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The methodology for calculating the interval of the shortwave radio link frequency correlation with the sphericity and small-scale inhomogeneities of the ionosphere

V P Pashintsev [1], N N Gakhova [2], A D Skorik[1], D V Alekseev[1], M A Senokosov[1]

[1] North Caucasus Federal University, 1, Pushkin Street, Stavropol 355009, Department of information security of automated systems
E-mail pashintsevp@mail.ru
[2] Belgorod State University, 85, Pobedy St., Belgorod, 308015, Department of applied informatics and information technologies, Russia
E-mail gahova@bsu.edu.ru

Abstract.The paper suggests the methodology for calculating the interval of the fading frequency correlation in the shortwave radio link with one discrete beam and its diffuse scattering. This methodology takes into account the effect of the sphericity and small-scale inhomogeneities of the ionosphere reflecting layer.

Keywords: short-wave coupling, ionosphere, sphericity, small-scale inhomogeneities, diffuse multipath, fading, frequency correlation interval.

1. Introduction

It is known [1] that in a shortwave (SW) radio link there can be one path (discrete beam) of the wave propagation in the reception point. In this case, the signal at the receiver input is almost always subject to the interference fading (amplitude and phase fluctuations) due to the diffuse scattering of a beam (a single wave) within small-scale inhomogeneities of the ionosphere reflecting layer F and the diffuse multipathing with the maximum relative delay time $\Delta\tau_{\mathrm{i\,max}} \approx 50\ldots200$ mcsec [1]. That is why the interval of the fading frequency correlation (or the band of undistorted transmission) of the single-beam SW radio link is constrained by the values $F_{\text{к}} \approx 1/\Delta\tau_i$ =20…5 kHz. If there are several (2-3) paths (discrete beams) of wave propagation in the reception point, their relative delay time within the range of SW communication R =1500…4000 km is $\Delta t_{\mathrm{i}} \approx 1\ldots3$ msec [1-3]. And the interval of the SW radio link frequency correlation with the discrete multipathing gets narrow up to $F_{\text{к}} \approx 1/\Delta t_i$ =1…0,3 kHz. Since it is usually assumed [1-3] that the frequency correlation interval in the SW radio link is $F_{\text{к}} \approx 0{,}3\ldots1$ kHz, the transmission rate $c_{\text{т}} = T_{\text{c}}^{-1}$ of simple binary signals (that is with the base $B_{\text{c}} = T_{\text{c}}F_0 = 1$, where T_{c} and $F_0 = 1/T_{\text{c}}$ are the signal length and width) does not usually exceed tens to hundreds bit/sec due to the necessity to meet the requirements of simultaneous elimination of the frequency selective fading (FSF) $F_{\text{к}}/F_0 >> 1$ and the intersymbol interference (ISI) $F_{\text{к}}/c_{\text{т}} = T_{\text{c}}F_{\text{к}} = F_{\text{к}}/F_0 >> 1$ [4, 5].

Using the known method [2] of the separation (radiation) of one discrete beam through narrowly directed receiving (transmitting) antennas enables providing the frequency correlation interval $F_к \approx 5\ldots20$ kHz in the SW radio link. Moreover, according to [2, 3] the percentage of the lifetime of the discrete-single-beam propagation models in the SW radio link is quite high on long-distance radio paths (85% when the communication range $R = 3000$ km, 64 % when $R = 4000$ km and 31 % when $R = 1500$ km). That is why in single-beam SW radio links, the signal transmission rate can significantly increase (by one order of magnitude and greater) if there are no FSF and ISI ($F_к / F_0 = F_к / c_т >> 1$). To quantify the maximum available values $c_т$ in the single-beam SW radio link, it is necessary to determine the value of the interval of the fading frequency correlation $F_к$.

