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Sea Surface Reflection and Power Attenuation Analysis of Radio Wave in UHF Satellite Communications

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Abstract

Ultra High Frequency (UHF) band is increasingly widely used in military maritime satellite communications due to its good communication performance. Electromagnetic wave emitted by satellite is reflected when reaching the sea surface, and multipath fading is very serious which causes interference on the received signal, especially when satellite elevation angle is low. In this paper, the UHF band multipath effects of sea surface were studied following the general principles of modeling in multipath effects. The numerical simulation was made based on Rayleigh criterion and the judgment basis was obtained which determines whether the specula reflected component or diffuse reflected component dominates in the reflected wave, and then the reflection coefficient of sea surface in different polarization modes were calculated. Finally, the power attenuation of reflected wave relative to direct wave for different wind speeds were simulated and analyzed. Numerical simulation results show that the greater the wind speed is, the greater the power attenuation of reflected wave will become and the more serious multipath fading will be. In addition, diffuse reflection attenuation is more serious than specular reflection.

Keywords: *sea surface multipath effects, sea surface reflection, power attenuation, UHF, maritime satellite communications*

1. Introduction

SATCOM has been very widely used in the civilian and military fields due to its advantages, such as a wide covered range, radio features, flexible networking, communication without geographical restrictions, communication costs independent of distance, etc. In satellite communication, the lower band of UHF (frequency range of 300MHz to 3000MHz) is usually used and VHF band (frequency range of 30MHz to 300MHz) is occasionally used. UHF has many unique advantages in military applications [1], such as the strong penetration signal and practical terminal, can achieve global reach and broadcasting network, user access is guaranteed and so on.

The multipath propagation component due to sea surface reflection is difficult to suppress when the electromagnetic wave emitted by satellite reaches the sea surface, especially in the region with lower satellite elevation angle which means 0°-20° here and the sea surface multipath fading is very obvious. Understanding the characteristics of multipath fading channel of sea surface and modeling of it are very necessary during the design of communication systems. As early as the 1950s, much attention has been given to multipath problem, and a large number of studies were made in the characteristics of sea surface electromagnetic dispersion, and multipath reflection models are established. Literature [2] made a research on the characteristics of L-band multipath fading due to sea surface reflection. Literature [3] studied the sea surface multipath model of meter band. In literature [4], sea surface multipath characteristics of C-band were measured and the test results were analyzed. Literature [5] simulated the process of multipath effect in the environment of calm and dynamic lake surface.

Currently, few researches have been made on UHF band electromagnetic reflection of sea surface and it is difficult to find complete and accurate test data as a result of the costly spend on actual measurement on the sea. Therefore, in this paper, the UHF band multipath

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effects of sea surface are analyzed, and sea surface reflection coefficient and power attenuation of reflected wave are calculated.

2. Multipath Fading and Sea Wea Height

In maritime satellite communications, partial electromagnetic signal transmitted from the satellite gets to the receiving antenna directly which is called the direct wave. The other partial reaches the receiving antenna by reflection from sea surface which is called the reflected wave. Then both enter the receiver in the way of vector superposition. Because the path distances of each electromagnetic wave are different, their arriving time and phase are different. A plurality of signals superimpose at the receiver which superpose in-phase at times and in reverse on occasion. As a result, the amplitudes of received signal change dramatically, which produce a decline. Signal attenuation caused by multipath is called multipath fading. The multipath effects model of sea surface is shown in Figure 1.

