Calculating Characteristics of HF Radio Waves Taking into Account Ionospheric Inhomogeneities

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Abstract —**In this paper, we present a method for calculating propagation characteristics of high - frequency radio waves reflecting one time and two times at ionospheric layer F2 under inhomogeneous conditions of the ionosphere. The proposed method provides accurate calculation of the maximum usable frequency(MUF). Results of calculating frequency dependence of radio field strength show that scattering of radio waves in the ionosphere leads to the possibility of receiving radio waves at frequencies exceeding the maximum usable frequencies.**

I. Introduction

To improve the quality of high-frequency (HF) telecommunications systems, it is necessary to predict the basic characteristics of radio waves as field strength and the maximum usable frequencies (MUF). By predicting field strength at receiving point, it allows us to select optimal power of radio transmitters and directional coefficients of receiving-transmitting antennas. According to calculated values of MUF, we can choose operating frequencies to ensure good quality of HF telecommunications systems. Currently, there are a number of papers devoted to predicting characteristics of HF signals reflecting at the ionosphere, for example, method based on a solution of parabolic equation [1], method [2], method of characteristics [3]. Methods [1]-[3] calculate the maximum usable frequency for one-hop propagation of HF radio waves (MUF1F2) quite accurately. Despite this, using these time-consuming methods requires a lot of computation time, since these methods are based on the computational integration of differential equations for constructing radio wave trajectory in the ionosphere. In addition, when calculating the maximum usable frequency for two-hop propagation of HF radio waves (MUF2F2) by these methods, the calculated MUF are often lower than the measured values. This fact is explained by influences of random inhomogeneities of the ionosphere, which are not considered in methods [1]- [3].

The purpose of this paper is to develop an approximate method for calculating MUF and filed strength of propagation modes 1F2 and 2F2 of HF radio waves taking into account regular and random inhomogeneities of the ionosphere.

II. Method of Calculating MUF Taking into Account Regular Inhomogenieties of the Ionosphere

To take into account the influence of horizontal inhomogeneities of the ionosphere on the MUF, method [4] is used. Following that method, in horizontally inhomogeneous ionosphere, reflection point of radio wave moves from the middle of the path in the region of higher critical frequencies $f0F2$ (Fig. 1).

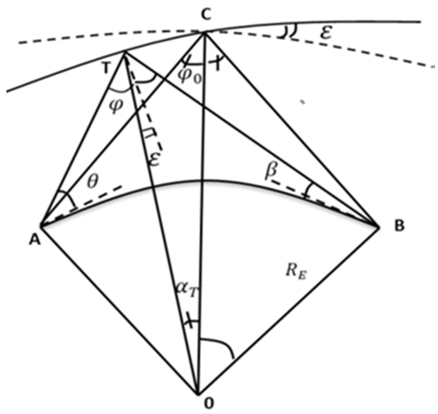

Fig. 1. Reflection of radio waves at equivalent inclined mirror model of the ionosphere

This factor leads to increase in MUF compared with MUF calculated in the horizontaly homogeneous ionosphere. To take into account the effect of the displacement of reflection point on the calculated MUF, we use formula for calculating MUF on path with a given length D (km) [5]:

$$\mathrm{MUF}(D) = K(D)\cdot(0.9\cdot f0F2)\cdot\sqrt{1+\tan^2(\varphi)}, \qquad (1)$$

In (1), K (D) is the correction factor for sphericity of the Earth, $K(D) = 1 + a^2 + \frac{a}{4}$, where $a = \frac{D}{2\cdot R_E}$ [5], R_E – earth radius, f0F2 – critical frequency of F2 layer at the reflection point, φ - the angles at which radio waves enter in the equivalent specular reflecting layer. By taking into account the change in parameters f0F2 and M (coefficient for determining the MUF at a distance of 3000 km) along the path, the expression for calculating the MUF(D) can be corrected by specifying the angle φ. For that, we calculate inclination angle of equivalent specular reflecting layer ε by expression:

$$\tan(\varepsilon) = \frac{h_{02} - h_{01}}{D_0},$$

where D_0 = 200 km, h_{01} and h_{02} are heights at points, which move from the middle of the path in both sides at the same distance of 100 km. We can obtain the values of h_{01} and h_{02} by using prognostic model of the ionosphere [6]. From Fig. 1 we can calculate the angle shift of reflection point α_T from the middle point by expressions:

$$\alpha_T \approx \tan(\varepsilon) \cdot \frac{\left|1 + A_0^2 - 2 \cdot A_0 \cdot \cos(\alpha)\right|}{A_0 \cdot \cos(\alpha) - 1}$$

$$\tan(\varphi) \approx \frac{\sin(\alpha) \cdot \cos(\alpha_T)}{A_0 - \cos(\alpha) \cdot \cos(\alpha_T)} \qquad (2)$$

Where $A_0 = 1 + \frac{h_0}{R_E}$, h_0 - height of reflecting layer at the middle of the path. Substituting the value $\tan(\varphi)$ from (2) into (1), we can compute the MUF(D) taking into account regular iohomogeneities of the ionosphere.

