HF RADAR OBSERVATIONS OF BACKCSATTERED ECHOES INDUCED BY SMALL-SCALE IRREGULARITIES OF SUBAURORAL F2 REGION IONOSPHERE*

V. P. Uryadov[(1)] , A. A. Ponyatov[(1)], O. I. Maksimenko[(2)], N. M. Boguta[(2)]

[(1)] ***Radiophysical Research Institute, 603950 Nizhny Novgorod, B.Pecherskaya st.25, Russia,***
E-mail: ur@nirfi.sci-nnov.ru
[(2)] ***Institute Radio Astronomy, 252142 Kiev, Ukraine***

ABSTRACT

Experimental results on the diagnostics of small-scale irregularities of subauroral F- region ionosphere obtained by means of mid-latitude Doppler HF radar are presented. It is found that decametre-scale irregularities responsible for HF backscatter exist on the equatorial wall of main ionospheric trough. The estimates of westward velocity of the irregularities and the intensity of electron density fluctuation have been made. Radiophysical aspect of presented data is discussed. It is established that refraction of radio waves in the ionosphere plays an important role in selection of scattering area on the latitude for the given HF radar position.

INTRODUCTION

The investigation of the high-latitude ionosphere is constantly drawing a great attention. This interest is determined by varied of the physical processes in high-latitude ionosphere as well as necessity studying an influence of the inhomogeneous structure on operation of the diverse radio electronic systems.
For study of the small-scale irregularities, the radar method is widely used. It is known that small-scale irregularities are elongated along of the Earth`s magnetic field. In order to ensure the condition perpendicularity of the radar wave vector to the magnetic field in the F-region, the radio waves must be undergone large refraction, i.e., the backscattered echoes from irregularities located in upper ionosphere can only be met for HF signals. The use of HF radar allowed to obtain the important data on small-scale irregularities in the high-latitude ionosphere [1-3]. Data about of small-scale irregularities of the subauroral ionosphere obtained with Doppler radar measurements have been relatively few that it is in certain degree connected with limited number of HF radars abled due to their geographic location to probe the subauroral ionosphere. In the paper the investigation results of the small-scale irregularities of the subauroral F-region ionosphere on the equatorward boundary of trough obtained using the mid-latitude HF Doppler radar are presented.

OBSERVATIONS AND RESULTS

The HF transmitter located in Dimer (Kiev region, Ukraine, 50.3°N, 30.5°E geographic co-ordinates) was used for sounding ionosphere. The transmitter operated in frequency range of 11...20 MHz and radiated in two direction: to north (azimuth A=0°) and to north-east(A=51°) with help of two horizontal rhombic antennas. The transmitter peak power is 25 kW. The pulse length and repetition rate were 1 ms and 20 Hz respectively. The reception of signals was performed on the same rhombic antennas and also on antenna array that consisted of eight wideband horizontal dipoles formed the four antenna pattern in a vertical plane with elevation beamwidth ~ 6°. The antenna array is used for measurement of the elevation angles of backscattered signals. The procedure of the Doppler measurements is stated in paper [4].

The measurements of HF backscattering were made in January-March 1985 and April 1987. In the most cases the signals of two types were observed : the type 1 with time delay $\tau_1 \approx 7$-10 ms and the type 2 with delay $\tau_2 \approx 13$-20 ms. The behaviour of the signals was told one from the other. The type 1 signals were received only in the evening and night hours and had more fast-fading as compared with type 2 signals. The coefficients of the time correlation of types 1 and 2 signals are different : $\tau_{c1} \sim 0.1$ s, $\tau_{c2} \sim 0.4$ s. The type 2 signals whose time delay increases with growth of the frequency were identified as the ground backscattering signals. Under switching the transmitter with antenna "north" to antenna "north-east" the level of the type 1 signal fell to 10-20 dB and the level of the type 2 signal either did not changed or slightly increased. The amplification of the level of type 2 signal probably associated with geometry of experiment since with north-east direction the ground backscattering signal is reflected from the Earth

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surface in region of the Ural mountains. The type 1 signals were identified as signals backscattered from the ionosphere irregularities. Fig. 1 gives the histogram of scattered signals occurrence in the dependence of the observation time averaged over all frequencies (~ 11-20 MHz). It can be seen that the scattered signal is generally received in the evening hours 20.00-24.00 LT with maximum occurrence in 21.00-22.00 LT. The scattered signals are received with ranges from 900 km to 1400 km with maximum occurrence at range D ~ 1200 km.

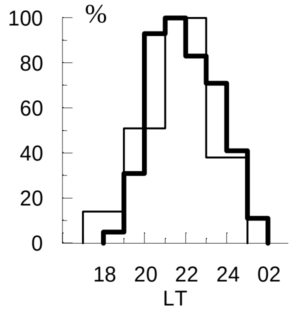

Fig. 1. Histogram of the diurnal occurrence of HF backscatter echoes; heavy and thin lines correspond to experimental and simulated data, respectively.