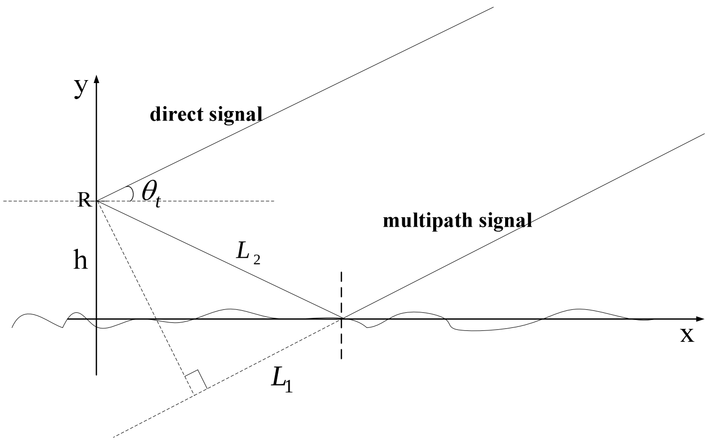


Figure 1. Sea Surface Multipath Effects Model

In Figure 1, h is the vertical distance from phase center of the antenna to the reflective surface, θ_t is satellite elevation angle. In this model, there are two paths from satellite to receiving antenna which are the direct wave and reflected wave. The satellite is very far away from the reflective surface compared with the antenna, so it is considered that signals reaching the antenna and the sea surface from same satellite are parallel [5].

Ocean wave is the reciprocating motion phenomenon of sea water under sea breeze. Different wind speeds corresponds to different wave heights. For non-calm sea surface, the irregular significant wave height is usually indicated as $H_{1/3}$, which is also known as the one third great wave. It is got by arranging the wave heights according to their sizes and then calculating the average height of 1/3 waves in front of the queue. Studies have shown that significant wave height can reflect the relationships of ocean wave growing. Taking the fully growing ocean wave as the background, Formula (1) is used to describe the relationship between wind speed and significant wave height [6].

$$H_{1/3} = 0.0214U^2 \quad (1)$$

Where, $H_{1/3}$ is the significant wave height, U is wind speed on the sea. Mean square wave height ρ_h refers to the mean square root value of wave height on ocean surface, and its relationship with significant wave height is as follows:

$$H_{1/3} = 4\rho_h \quad (2)$$

Table 1 lists the values of significant wave height and mean square wave height under different wind speeds.

Table 1. Significant Wave Height and Mean Square Wave Height

Wind speed U(m/s)	Significant wave height $H_{1/3}$ (m)	Mean square wave height ρ_h (m)
1	0.0214	0.00535
3	0.1926	0.04815
5	0.5350	0.13375
7	1.0486	0.26215
9	1.7334	0.43335
11	2.5894	0.64735
13	3.6166	0.90415
15	4.815	1.20375

3. Sea Surface Reflection

3.1. Rayleigh Criterion

Surface can be divided into smooth surface and rough surface according to the roughness degree of reflective surface. On a smooth flat surface, the surface specular reflection is dominant. On a rough surface, it produces diffuse reflection either. When the undulating wave height difference satisfies Rayleigh criterion described as in Formula (3), it is generally considered the sea surface is smooth and produces specular reflection only [3].

$$\rho_h < \frac{1}{8}\frac{\lambda}{\sin\theta_t} \quad (3)$$

Where, ρ_h is the mean square wave height, λ is the wavelength of the incident wave, θ_t is the satellite elevation angle. Literature [7] gives the elevation angle calculation formula of satellite receiving antenna.

$$E = \arctan\left[\frac{\cos(G)\cos(L) - R_{DP}/R_{WG}}{\sqrt{1-\cos^2(G)\cos^2(L)}}\right] \quad (4)$$

Where, E is elevation angle, L is the latitude of the receiving point at sea, G is the longitude difference between receiving point and satellite, R_{DP} is the radius of the earth receiving point, R_{WG} is synchronous orbit radius of satellite.

As is shown in Figure 2, abscissa is satellite elevation angle, y-axis is mean square wave height and two curves are Rayleigh curves when frequencies are 240MHz and 320MHz, respectively. It is can be seen that when frequency is 240MHz and wind speed is less than 7m/s, the sea surface is regarded smooth. When frequency is 320MHz and satellite elevation angle $\theta_t > 14^\circ$, the sea surface can not be regarded smooth and specular reflection model can not be used as the sea surface multipath model. So, conclusion can be got that whether the sea surface is smooth or not is related with the wind speed on sea, electromagnetic wave frequency and satellite elevation angle.

