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Radio Propagation Model by Reflections Off Varied Surfaces

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Abstract: ***On high frequency, radio waves can travel along atmosphere by reflecting off different earth surfaces and ionosphere. How long can the waves travel and how many times can the waves reflect off varied earth surfaces and ionosphere are the most concerned questions. Our paper aims at establishing a reliable model estimating radio waves travelling and reflecting. ignoring energy loss on ionosphere, we developed a model dealing with the situation that a point land source transmits radio waves and turbulent sea surface reflection occurs only once right after the first reflection off ionosphere. The result proves that turbulent ocean surface weakens the signal much more than calm ocean surface, leading to less reflections.[1]***

Keywords: radio propagation, reflect on surfaces

1. Introduction

Radio waves are a type of electromagnetic radiation which are widely used for fixed and mobile radio communication, broadcasting, radar, and other navigation systems. For radio waves at high frequencies (HF, defined to be 3-30MHZ), radio waves can reflect off conductive layers of charged particles (ions) in a part of the atmosphere called the ionosphere[2], and then return to the earth with another reflection off the earth, which is called Multi-hop propagation. By multiple successive hops, communication at long distance can be achieved. Among all the factors, the characteristics of the reflecting surface determine the strength of the reflected wave and how far the signal will ultimately travel while maintaining useful signal integrity. In this paper, a geometric wave transmission model considering emission angle, multiple reflection, etc is decided, the model is modified by excluding Fresnel equations and adding diffuse reflection theory.

2. The Model

In this section, we find the maximum number of hops in different scenarios such as varying launch angle.

2.1 Determination or calculation of noise

Atmospheric noise is the main part of radio noise on the calm sea so that it can be described by the following equation.

$$P_{\text{noise}} / \Delta S = 1.256 \times 10^{-7} W / m^2$$

In this equation, quantitative value $1.256\times10^{-7} W/\mathrm{m}^2$ is an experimental value given by reference[7]. As a result, we're going to use this value right here.

2.2 Signal propagation process and determination of the area of signal zone

We consider the antenna to be directive, and transmits signals in a certain solid angle range. As the transmission goes on, the area that the signal covers grows larger, regardless of the reflection effects. Extracting the plane through the center of earth and the symmetric axis of the solid angle, we drew a figure to show the first two reflections on ionosphere and sea surface (Figure 1).

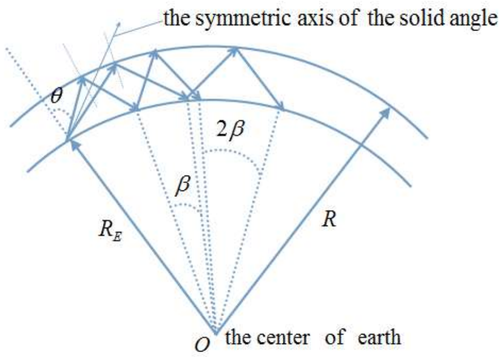

Figure 1: Signal propagation process

The following reflections obey the law of specular reflection. As for reflection on the turbulent sea surface, we only take the direction, which is the same with specular one, into consideration, because of the need of comparison. The diameters of the signal areas on sea surface grow, for the central angle adds β every time. The area of signal zones could be described by the following formula.

$$S(n) = \frac{\pi}{4}\left[(n+1)\ \beta R_E\right]^2$$

$$\beta = 2arc\sin\left[\frac{\sin(\theta+\mathrm{d}\theta)}{R}\cdot l_0\right] - 2arc\sin\left[\frac{\sin(\theta)}{R}\cdot l_0\right]$$

$$l_0(\theta) = -R_E\cos(\theta) + \sqrt{R_E{}^2\cos(\theta)^2 + R^2 - R_E{}^2}$$

Where $l_0(\theta)$ is the distance between the ocean and ionosphere, $\mathrm{d}\theta$ is the plane angle of the solid angle.

2.3 Loss of radio waves while traveling

In the process of propagation, the strength of radio waves will be attenuated mainly in three sections, which are the surface of the ionosphere, the surface of the ocean and the atmosphere. The propagation of radio waves in the atmosphere is shown in the Figure 2.

