Multi-Hop HF Electromagnetic Wave Reflection Model Based on Improved Genetic Algorithm

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ABSTRACT

The research of dynamic sea level electromagnetic reflection and its roughness has important theoretical significance and broad application prospect in the fields of ocean microwave remote sensing, radar guidance and interception, target recognition and feature extraction.

In order to study the multi-hop propagation of HF radio waves on the ocean surface, this paper fully considers the whole process of signal loss caused by multi-hop propagation of high-frequency radio waves in the ocean. The model of ocean signal reflection loss is established by Fresnel reflection coefficient and three-dimensional ocean wave PM spectrum modeling, and the roughness correction coefficient is used to apply the model to the turbulent ocean. By genetic algorithm based on classical nonlinear optimization to solve the model, the maximum number of hops without distortion signal is obtained, which has the advantage of ensuring excellent global search ability and greatly improving the local search ability of the algorithm.

KEYWORDS

Multi-hop radio waves, ocean signal reflection, multivariate optimization, improved genetic algorithm.

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INTRODUCTION

Today, with the continuous development of marine resources, the continuous development of maritime transport and the continuous development of naval combat tactics, marine wireless communications have become even more important. There is now the shortwave communication technology, and shortwave band radio wave transmission in two forms: one is the ground wave propagation, one is sky wave propagation[1]. Among them, to realize long-distance mobile communications at sea, it is necessary to rely on sky wave propagation, that is, a way of transmitting radio waves to reach the ground receiving point through high altitude ionospheric reflection[2]. However, unlike terrestrial communications, marine wireless communications have become very difficult due to the complex and changeable environmental factors in the marine space, such as the wave changes caused by wind speed changes, the unevenness of the salinity density in seawater, and the unsustainability of seawater conductivity[2]. Among these factors, the reflecting surface determines the intensity of the reflected wave and determines the distance that the signal propagates. So the reflection on the sea has a great influence on the spread of radio waves. The seawater electromagnetic gradient, magnetic permeability, the height and angle of the reflection surface are changing at all times, leading to the difficulty of studying the problem. Therefore, the establishment of marine signal reflection model for the study of the performance of marine wireless channel is very meaningful.

Statement of the Problem

We tend to set up a model that simulates how the radio waves reflect on the ocean and compare the intensity of the first reflection of the radio waves on the raging and calm ocean and further calculate the maximum number of hops that can be taken on the calm sea. Then to compare the high-frequency reflections at sea with the high-frequency reflections of rough terrain and smooth terrains.

In order to solve these problems, we give some assumptions which are necessary for us to clarify our models. Using the Longley-Rice model and the semi-empirical model, we consider the signal attenuation of radio waves in space and through ionospheric reflections. Then we set up the model of ocean signal reflection loss through the modeling of three-dimensional ocean wave PM spectrum and Fresnel complex reflection coefficient, and compare calm and raging seas. Finally, we use genetic algorithm to find the maximum number of hops in the calm ocean. We set up Rugged terrain and smooth terrain signal reflection loss model, and compare the ocean signal reflection loss model with this model.

Assumptions and Justification

● When studying the high frequency reflections of the oceans, the sun conditions, the seasons and the day remain constant.
The speed of the ocean is negligible relative to high-frequency waves.

Ignore the impact of the atmosphere on the radio wave speed.

Ionosphere is a static and stable spherical shell.

Sea water is an isotropic homogeneous medium.

| Symbol | Definition |
|--------|------------|
| \(d\)  | The propagation distance |
| \(f\)  | The frequency of high-frequency radio |
| \(L_b\) | Transmission loss in air |
| \(L_i\) | The ionospheric absorption loss |
| \(\Delta\) | The ray elevation angle |
| \(\bar{\varepsilon}\) | The complex permittivity of seawater |
| \(\varepsilon_r\) | The relative permittivity of seawater |
| \(\sigma\) | The sea water conductivity |
| \(R_V\) | The vertical polarized wave reflection coefficient |
| \(R_H\) | The reflection coefficient of horizontal polarized wave |
| \(L_g\) | The transmission loss through the ocean reflection |
| \(\gamma\) | The reflection correction factor |
| \(\theta\) | The grazing angle |
| \(h_x\) | The root mean square height of the rough surface |
| \(\rho\) | Signal to noise ratio |
| PS     | The effective power signal |
| PN     | The effective power noise |

**Notations**

Where we define the main parameters while specific value of those parameters will be given later.