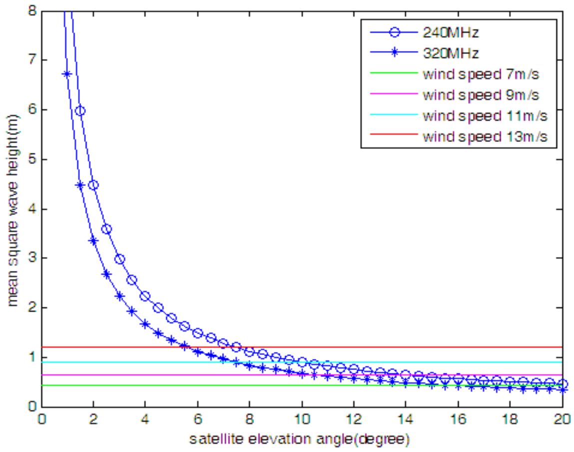


Figure 2. Rayleigh Curves and Satellite Elevation Angle

3.2. Specular Reflection Coefficient

For the ideal reflecting surface that is completely smooth, the surface reflection coefficient ρ is equal with Fresnel reflection coefficients ρ_0, namely $\rho = \rho_0$. Fresnel reflection coefficient is ascertained by electromagnetic wave frequency, polarization mode, satellite elevation angle and surface type [8]. The vertical polarization is given by:

$$\rho_0 = \frac{\varepsilon \sin \theta_t - \sqrt{\varepsilon - \cos^2 \theta_t}}{\varepsilon \sin \theta_t + \sqrt{\varepsilon - \cos^2 \theta_t}} \quad (5)$$

Horizontal polarization is given by:

$$\rho_0 = \frac{\sin \theta_t - \sqrt{\varepsilon - \cos^2 \theta_t}}{\sin \theta_t + \sqrt{\varepsilon - \cos^2 \theta_t}} \quad (6)$$

Where, ε is the water complex permittivity. The complex permittivity values are related to the type of surface. In terms of the electromagnetic wave frequencies we studied, the specific calculation expressions of water complex permittivity are as follows [9]:

$$\varepsilon = \varepsilon' - i\varepsilon'' \quad (7)$$

Where,

$$\varepsilon' = \varepsilon_{ir} + \frac{\varepsilon_s - \varepsilon_{ir}}{1 + (2\pi f \tau)^2}$$

$$\varepsilon'' = \frac{2\pi f \tau (\varepsilon_s - \varepsilon_{ir})}{1 + (2\pi f \tau)^2} + \frac{\sigma_s}{2\pi \varepsilon_0 f}$$

Where, f is frequency of electromagnetic wave and unit is Hz, ε_0 is the permittivity of free space and $\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{F/m}$, ε_{ir} is the sea water dielectric permittivity and $\varepsilon_{ir} = 4.9$. τ is the relaxation time of sea water, σ_s and ε_s are the ionic conductivity and the static permittivity of sea water, respectively. ε_s, τ and σ_s can be calculated by the following Fomulars:

$$\varepsilon_s = \varepsilon(T)\cdot a$$

$$\varepsilon(T) = 87.134 - 1.949\times10^{-1}T - 1.276\times10^{-2}T^2 + 2.491\times10^{-4}T^3$$

$$a = 1.0 + 1.613\times10^{-5}TS - 3.656\times10^{-3}S + 3.21\times10^{-5}S^2 - 4.232\times10^{-7}S^3$$

$$\tau = \tau(T)\cdot b$$

$$\tau(T) = \frac{1}{2\pi}\left(1.111\times10^{-10} - 3.824\times10^{-12}T + 6.938\times10^{-14}T^2 - 5.096\times10^{-16}T^3\right)$$

$$b = 1.0 + 2.828\times10^{-5}TS - 7.638\times10^{-4}S - 7.760\times10^{-6}S^2 + 1.105\times10^{-8}S^3$$

$$\sigma_s = \sigma(25,S)e^{-\Delta\phi}$$

$$\sigma(25,S) = S\left(0.18252 - 1.4619\times10^{-3}S + 2.093\times10^{-5}S^2 - 1.282\times10^{-7}S^3\right)$$

$$\Delta = 25 - T$$

$$\begin{aligned}\phi = {} & 2.033\times10^{-2} + 1.266\times10^{-4}\Delta + 2.464\times10^{-6}\Delta^2 \\ & - S\left(1.849\times10^{-5} - 2.551\times10^{-7}\Delta + 2.551\times10^{-8}\Delta^2\right)\end{aligned}$$

In Formulas above, water temperature T is taken as 28℃and the global average value of salinity S is 3.254%.