The interval of the fading frequency correlation $F_к$ in SW radio links with multipathing (both discrete and diffuse) is usually determined experimentally [1, 4]. There is the method [5] that enables estimating analytically the value of the frequency correlation interval $F_к$ in the single-beam SW radio link considering the plane ionosphere reflecting layer (with diffuse scattering) but with the Earth sphericity. The impact of the ionosphere sphericity on the various paths of the wave propagation is considered in works [7, 8], which is of great significance for long-distance SW radio paths. However, the method suggested in [7, 8] does not enable quantifying all the parameters of the wave path in the single-beam SW radio link that is necessary to determine $F_к$. Therefore, the known methods [6 – 8] require generalizing and specifying.

The goal of the paper is to develop the methodology to calculate the interval of the fading frequency correlation in the shortwave radio link with one discrete beam with the diffuse multipathing which considers the impact of sphericity and small-scale inhomogeneities of the ionosphere reflecting layer F.

2. Method for calculating the frequency correlation interval of a short-wave radio line

According to [6], the interval of fading frequency correlation in the single-beam SW radio link with the diffuse multipathing is described by the expression

$$F_к = f_0 \Big/ \left(\sigma_\varphi \sqrt{2 + d_1^2} \right), \tag{1}$$

where f_0 is the radio carrier (operating frequency) of the SW radio link [Hz]; σ_φ is the mean-square deviation of fluctuations (distortions) of the wave phase front at the output of the ionosphere reflecting layer F with small-scale inhomogeneities [rad]; $d_1^2 \geq 1$ is the diffraction parameter characterizing the rise in diffraction effects when the wave front removes from the reflecting layer of the inhomogeneous ionosphere to the reception point.

The mean-square deviation (MSD) of the wave phase front fluctuations at the output of the ionosphere layer F in the SW range is described by the standard expression common to transionospheric radio links with small-scale inhomogeneities of any frequency ranges [6, 9-11]

$$\sigma_\varphi = \left(80{,}8\,\pi / c\, f_0 \right) \beta\, \overline{N\left(h_{re}\right)} \sqrt{2\, l_0\, L_{eq}}\,, \tag{2}$$

where $c = 3 \cdot 10^8$ [m/sec] is the speed of light in vacuum; coefficient 80.8 is expressed in [m^3/sec^2] in SI system; $\beta \approx 10^{-3} \ldots 10^{-2}$ is the rate of small-scale ionospheric inhomogeneities; l_0 is the largest length of ionospheric inhomogeneities [m]; L_{eq} is the equivalent homogeneous wave propagation path in the ionosphere reflecting layer F [m] which corresponds to the length of the imaginary curved path of wave propagation in the “tube” from the input to the output of the ionosphere reflecting layer F with average electron concentration $\overline{N(h)} = const$ of constant (homogeneous) height (h) that corresponds to its maximum value at the height $h = h_{re}$ of wave reflection $\overline{N\left(h_{re}\right)}$ [m^{-3}].

The diffraction parameter included in (1) is determined by the expression [6, 9,10]

$$d_1^2 = \frac{3\,L^2 - 3\,L\,L_{eq} + L_{eq}^2}{6\left(2\,\pi\,f_0/c\right)^2}\left(8\,l_0^2\,l_\text{i}^2\right)^{-1}. \qquad (3)$$

Here, $L = L_{eq} + L_{fs}$ is the sum of the equivalent homogenous propagation path in the reflecting layer F and the wave propagation path in the free space L_{fs} [m] behind the ionosphere, that is from the output of the reflecting layer to the reception point; l_i is the smallest length of ionospheric inhomogeneities [m].

The wave operating frequency, that is at the angle φ_0 to the lower limit $h = h_0$ of the spherical reflecting layer F of the ionosphere, is linked to the frequency of the equivalent wave directed vertically $f_v = \left[80{,}8\,\overline{N\left(h_{re}\right)}\right]^{0{,}5}$ by the known ratio [3, 6]

$$f_0 = f_v K_\text{s} \sec\varphi_0 = \left[80{,}8\,\overline{N\left(h_{re}\right)}\right]^{0{,}5} K_\text{s} \sec\varphi_0\,, \qquad (4)$$

where $K_\text{s} \le 1$ is the coefficient of the Earth and ionosphere sphericity.