**MODEL I: OCEAN SIGNAL REFLECTION LOSS MODEL**

**Model Establishment**

High-frequency signals spread over the ocean take roughly three steps, propagating in the air, undergoing ionospheric reflection, and being reflected by the ocean. After the high-frequency signal propagation is a continuous cycle of these three steps to repeat, so we first study a cycle that is a high-frequency signal hopping spread. Based on a complete jump, we further study the multiple jumps of high frequency signals. Signals propagate through vibrations in the medium, and different medium have different physical optical characteristics.
HIGH-FREQUENCY SIGNALS SPREAD IN THE AIR

Here, we use a semi-statistical semi-deterministic Longley-Rice model[4]. Longley-Rice model transmission loss:

\[ L_b = L_{ref} + L_{free} \]  \hspace{1cm} (1)

Among which:

\[ L_{free} = 32.45 + 20\log d + 20\log f \]

\[ L_{ref}(d) = \begin{cases} \max(0, L_{be} + k_1 d + k_2 \log d) & d_{min} \leq d \leq d_{LS} \\ L_{bed} + m_d d & d_{LS} \leq d \leq d_x \\ L_{bes} + m_s d & d_x \leq d \end{cases} \]  \hspace{1cm} (2)

Where: d for the propagation distance. f is the radio frequency. \( d_{LS} \) is the smooth ground distance. \( d_x \) means that the diffraction loss is equal to the scattering loss. \( L_{be} \) is the propagation loss of line-of-sight in free space. \( L_{bed} \) is the diffraction loss. \( L_{bes} \) is the scattering propagation loss. \( k_1 \) and \( k_2 \) are propagation loss coefficients. \( m_d \) and \( m_s \) are the diffraction and scattering loss coefficients, respectively.

HIGH-FREQUENCY SIGNALS ARE REFLECTED BY THE IONOSPHERE

However, since ionospheric absorption loss of high-frequency signals is very small, usually within 10dB, we can assume that the ionosphere is a relatively stable structure. Through the literature[2] we know that the trajectory of electromagnetic waves in the ionosphere is a smooth curve. We approximate the trajectory to specular reflection, that is, the reflection angle equals the angle of incidence. The simplified ionosphere is as follows:

![Radio wave reflection path schematic](image)

Figure 1. Radio wave reflection path schematic.
Then calculate the ionospheric absorption loss based on the following semi-empirical formula.

$$L_i = 1 \frac{677.2 \sec i_{100}}{(f + f_H)^{1.98} + 10.2} \text{ (dB)}$$

$$I = (1 + 0.0037 \overline{R}_{12})(\cos 0.881\chi)^{1.3}$$

$$i_{100} = \arcsin(0.985 \cos \Delta)$$

Where, $I$ is the absorption coefficient, $i_{100}$ is the incident angle of electric wave at 100km height, $\Delta$ is the ray elevation angle, $f_H$ is the magnetic rotation frequency at 100km height. In the simulation calculation, using the method of typical values in key areas to simplify. $\overline{R}_{12}$ is the number of sunspots "December moving average". $\chi$ is the sun's angle.[5]

HIGH FREQUENCY SIGNALS ARE REFLECTED BY THE OCEAN

A large number of statistical experiments show that the dielectric constant of seawater and salt content, the frequency of external electric field and the seawater temperature, We use the seawater complex dielectric constant function Debye:[7]

$$\tilde{\varepsilon} = \varepsilon_{\infty} + \frac{\varepsilon_r - \varepsilon_{\infty}}{1 + (j2\pi ft)^{1-\alpha}} - j\frac{\sigma}{2\pi f\varepsilon_0}$$