III. Method of Calculating MUF2F2

To calculate the maximum usable frequency for two-hop HF propagation (MU2F2, the conventional method calculating MUF2F2 [5] is used, but that method does not consider random inhomogeneities of the ionosphere. In that paper we use method that indirectly takes into account the random inhomogeneities of the ionosphere [4]. Following that method, calculation starts with the same jump length $D_1 = D_2 = D/2$ and we calculate $MUF(D_1)$ and $MUF(D_2)$ by formula (1) presented in Section I. If $MUF(D_1) \geq MUF(D_2)$, then we reduce length of D_1 by 10 km (or another value), that means: $D_1 = D_1 - 10$ (km) and $D_2 = D - D_1$, and calculate MUF(D1), MUF(D2) and $|MUF(D_1) - MUF(D_2)|$.The calculation process is repeated until $|МПЧ(D_1) - МПЧ(D_2)| \leq 0.1$ (MHz). Then, the value of *MUF2F2* can be found by expression: $MUF2F2(D) = \frac{MUF(D_1) + MUF(D_2)}{2}$. If $MUF(D_1)$ is less than $MUF(D_2)$, then we increase D_1 by 10 km and calculate the length of D_2 by formula $D_2 = D - D_1$. Further calculation process is carried out similarly.

IV. Results of Calculation MUF1F2 and MUF2F2

To assess the accuracy of the proposed method, we present example of calculating the MUF on three paths: Khabarovsk – Irkutsk (path length of 2350 km), Norilsk – Irkutsk (1437 km) and Magadan – Irkutsk (2690 km) and compare calculation results with measured data of MUF1F2 and MUF2F2 on these paths presented in [7].

Input data for calculating the MUF are: geographical coordinates of the reception and transmission points: Khabarovsk (48.5^0 lat., 135.1^0 long.), Norilsk (69.2^0 lat., 88.26^0 long.), Magadan (60^0 lat., 151^0 long.), Irkutsk (52.5^0 lat., 104^0 long.); the date of calculations - March 17, 2015. According to data from [8], the Wolf number (W) - index of solar activity related to the number of sunspots on that day is 62. To assess the accuracy of calculating MUF, we calculate the root mean square error (RMSE). The value RMSE is calculated by formula:

$$RMSE = \sqrt{\sum_{i=1}^{n} (MUF_{Ei} - MUF)^2 / n} \qquad (3)$$

where MUF_{Ei}, MUF_i - measured and calculated values of the MUF at time *i* (*i* = 1,2..24), respectively.

Table I and II show RMSE of calculation of MUF1F2 and MUF2F2 taking into account inhomogeneities of the ionosphere. In order to estimate the influence of ionospheric iohomogeneities on MUF, we also compute RMSE of calculating MUF1F2 and MUF2F2 by conventional method [5] that no considering ionhomogeneities of the ionosphere.

TABLE I
RMSE of calculations MUF1F2

Paths	Proposed method	Conventional method
	RMSE (MHz)	RMSE (MHz)
Khabarovs – Irkutsk	4,48	4,5
Norilsk – Irkutsk	2,85	2,9
Magadan – Irkutsk	3,58	3,66

TABLE III
RMSE of calculations MUF2F2

Paths	Proposed method	Conventional method
	RMSE (MHz)	RMSE (MHz)
Khabarovs – Irkutsk	2,1	3,4
Norilsk – Irkutsk	1,17	2,26
Magadan – Irkutsk	2,73	4,59

Tables I and II have shown that by taking into account the inhomogeneities of the ionosphere makes it possible to increase the accuracy of calculations of MUF1F2 and MUF2F2.

Especially, for mode 2F2 – by considering influences of regular and random inhomogeneous of the ionosphere the calculation error can be reduced to 48 %.

V. Calculation of Field Strength of Radio waves Taking into Account Regular and Random Inhomogeneities of the Ionosphere

The field strength E (mV/m) of radio waves reflecting n-time from the ionosphere can be calculated by formula [4]:

$$E = \frac{173 \cdot \sqrt{P \cdot G} \cdot F(\theta) \cdot e^{-K} \cdot 10^{(L_0 - L_S)/20} \cdot 0.8^{n-1}}{D} \quad (4)$$

Where P is the radio transmitter power in kW, G is a gain of transmitting antenna, $F(\theta)$ is an antenna pattern in vertical plane, K is absorption coefficient of radio waves in the ionosphere, *n* is the reflecting number of radio waves from the ionosphere, L_0 and L_S are relative propagation losses without taking into account radio wave scattering in the ionosphere and taking into account radio wave scattering in the ionosphere, respectively.