If (4) is substituted in (2), the expression for the MSD of phase fluctuations at the wave front at the output of the spherical reflecting layer F of the ionosphere with small-scale inhomogeneities can be written as [6, 12-16]

$$\sigma_\varphi = \pi\beta\,f_0\sqrt{2\,l_0\,L_{eq}}\Big/c\,K_\text{s}^2\sec^2\varphi_0\,. \qquad (5)$$

According to (5), the MSD of the fluctuations of the wave phase front at the ionosphere output in the single-beam SW radio link rises with the increase of the operating frequency (and approaches to its maximum usable frequency), the rate of the ionosphere small-scale inhomogeneities β (which characterizes the degree of the ionosphere diffuseness [17] and can increase to the values $\beta \approx 10^{-1}$), the equivalent homogenous path of the wave propagation in the ionosphere reflecting layer L_{eq} and with the decrease of the Earth and ionosphere sphericity coefficient K_s and the angle of the wave incidence φ_0 to the lower limit of the spherical reflecting layer of the ionosphere.

Thus, to calculate the interval $F_\text{к}$ of the frequency correlation of the SW radio link with one discrete beam taking into consideration the sphericity of the reflecting layer F and diffuse scattering on the small-scale inhomogeneities of the ionosphere according to the expressions (1-5), the values K_s, L_{eq}, L_{fs} and φ_0 should be determined.

The expressions to calculate the coefficient of the sphericity and equivalent homogenous path of the wave propagation in the spherical reflecting layer F of the ionosphere of the single-beam SW radio link are given in [7]:

$$K_\text{s} = \left\{1 + \frac{2\,f_\text{cr}^2\,C_1(1-C_1)}{f_0^2\cos^2\varphi_0}\left[1 - \left(1 - \frac{f_0^2\cos^2\varphi_0}{f_\text{cr}^2 C_1^2}\right)^{\frac{1}{2}}\right]\right\}^{-\frac{1}{2}}; \qquad (6)$$

$$L_{eq} = \frac{L_\text{F}}{2}\left[1 + \frac{f_\text{cr}^2 C_1(4\text{-}3C_1)}{f_0^2\cos^2\varphi_0} - \frac{2Z_\text{m}(4\text{-}3C_1)}{L_g\cos\varphi_0}\right]K_\text{s}^2\,. \qquad (7)$$

Here, $f_\text{cr} = \left[80{,}8\,\overline{N\left(h_\text{m}\right)}\right]^{0{,}5}$ is the critical frequency of the ionosphere reflecting layer [Hz] at the height $h_\text{m} = h_0 + z_\text{m}$ with maximum mean value of the electron concentration $\overline{N\left(h_\text{m}\right)}$, where Z_m is the half-thickness of the ionosphere reflecting layer F [m];

$$C_1 = 1 - \frac{f_0^2}{f_{\text{cr}}^2} \frac{Z_{\text{m}} \sin^2 \varphi_0}{R_E + h_0} \le 1 \tag{8}$$

is the coefficient that characterizes the rate of decline f_{cr} in the spherical reflecting layer F of the ionosphere as compared to the plane one; $R_E \approx 6370 \cdot 10^3$ [m] is the radius of the Earth;

$$L_{\text{F}} \approx L_g - \frac{L_g}{4\sec^2 \varphi_0} - \frac{L_g}{4} \frac{f_{\text{cr}}^2}{f_0^2} C_1 (4\text{-}3C_1) + \frac{Z_{\text{m}}(4\text{-}3C_1)}{2\sec\varphi_0}; \tag{9}$$

$$L_g = Z_{\text{m}} \frac{f_0}{f_{\text{cr}}} \ln \frac{1 + f_0 \cos\varphi_0 / f_{\text{cr}} C_1}{1 - f_0 \cos\varphi_0 / f_{\text{cr}} C_1} \tag{10}$$

is the actual (L_{F}) and group (L_g) paths of the wave propagation in the spherical reflecting layer F of the ionosphere [m].

