*Moscow University Physics Bulletin*
*Vol. 53, No. 1, pp. 30–34, 1998*

*Vestnik Moskovskogo Universiteta. Fizika*
*UDC 538.565.3*

## RADIOPHYSICS

# REGIONS OF NOISE-IMMUNE DATA RECEPTION OVER IONOSPHERIC RADIO COMMUNICATION LINKS WITH SELECTIVE EXCITATION OF CHARACTERISTIC WAVES

V. V. Balinov, Yu. V. Berezin, S. E. Polishchuk, and D. E. Ryzhov

**Noise-immune reception regions for selective excitation of characteristic waves in an ionospheric communication link are investigated. It is shown that for ionospheric paths to 16 $Z_m$ long, the area of noise-immune reception is about $S \sim 50\,Z_m^2$ (at the ionospheric layer half-depth $Z_m = 100$ km, $S \sim 500{,}000$ sq. km). The area $S$ for different azimuthal angles and different radio path lengths is evaluated. It is shown that vertical wave incidence creates especially favorable conditions for implementing regional ionospheric radio communication networks with single-path propagation of radio waves and, consequently, highly reliable data transmission.**

The amplitude of a radio wave reflected from the ionosphere suffers deep fadings due to ordinary and extraordinary components interference. This significantly degrades the quality of data transmitted over an ionospheric communication link. The method of selective characteristic wave excitation (SCWE) in the ionosphere [1] ensures propagation of a single characteristic wave (CW) only, for example, $E_1$, in the ionospheric communication link.

Considering the physical conditions of radio wave propagation in the anisotropic ionosphere, it is clear that the single-path propagation of electromagnetic field in an ionospheric channel will be realized only for certain points on the Earth's surface. With the point of reception moving away from such a "target point", a second CW, $E_2$, will be excited in the ionosphere. Its intensity will depend on the difference of coordinates of the reception and "target" points.

The appearance of the second CW leads to interference fading, which degrades the quality of data transmitted over the link.

Thus the following questions arise: How does the quality of SCWE ionospheric reception depend on the degree of deviation between the reception and "target" points? What are the shapes and areas of Earth's surface regions with the same noise-immunity level?

In order to answer these questions, we consider the following problem. Suppose that we have an ionospheric SCWE radio communication link whose length and operating frequency may vary.

We introduce the Cartesian coordinate system on the Earth's surface, placing at its center (point 0 in Fig. 1*a*) an electromagnetic wave emitter with an isotropic pattern (Fig. 1*a*). The receiver may be positioned at any point on the Earth's surface.

We define the quantitative measure of selective CW excitation as the wave intensity ratio ($Q = E_2^2/E_1^2$) at any point on the Earth's surface. At the best-reception point, $Q = 0$. The value of $Q$ will increase as the receiver is moved away from this point.

The purpose of our study is to determine the shape and area of the region $S$ around the target point, within which the CW intensity ratio $Q$ is smaller than the specified value $Q_i$. This region will be called the region of noise-immune reception (NIR) for the given radio path.

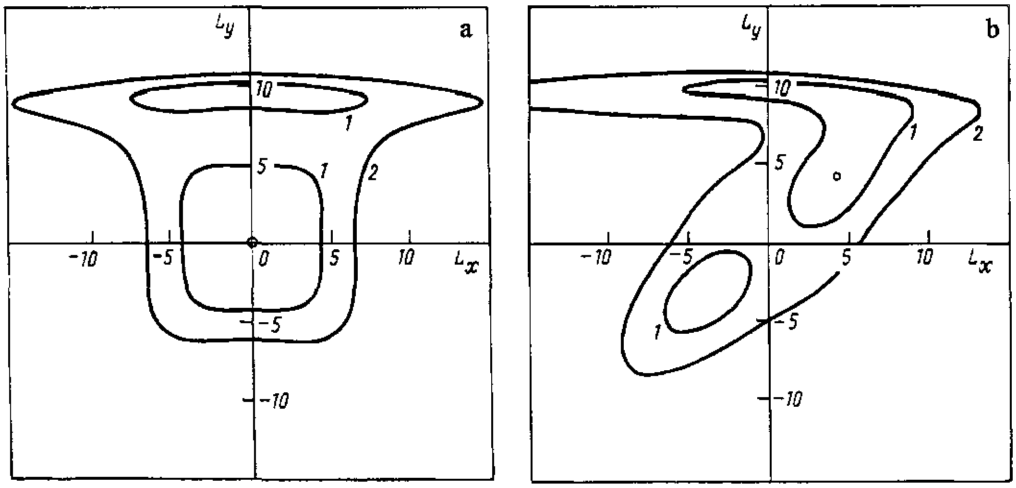


**Fig. 1**

Configurations of noise-immune reception regions for vertical ($a$) and oblique ($b$, $\varphi = 45°$, $L = 6\,Z_m$) wave incidence onto the ionosphere: $Q_i = 0.03$ (*1*) and 0.10 (*2*).

The problem is solved based on the following assumptions.