The spectral measurements of the HF backscatter induced by small-scale irregularities of the subauroral F-region ionosphere were carried out in April 1987 from 20.00 to 24.00 LT. Fig. 2 illustrates the examples of Doppler spectra obtained at frequency 16.6 MHz on 2 April 1987. The peculiarity of the measured spectra is a small Doppler shift of frequency ($F_d \approx$ 0...2 Hz) with bandwidth $\Delta F_d \approx$ 4.5 - 7 Hz. The displacement of spectrum in side of negative values of Doppler shift takes place near of local midnight. We interpreted the results of spectral measurements in assumption of the westward drift velocity of small-scale irregularities of the subauroral F-region [5] and also an influence the finite transmitter antenna beamwidth on the measurements. For the given geometry of the experiment when the main lobe of antenna was directed to north the broadening of the spectra was formed by Doppler shift on edges of the antenna pattern. The position of spectrum on the frequency axis will defined by relationship between half-beam width antenna pattern $\Delta\varphi$ and angle α composed of the drift velocity vector of irregularities with westward direction (see Fig. 3). Under this the case when $\alpha \approx 0$ corresponds to the example of spectrum shown in Fig. 2a, the case when $\alpha < \Delta\varphi$ corresponds to Fig. 2b and $\alpha \approx \Delta\varphi$ corresponds to Fig. 2c. Over broadening of spectrum ΔF_d can estimate the velocity V and the angle α. For example, for the case shown in Fig. 3 and which corresponds to condition $\alpha < \Delta\varphi$, the Doppler shifts on the edges of spectrum are equal $F_{1d} \approx -(2V\backslash\lambda)\sin(\beta_1 + \alpha)$, $F_{2d} \approx (2V\backslash\lambda)\sin(\beta_2 - \alpha)$, where β_1 and β_2 are angles between of radar wave vector with direction to north for extreme points of scattered volume in the limits of a main lobe antennas where are fulfilled the conditions of the aspect scattering radio waves for given geometry. In order to determine angles β_1 and β_2 the calculation of HF scattering on the field-aligned irregularities using the range measurements to scattered volume and elevation angles was made. According to calculation for value $\Delta\varphi = 7°$ [6] the angles β_1 and β_2 are found in interval 7...8°. Then for the typical values F_{1d} = -4.5...-3.5 Hz, F_{2d} = 0.5...3.5 Hz we obtain V ≈ 150-240 m/s. The direction of the drift velocity relatively of westward varied in limits of $\alpha \approx$ 0...7°.

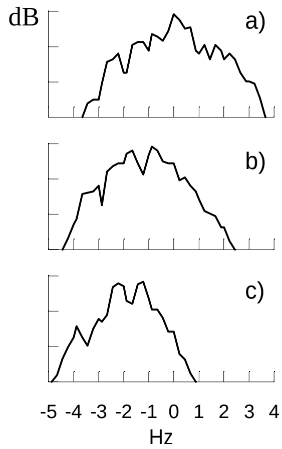

Fig. 2. Examples of subpolar HF Doppler spectra obtained at frequency 16.6 MHz in Dimer, region, Ukraine. 02 April 1987

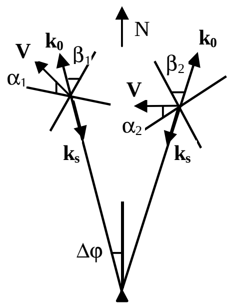

Fig. 3. Geometry of backscattered radio waves on moving westward small-scale irregularities for a finite antenna beamwidth

CALCULATOINS

In order to localize the ionosphere region responsible for HF backscatter the calculation of ray-tracing scattering radio wave on field-aligned irregularities were carried out by the method given by Filipp et.al. [7] using the measurements of elevation angles and time delay of the scattered signals. The scattered signals are received in range interval 900-1400 km from Dimer. The elevation angles were in interval of 10° ± 3°. Ray tracing was carried out using the long-term prediction for February 1985. Results of the calculation into meridional plane are presented in Fig. 4. In Figure for every ray are shown the elevation angle and the rectangles superimposed on the ray indicate the regions where the radar wave vector is perpendicularity to the Earth's magnetic field and which correspond to observed time delay of backscattered signals. It can be seen that HF backscatter occurs from the F-region subauroral ionosphere at the altitudes 220-320 km. Over the distance the position of scattered region corresponds to interval of geomagnetic latitudes $\varphi_m \approx$ 57-58.5°, which coincides with the location of equatorial wall of the trough [8].

