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MCM/ICM

Summary Sheet

HF Channel Model of Random Sea Wave Model

Abstract

HF communication is the main means of the remote communication between ships on the sea. Therefore, it is an inevitable subject to improve the communication quality. This paper begins the research from the perspective of HF maritime communication; explore the transmission mode of radio wave on the ocean. By setting up the Sea Wave Model and through the theory of the reflection principle of the electromagnetic waves, the reflection model of radio wave in the calm sea is built. Using the analytical method of power spectrum and frequency spectrum and by the Monte Carlo stochastic method of MATLAB simulation, the random sea surface of the wind drive is simulated. Through the obtained model, the propagation of radio waves on the sea surface is analyzed. Compared to the sea, the continent condition is more complicated. Therefore, we analyze the common denominator between land and sea. Based on the ocean wave model, we analyze the terrestrial transmission of radio waves; set up the model of Ground Clutter, and map it into multi-dimensional vector with the weakening model of sea. A ship swing model is built for the communication problem of ships, and the sea channel model which is proposed based on the Longley-Rice model and the sea double-path model. Finally, the relationship between transmission loss and distance is analyzed by MATLAB simulation.

Key words: Sea wave model Analytical method of power spectrum Monte Carlo stochastic method ship swing model Sea double-path model

I. The Description of the Problem

Short-wave communication has always occupied an important position in long-distance communication, which is considered as an effective and economical means of long-distance military communication, and widely used in military strategy and tactical communication. In order to improve the quality of short-wave communication, the channel characteristics of short-wave circuit must be understood. Among the many factors that affect the maritime radio transmission, we focus on the reflection of the sea surface, and establish the mathematical model of maritime radio signal transmission.

The process of transmitting radio waves over the ocean should at least consider the loss of two aspects：

- Radio waves transmit losses in the atmosphere.
- Radio waves reflect losses on the sea.

The factors that affect the reflection loss of radio waves on the sea surface are：

- Radio waves sweep the incident Angle
- parameters such as the size of the waves
- Sea surface electromagnetic parameter

We will study the effects of temperature factors on the radio loss, regardless of the salinity of the sea surface。 Then the initial conditions are determined by the following factors：

- The intensity of radio waves.
- Incidence Angle
- The highest available frequency of radio waves.

From the above basic assumptions and initial conditions, a simple initial model can be established. The attenuation coefficient is obtained by unifying the loss of radio waves in the atmosphere and the loss of reflection on the calm sea surface. And then, the three-dimensional model of the wave is built to get the attenuation coefficient of the turbulent waves. The free space loss model based on the FRIIS transmission formula and the flat ground model based on double diameter are used. The simple model is optimized and improved so that it is suitable for the signal strength change received by the receiver in the shaking condition. Due to the distance between the normal receiver and the actual transmitter, the influence of the radius of curvature of the earth must be considered.

II. Models

2.1 Basic Model

2.1.1 *Assumptions*

- The effect of ionosphere on radio waves remains unchanged.

- The propagation of electromagnetic waves before reaching the ionosphere is considered as propagation in the ideal medium space.
- The rough sea is seen as a fluctuating sea surface caused by a one-way wind.

2.1.2 Model

E_0: The intensity of carrier signals emitted by the launching station.

E_1: The intensity of the signal entering the ionosphere.

E_2: Signal strength leaving the ionosphere

E_3: The intensity of the signal as it enters the sea.

First, consider the process of sending short waves from a single point on the ground to the first surface reflection. Short-wave emission is first transmitted in the air. When it reaches the ionosphere, it is reflected and then transmitted to the sea surface by air. During the process, two air propagation losses and ionospheric absorption losses are obtained.

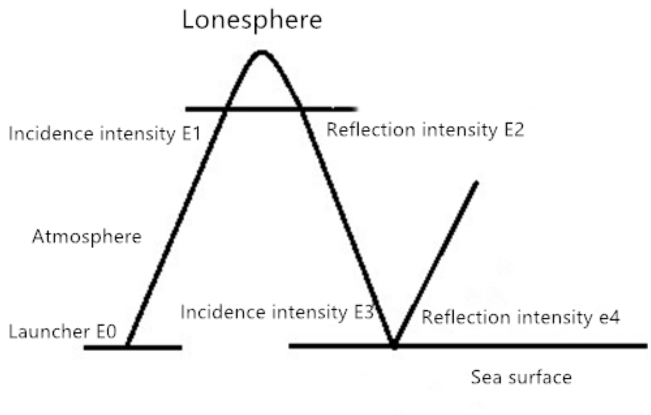

Figure1 Radio wave ocean transport model.

The initial energy of radio waves:

$$E_0 = 10\lg(P)$$

Propagation loss in the air:

$$Ls = 20\lg\left(\frac{4\pi df}{c}\right)^2$$

Propagation loss in the ionosphere: Refer to the IRI-2001 ionospheric model. Using ray tracing technology, the plane wave can be expressed as:

$$E = \mathrm{E}_0 \mathrm{e}^{j(wt - nk_0 r)}$$

In the formula,

$$k=\frac{2\pi}{\lambda};k_0=\frac{2\pi}{\lambda_0};\quad n=\mu-j\chi$$

Ignore the magnetic field's A-H formula,

$$\beta=\frac{\omega}{c}\operatorname{Im}\sqrt{1-\frac{X}{1-jZ}}$$

c : The speed of light in a vacuum;
ω : The angular frequency of the waves passing through the plasma

$$X=\frac{\omega_p}{\omega},$$

ω_p : The angular frequency of the plasma, which is a function of space position

$$Z=\frac{\omega_c}{\omega}$$

ω_c : Electron collision angular frequency

The collision process is the source of the ohm heating mechanism of the ionosphere. The effect of the lower ionosphere heating is particularly obvious. Obviously near the reflective height anomaly absorption mechanism will play a more important influence. The impact of collisions is also not negligible.