Fresnel formula is used to calculate the reflection coefficient of completely smooth interface. However, in actual situation, the sea surface can not be absolutely smooth with some fluctuation. If the reflective surface is with certain roughness, but is relatively flat, in other words, it satisfies the Rayleigh Criterion, then the specula reflection coefficient can be expressed as:

$$\rho = \rho_0\rho_s \tag{8}$$

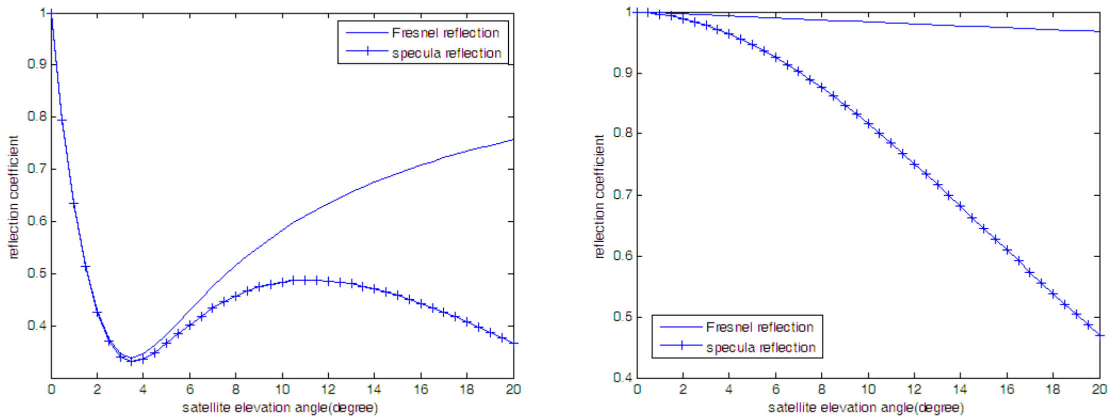
Where, ρ_s is the specular scattering factor, which denotes that the roughness of reflective surface makes the amplitude of specular reflection attenuate and its values are as follows [10]:

$$\rho_s{}^2 = \begin{cases} \exp\left[-2(2\pi\Gamma)^2\right] & 0 < \Gamma < 0.1 \\ \dfrac{0.812537}{1 + 2(2\pi\Gamma)^2} & \Gamma > 0.1 \end{cases} \tag{9}$$

Γ is the roughness factor of rough surface which is described as follows:

$$\Gamma = \sigma_h \sin\theta_t / \lambda \tag{10}$$

Assumed that the incident wave frequency is 320MHz and wind speed is 7m/s, in vertical and horizontal polarization modes, the Fresnel reflection coefficients and specula reflection coefficients with the introduction of specular scattering factor of the sea are compared in Figure 3.



(a) Vertical polarization (b) Horizontal polarization

Figure 3. Fresnel and Specular Reflection Coefficient in Different Polarization Modes

As can be seen from Figure 3, the amplitude of Fresnel reflection coefficient in vertical polarization mode is smaller compared with in horizontal polarization mode. The latter is almost as large as 1. Compared with Fresnel reflection coefficient of ideal interface, the amplitude of specular reflection coefficient is somewhat attenuated with introduction of specular scatter factor. Specular scatter factor has a greater impact on horizontal polarization mode than on vertical polarization mode.