It is well known that effects of ionospheric propagation play an important role in the observation of HF backscatter echo from field-aligned irregularities. In order to estimate the role of radio waves refraction in aspect scattering we performed ray-tracing for HF radar situated in Dimer Kiev region, Ukraine. Calculations were carried out in the meridional plane in northward from the radar. Field-aligned scattering is calculated along every ray passed inside the ionosphere with step of 1 km. The step over elevation angle is equal to 0.2°. The ionospheric parameters were set over long-term prediction for February 1985. The simulation histogram distribution of scattered centres satisfied of the backscatter condition from field-aligned irregularities is shown by a thin line in Fig. 1. It is seen that there is good agreement between of measurements and modelled data.

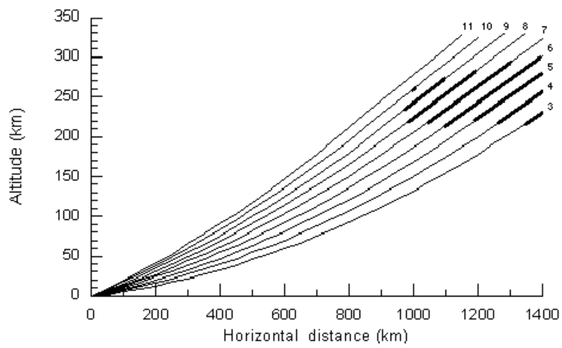

Fig. 4. Ray tracing at frequency 16.6 MHz in a geographic meridian plane for HF radar located in Dimer. 22 LT, February 1985. The rectangles plotted on the rays indicate that the ray is perpendicular to the magnetic field. The elevation angles are pointed out near curves.

The measurements of the scattered signal power were used for estimation of the intensity of the small-scale irregularities responsible for HF backscatter echoes. The expression for the received power of scattered signal may be written in form

$$\mathrm{P}_s = \frac{\mathrm{P}_o \lambda^2 L}{16\pi^2} \int \frac{G_t(\theta,\varphi) G_r(\theta,\varphi) \sigma \, dv}{r_1^2 r_2^2} \tag{1}$$

where P_o is the transmitter power, λ is the length of wave, G_t and G_r are gains of transmitting and receiving antennas, L - is the loss of signal, r_1 and r_2 are ranges from transmitter and receiver to scattered volume. $\sigma = \frac{\pi}{2} k_o^4 \Phi_\varepsilon(k) \sin^2\chi$ is the radar cross section per unit volume of scatter, $k_o = \omega/c$ is the wave number of the transmitted signal, $\Phi_\varepsilon(k)$ is the power spectrum of the fluctuation dielectric permittivity, χ is the angle between wave vector of scattered signal and the electric field vector of the incident wave. For estimation of the intensity small-scale irregularities induced by HF backscattering we use the power law of the spectrum on $k_\perp$ into orthogonal plane to magnetic field and Gaussian spectrum on $k_{||}$ [9].

$$\Phi_\varepsilon(|k|) = C_\varepsilon^2 \left[1 + \left(\frac{k_\perp}{K}\right)^2\right]^{-p/2} \exp\left(-k_{//}^2 l_{//}^2 / 4\right) \tag{2}$$

Here $K = 2\pi/\Lambda$, Λ and $l_{||}$ are outer and longitudinal scales of irregularities, respectively, p is the spectral index. The constant C_ε is defined from condition of normalization

$$\int \Phi_\varepsilon(\vec{k}) d^3k = \frac{\omega_o^4}{\omega^4} < (\Delta N / N)^2 > \tag{3}$$

Where ω_o is the plasma frequency, $<(\Delta N/N)^2>$ is the mean square of total relative fluctuation of the electron concentration. Taking for backscattering $r_1 = r_2 = r$, $\sin^2\chi = 1$ and introducing the angle ψ between the radar wave vector k_o and the direction of the irregularities elongation ($k_{||} = 2k_o \cos\psi$; $k_\perp = 2k_o \sin\psi$) after substitution (2) - (3) into (1) the sub-integral expression can be rewritten as

$$\int \frac{G_t G_r \exp\left[-4\pi^2 (l_{//}/\lambda)^2 \cos^2\psi\right] dr \sin\theta d\theta d\varphi}{r^2 \left[1 + 4(\Lambda/\lambda)^2 \sin^2\psi\right]^{p/2}} \tag{4}$$