The total collision frequency of the electron:

$$\upsilon_e=\upsilon_{e,N_2}+\upsilon_{e,O_2},+\upsilon_{e,O}+\upsilon_{e,H_e}+\upsilon_{e,NO^+}+\upsilon_{e,O_2^+}+\upsilon_{e,O^+}$$

To sum up, the total absorption can be obtained in the ionosphere:

$$L=8.68\int_s \beta dS(dB)$$

Then:

$$E_3=E_0-L-2Ls$$

2.1.3 Use the basic model to discuss the situation of calm seas

Let's assume that the wireless shortwave is perpendicular to the sea level. The surface electromagnetic properties affect the reflection intensity of the waves. The characteristic impedance of the sea surface can be determined by the permittivity and permeability. Finally, the surface reflection coefficient can be obtained by equation. Given the basic conditions of the model, we build the following equation.

Sea surface conductivity: $\varepsilon_1=\varepsilon_r.\varepsilon_0$

The permeability of the sea surface: $\mu_1=\mu_r.\mu_0$

The conductivity of the sea surface: σ_1

The effect of temperature and salinity on sea surface parameters is not considered.

The characteristic impedance of the sea:

$$\eta_1 = \sqrt{\frac{\mu_1}{\varepsilon_1}}\left(1 - j\frac{\sigma_1}{\omega\varepsilon_1}\right)^{-\frac{1}{2}}$$

Air is the ideal medium, and the conductivity of the air is taken as 0.

The characteristic impedance of the air:

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

The reflection coefficient of short wave in air - sea surface is given by the following formula:

$$\Gamma = \frac{\eta_1 - \eta_0}{\eta_1 + \eta_0}$$

So, $E_4 = kE_3$

2.1.4 Use the basic model to discuss the situation of Rough sea surface

In order to study the effect of the wave motion on the receiving signal strength, we established the model of the sea surface fluctuation at constant wind speed.

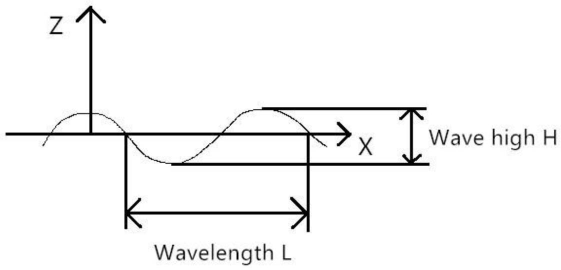

Figure2 Wave diagram

There is a receiving point on the sea surface. The location of the receiving point on the sea surface is (x_0, y_0).

υ: The wind speed

H: The height of the wave

h: mean wave height

The wave function at time t (x, y)

$$z(x,y,t) = r\cos(k\sqrt{(x-x_0)^2-(y-y_0)^2}+\omega t)$$

According to the theory of deep water wave:

$$L = \frac{gT^2}{2\pi}$$

According to the wave energy spectrum formula:

$$H = 7.065\times10^{-3}v^{2.5}$$

$$\omega = \frac{g}{T}\sqrt{\frac{2}{3}},\quad T = \frac{2\pi}{\omega},\quad k = \frac{2\pi}{\omega}$$

$$r = 3.5325\times10^{-3}v^{2.5}$$

$$k = \frac{2g}{3v^2}$$

According to the above formula, the basic parameters of wave waveform at a certain wind speed can be obtained:

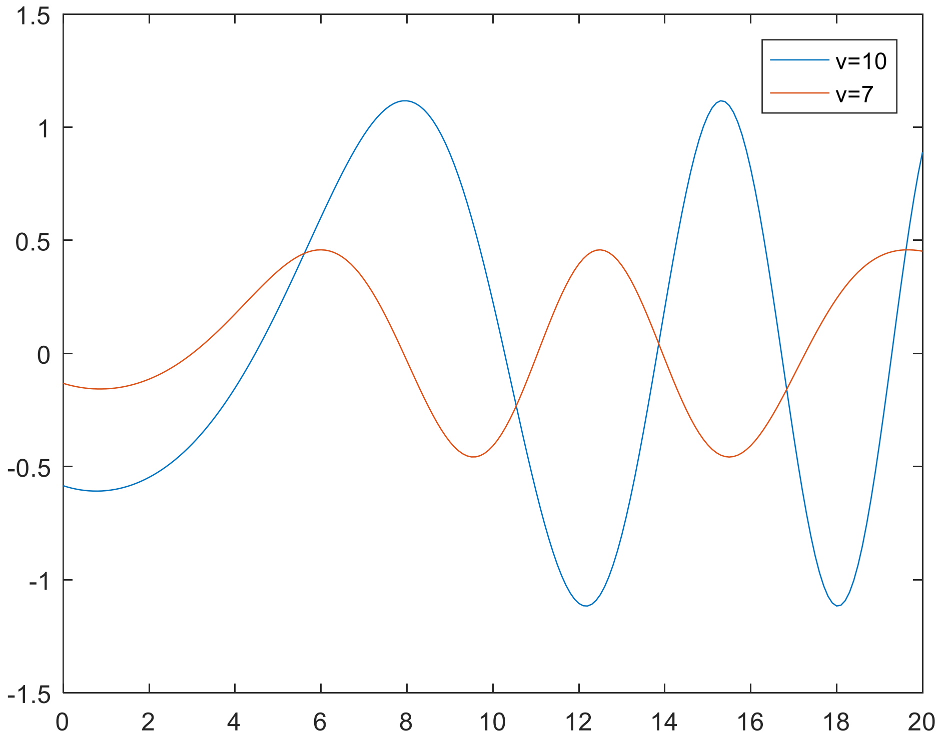

Figure3 the section of wave

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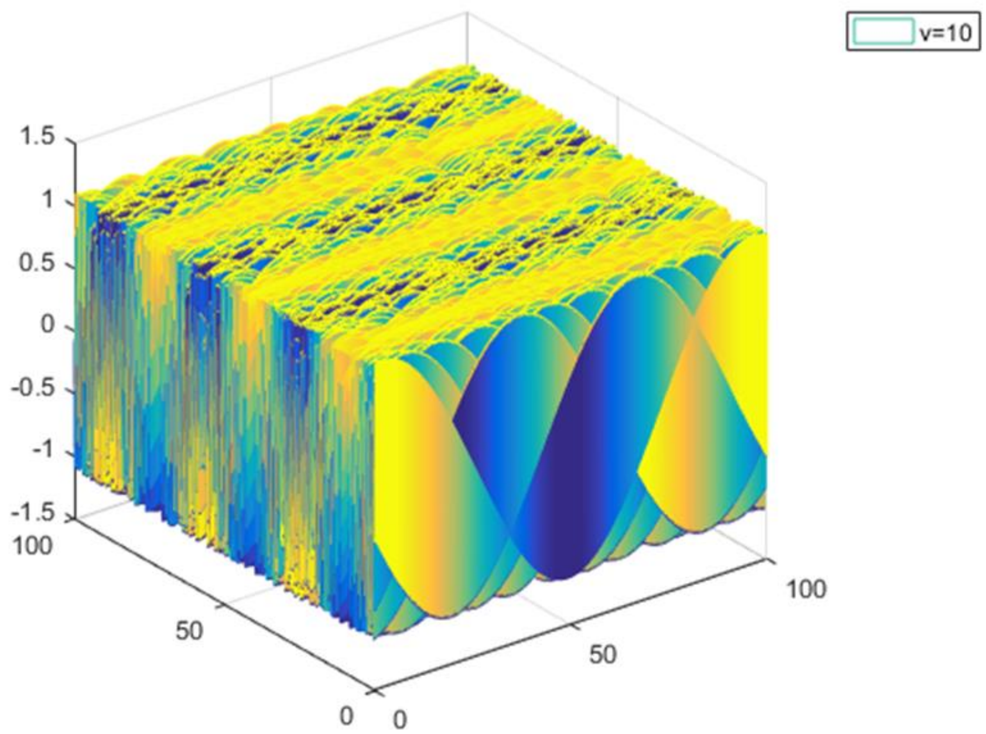

Figure4 a fluctuating sea surface caused by a one-way wind

Because the sea surface is a wave model caused by one-way wind, the wave direction of the wave can be seen in the same vertical plane as the direction of the incident radio wave. By Fresnel formula, we can get reflection coefficient:

$$\Gamma=\frac{\cos\theta-\sqrt{\frac{\varepsilon_1}{\varepsilon_0}-\sin^2\theta}}{\cos\theta+\sqrt{\frac{\varepsilon_1}{\varepsilon_0}-\sin^2\theta}}$$

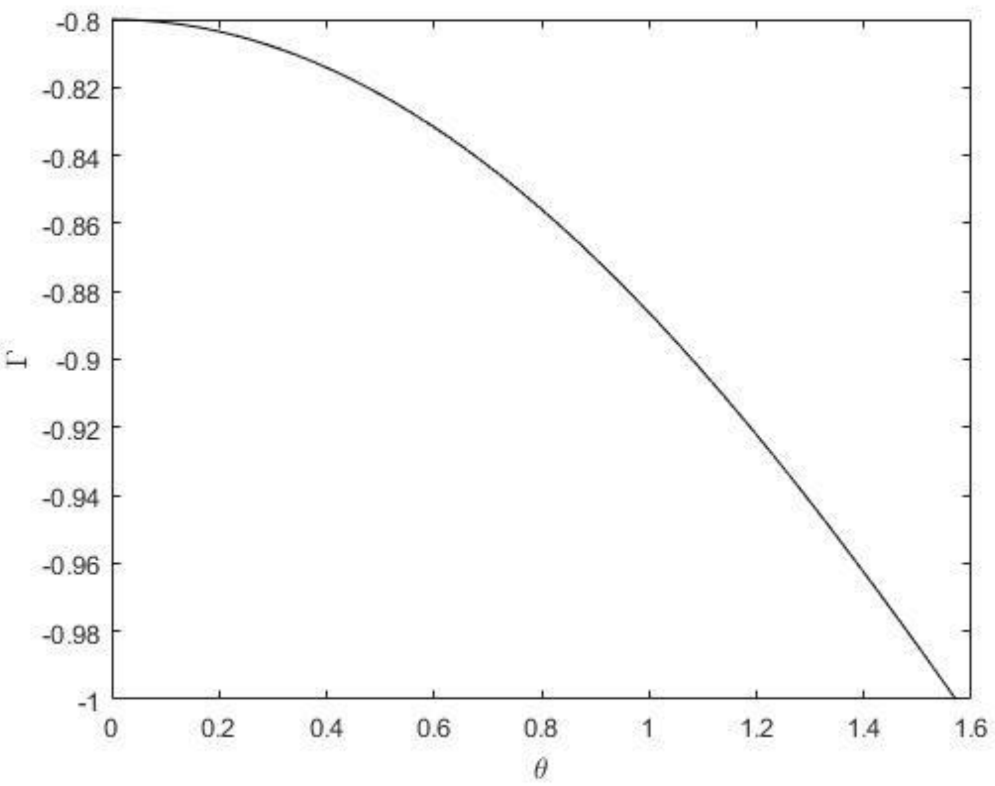

Figure5 the relation between incident Angle and reflection coefficient

On the rough sea surface,

$$E_4'=\mathrm{KE}_3$$

It is intuitively obvious that the modulus of reflection coefficient increases with the increase of incidence Angle. The modulus of the reflection coefficient is the largest. So the wave reflection coefficient of the surface must be less than or equal to the calm sea surface reflection coefficient, namely the first reflection from a rough surface reflection strength must be less than or equal to the calm sea first reflection intensity.

