pulse power 2 kW,

- pulse duration 135 ± 15 ms,
- switching rate 50 Hz,
- measured height range of reflecting layers 80–800 km.

The impulse signal in the vertical-incidence sounding mode is emitted by a broad-band delta-type antenna. Half-wave dipoles tuned to the medium frequency of the working range (50 m) were used in the measuring facility as spaced reception antennas. The antennas are located at the corners of a right-angled triangle oriented to the cardinal points, with the sides 100 m long (see Fig. 1).

On performing an analogue processing for each of the three antennas, we obtain time series of the amplitude of the ionosphere-reflected radio signal, as well as the SIN- and COS-quadrature components of the signal. The amplitude time series are processed by the Similar Fading Method (SFM) (Mirkotan and Kushnerevsky, 1964; Burke, 1970). This is based on determining time delays between similar variations in the radio signal amplitude (see Appendix A). It is reasonably well justified physically and has been used for decades at a network of stations (including Norilsk) for determining velocity and direction of travelling small-scale ionospheric irregularity (Zherebtsov et al., 1988). The SIN- and COS-components of the radio signal are processed using the SADM (Afraimovich, 1997; Afraimovich et al., 1999) (see Appendix A). This method has been employed since the beginning of the 1970s, and its validity is now confirmed by model calculations and comparisons with existing results. We pioneered in applying this technique to process the measurements from Norilsk.

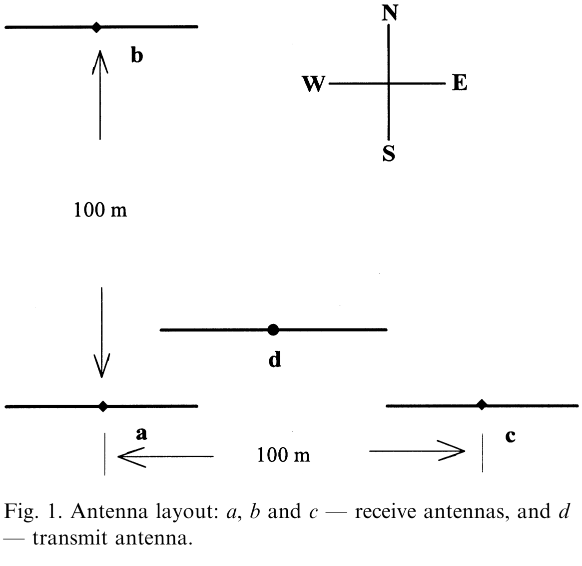

Fig. 1. Antenna layout: *a*, *b* and *c* — receive antennas, and *d* — transmit antenna.

3. Experimental results

The experimental data were obtained at the ionospheric facility of the Norilsk in March 1995, August–September 1995, and in February–March 1996. Fig. 2 shows the plots of drift directions $\alpha(t)$ and velocities $v(t)$ of the E_{sr}-layer irregularities during the geomagnetic disturbance of 5th March, 1995 ($K_p = 3$) calculated by SADM method and by the Similar Fading Method. The axis of the ordinates indicates the azimuth a of the travelling direction α in degrees, counted clockwise from North. It is evident that the travelling directions and velocities obtained by different methods do not coincide. Small-scale irregularities are moving westward. This is associated with the eastward electrojet flowing in the evening sector of the auroral iono-