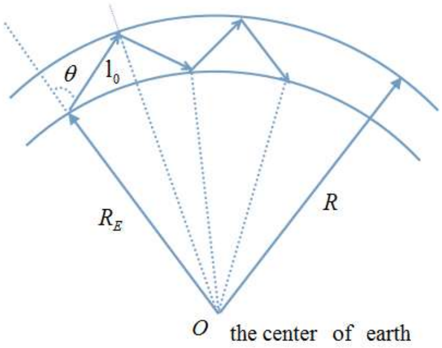

Figure 2: The propagation of radio waves

2.3.1 Loss in the atmosphere

The propagation of radio waves obey low of absorption and low of scattering. The strength of radio waves propagating in the atmosphere reduces to:

$$P = P_0 \cdot \mathrm{e}^{-(\alpha_a + \alpha_s) l_0}$$

Where α_a is the coefficients of absorption and α_s is the coefficients of scattering, and P illustrates the power after reflections, P0 is the initial power, while l0 is the distance the radio wave travels.

2.3.2 Loss at the surface of the ionosphere

At high frequencies, radio waves can reflect off ionosphere. In the actual situation, the loss of the ionospheric reflection is extremely small so that we can ignore it.

2.3.3 Loss at the surface of calm ocean

For mirror reflection, Fresnel formula can help to calculate the strength of the reflected waves. As the polarization directions of radio waves are random, it can be considered that the strength of radio waves are equal in each direction of polarization. According to the decomposition of the vector, the vibration of each wave is decomposed into S-component and P-component, each of which is orthogonal to the other. After n reflections on the sea surface, the amplitude of S-component and P-component can be described as

$$A_s = A\cos(\gamma)\cdot {r_s}^n$$

$$A_p = A\sin(\gamma)\cdot {r_p}^n$$

Where A is the amplitude of the incident wave, and γ is azimuth of the polarization plane. r_s is the reflecting ratio of amplitude of S-component, r_p is that of P-component.

In order to figure out the sum of the energies of the waves in each polarization direction, we need to use definite integrals. The final power can be expressed as

$$P_f = \int_0^{\pi} ({A_s}^2 + {A_p}^2) d\gamma = \frac{P_0}{2}\cdot\left({r_s}^{2n} + {r_p}^{2n}\right)$$

The power spectral density of the signal:

$$\frac{P_f}{S} = \frac{2P_0\cdot({r_s}^{2n} + {r_p}^{2n})}{\pi[(n+1)\beta R_E]^2}$$

Where r_s and r_p are calculated using several refractive index [5, 6] and angle by part of Fresnel equations. P_f is the final power. S is the area of sea surface that is covered by valid radio wave . βis shown in figure 2, and R_E is the radius of the earth.

2.3.4 Loss at the surface of turbulent ocean

A turbulent ocean is one in which wave heights, shapes, and frequencies change rapidly, and the direction of wave travel may also change. When the accident waves reach the surface of the turbulent ocean, a large proportion of the reflected wave deviates from the original path because of the shape change of the sea surface. [3]

Because of the characteristics of randomness, the actual waves can be regarded as a result of sine wave superposition with different frequencies, different propagation directions, different wave heights and different initial phases. Based on this theory, the paper uses linear filtering to simulate the turbulent waves[7]. And its expression is：

$$\eta(x,t) = \sum_{i=1}^{M} \eta_i(x,t) = \sum_{i=1}^{M} a_i \cos(k_i x - w_i t + \theta_i)$$

Where η_i is the i^{th} component wave function of the entire sea wave. M is the number of component wave functions. α_i is amplitude. k_i is wave number. ω_i is angular velocity, andθ_i is initial phase.