The value of L can be calculated by formula [4] :

$$L = 10 \cdot \lg\left(\left(R_E \cdot \Delta \cdot \sin\left(\frac{D}{R_E}\right) \cdot \sin(\beta)\right) / (n \cdot \delta \cdot \cos(\theta))\right) \quad (5)$$

where δ is a step of elevation angle, Δ is integration area in the vicinity of the radio path with length D, n - number of rays that fall in the vicinity of distance D, θ and β - mean values of elevation and reception angles, respectively. To calculate the relative propagation losses L, we need to compute propagation characteristics of radio waves such as: elevation and arrival angles, propagation distance. To do that, we use equivalence theorems [5] to calculate these characteristics of radio wave propagation (Fig. 2).

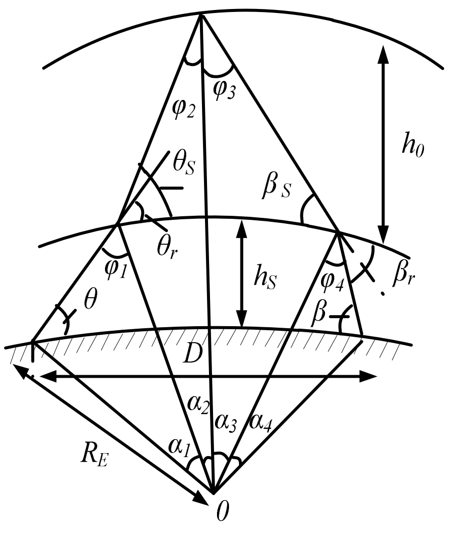

Fig.2. Trajectory of HF radio waves in the horizontally inhomogeneous scattering ionosphere

To determine the reflection points of radio waves we assume h_0 - heights of reflection points of rays from layer F2 for paths of length D. Value of h_0 can be determined by solving system of equations:

$$h_0 = h_{01} + R_E \cdot (\alpha_1 + \alpha_2) \cdot \tan(\varepsilon) \quad (6)$$

$$\tan(\varepsilon) = (h_{02} - h_{01}) / D \quad (7)$$

$$\alpha_2 = \pi/2 - \varphi_2 - \theta_r \quad (8)$$

$$\sin(\varphi_2) = (R_E + hs) \cdot \cos(\theta_r) / (R + h_0) \quad (9)$$

Where ε is angle of inclination of reflecting layer; h_{01} and h_{02} are heights of the reflecting layer at points of transmitter and receiver, respectively.

To calculate h_{01} and h_{02} we use formula Shimazaki [9]:

$$h = 1490 / M(3000) - 176 \quad (10)$$

Where $M(3000)$ - the propagation coefficient for path of 3000 km length [5]. Values of M(3000) and critical frequency f0F2 are predicted when specifying geographic coordinates, day time and levels of solar activity by using diagnostic model of the ionosphere [6].

Angles α_2, φ_2 can be found by iterative process using formulas (6-9), where for the begining approximation we take $h_0 = h_{01}$. We calculate φ_2 from (9), α_2 from (8) and specify the value h_0 from (6). The obtained value h_0 is used to clarify the value φ_2 from (9), then α_2 from (8). The calculation process stops when difference between the previous and the current value of α_2 is less than 0.001^0.

To take into account the scattering of radio waves in the ionosphere, we use method presented in our previous work [10]. Following that method, the entry angles of radio waves into the ionosphere θ_r and the exit angles from the ionosphere β_r experience random perturbation, and therefore these angles become: $\theta_r = \theta_S + \gamma_1$, $\beta_r = \beta_S + \gamma_2$, where the random values γ_1 and γ_2 have the same characteristics (Gaussian distribution) and have an average deviation of 0. the standard deviations are equal to scattering parameters *S* of the ionosphere.

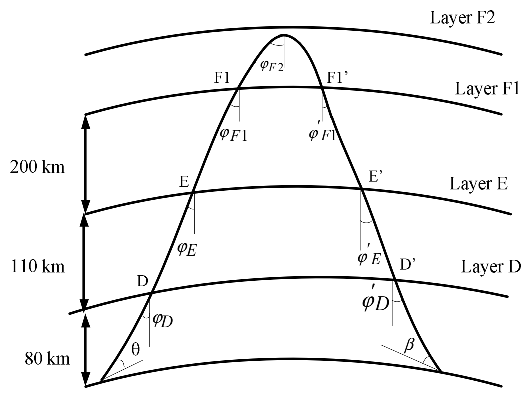

Fig. 3. Ionospheric model used to calculate absorption coefficient of HF radio waves, reflecting from the ionosphere

For calculating absorption coefficient *K* of radio waves in layers D, E, F1, F2 we use ionospheric model [11] (Fig. 3). According to that model, heights of layers D, E, F1 are 90,110 and 200 km, respectively.