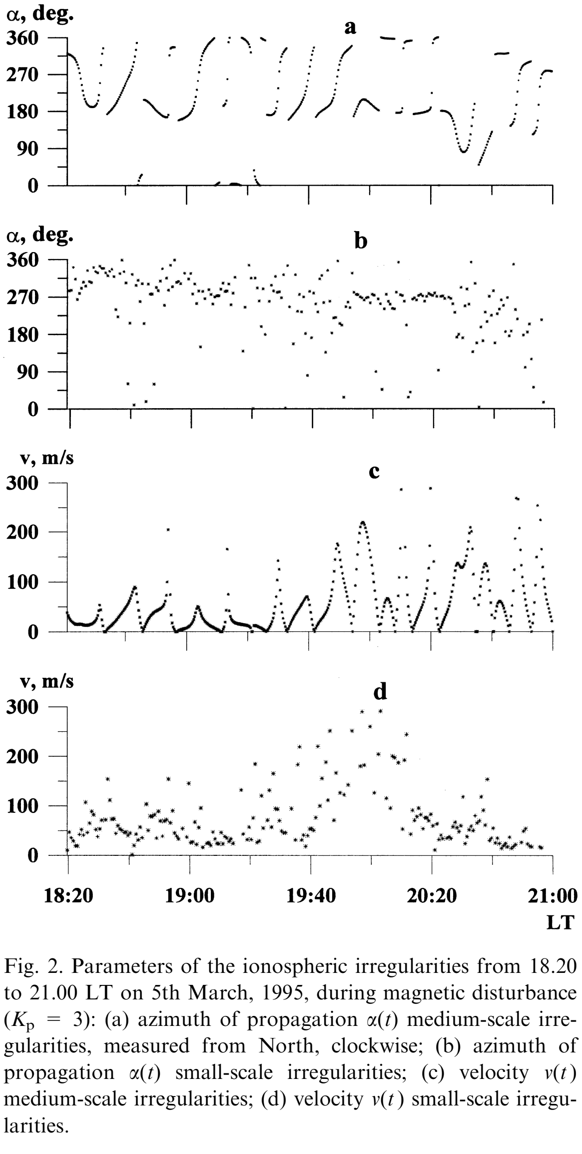

Fig. 2. Parameters of the ionospheric irregularities from 18.20 to 21.00 LT on 5th March, 1995, during magnetic disturbance ($K_p = 3$): (a) azimuth of propagation $\alpha(t)$ medium-scale irregularities, measured from North, clockwise; (b) azimuth of propagation $\alpha(t)$ small-scale irregularities; (c) velocity $v(t)$ medium-scale irregularities; (d) velocity $v(t)$ small-scale irregularities.

Table 1
Characteristics of the ionosphere-reflected signal, and parameters of ionospheric irregularities of the high-latitude ionosphere

	F2-layer, $K_p < 3$		F2-layer, $K_p \geq 3$		E_s-layer	
Frequency Doppler shift (Hz)	−0.2–0.1		−0.3–0.2		−0.3–0.2	
Width of the Doppler spectrum (Hz)	0.1–0.3		0.1–0.4		0.1–0.8	
Irregularities	Small-scale	Medium-scale	Small-scale	Medium-scale	Small-scale	Medium-scale
Travelling direction (°)	90, 270	180	270	220–240	0, 270	180
Velocity (m/s)	100–150	10–40	150–200	10–30	40–100, up to 1000	10–30
Velocity rms (m/s)	230	70	245	120	280	60

sphere over Norilsk during disturbed geomagnetic conditions. Medium-scale irregularities are moving predominantly southward; the presence of the northward direction was caused by the uncertainty of estimating the azimuth using the SADM method (Afraimovich et al., 1999).

The direction $P(\alpha)$ and velocity $P(v)$ distributions of travelling electron density irregularities have been analysed for the F2-layer under quiet geomagnetic conditions ($K_p < 3$), for the F2-layer under disturbed geomagnetic conditions ($Kp \geq 3$), and for the sporadic E-layer ($K_p \approx 3$). The integration time for obtaining each of the counts presented below was 40 s. Intervals with the cross-correlation coefficient larger than 0.5 were considered, which comprised 80% of the total number of intervals. Figs. 3 and 4 present the histograms of the $P(\alpha)$- and $P(v)$-distributions obtained using the above-mentioned methods of processing. For the $P(\alpha)$-distributions, the axis of the ordinates indicates the azimuth of propagation direction α measured clockwise from North. For the $P(v)$-distribution, the velocity of irregularities (m/s) is along the axis of the ordinates. The histograms of the travelling direction distribution of small-scale irregularities $P(\alpha)$ have two maxima. This is caused by the uncertainty of determining the direction when processing the data using the SADM method (Afraimovich et al., 1999). From geophysical considerations, we decided to use one travelling direction in the analysis.

1. The F2-layer was observed under quiet geomagnetic conditions ($K_p < 3$, August–September 1995, about 20 h of observation); the observations were carried out from 18 LT to 22 LT. The Doppler shift lies in the range from −0.2 to 0.1 Hz. The Doppler spectrum width varies from 0.1 to 0.3 Hz. For small-scale irregularities, the travelling direction is eastward or north-westward (see Fig. 3(a)), with the most probable velocity values of 100–150 and the rms of 230 m/s (see Fig. 3(b)). For medium-scale wave irregularities, the predominant travelling direction is southward (see Fig. 4(a)), with the most probable velocity values of 10–40 m/s and the rms of 70 m/s (see Fig. 4(b)).