Based on this model, a MATLAB program is designed to simulate the turbulent waves as follows:

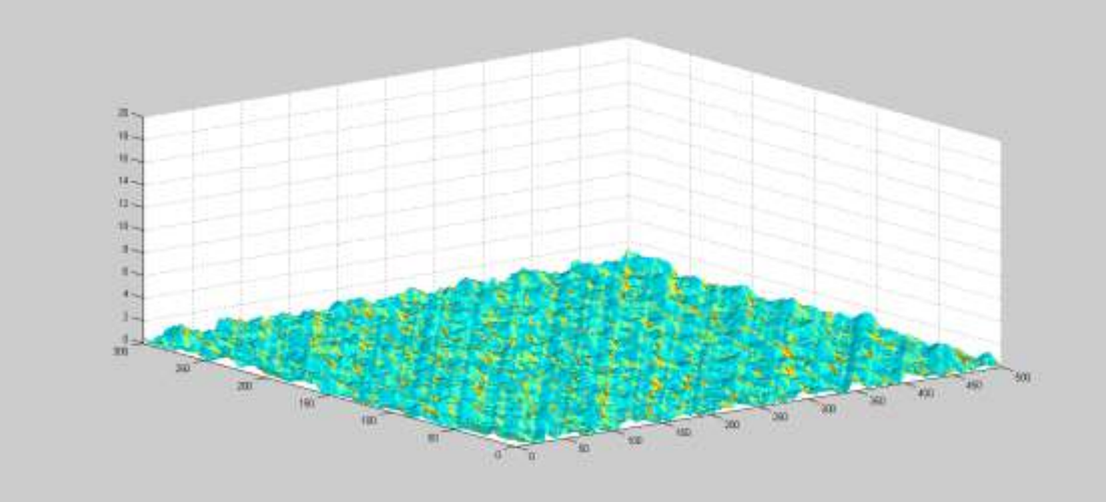

Figure 3: Simulated ocean wave

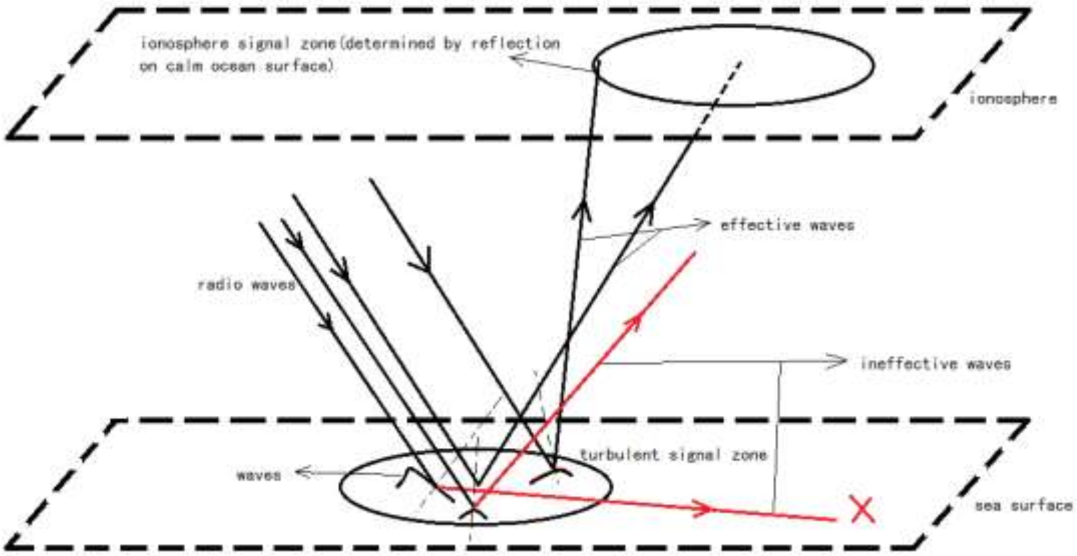

Figure 4: The propagation of radio waves on the turbulent ocean surface

Fig.4 shows the propagation of radio waves between the surface of turbulent ocean and the ionosphere. The turbulent signal zone and the ionosphere signal zone can be determined by mirror reflection. The black lines represent the radio waves which are successfully propagated and the corresponding positions on the surface are valid positions. The red line represents the radio waves lost. Therefore, the strength of the reflected radio waves depends on the ratio of the area of valid positions to the entire reflector.