In fact, the formation of the waves cannot be caused by a one-way wind alone. Waves are superimposed by a large scale of gravitational waves and small scales of capillary waves. The previously established ocean wave model does not meet the actual requirements.

Considering that the waves are random. We can think of waves as being emitted from one source. It is composed of different amplitudes, frequencies, initial phases and sinusoidal waves of different directions. Suppose that the initial phases of these sine waves are random. The propagation direction of these waves obeys uniform distribution. So the model of the sea surface is the superposition of the sine waves of different frequencies. Based on this assumption, we can simulate 3Dl random waves from both the frequency and the direction of propagation.

The calculation process and its calculation are too complicated. So we just show the 3D model made by MATLAB.

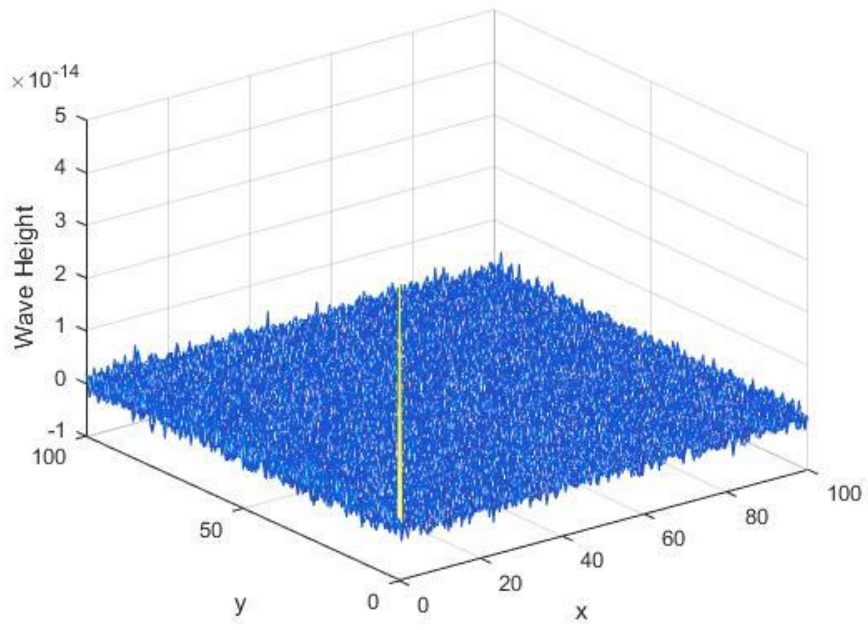

Figure6 Random wave model

For random sea surface reflection, the smooth surface reflection coefficient is used to multiply the rough correction factor.

R': Rough sea surface reflection coefficient

κ: Rough sea surface reflection coefficient

According to the CCTR theory:

$R'=\kappa R$

$$\kappa=-\frac{1}{\sqrt{3.2g-2+\sqrt{(3.2g)^2-7g+9}}}$$

$$g=0.5\left(\frac{4\pi hf\sin\theta}{c}\right)^2$$

h: Sea level root mean square height, It is based on the Phillips (1966) wave model.

$$h=0.0051\omega^2$$

ω: Wind speed near the sea level.

According to the above method, the relationship between reflection coefficient and frequency is calculated.

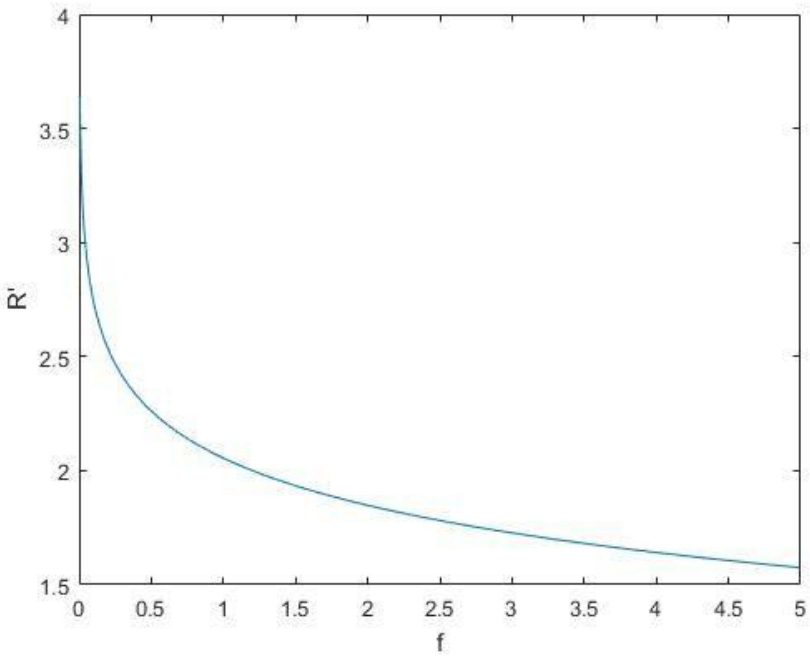

Figure7 the relationship between the reflection coefficient and the frequency

2.1.5 Solution and Result

The second time the signal reaches the surface of the sea, the intensity of the signal is:

$$E=\left(E_0\text{-}Ld\right)k^2-Ld\times k$$

The third time the signal reaches the surface of the sea:

$$E=\left(E_0\text{-}Ld\right)k^2-Ld\times k^2-Ld\times k$$

Any time a signal reaches the surface of the sea:

$$E=\left(E_0-Ld\right)\times k^{n+1}-Ld\times k^n-Ld\times k^{n-1}-\cdots\cdots-Ld\times k^2-Ld\times k$$