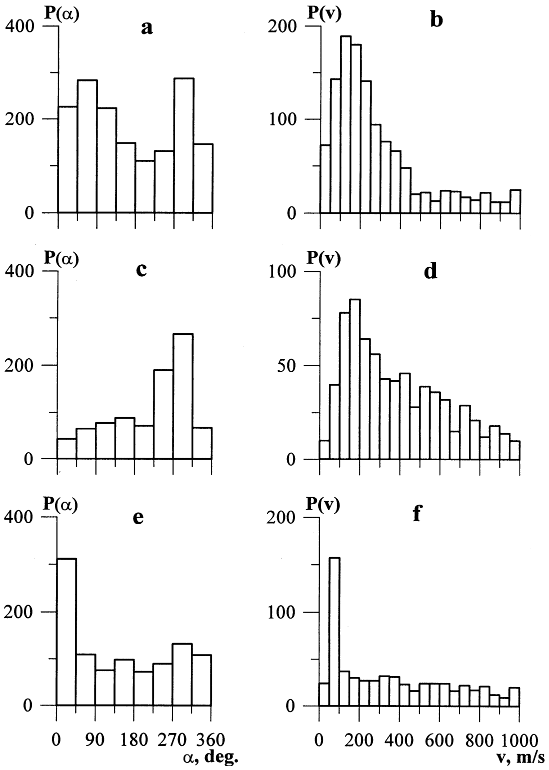

Fig. 3. Distribution of propagation directions $P(\alpha)$ and velocities $P(v)$ of small-scale ionospheric irregularities obtained by the Similar Fading Method (SFM). The azimuth of the propagation direction is measured in degrees, clockwise from North. The following $P(\alpha)$ and $P(v)$ distributions are shown: (a) and (b) for the F2-layer under quiet geomagnetic conditions ($K_p < 3$, August–September 1995); (c) and (d) distributions for the F2-layer under disturbed geomagnetic conditions ($K_p \geq 3$, February–March 1995 and 1996); (e) and (f) for the ionospheric E_s-layer ($K_p \approx 3$, February–March 1996).

2. The F2-layer was observed under disturbed magnetic conditions ($K_p \geq 3$, February–March 1995–1996, about 20 h of observation); the observations were carried out from 14 LT to 18 LT. The Doppler shift lies in the range from −0.3 to 0.2 Hz. The

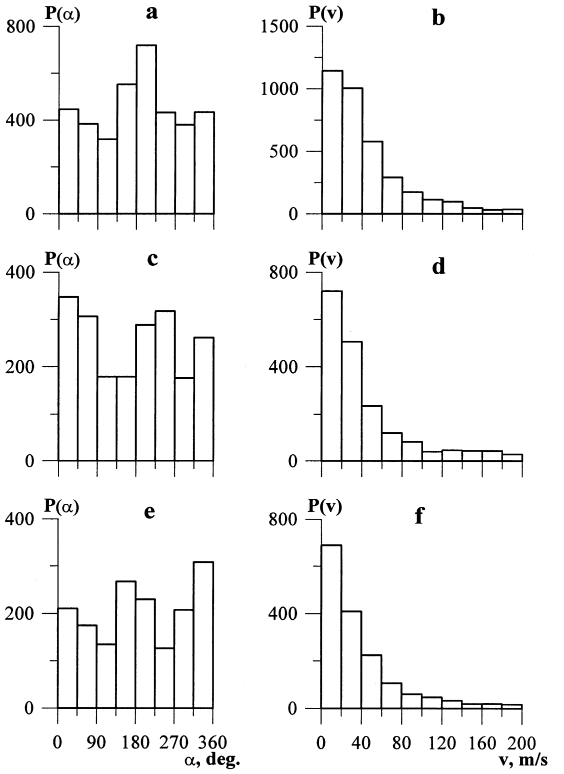

Fig. 4. Distribution of propagation directions $P(\alpha)$ and velocities $P(v)$ of medium-scale ionospheric disturbances obtained by Statistical Angle-of-arrival and Doppler Method (SADM): (a) and (b) for the F2-layer under quiet geomagnetic conditions ($K_p < 3$, August–September 1995); (c) and (d) for the F2-layer under disturbed geomagnetic conditions ($K_p \geq 3$, February–March 1995 and 1996); (e) and (f) for the ionospheric E_s-layer ($K_p \approx 3$, February–March 1996).

Doppler spectrum width varies from 0.1 to 0.4 Hz. For small-scale irregularities, the travelling direction is mostly westward (see Fig. 3(c)), with the most probable velocity values within 150–200 m/s and the rms of 250 m/s (see Fig. 3(d)). For medium-scale wave irregularities, the predominant travelling direction is south-westward (see Fig. 4(c)), with the most probable velocity values somewhat decreasing to 10–30 m/s and the rms of 120 m/s (see Fig. 4(d)).