Considering the geometry of the wave propagation in the free space behind the ionosphere, its path L_{fs} from the output point from the reflecting layer F to the reception point can be determined as

$$L_{fs} = \frac{R_E}{\sin\varphi_0} \sin\gamma = \frac{R_E}{\sin\varphi_0} \sin\left\{ \arcsin\left[\sin\varphi_0 \left(1 + \frac{h_0}{R_E} \right) \right] - \varphi_0 \right\}, \tag{11}$$

where γ is the geocentrical angle [rad] that corresponds to the wave straight path from the reflecting layer output to the reception point of L_{fs} length.

To calculate the values C_1 (8), K_{s} (6), L_g (10), L_{F} (9), L_{eq} (7), L_{fs} (11), d_1^2 (3) and σ_φ (5) which determine the interval $F_{\text{к}}$ (1) of the frequency correlation of the SW radio link with one discrete beam with the sphericity and diffuse scattering of the reflecting layer F, it is necessary to determine the wave incidence angle φ_0 onto the lower limit (h_0) of the ionosphere reflecting layer F. To obtain the analytic expression for φ_0 considering the Earth and ionosphere sphericity is rather a difficult task. However, according to [18], the angle φ_0 can be determined if the functional dependence $R = \Psi(\varphi_0)$ of the SW communication range R (over the Earth surface) on the angle φ_0 for the known values of the operating frequency f_0 as well as the parameters of the ionosphere reflecting layer (h_0, Z_{m}, f_{cr}) and the specified range of communication $R = R_{\text{pre}}$ is previously found.

According to [18], the range of SW communication over the Earth R involves the sections R_1 and R_2 that correspond to the ionosphere and extra-ionosphere parts of its path and is determined as

$$R = R_1 + R_2 \approx \frac{R_E}{R_E + h_0} \sin\varphi_0 \frac{f_0}{f_{\text{cr}}} Z_m \ln\left[\left(1 - \frac{f_0^2}{f_{\text{cr}}^2} \frac{Z_m \sin^2 \varphi_0}{R_E + h_0} + \frac{f_0}{f_{\text{cr}}} \cos\varphi_0 \right) \Big/ \left(1 - \frac{f_0^2}{f_{\text{cr}}^2} \frac{Z_m \sin^2 \varphi_0}{R_E + h_0} - \frac{f_0}{f_{\text{cr}}} \cos\varphi_0 \right) \right] +$$

$$+ 2R_E \left[\operatorname{ctg}\varphi_0 - \left(\operatorname{ctg}^2 \varphi_0 - 2h_0 / R_E \right)^{\frac{1}{2}} \right]. \tag{12}$$

According the functional dependence (12) $R = \Psi(\varphi_0)$, when the operating frequency f_0 is given and the ionosphere parameters (h_0, Z_{m}, f_{cr}) are known, it is possible to determine (either in graphically or numerically) the wave incidence angle φ_0 onto the spherical ionosphere, which corresponds to the specified range of the SW communication $R = R_{\text{pre}}$.

Let us see how the interval of the frequency correlation $F_{\text{к}}$ (1) of the single-beam SW radio link for various values of the operating frequency f_0 is calculated based on the definition of the wave incidence angle φ_0 onto the lower limit of the ionosphere reflecting layer F according to the dependence (12) $R = \Psi(\varphi_0)$ when the communication range $R = R_{\text{cr}}$ is given and according to the expressions C_1 (8), L_g (10), L_{F} (9), K_{s} (6), L_{eq} (7), L_{fs} (11), d_1^2 (3) and σ_φ (5).