Take the figure drawn by computer as the surface of reflection. Select the points on the surface of reflection equidistantly, and calculate the normal vectors at each point by computer. Then the direction vectors of the reflected wave can be determined by normal vectors, that is Similar to the points in ionospheric plane. If a crossover point is in the ionosphere zone, the corresponding radio wave is valid. Oppositely, if not, the radio wave is invalid. The ratio of the valid points to all points can approximately substitute the ratio of the valid area to the whole area. Therefore, the strength of the reflected signal can be calculated according to those data. In the simulation, 90000 equidistance points are selected for the above calculation and the results are as follows.

Table 1: The power of the reflected signal (the angle of incident signal is $\pi/6$)

The levels of waves	0 (calm ocean)	3	7
1	2.2(w)	0.6678(w)	0.7110(w)
2	2.2(w)	0.9733(w)	0.4480(w)
3	2.2(w)	0.8905(w)	0.3098(w)
4	2.2(w)	0.7504(w)	0.4840(w)
5	2.2(w)	0.6212(w)	0.6123(w)
6	2.2(w)	1.1502(w)	0.3940(w)

2.4 Results

Integrate all the loss factors, and the final power density can be described as

$$\frac{P_{\text{f-calm}}}{S}(\mathrm{n})=\frac{2P_0\cdot(r_s{}^{2n}+r_p{}^{2n})}{\pi\left[(n+1)\beta R_E\right]^2}\cdot \mathrm{e}^{-2(n+1)(\alpha_a+\alpha_s)l_0}$$

$$\frac{P_{\text{f-turbulent}}}{S}(\mathrm{n})=\frac{2P_{\text{turbulent}}\cdot(r_s{}^{2n\text{-}2}+r_p{}^{2n\text{-}2})}{\pi\left[(n+1)\beta R_E\right]^2}\cdot \mathrm{e}^{-2n(\alpha_a+\alpha_s)l_0}$$

$P_{\text{f-calm}}$ is the final wave power on calm surface, while $P_{\text{f-turbulent}}$ is that on turbulent surface.

In order to calculate the maximum number of hops the signal can take before its strength falls below a usable signal-tonoise ratio (SNR) threshold of 10 dB. We give the following formula:

$$\frac{P_{\mathrm{f}-calm}}{S}(n+1)\le\frac{10P_{noise}}{\Delta S}\le\frac{P_{\mathrm{f}-calm}}{S}(n)$$

$$\frac{P_{\mathrm{f-turbulent}}}{S}(n+1)\le\frac{10P_{noise}}{\Delta S}\le\frac{P_{\mathrm{f-turbulent}}}{S}(n)$$

The magnitude of n changes with varying θ , the relationship between n and θ is shown in Figure 5.and table 2.

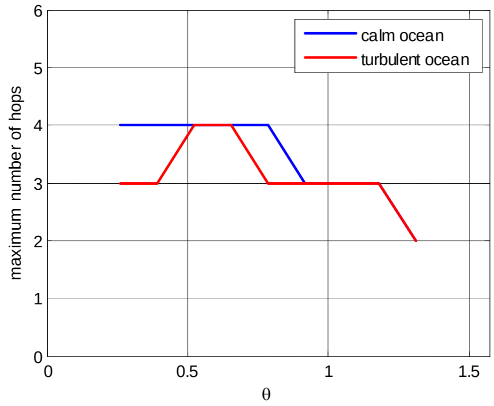

Figure 5: n - θ diagram of calm ocean and turbulent ocean

Table 2: The simulation data of θ and n

θ	n − calm ocean	n − *turbulent ocean*
π/12	4	3
π/8	4	3
π/6	4	4
5π/24	4	4
π/4	4	3
7π/24	3	3
π/3	3	3
3π/8	3	3
5π/12	2	2

3. Conclusion

In this paper, we developed a model dealing with the situation that a point land source transmits radio waves and turbulent sea surface reflection occurs only once right after the first reflection off ionosphere. The result proves that turbulent ocean surface weakens the signal much more than calm ocean surface, leading to less reflections.

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