3. For Sporadic E-layer studies ($K_p \approx 3$, February–March 1995–1996, about 15 h of observation), the observations were carried out from 18 to 22 LT. The Doppler shift lies in the range from −0.3 to 0.2 Hz. The Doppler spectrum width varies from 0.1 to 0.8 Hz. For the most part, small-scale irregularities travel in a northward and westward direction (see Fig. 3(e)). The velocity distribution peaks at velocities 20–100 m/s. Velocities were recorded up to 1000 m/s (rms of 280 m/s) (see Fig. 3(f)). The predominant propagation direction for medium-scale irregularities was southward (see Fig. 4(e)), with the most probable velocity values being 10–30 m/s and the rms 60 m/s (see Fig. 4(f)).

4. Discussion

In this paper, dynamic parameters of different-scale irregularities under different geophysical conditions were investigated. In August–September, for the planetary index of magnetic activity $K_p < 3$, the main ionospheric trough lay significantly further South than Norilsk, and the ionosphere — according to Zherebtsov et al. (1986) — was a mid-latitude one. In February–March, from the standpoint of the dynamic regime, the ionosphere at the F2-layer heights over Norilsk can be considered auroral (Razuvaev, 1986). In most cases (90%) we observed a sporadic E-layer with a delay (E_{sr}).

This paper is based on using the D1-method to obtain dynamic parameters of small-scale irregularities (typical size 3–5 km) and the phase-difference method to obtain parameters of medium-scale wave irregularities (time scale 10–30 min, spatial scale - tens of kilometres), The results of our analysis (Figs. 2–4) indicate that different-scale irregularities travel in different directions and with different velocities.

The prevailing propagation direction of small-scale irregularities for the F2-layer under quiet geophysical conditions is eastward and westward, with velocities ranging from 100 to 150 m/s. Such a character of their movement testifies that the ionospheric plasma is set in motion by the magnetospheric convection electric field. Propagation directions of small-scale irregularities coincide with those obtained at Norilsk by the D1-method during the 1960s–1970s (Ferberg, 1980; Zherebtsov et al., 1988). The most probable velocity which are obtained somewhat exceeds that observed earlier (60–70 m/s) (Ferberg, 1980). Under disturbed conditions ($K_p \geq 3$) the electric field is enhanced (Zherebtsov et al., 1988), and the auroral zone is nearing Norilsk. Also, the drift of the small-scale F2-layer irregularities in the evening sector is nearly totally determined by the eastward electrojet, i.e. the irregularities are predominantly directed westward. Their velocity increases significantly. For the sporadic E-layer, the travelling direction of irregularities has a significant northward component. Such a result was also obtained at Norilsk in earlier studies (Zherebtsov et al., 1988). One conceivable reason is that, with increasing geomagnetic activity, the auroral oval shifts to lower latitudes and hence can lie somewhat further South than Norilsk. What this means is that the region of ionospheric plasma heating by charged particle fluxes and electric currents is to the South of Norilsk. In this case the plasma is drifting from the region of heating, northward. Furthermore, the E_s-layer is notable for its velocity distribution (see Fig. 2(f)). High velocities of small-scale irregularities ranging from 500 to 1000 m/s were also obtained for the E_s-layer at Norilsk in the 1970s (Zherebtsov, 1971).

Medium-scale wave irregularities are ionospheric manifestations of acoustic-gravity waves (Hocke and Schlegel, 1996). It is anticipated that there are several possible sources generating medium-scale wave disturbances. Thus, the sources discussed by Hunsucker (1982) are associated with the ionospheric response to particle precipitations in the midnight sector, with travelling auroral arcs, and with the boundary between the eastward and westward auroral electrojets (Harang discontinuity). According to our measurements, medium-scale wave disturbances travel in a southward direction with velocities on the order of tens of meters per second (see Fig. 4). Also, the travelling velocity is virtually independent of the level of ionospheric disturbance and of the type of layer. Under disturbed geomagnetic conditions in the F2-layer, the vector of propagation direction is displaced to the South-East (see Fig. 2(c)). Conceivably the reason is that the source of wave irregularities is located in the North-East, in the midnight sector.

No evidence for the correlation between small- and medium-scale irregularities was detected. One forms an impression that different-scale irregularities travel independently of each other. For instance, geomagnetic activity influences the velocity of small-scale irregularities, but leaves the velocity of medium-scale irregularities virtually unaffected.