For the communication range $R_{\text{pre}} = 3000$ km and standard parameters [2, 3, 9-14, 16, 18] of the inhomogeneous layer of the ionosphere $F2$ ($h_0 = 300$ km, $Z_{\text{m}} = 200$ km, $f_{\text{cr}} = 5,7$ MHz, $l_0 = 390$ m, $l_{\text{i}} = 10$ m, $\beta = 10^{-2}$), the variations of the specified features of the wave in the single-beam SW radio link with various values f_0 are given in Table 1.

Table 1. variations features of the wave in the single-beam SW radio link with various values

f_0, MHz	φ_0, degrees	C_1	L_g, km	L_{F}, km	K_{s}	L_{eq}, km	L_{fs}, km	d_1^2	σ_φ, rad	γ^2	$F_{\text{к}}$, kHz
12.3	69.15	0.878	1168	1104	0.918	799	1061	$1.4\cdot10^5$	4.84	$7\cdot10^{-11}$	6.91
11.13	70.86	0.898	698	668	0.939	465	1254	$1.7\cdot10^5$	2.71	$6\cdot10^{-4}$	10.03
9.89	71.41	0.919	483	465	0.954	319	1346	$2.2\cdot10^5$	1.82	0.04	11.63
8.66	71.71	0.938	341	329	0.966	223	1408	$2.9\cdot10^5$	1.26	0.26	12.76
7.42	71.91	0.954	236	228	0.976	154	1454	$4\cdot10^5$	0.86	0.92	13.62
6.18	72.03	0.968	156	151	0.983	102	1490	$5.8\cdot10^5$	0.57	2.6	14.28

The analysis of the results given in Table 1 shows the following. As the operating frequency in the single-beam SW radio link drops against the value of the maximum usable frequency (MUF) $f_{\text{MUF}} = 12,37$ MHz, within the range from f_0=12,3…6,18 MHz there happens an insignificant rise of the angle φ_0, and in this case the specified communication range $R_{\text{pre}} = 3000$ km is ensured. And the values of coefficients C_1 (8) and K_{s} (6) increase approaching to 1 (this can be explained by the fact that the height of the wave reflection h_{re} decreases as well as the degree of the impact of the sphericity of the ionosphere reflecting layer). The lengths of the group and phase paths of the wave propagation in the ionosphere reflecting layer F L_g (10) and L_{F} (9) decrease and, as a result, the equivalent homogenous path (7) significantly decreases (from L_{eq}=799 km to 102 km). The decrease of values f_0 and $\sqrt{L_{eq}}$ in the numerator and the increases of K_{s}^2 and $\sec^2\varphi_0$ in the denominator of the expression (5) are responsible for the significant decrease of MSD of the phase fluctuations at the wave front at the output of the inhomogeneous reflecting layer of the ionosphere. The decrease of σ_φ with the operating frequency f_0 lowering ensures expanding the interval of the frequency correlation of the single-beam SW radio link (1) $F_{\text{к}} \square f_0/\sigma_\varphi$ despite some increase of diffraction effects at the front of the received wave (that is the increase of d_1^2 (3) due to the rise of L_{fs} (12)).

The diagrams of the dependences of the MSD of phase fluctuations at the wave front at the output of the ionosphere $\sigma_\varphi = \psi(f_0)$ and the interval of the frequency correlation of the single-beam SW radio link $F_{\text{к}} = \psi(f_0)$ on the selection of the operating frequency f_0 are presented in Figure1.