For antennas used with a broad pattern and extended on the altitude of scatter region, the vertical scale of scattering volume will defined by the Gaussian cut-off under deflection of the scattered radiation from the mirror direction. Under this $\Delta\theta \sim \Delta\psi \sim \lambda/2\pi l_{||}$. The horizontal scale of scatter volume is defined by beamwidth of transmitting horizontal rhombic antennas into the azimuthal plane which it makes the value $2\Delta\varphi = 14°$ [6]. The scale of the scatter region Δr in direction of scatter vector can be estimated over spreading of the pulse signal $\Delta r = c(\tau_r - \tau_t)/2$, where τ_t and τ_r are duration of the radiating and receiving signals, respectively, c is the velocity of light. For values τ_t = 1 ms, $\tau_r \approx 1{,}7$ ms, r $\approx$ 1000 km, $l_{||}/\lambda = 5$ (for the case of backscattering ($l_\perp = \lambda/2$) this value corresponds to anisotropy of the irregularities $l_{\parallel} / l_{\perp} = 10$) the effective size of the scatter volume is equal to $V_{eff} \sim 3{\cdot}10^5$ km^3 . After substitution into (1) values $P_o = 2.5{\cdot}10^4$ W , $P_s = 6{\cdot}10^{-14}$W, $\Lambda / \lambda = 10$, f =16.6 MHz, f_o = 4 MHz, $G_t{\cdot}Gr = 500$, p =2.5, L = 0,3 we obtain $[\langle(\Delta N/N)^2\rangle]^{1/2} \approx 1.7{\cdot}10^{-3}$.

CONCLUSIONS

We believe that in interpreting HF backscatter echo two factors should be distinguished. The first is the radiophysical aspect associated with ionospheric ray path bending when due to refraction the condition of perpendicularity of radar wave vector to magnetic field is reached. The secondly is the geophysical conditions occurrence the small-scale irregularities responsible for HF backscatter echo.

The ray-tracing simulation and comparison with experimental data show that radio wave refraction plays the important role in selection of small-scale irregularities on the range for the given HF radar position. The occurrence of HF backscatter clearly fell when value of foF2 was less than 3.0 MHz for St.Peterburgh located from radar to north for distance ~ 1000 km.

As far as it is concerned the geophysical aspect note that HF backscatter echo was observed under quiet and moderate disturbed conditions (Kp $\approx$ 2-4) in the evening and night hours generally in days with negative B_y component of the IMF which makes difficult to begin the magnetic storm. In the most cases the appearance of HF backscatter echo was accompanied by spread-F on the ionograms of the vertical sounding at Moscow and St.Peterburgh.

It is presented that joint action such factors as geometry of field-aligned scattering associated with refraction HF as well as the location and movement the equatorial boundary of the trough and statistical ionospheric irregularities determine the experimental dependence of diurnal occurrence HF backscattering and its distribution on the range.
Note in conclusion that use of the middle latitude Doppler HF radar in Kiev region (Ukraine) allowed to determine an important additional information on the subauroral European sector of the F layer ionosphere irregularities during quiet solar period.

REFERENCES

[1] J. M. Ruohoniemi and R. A. Greenwald, “Rates of scattering occurrence in routine HF radar observations during solar cycle maximum,” *Radio Sci.* , vol. 32, pp.1051-1070, May 1997.

[2] L. Kersley, S. E. Pryse, and P. A. Bradley, “Comparison of boundaries for HF auroral backscatter and VHF scintillation ,” *J Atm. Terr. Phys*. vol.57, pp.169-176, February 1995.

[3] R. Andre, C. Hanuise, J.-P. Villain, and J.-C. Cersier, ” HF radars: Multifrequency study of refraction effects and localization of scattering,” *Radio Sci*., vol. 32, pp.153-168, January 1997.

[4] N. M. Boguta, Yu. V. Noga, and V. P. Uryadov , “Spectral characteristics of HF backscattered signals,” *Geomagnet. aeronom*., vol. 29, pp. 678-680, July 1989 (in Russian).

[5] E. Nielsen, and K. Schlegel, “A first comparision of STARE and EISCAT electron drift velocity measurements,” *J. Geoph. Res.*, vol. 88, pp. 5745-5750, July 1983.

[6] G. Z. Aizenberg, S. P. Belousova, E. M. Jurbenko,, G. A. Kliger, and A. G. Kurashov, *Short-wave antennas*. Moscow, Radio and Communication, pp. 277-312, 1985 (in Russian).

[7] N. D. Filipp, N. Sh. Blaunstein, L. M. Erukhimov, V. A. Ivanov, and V. P. Uryadov, *Modern methods of investigation of dynamic processes in ionosphere*. Kishinev, Shtiintsa, pp.81-95, 1991.

[8] N. J. Miller, “The main electron trough during the rising solar cycle,” *J. Geoph. Res* , vol. 75, pp.7175-7181, December 1970.

[9] B. N. Gershman, L. M. Erukhimov, and Yu. Ya Yashin,. *Wave phenomena in ionosphere and cosmic plasma*. Moscow, Nauka, pp.10-43,1984.