Where $\tilde{\varepsilon}$ is the complex permittivity of seawater, $\varepsilon_r$ is the relative permittivity of seawater, $\varepsilon_{\infty}$ is the permittivity of seawater at infinite frequency, $\tau$ is the relaxation time, $\alpha$ is the empirical number that characterizes the distribution of relaxation time, generally 0. $\sigma$ is the sea water conductivity, $\varepsilon_0$ is the permittivity of free space. $f$ for high frequency radio frequency.

The equation above can be simplified as:[6]:

$$\tilde{\varepsilon} = \varepsilon_r + i60 \lambda \sigma$$

In order to calculate seawater relative permittivity $\varepsilon_r$ and seawater conductivity $\sigma$, Dielectric Initialization (DIEINIT) SU[8] was used. DIEINIT SU is a way to determine, respectively, the relative permittivity and relative permittivity of general surface media as a function of frequency. Here, DIEIINT SU is used only for seawater. Through the polynomial fitting function, we get the expression of relative permittivity $\varepsilon_r$ of seawater[6]:

708
\[ \varepsilon_r = \begin{cases} 
70 & f \leq 2253.589 \\
\frac{1}{a + bf + cf^2 + df^3 + ef^4} & f > 2253.589 
\end{cases} \]  \hspace{1cm} (6)

Where, \( f \) is the frequency of high-frequency radio, in units of MHz.

From (6) we can see that the high-frequency radio frequency of 3 ~ 30MHz, far less than the sub-value. Therefore, we believe that seawater relative dielectric constant \( \varepsilon_r \) is a constant value of 70.

Similarly we can get the seawater conductivity \( \sigma \) expression [6]:

\[ \sigma = \begin{cases} 
5.0 & f \leq 1106.207 \\
\frac{r + sf + tf^2}{1 + uf + vf^2 + wf^3} & f > 1106.207 
\end{cases} \]  \hspace{1cm} (7)

Where, \( f \) is the frequency of high-frequency radio, in units of MHz;

By the same formula (7) can be seen, we find that the frequency band is far less than the high-frequency segment. So we also think that sea water conductivity \( \sigma \) is a constant value of 5.0.

| TABLE II. PARAMETER VALUE. |
|-----------------------------|
| Related parameters | Statistics |
| a | \( 1.411 \times 10^2 \) |
| b | \( -5.212 \times 10^{-8} \) |
| c | \( 5.855 \times 10^{-11} \) |
| d | \( -7.671 \times 10^{-16} \) |
| e | \( 2.985 \times 10^{-24} \) |

| TABLE III. CORRELATION COEFFICIENT VALUE. |
|-------------------------------------------|
| Related parameters | Statistics |
| r | 3.858 |
| s | \( 9.135 \times 10^{-4} \) |
| t | \( 1.531 \times 10^{-8} \) |
| u | \( -2.112 \times 10^{-5} \) |
| v | \( 6.573 \times 10^{-10} \) |
| w | \( -1.965 \times 10^{-15} \) |

Through the above, the sea surface permittivity \( \varepsilon \) can be obtained. What needs to be studied next is the relationship between the complex dielectric constant of sea surface and the reflection intensity of high-frequency waves. The calculation of the reflection intensity of high-frequency waves is also the calculation of the propagation loss when reflected by the sea. Through the literature[9] we know that
the propagation loss of the electric wave when reflected by the sea surface is related to the reflection coefficient of the horizontal polarized wave and the vertical polarized wave, and the relationship is as follows:

$$L_g = 10\log \left[ \frac{|R_V|^2 + |R_H|^2}{2} \right] \text{ (dB)}$$ (8)

Among them, $L_g$ is the transmission loss through the ocean reflection. $R_V$ is the vertical polarized wave reflection coefficient. $R_H$ is the reflection coefficient of horizontal polarized wave.