According to this recursive formula, we can estimate the maximum number of hops that the signal can take before its strength falls below a useable signal-to-noise ratio threshold of 10 db.

2.2 The comparison of signals between the sea and the rugged mountain areas.

2.2.1 Simulation results of mountain model.

By consulting the literature，the mountain model can be simulated by MATLAB. As the figure 6 shows:

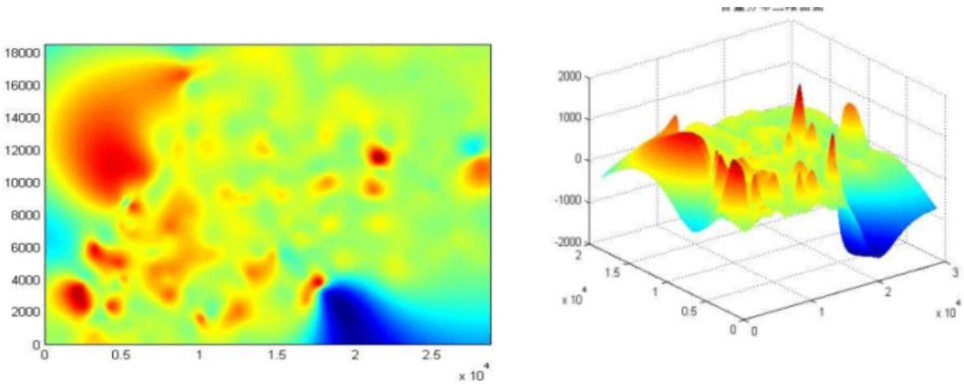

Figure8 Mountain mode

We modeled the ground clutter of different terrain. The power spectral density function of ground clutter can be represented by Gauss function.

$$s(f) = \exp\left[-\left(\frac{f}{f_{3dB}} \right)^2 \right]$$

$$f_{3dB} = 1.33 \exp(0.2634\upsilon)$$

2.2.2 The difference

According to the model established by sea clutter, the forward reflection coefficient of ground clutter should also be related to the frequency of radio waves. Moreover, the forward reflection coefficient of ground clutter is related to the terrain and the direction and velocity of the wind. The larger the wind speed, the smaller the forward reflection coefficient. He relationship between the attenuation coefficient and distance of the region is compared with the relation graph of the sea surface by MATLAB simulation.

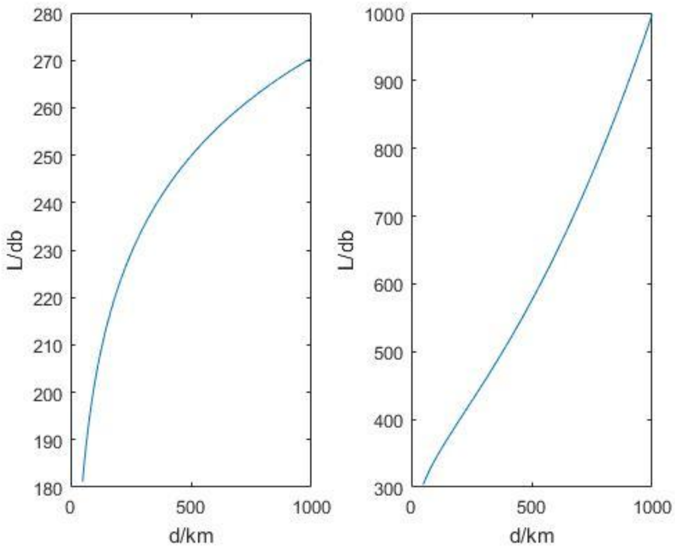

Figure9 the relationship between attenuation coefficient and distance

2.2.3 The same

Sea and land clutter is not entirely unrelated. The grassland on land is similar to the sea, which is similar to the calm sea in the absence of wind, and is similar to rough sea surface in the case of wind. Analog sea clutter, the clutter distribution of ground clutter can be described by Rayleigh distribution.

III. Improved Models

3.1 The foundation of Model

Treating the receiving points as a fixed point, we establish a model in the above. In the actual mobile communication ships on the sea, the receiving antenna elevation angle and roll angle changing will cause the transmission loss of radio waves on the sea, and the change of transmitting station distance at the same time the ship will cause variations in the radio waves.

3.2 Ship Swing Model

Because of the ship sloshing up and down, around and around the waves, we can establish a six degree of freedom motion model $(x, y, z, \alpha, \beta, \gamma)$ for a ship. At first, a spherical coordinate system (o, x, y, z) based on an earth is set up, and the O point is the center of the earth. The movement of the ship can be expressed as:

Rectilinear motion along the Z axis；

Rotate around the X axis；

Rotate around the Y axis；

Because the antenna on a ship is stationary relative to the hull, the position of the antenna, the angle of radiation, and the angle of reception can also be described in this spherical coordinate system.