1. The electron concentration in the ionosphere varies with height according to a parabolic law.
2. The transmitter and receiver are connected by one or two CW paths; multiple reflections from the ionosphere are absent (a single-hop path is considered).

The task of finding the shape and area of the NIR region is divided into several stages.

It is well known [2] that the limiting polarization of a wave which enters (or leaves) the ionosphere is determined by the angle between the wave vector **k** and the Earth's magnetic field $\mathbf{H}_0$. This angle can be expressed in terms of certain problem parameters (in particular, the wave's ionosphere incidence angle $\phi_0$) based on the well-known formulas [2, 3]. In order to find the angle $\phi_0$, we neglect the ionosphere's anisotropy and use the approximation of flat-layered ionosphere. Under these approximations, $\phi_0$ can be found from the equation

$$L = \left(2h_0 + Z_m \frac{f_v}{f_c} \ln \frac{f_c + f_v}{f_c - f_v}\right) \tan\phi_0, \tag{1}$$

where $L$ is the radio path length, $h_0$ is the bottom altitude of the ionospheric layer, $Z_m$ is the layer's half-depth, $f_c$ is the critical frequency, $f_v = f\cos\phi_0$, $f$ is the operating frequency.

The ionosphere's anisotropy will be taken into account in explicit form when finding the limiting polarization.

For the given radio path, the polarization of a CW at its entry into the ionosphere can be found from the well-known formulas [2, 3]. Specifying a point of reception, one can calculate the limiting polarization of the CW in the ionosphere, and then find the polarization to be set up on the transmitting antenna in order to ensure the excitation of only one wave. (This will happen if the transmitted wave's polarization coincides with the limiting polarization of a CW at its entry into the ionosphere.) We recall that in the SCWE method only one CW exists at the target point, therefore $Q = 0$ for that wave.

In order to find the NIR region, we change the reception point coordinates on the Earth's surface and calculate repeatedly the two limiting CW polarizations for the new point. Then the wave emitted by the transmitting antenna is decomposed in the basis of the two calculated polarizations, which yields the amplitudes of both CWs generated. The NIR region is the set of all reception points where the inequality $Q \leq Q_i$ is satisfied.

The region outlines for different azimuthal angles $\varphi$ and different path lengths are shown in Fig. 1$a, b$. The transmitter is located at the origin of coordinates, the point of selective CW excitation is marked by a small circle. The Earth's magnetic field in Fig. 1$a, b$ is directed to the north. In the calculations, the transmitter coordinates were taken 56° N., 37.5° E. (Moscow). The distance $L$ between the transmission and reception points is expressed in terms of the ionospheric layer's half-depth $Z_m$, $L = gZ_m$, where $g$ is a dimensionless parameter. The ionospheric layer's bottom altitude $h_0$ was assumed to be $2\,Z_m$, the operating-to-critical frequency ratio $f/f_c = 0.9$.

Figure 1*a* corresponds to vertical wave incidence onto the ionosphere, Fig. 1*b* to oblique incidence with the azimuthal angle $\varphi = 45°$ and $L = 6\,Z_m$.

The outlines of noise-immune reception regions correspond to $Q_i = 0.03$ and 0.1 (curves *1* and *2*, respectively).

As seen from Fig. 1, the SCWE NIR region has an intricate shape that depends on the radio path's length and orientation relative to the Earth's magnetic field, and on the specified ratio of CW intensities $Q_i$. The value of $Q_i$ strongly affects the size of the NIR region. For instance, at the path of length $L = 6\,Z_m$, the region area corresponding to $Q_i = 0.03$ is (15–40) $Z_m$, while that corresponding to $Q_i = 0.1$ is (150–200) $Z_m$. (Assuming $Z_m = 100$ km, this corresponds to $L = 600$ km and $S = 150$–400 and 1500–2000 thou sq. km, respectively.)

In addition to the primary NIR region, other regions also appear. The physical cause for the appearance of these additional NIR regions requires special investigation. It is obvious, however, that when omnidirectional emission is employed (we have assumed an isotropic radiation pattern), all possible orientations of radio paths should be considered.

Figure 1*a* deserves special attention. It depicts the NIR region for vertical wave incidence onto the ionosphere ($L = 0$). This case is very convenient from the practical standpoint. Firstly, the area of the NIR region around the point of transmission is relatively large (for $Q_i = 0.03$ the area is $75\,Z_m^2$; at $Z_m = 100$ km, it amounts to $S = 75\,000$ sq. km). Secondly, in order to support bidirectional data transmission over an SCWE radio link with oblique wave incidence onto the ionosphere, polarization diagnostics must be carried out at both points of transmission, while in the case of vertical incidence it suffices to perform diagnostics only at one point, simply using the obtained data at the other point. Thus, it is possible to create in the NIR region (without multiple diagnostics) a regional network of ionospheric radio communications with single-path wave propagation, i.e., a network with the highest noise immunity and data transmission rates [4].