According to our measurements, medium-scale wave disturbances travel in a southward direction with velocities on the order of tens of meters per second (see Fig. 4). Also, the travelling velocity is virtually independent of the level of ionospheric disturbance and of the type of the layer. Under disturbed geomagnetic conditions in the F2-layer, the vector of propagation direction is displaced to the South-East (see Fig. 4(c)). Conceivably the reason is that the source of wave irregularities is located in the North-East, in the midnight sector.

5. Conclusion

In Russia's high-latitude zone, an ionospheric research facility was established with the scientific focus to provide parameters of both small-scale and medium-scale irregularities simultaneously. The observations obtained at the Norilsk IMIS in 1995–1996 were used to analyse the propagation velocities and directions of small-scale and medium-scale irregularities. It has been established experimentally that small-scale and medium-scale irregularities of the high-latitude ionosphere travel in different directions and with different velocities (small-scale and medium-scale irregularities, respectively, are eastward or westward and southward, with velocities of 100–150 m/s and 10–40 m/s). The results show good agreement with earlier experimental data from Norilsk, as well as with theoretical and experimental results on the processes in the high-latitude ionosphere.

Acknowledgements

We are grateful to V.V. Klimenko and O.N. Boitman for help in carrying out the experiments. This work was done with support from the Russian Foundation for Basic Research — grants Nos. 97-02-96060 and 99-05-64753.

Appendix A

Amplitude time series were processed by the Similar-Fading Method. Cross-correlation functions of amplitudes recorded at three antennas at time steps of 40 s were calculated, the time shifts between maxima of the cross-correlation functions were determined, and these shifts were used to infer the propagation velocity and direction by classical formulae (Mirkotan and Kushnerevsky, 1964; Burke, 1970):

$$V_{ab} = \frac{d_{ab}}{t_b - t_a}; \quad V_{ac} = \frac{d_{ac}}{t_c - t_a}; \quad \frac{1}{V^2} = \frac{1}{V_{ab}^2 + V_{ac}^2};$$

$$\cot \alpha = \frac{V_{ab}}{V_{ac}}.$$

where a is the reference antenna, b and c are, respectively, the northern and eastern antennas (they are located at the corners of a right-angled triangle), t is the time of appearance of such recordings at each of the antennas, and d is the antenna space separation, α is the travelling direction of the irregularities.

We calculated the velocity $v(t)$ and direction $\alpha(t)$ of medium-scale wave irregularities on the basis of the following characteristics of the ionosphere-reflected radio signal which were obtained at steps of 40 s using algorithms described by Afraimovich (1997):

- variations of the phase time derivative $\phi_t'(t)$ which were determined when measuring the frequency Doppler shift; and

- variations of the phase spatial derivatives $\phi'_x(t)$ and $\phi'_y(t)$, that are proportional to changes of the angle-of-arrival components and are calculated when measuring phase differences between signals from spaced antennas.

Continuous series of these parameters were filtered in the range of 10–30 min periods most typical of medium-scale irregularities. Data on the irregularity dynamics were obtained using the statistical SADM method of determining the propagation velocity $v(t)$ and direction $\alpha(t)$ of the phase front of the radio signal in the antenna array plane (Afraimovich, 1997) which is a generalisation of the method suggested by Mercier (1986).

The commonly accepted model of local density variations in the analysis of medium-scale wave irregularities in experiments exploiting the ionosphere-reflected radio signal (Afraimovich et al., 1978; Waldock and Jones, 1986) is

$$\delta N = \delta N_0 \sin\left(K_x x + K_y y - \Omega t + \varphi_0\right)$$

where N_0 is the undisturbed value of electron density; δN, K_x, K_y, Ω respectively, are the amplitude, the x- and y-projection of the wave vector, and the disturbance angular frequency; φ_0 — is being the initial disturbance phase.

It is assumed that the receive antenna separation is much smaller than the typical spatial scale of the disturbance, and the time interval between counts is much shorter than the time scale of the disturbance. Then the propagation velocity $v(t)$ and direction $\alpha(t)$ of the phase front at each particular time can be determined as

$$W_y(t) = \frac{\phi'_y(t)}{\phi'_t(t)}; \qquad Wx(t) = \frac{\phi'_x(t)}{\phi'_t(t)}$$

$$v(t) = \frac{1}{\sqrt{W_x^2(t) + W_y^2(t)}}; \qquad \alpha(t) = \arctan\left(\frac{W_x(t)}{W_y(t)}\right)$$

In real situations such an ideal model of the planar wave is of course not realized; therefore, this method permits the propagation direction to be determined to within modulo 180°.

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