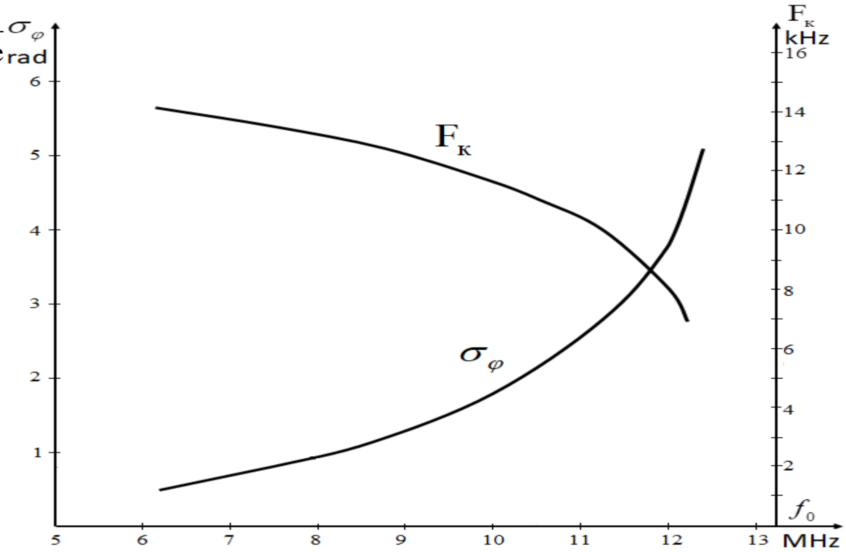

Figure 1. Dependences of the phase fluctuations at the wave front at the inhomogeneous ionosphere output and the interval of the frequency correlation of the single-beam SW radio link on the operating frequency selection

The analysis of Figure 1 shows that as the operating frequency of the single-beam SW radio link approaches to MUF, phase fluctuations at the front of the output wave increase from $\sigma_\varphi \approx 0{,}57$ to 4.8 rad. This results in increasing the parameter of the Rician fading of received signals, which is determined as [6, 12, 14-16]

$$\gamma^2 = \left[\exp(\sigma_\varphi^2) - 1\right]^{-1} \geq 0, \tag{13}$$

from $\gamma^2 \approx 2.6$ to $\gamma^2 \approx 7 \cdot 10^{-11}$, which practically corresponds to the case when general Rayleigh fading (when $\gamma^2 = 0$) occurs. Moreover, the interval of the frequency correlation of the single-beam SW radio link becomes twofold narrower – from $F_к \approx 14.3$ kHz to 6.9 kHz.

The reliability of the results is confirmed by the fact that the calculated values of the frequency correlation interval of the single-beam SW radio link ($F_к \approx 6{,}91 \ldots 14{,}28$ kHz), constrained by the diffuse multipathing, approximately correspond to the known experimental data [1] ($F_к \approx 5 \ldots 20$ kHz) for standard parameters of the spherical inhomogeneous reflecting layer of the ionosphere and various values f_0.

Thus, the methodology is developed to calculate the interval $F_к$ of the frequency correlation of the single-beam SW radio link with the sphericity of the inhomogeneous reflecting layer of the ionosphere under the diffuse multipathing based on the definition of the φ_0 angle (according to (12)) and a set of analytical expressions (8, 10, 9, 6, 7, 11, 3, 5, 1).

This methodology includes the following stages:

1. Based on the measurement of the frequency-height characteristics (FHC) of the ionosphere layer F (f_{cr}, h_0, Z_{m}) for the selected values of the operating frequencies of the single-beam SW radio link by the ionosphere vertical sounding (IVS) station, a number of functional dependencies can be established $R = \Psi(\varphi_0, f_0)$.

2. For the selected operating frequencies f_0, it is possible to determine graphically or numerically the wave incidence angle φ_0 onto the lower limit of the ionosphere reflecting layer F that corresponds to the specified range of the SW communication $R = R_{\text{pre}}$.

3. For the found value of the wave incidence angle φ_0 with the frequency f_0 onto the lower limit of the ionosphere reflecting layer F with the known parameters (f_{cr}, h_0, Z_{m}), which ensures the specified range of the SW communication $R = R_{\text{pre}}$, the coefficient that characterizes the rate of decline f_{cr} within the spherical reflecting layer F of the ionosphere as compared to the plane one (8) $C_1 = \psi(f_0, \varphi_0, f_{\text{cr}}, h_0, Z_{\text{m}})$ is determined.