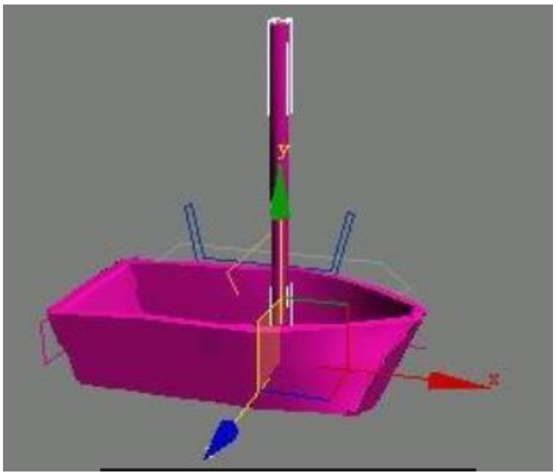

Figure10 3D model of a ship

According to the literature (Hall et al, 1996), the maximum angle deviation of the vertical polarized antenna can be derived from the approximate geometric relation. Considering the maximum angle deviation of the vertical polarized antenna and regarding the wave motion of the ship as a tangent plane on the wave in the random wave model, we can obtain the maximum angle of the ship's sloshing angle.

$$\theta_{\max} = \arcsin \frac{\pi H_{\max}}{\sqrt{\lambda_{sea}^2 + \pi^2 H_{\max}^2}}$$

The $H_{\max}$ is the maximum height of the wave, and the λ_{sea} is the wave wavelength.

3.3 A sea channel model based on Longley-Rice model and ship motion

The Longley-Rise model is suitable for predicting the variation of communication field strength with a wide range of communication distance and complex electromagnetic propagation environment, but it is difficult to predict the field strength within short distance (within 1km). So we need to supplement and correct it by using sea double-path model.

The sea double-path model is very accurate in predicting the high frequency signal intensity in the 1km range of the sea, and the sea double-path model is shown as shown in the figure.

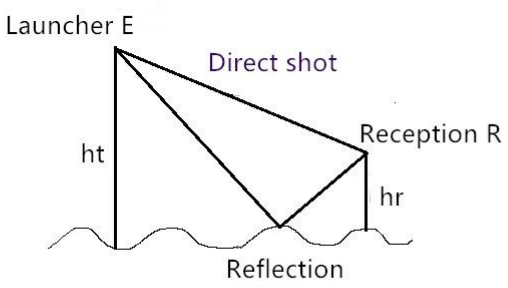

Figure11 schematic diagram of dual diameter propagation model

Path difference between direct and sea surface reflection

$$\Delta = r_2 - r_1 = \sqrt{\left(h_t + h_r\right)^2 + d^2} - \sqrt{\left(h_t - h_r\right)^2 + d^2} \approx \frac{2h_t + h_r}{d}$$

In the form, r_1 and r_2 are the distance between the transceiver and the reflection point, and h_t, h_r is the height of the transceiver antenna, and d is the distance between the transceiver.

Therefore, the phase difference between the two electric field components is as follows:

$$\theta_{\Delta} = \frac{4\pi h_t h_f}{\lambda d}$$

In the formula, θ_{Δ} is the phase difference, and λ is the wavelength.

The square of the ratio of the received field strength to the free space field strength is as follows:

$$\left|\frac{E_{rec}}{E_{fs}}\right|^2 \approx 4\left[\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right]^2$$

In the formula, E_{rec} is the receiving field, and E_{fs} is the free space field strength. This formula provides the accurate receiving electric field strength for the double path model.

$$\frac{P_r}{P_c} = 4\left[\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right]^2 \times \left(\frac{\lambda}{4\pi d}\right)^2 \approx (\frac{h_t h_r}{d^2})^2$$

Based on the measured data of the reference, the MATLAB simulation analysis of the model is carried out. The comparison between the double-path model and the measured data shows that the loss prediction of the double-path model is basically consistent with the measured data in the 1km path distance.