Then, we compute absorption coefficient by formula [4]:

$$K = \frac{1.5 \cdot f_0E_D{}^2}{(f+f_g)\cdot \cos\varphi_D} + \frac{1.25 \cdot f_0E_E{}^2}{(f+f_g)\cdot \cos\varphi_E} + \frac{0.2 \cdot f_0E_{F1}{}^2}{(f+f_g)\cdot \cos\varphi_{F1}}$$
$$+ \frac{1.5 \cdot f_0E'_D{}^2}{(f+f_g)\cdot \cos\varphi'_D} + \frac{1.25 \cdot f_0E'_E{}^2}{(f+f_g)\cdot \cos\varphi'_E} + \frac{0.2 \cdot f_0E'_{F1}{}^2}{(f+f_g)\cdot \cos\varphi'_{F1}}$$
$$+0.02\cdot f2 \cdot \cos^3(\varphi_{F2}) \qquad (11)$$

where (f_0E_D, f_0E_E , f_0E_{F1}) and ($f_0E'_D$, $f_0E'_E$, $f_0E'_{F1}$) – critical frequencies of E layer at points (D, E, F1) and (D', E', $F1'$) (Fig. 3), respectively; f_g - gyro frequency of 1.4 MHz.

From the presented method, we developed a program for calculating field strength of HF radio waves.The input data for calculation are: geographic coordinates of transmission and reception points, the Wolf number, operating frequency, date and time, scattering parameter *S*.

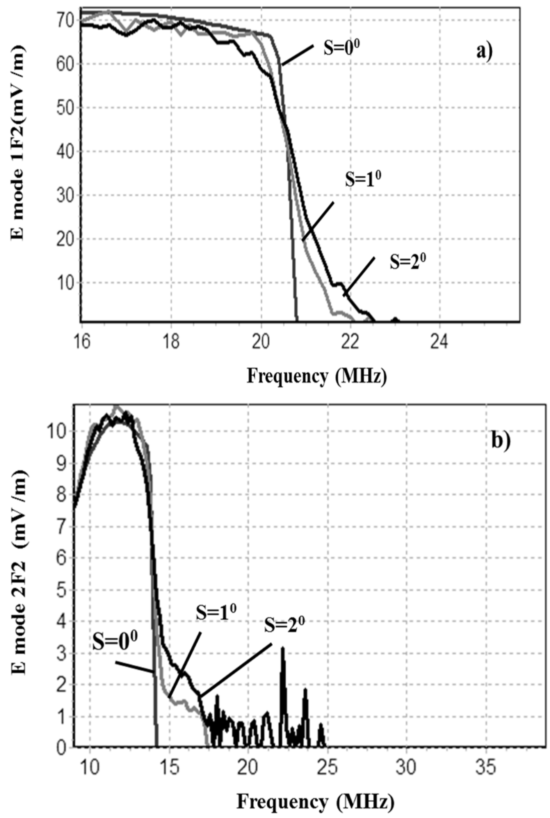

Fig. 4. Frequency dependence of field strengths of mode 1F2 (a) and 2F2 (b) under different values of scattering parameter *S*

Fig. 4 shows simulation results of frequency dependence of field strength with various scattering parameters (S = 1^0, 2^0, and 3^0) for a path length of 2300 km, the Wolf number = 167, transmitter power - 1000 W, directional factor- 30, the scattering height of the reflecting layer is 100 km.

From fig. 4 we can see that in case of absence of radio wave scattering in the ionosphere, field strength decreases sharply at the operating frequency upper 20.8 MHz for mode 1F2 and 14.2 MHz for mode 2F2. By taking into account scattering of radio waves in the ionosphere with the scattering parameter $S = 1^0$, we can receive radio waves with an operating frequency higher than in prvious case (up to 22 MHz for mode 1F2 and to 17.5 MHz for mode 2F2). When scattering parameter increases (S= 2^0), frequency at which radio waves can be received also increases to 22 MHz for mode 1F2 and to 17.5 for mode 2F2.

VI. Conclusion

The article presents method for calculating the MUF and field strength of propagation modes 1F2 and 2F2 of HF radio waves taking into account inhomogeneities of the ionosphere. It has shown that the proposed method reduce calculation error of MUF, especially for mode 2F2. The calculation results of field strength of HF radio waves indicated that scattering of radio waves in the ionosphere increases the maximum usable frequencies of HF radio links.

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