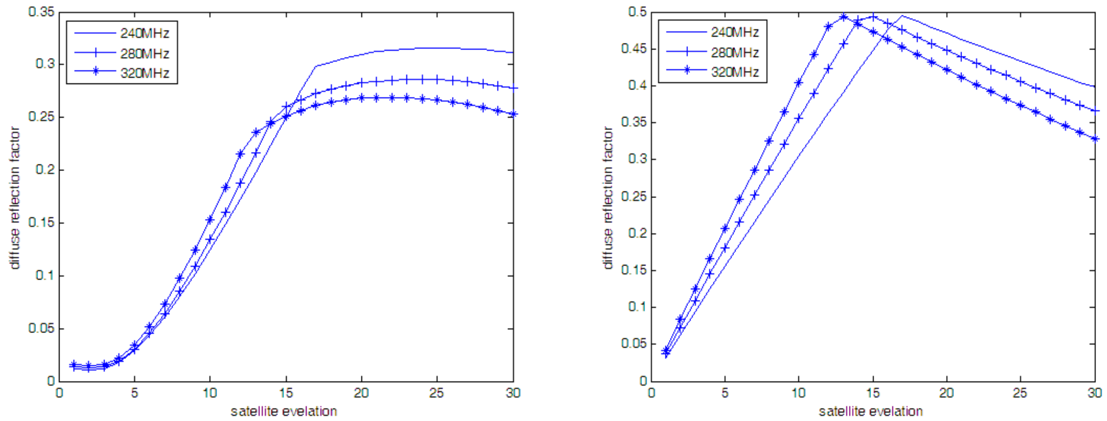
3.3. Diffuse Reflection Factor

When the sea surface is so rough that Rayleigh criterion can not be met, specular reflection reduces and diffuse reflection increases with the increase of roughness. The power reflected to antenna from sea surface is mainly contributed by diffuse reflection. It occurs on area much larger than the first Fresnel zone whose phase is not related and amplitude fluctuation is large. Geometrical optics theory dose not satisfy diffuse reflection which means that the incidence angle is not equal to reflection angle and unable to establish geometrical relationship with the direct wave. The diffuse reflection coefficient of rough surface is defined by the following Formula (11):

$$\beta = \rho_0 \rho_d \tag{11}$$

Where, ρ_d is diffuse reflection factor which is a complex function of satellite elevation angle θ_t, mean square wave height ρ_h, wavelength electromagnetic wave λ. The approximations of diffuse reflection factor are got through theoretical research [11]:

$$\rho_d = \begin{cases} \sqrt{2}\left|\rho_0\right| 3.68\,\Gamma, & 0 < \Gamma < 0.1 \\ \sqrt{2}\left|\rho_0\right| (0.454 - 0.858\,\Gamma), & 0.1 < \Gamma < 0.5 \\ \sqrt{2}\left|\rho_0\right| 0.025, & \Gamma \geq 0.5 \end{cases} \tag{12}$$



(a) Vertical polarization (b) Horizontal polarization

Figure 4. Diffuse Reflection Factor in Different Polarization Modes

Figure 4 shows the relation curve of diffuse reflection factor and satellite elevation angle of different electromagnetic wave frequencies in sea state 4. It can be seen from the simulation, with the satellite elevation angle increases, the diffuse reflection coefficient amplitudes increase within a certain elevation and begins to decrease after reaching a limit value. Besides, it is not always true that the higher the frequency is, the larger the diffuse reflection factor becomes.

4. Analyses on Received Power

In maritime satellite communications business, the received signal is generally the synthesis of three components, namely direct wave, specula reflected wave and diffuse reflected wave. If the reflective wave comes from the first Fresnel zone meeting Rayleigh criterion, which denotes that sea surface is relatively smooth, the specular reflection is dominant. At this point, the diffuse component is so little effective that can be regarded as noise to deal with. When the sea became very rough, the diffuse reflection is dominant and the specular reflection can be ignored.

4.1. Direct Wave Power

Considering the pure air channel, power attenuation of electromagnetic waves corresponds to the propagation loss in free space L_p. Free-space loss is the basic propagation loss mode, and signal power received by antenna is only a small part of the transmitting antenna radiation power as most energy is spread out to the other directions. The farther the work distance and the larger the ball area are, the less power receiver will intercepte, namely the larger propagation loss will be. L_p can be represented by Formula (13). Where, R is communication distance.

$$L_p = \left(\frac{4\pi R}{\lambda} \right)^2 \qquad (13)$$

Free-space propagation is the most basic and simple means of radio wave communication. The electromagnetic wave propagates in the free space after emitting from the omnidirectional antenna whose energy will spread to a sphere face. Assuming that the transmitter gain is G_t , receiver gain is G_r .The relationship between the received power and the transmission power can be expressed as:

$$P_r = P_t \cdot G_t \cdot G_r \cdot L_p \qquad (14)$$

4.2. Reflection Wave Power

The reception power of reflected wave can be got according to the sea surface reflection coefficient. It is acknowledged that the occupied proportion of reflected power is equal to the square of reflection coefficient. The received power of reflected wave from sea surface relative to the direct wave can be calculated as:

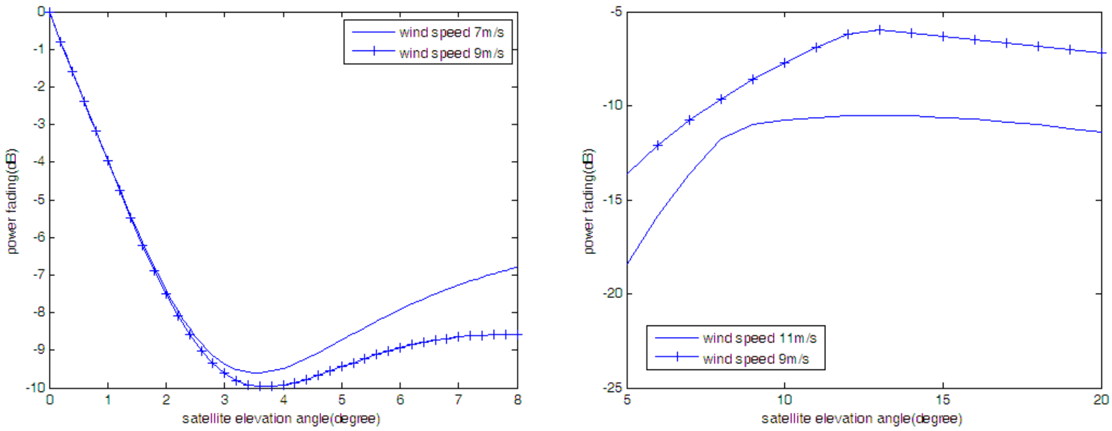
$$P = D_r + 10\lg r^2 \text{ (dB)} \tag{15}$$

Where, r is the reflection coefficient of sea surface and $r = \rho$ when the specular reflection is dominant, otherwise $r = \beta$, D_r is the relative antenna gain in the direction of the specular reflection point on the sea. The relative antenna gain is approximately given by [12]:

$$D_r = -4 \times 10^{-4}\left(10^{G_r/10} - 1\right)\left(1.5\theta_t\right)^2 \tag{16}$$

4.3. Simulation Analysis

The simulation parameters are set as: receiver gain $G_r = 11$ dB, polarization mode is vertical, electromagnetic wave frequency $f = 320$ MHz. The received power of specular reflection wave and diffuse reflection wave relative to the direct wave in different wind speeds are shown in Figure 5.



(a) Specular reflection wave (b) Diffuse reflection wave

Figure 5. Power Fading of Specular and Diffuse Reflection Wave Relative to Direct Wave in Different Wind Speeds

As can be seen from Figure 5, the greater the wind speed, the greater the power attenuation denoting multipath fading phenomenon of sea surface is more severe. In the studied range of satellite elevation angle, the maximum power attenuation of specular reflection wave is -10dB, while that of diffuse reflection can reach to -18dB, which mean that diffuse reflection attenuation is more serious than specular reflection.

5. Conclusion

In maritime satellite communications, sea surface has a strong reflection effect on satellite signal, resulting in multipath fading, especially in areas with low satellite elevation angle. In this paper, the UHF band multipath effects of sea surface are studied following the general principles of modeling in multipath effects. The judgment basis is obtained which determines whether specula reflected wave or diffuse reflected wave dominates in the reflected wave based on Rayleigh criterion. The power attenuation relative to direct wave of specula reflected wave on smooth sea surface and diffuse reflected wave on rough sea surface are simulated and analyzed in base of calculating the reflection coefficient. Simulation results show that the greater the wind speed is, the greater the power attenuation of reflected wave will become and the more serious multipath fading will be. In addition, diffuse reflection attenuation is more serious than specular reflection. So far, there is no accurate measured data on UHF band electromagnetic reflection of sea surface and these conclusions can provide reference for multipath effect analysis of sea surface in data post-processing stage in Maritime satellite communications.

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