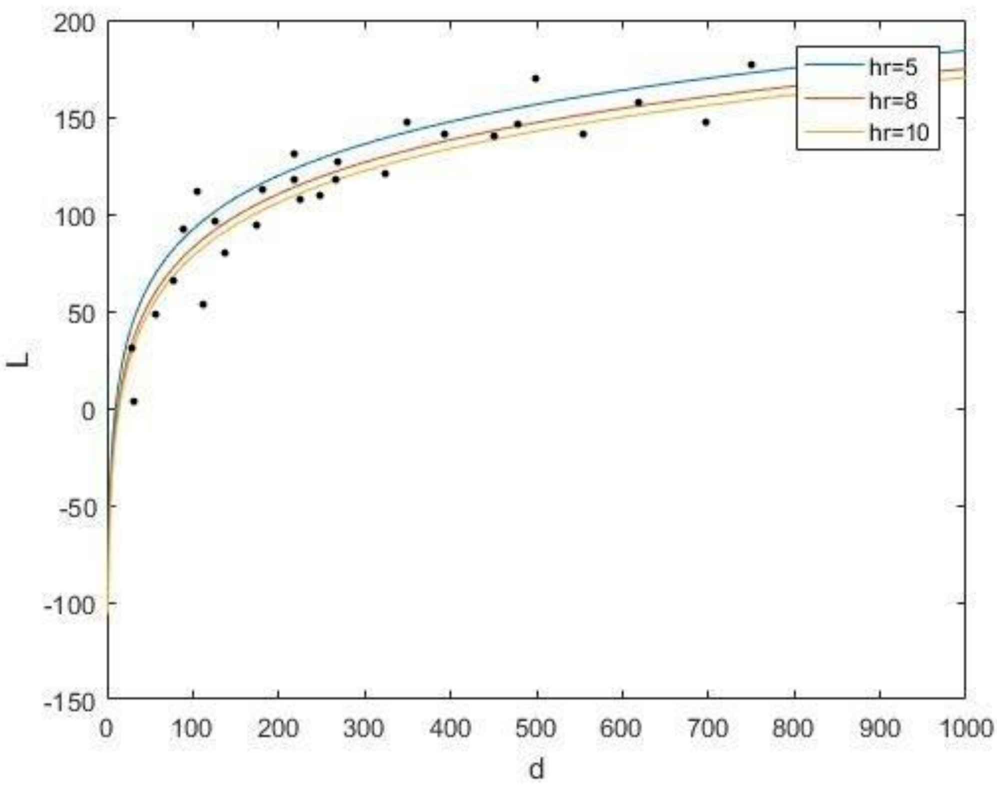

Figure12 the function diagram of loss value and distance

The Longley-Rice radio wave transmission model is based on the Radio propagation theory, and predicts loss values based on different propagation ranges:

In the visual distance, the reflection and transmission mechanism is the main mechanism;

Beyond the horizon, the diffraction propagation mechanism is the main mechanism;

For a larger distance (far beyond the horizon)， forward scattering mechanism is the main mechanism;

The Longley-Rice model gives the relevant modifying factors in different environments and the calculation formula of the reference attenuation value. The parameters used in the formula include frequency, irregular terrain parameters and the initial antenna height, the location standard of the first antenna, the distance between the transceiver, the refractive index of the ground, the climate type and the polarization mode. The model uses the following formula to calculate the reference value of the transmission loss beyond the free space.

$$A_{ref} = \begin{cases} \max\left(0, A_{ed} + K_1 d + K_2 \ln\left(\dfrac{d}{d_{LS}}\right)\right) & d_{\min} \le d \le d_{LS} \\ A_{ed} + m_d d & d_{LS} \le d \le d_x \\ A_{es} + m_s d & d_x \le d \end{cases}$$

In the formula, $d_{\min} \le d \le d_{LS}$ is the distance of line-of-sight propagation, $d_{LS} \le d \le d_x$ is the Diffraction, $d_x \le d$ is the Scattering

The formula for the reference value of the propagation decay of the diffraction range:

$$Can\ be\ set\ X_{ae} = \left(kg_e^2\right)^{-\frac{1}{3}}$$

$$d_3 = \max(d_{Ls}, d_L + 1.3787X_{ae}),$$

$$w = \frac{1}{1+0.1\sqrt{Q}}$$

$$d_4 = d_3 + 2.7574X_{ae}, A_3 = A_{diff}\left(d_3\right),$$

$$A_4 = A_{diff}\left(d_4\right), \quad m_d = \left(A_4 - A_3\right)/\left(d_4 - d_3\right),$$

$$A_{ed} = A_3 - m_d d_3, A_{diff}\left(s\right) = \left(1-w\right)A_k + wA_\gamma + A_{\gamma 0},$$

$$Q = \min\left(\frac{k}{2p}Dh\left(s\right), 1000\right)\left(\frac{h_{e1}h_{e2}}{h_{g1}h_{g2}}\right)^{1/2} + \frac{d_L + q_e / g_e}{s}$$

So:

$$A_{fo} = \min\left[15, 5\log\left(1 + akh_{g1}h_{g2}s_h\left(d_{Ls}\right)\right)\right]$$

$$a = 4.77\times 10^{-4}m^{-2}$$

$$A_k = F_n(v_1) + \mathrm{F}_n\left(v_2\right)$$

$$F_n(v) = 20\log\left|\frac{1}{\sqrt{2}i}\int_v^{\infty} e^{ixv^2/2}du\right|$$

The calculation formula of the median of transmission decay reference in the range of sight distance:

$$\text{Assumptions } A_2 = A_{ed} + m_d d_2, d_2 = d_{Ls},$$

$$A_1 = A_{los}(d_1), A_0 = A_{los}(d_0), d_1 = \frac{3}{4}d_0 + \frac{1}{4}d_L, d_0 = \min(\frac{1}{2}d_L, 1.908kh_{e1}h_{e2})$$

So:

$$K_2' = \max\left[0, \frac{\left(d_2 - d_0\right)\left(A_1 - A_0\right) - (d_1 - d_0)(A_2 - A_0)}{\left(d_2 - d_0\right)\ln\left(A_1 - A_0\right) - (d_1 - d_0)\ln(A_2 - A_0)}\right],$$

$$K_1' = (A_2 - A_0 - K_2' \ln(d_2 / d_0)) / (d_2 - d_0)$$

$$If \;\; K_1' \geq 0 \; then \; \mathrm{K}_1 = K', \;\; K_2 = K_2'$$

$$If \;\; K_1' < 0, then \quad K_1' = 0, K_2 = K_2'', K_2'' = (A_2 - A_1) / \ln(d_2 / d_1)$$

In this way, the calculation formula of the median of the distance transmission decay reference can be obtained.

$$A_{los} = (1 - w) / A_d + wA_t, \;\; A_d = A_{ed} + m_d s$$

Among them

$$A_t = -20 \log \left| 1 + R_e e^{id} \right| 。$$

The calculation formula of the mean value of the weak range of the scattering range:

$$d_x = \max\left[d_{LS}, d_L X_{ae} \log(kH_s), (A_5 - A_{ed} - m_s d_5) / (m_d - m_s) \right],$$

$$m_s = (A_6 - A_5) / D, A_6 = A_{c\alpha t}(d_6),$$

$$A_5 = A_{c\alpha t}(d_6),$$

$$d_6 = d_5 + D_s, D_s = 200km, d_5 = d_L + D_s,$$

$$H_s = 47.7$$

Thus the scattering range fading reference median calculation formula:

$$A_{xat}(s) = 10 \log(kHq^4) + F(q_3, N_s) + H_0$$

$$\theta = \theta_e + \gamma_e s, \theta' = \theta_{e1} + \theta_{e2} + \gamma_{es}$$