Let us discuss the region area dependence on the path length with azimuthal angle $\varphi$ as a parameter. Two examples of this dependence are given in Fig. 2 (at $Q_i = 0.03$). Curve *1* corresponds to $\varphi = 150°$, curve *2* to $\varphi = 30°$. The region area remains almost the same for short distances ($L < 4\,Z_m$), falls abruptly at $L \cong 5\,Z_m$ to one fifth of its original value, then slowly grows. The sharp reduction of the region area is due to splitting of a single region around the transmission point (see Fig. 1) into two regions located on both sides of the transmitter (see Fig. 2).

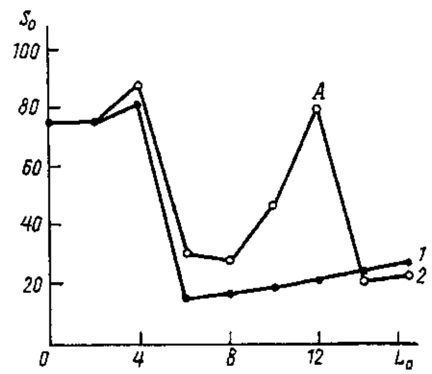


**Fig. 2**

NIR region area as a function of radio path length for different azimuthal angles $\varphi = 150°$ (*1*) and 30° (*2*).

For azimuthal angles greater than 90°, the path length dependences of the region area almost coincide with curve *1*, while for angles smaller than 90° the curves display a typical peak (point *A* in Fig. 2). This peak is associated with a qualitative change in the configuration of the NIR region for large path lengths.

Now we discuss the dependence of the NIR region area on the path orientation with respect to the Earth's magnetic field. The path distance $L$ will play the role of a parameter. Two examples of this dependence are given in Fig. 3 (curves *2* and *3*) for $Q_i = 0.03$. Curve *2* corresponds to the distance $L = 6\,Z_m$, curve *3* to $L = 16\,Z_m$. Straight line *1* indicates the region area for a path of zero length. For small path lengths (about $2\,Z_m$ or shorter), the curve $S(\varphi)$ behaves similarly to straight line *1*. For greater distances, the following feature is observed in the curve $S(\varphi)$: if the path's azimuthal angle is larger than 90°, the area remains virtually independent of the path orientation; for angles smaller than 90° one observes a complex behavior of $S$ as a function of $\varphi$, which we do not analyze in this article.

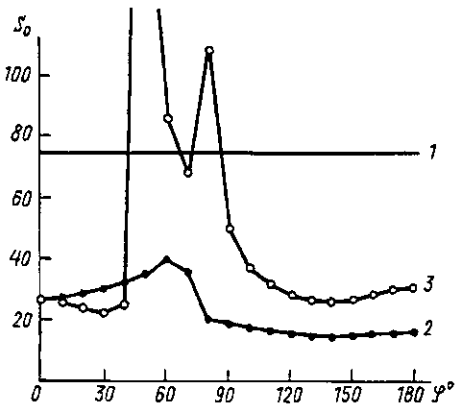


**Fig. 3**

NIR region area as a function of azimuthal angle for different radio path lengths: $L = 0$ (*1*), $L = 6\,Z_m$ (*2*), and $L = 16\,Z_m$ (*3*).

It is well known that the ionosphere's parameters may fluctuate within certain limits. The configurations and areas of the NIR region were studied as functions of the ionospheric layer half-depth $Z_m$, the operating-to-critical frequency ratio $f/f_c$, and the ionosphere bottom altitude $h_0$, because these parameters are subject to diurnal fluctuations. The value of $Z_m$ was varied between 100 and 50 km, $f/f_c$ from 0.9 to 0.6, and $h_0$ from 1.5 to $3\,Z_m$.

Variation of the ionosphere's parameters in these limits affected only the area of the NIR region, while its configuration remained the same. The region size is practically a linear function of the altitude $h_0$ and weakly depends on $Z_m$ and $f/f_c$. Under fluctuations of $Z_m$ and $f/f_c$ the region area change is the greatest at the zero path length and amounts to 20–30%. At the path distances exceeding 500 km it is less than 10%.

The results produced in this study allow the following conclusions to be drawn.

1. The ionospheric radio communication links with selective CW excitation induce reception regions of high noise immunity on the Earth's surface. The areas of such regions may amount to several hundred thousands of square kilometers.

2. The NIR regions have no simple configurations (such as circles, polygons, or ellipses) and cannot be described by simple formulas.

3. The region configuration explicitly depends on two parameters: the radio path's length and orientation relative to the plane of the Earth's magnetic meridian.

4. The NIR region configuration and area depend but weakly on the ionospheric layer half-depth fluctuations and the operating-to-critical frequency ratio though they depend strongly on the altitude of the ionospheric layer bottom.

Of especial interest is the NIR region in the case of vertical wave incidence onto the ionosphere, because inside this region there can be created (without extra diagnostics) a regional network of ionospheric radio communications with single-path wave propagation.

Thus, the SCWE method allows one to create very large regions on the Earth's surface where only one beam of a wave reflected by the ionosphere is received, i.e., to create single-path ionospheric radio communication links of optimal data transmission quality [4].

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11 April 1997 Department of Radiophysics