4. Taking into account $C_1=\psi(f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}})$, the group (10) $L_g=\psi(f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1)$ and actual (9) $L_{\text{F}}=\psi(L_g,f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}})$ paths of the wave propagation within the spherical reflecting layer of the ionosphere F are determined as well as the coefficient of the Earth and ionosphere sphericity (6) $K_{\text{s}}=\psi(f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1)$.

5. Taking into account these dependences, the length of the equivalent homogenous path of the wave propagation within the spherical reflecting layer of the ionosphere of the single-beam SW radio link (7) $L_E=\psi(L_{\text{F}},L_g,f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1,K_s)$ is determined .

6. According to the found wave incidence angle φ_0 onto the lower limit of the ionosphere layer F and the height of this limit h_0, the wave path in the free space behind the ionosphere from the output point from the layer to the reception point (11) $L_{fs}=\psi(\varphi_0,h_0)$ is determined .

7. According to the found values of the equivalent homogenous path of the wave propagation with the frequency f_0 in the spherical reflecting layer F of the ionosphere of the single-beam SW radio link (7) $L_{eq}=\psi(L_{\text{F}},L_g,f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1,K_s)$ and the sum of this path $L=L_{eq}+L_{fs}$ and the length of the wave propagation in the free space behind the ionosphere (11) $L_{fs}=\psi(\varphi_0,h_0)$, taking into account the known lengths (the smallest l_{i} and the greatest l_0) of the ionosphere inhomogeneities, the diffraction parameter (3) $d_1^2=\psi(f_0,L_{eq},L_{\text{s}},l_{\text{i}},l_0)$ is determined .

8. For the selected operating frequency f_0 and the found wave incidence angle φ_0 onto the lower limit of the ionosphere reflecting layer F, the coefficient of the Earth and ionosphere sphericity (6) $K_{\text{s}}=\psi(f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1)$ and the equivalent homogenous path of the wave propagation with the frequency f_0 in the spherical reflecting layer F of the ionosphere (7) $L_{eq}=\psi(L_{\text{F}},L_g,f_0,\varphi_0,f_{\text{cr}},h_0,Z_{\text{m}},C_1,K_s)$, it is possible to determine the MSD of the phase fluctuation at the wave front at the output of the spherical reflceting layer F of the ionosphere with small-scale inhomogeneities (with the known values of their maximum length l_0 and rate β) according to (5) $\sigma_\varphi=\psi(f_0,\varphi_0,K_{\text{s}},L_{eq},l_0,\beta)$.

9. For the selected operating frequency f_0 and found values of the MSD of the phase fluctuations at the wave front at the output of the spherical reflecting layer F of the ionosphere with small-scale inhomogeneities (5) $\sigma_\varphi=\psi(f_0,\varphi_0,K_{\text{s}},L_{eq},l_0,\beta)$ and the diffraction parameter (3) $d_1^2=\psi(f_0,L_{eq},L_{fs},l_{\text{i}},l_0)$, the interval of the fading frequency correlation in the single-beam SW radio link with the diffuse multipathing (1) $F_{\text{к}}=\psi(f_0,\sigma_\varphi,d_1^2)$ is determined.

3. Conclusion.

The application of the developed methodology allows you to (selection) of one discrete beam by the data of sounding the parameters of the ionosphere layer F (f_{cr}, h_0, Z_{m}, l_{i}, l_0, β), the application of this methodology enables selecting (lowering) the operating frequency f_0 that ensures the significant decrease of the phase fluctuations at the wave front at the output of the spherical reflecting layer F of the ionosphere with small-scale inhomogeneities (5) $\sigma_\varphi \sim f_0\beta\sqrt{L_{eq}}\big/K_{\text{s}}^2\sec^2\varphi_0$, which leads to the decrease in the depth of interference fading (that is the increase in the Rice parameter (13) $\gamma^2 \sim 1\big/\sigma_\varphi^2$) and the expansion of the interval of the fading frequency correlation (1) $F_{\text{к}} \sim f_0\big/\sigma_\varphi$ in the single-beam SW radio link.