Function $F(\theta s, \;\; N_s)$ is a function defined by reference

H_0 is Frequency gain factor

Next we use MATLAB to simulate the improved model. Select a certain area on the surface of the sea, the latitude of the sea corresponding to the radius of curvature of the earth 6375km, temperate maritime climate. The relative permittivity of the sea surface is 81 F / m, and the conductivity is 5.000 s / m. Transmitter antenna height of 10 meters. The loss of radio waves is discussed at line-of-sight, over the horizon, and at a distance further away.

The following graph is obtained from the above conditions:

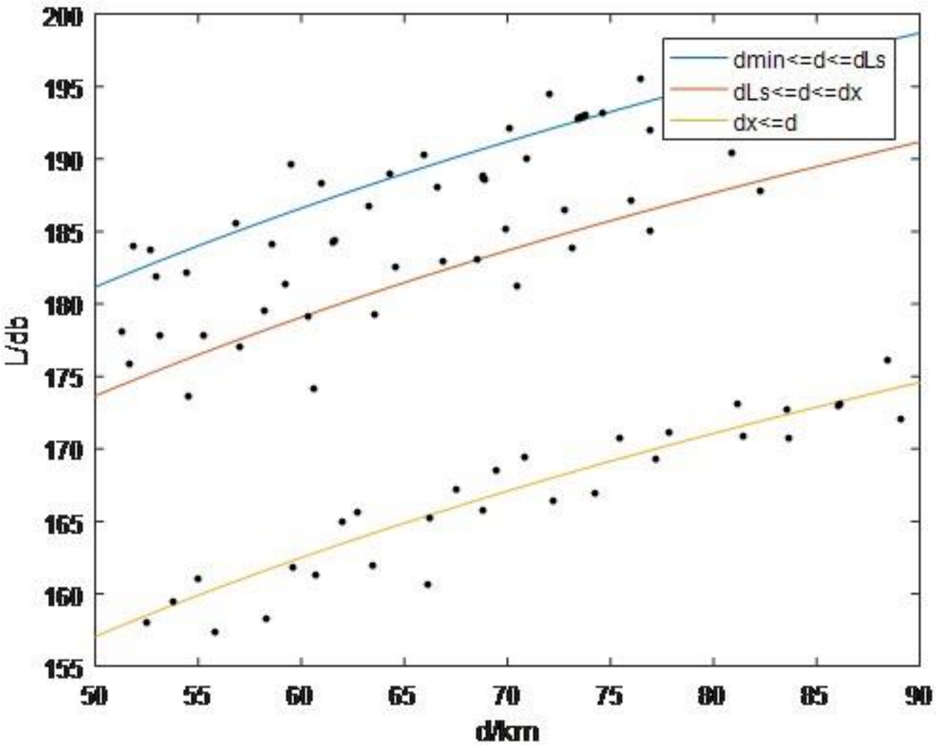

Figure 13 relationship between Loss and Distance under Three Transmission Mechanisms

The simulation results are in good agreement with the measured data, indicating that the improved model is suitable for the ships operating at sea.

IV. Conclusions and Future Work

Our model is very intuitive and easy to understand. After reviewing the literature data, we found that our model is in good agreement with our diagram and that the evaluation of the actual situation is very reasonable. After establishing some reasonable assumptions, a maritime communication model was established to better evaluate the transmission of radio waves under different sea conditions. Considering the actual navigational conditions of the ship, a ship sway model was established to make the whole model more realistic.

At present, the demand for maritime transport has increased dramatically. The model in this paper can be applied to maritime navigation in ships to reduce communication losses. There are other uses of this model, such as analyzing the transmission of radio waves in mountainous areas, the situation of radar transmitting and receiving radio waves and so on.

V. Synopsis (IEEE)

Modern economic development is increasingly dependent on the oceans. Broadband mobile wireless networks cover most of the earth on land, while maritime broadband mobile communications lags far behind terrestrial wireless communications. There are a lot of researches on the model of marine radio wave transmission at present. It is difficult to accurately describe it due to the complex and changing ocean conditions, the measurement environment is limited. By simulating the situation of the sea surface and the ship swaying, the channel model can be obtained more accurately, which is of great help to the marine communication of ships.

In this paper, we study the situation of radio wave transmission at sea, and set up the model of maritime communication. At first, we describe the attenuation of radio waves on the sea surface, and discuss the analysis of the calm sea surface and the wave surface sea respectively which are based on the difference of ocean conditions. Then we analyze the relationship between attenuation coefficient and incident angle. The Monte Carlo random method using MATLAB simulates wind-driven random sea surface. Using power spectrum and frequency analysis method to establish sea clutter and draw the conclusion that the reflection coefficient decay rapidly with the increase of frequency. According to the established random sea-wave model, combined with the complicated ground clutter in the terrestrial environment, the difference between ocean and terrestrial wireless propagation is contrasted. Finally, the three-dimensional modeling of the ship's sway caused by the wave fluctuation was conducted. The Longley-Rice model and the dual-path model were used to analyze the status of the ship's marine communication. The model proposed in this paper has certain reference value for the study of maritime transmission of radio waves and maritime communications. It can also be used to improve the quality of marine communications and optimize the layout of marine transmitting stations.

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