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References

[1] Stein S Jones D 1971 *Principles of modern communication theory and their application to the transmission of discrete messages* (Moscow: Svyaz)

[2] Khmelnitsky E A 1975 *Evaluation of the real noise immunity of receiving signals in the HF range* (Moscow: Svyaz)

[3] Cherenkova E L Chernyshov O V 1984 *Propagation of radio waves* (Moscow: Radio and communications)

[4] Volkov L N Nemirovsky M S Shinakov Yu S 2005 *Digital radio communication Systems: basic methods and characteristics* (Moscow: EKO-Trenz)

[5] Pashintsev V P Borovlev I I 2003 Messages transmission opportunity rise in one-path decameter radio link because of choice of optimal signals transmissions rate *Izvestiya Vysshikh Uchebnykh Zavedenij Radioelektronika* No 46(11) pp 26-33

[6] Pashintsev V P Kolosov L V Tishkin S A Antonov V V 1996 Application of the phase-screen theory for developing a model of a one-hop decameter communication link *Journal of Communications Technology and Electronics* No 41(1) pp 16-21

[7] Pashintsev V P Tishkin S A Smirnov A A Borovlev I I 2001 Equivalent path of decameter wave propagation in the spherical-layered ionosphere *Journal of Radioelectronics* No 8

[8] Pashintsev V P Solchatov M E Kondrashin A Ye Senokosova A V 2005 Maximal frequency of reflection of a decameter wave from the spherically stratified ionosphere *Radioelektronics and Communications Systems* No 48(5) pp 8-14

[9] Knepp D L 1983 Multiple phase-screen calculation of the temporal behavior of stochastic waves *Proc of the IEEE* Vol 71 No 6 pp 722-737

[10] Maslov O N Pashintsev V P 2006 Models of transionospheric radio channels and interference stability of space communication systems *The information and communication technologies* (Samara: pgati) Vol 4 p 358

[11] Pashintsev V P Kolosov L V Tishkin S A Smirnov A A 1999 Influence of the Ionosphere on Signal Detection in Space Communications Systems *Journal of Communications Technology and Electronics* No 44(2) pp 132-139

[12] Pashintsev V P Tishkin S A Ivannikov A I Borovlev I I 2001 Calculating the fading depth parameter in single-beam decameter radio link *Izvestiya Vysshikh Uchebnykh Zavedenij Radioelektronika* No 44(12) pp 57-65

[13] Pashintsev V P Koval S A Potyagov D A Spirin A M 2010 Estimation of noise error when measuring virtual height during diffusivity of ionospheric F layer *Radioelektronics and Communications Systems* Vol 53 No 7 pp 348-355

[14] Pashintsev V P Tishkin S A Ivannikov A I Solchatov M E 2001 Determining the optimal working and least applicable frequency of the DCM radio line with the depth of fast fading *Elektrosvyaz* No 12 pp 16-19

[15] Pashintsev V P Chipiga A F Shevchenko V A Kiselev D P 2016 Influence of ion-sphere diffusivity on the optimal operating frequency of a decameter radio line *Izvestiya Samar-go scientific center of the Russian Academy of Sciences* Vol 18 No 2(3) pp 946-951.

[16] Pashintsev V P Skorik A D Koval C A Kiselev D P Senokosov M A 2019 Dependence of communication reliability in a decameter radio line on the choice of the operating frequency with consideration of signal-interference situation and ionosphere diffusivity *Management communication and security systems* No 4 pp 300-322

[17] Pashintsev V P Omelchuk A V Koval S A Galushko Yu I 2009 Method for determining the magnitude of the intensity of inhomogeneities based on ionospheric sounding data *Dual technologies* No 1 pp 38-42

[18] Davis K 1973 *Radio Waves in the ionosphere* (Moscow: Mir)