Then for the smooth sea, which is calm ocean, use the Get Reflection Coefficient (GETREFCOEF) SU[8]. GETREFCOEF SU is a way to determine the Fresnel complex reflection coefficient using the grazing angle $\theta$. The relationship between Fresnel complex reflection coefficient and grazing angle is as follows:

$$R_V = \frac{\bar{\varepsilon}\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\bar{\varepsilon}\sin\theta + \sqrt{\varepsilon - \cos^2\theta}}$$

$$R_H = \frac{\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\sin\theta + \sqrt{\varepsilon - \cos^2\theta}}$$ (9)

Where, $\theta$ is the grazing angle.

Figure 2. Simulation analysis with rough sea correction factor $\gamma$.

ROUGH SEA SURFACE REFLECTION COEFFICIENT CALCULATION

Taking into account the wave height of the sea surface and the electromagnetic gradient, a reflection correction factor is given[6]:

710
\[
\gamma = \frac{1}{\sqrt{3.2g - 2 + \sqrt{(3.2g)^2 - 7g + 9}}} + \frac{1}{87.134 - 0.1949T - 0.01276T^2}
\] 

(10)

Among which: \(g = 0.5 \left( \frac{4\pi h f \sin \theta}{c} \right)^2 \). \(c\) is the speed of light. \(f\) is the frequency of electromagnetic waves.

THREE-DIMENSIONAL OCEAN WAVE PM SPECTRUM MODELING

Highly fluctuating sea spectrum is an effective way to describe the highly undulating morphology of the ocean surface. We use three-dimensional PM oceanography to characterize ocean surface fluctuations[7].

The spectral function of three-dimensional rough surface is expressed as:

\[
W(K, \varphi) = \frac{\alpha}{2K^4} e^{-\frac{\beta g^2}{K^4} \cos^2(\varphi - \mu)}
\] 

(11)

We obtain the correlation coefficient \(C(x, y)\) of three-dimensional rough surface undulation under different wind levels by using Spectral Fast Fourier Transform and Inverse Fourier Transform:

\[
W(K_x, K_y) = \frac{1}{2\pi} \int \int C(x, y) e^{j(K_x x + K_y y)} \, dx \, dy
\]

\[
C(x, y) = \int \int W(K_x, K_y) e^{-j(K_x x + K_y y)} \, dK_x \, dK_y
\]

(12)

Ocean surface as shown:

Figure 3. Light breeze. Figure 4. Gentle breeze.
HIGH-FREQUENCY ELECTROMAGNETIC WAVE SIGNAL TO NOISE RATIO CONTROL

The sound power level is introduced here, which is the base 10 logarithm of the ratio of the sound power to the reference sound power multiplied by 10, in decibels, with the numerical expression:

\[ L_W = 10\log \left( \frac{P_N}{P_D} \right) \]  

(13)

Common reference sound power PD is \( 10^{-12}\) W.

Signal to noise ratio is the unit of measurement DB, which is calculated as follows:

\[ \rho = 10\log \left( \frac{P_S}{P_N} \right) \]  

(14)

PS and PN represent the effective power signal and noise, respectively.

OCEAN SIGNAL REFLECTION ATTENUATION MODEL

With the spread of wireless signals, signal to noise ratio gradually reduced, but to ensure that the signal is not distorted, the signal to noise ratio cannot be less than 10DB.

\[ \rho - n(L_i + L_g + L_b) \geq 10 \]  

(15)

Then:
\[
\max \ n = \frac{\rho - 10}{L_i + L_g + L_b}
\] (16)

\[
\begin{aligned}
L_b &= L_{\text{ref}} + L_{\text{free}} \\
L_{\text{free}} &= 32.45 + 20\log d + 20\log f \\
L_{\text{ref}} &= L_{\text{bes}} + m_s d \\
L_g &= 10\log \left[ \frac{|R_V|^2 + |R_H|^2}{2} \right] \text{(dB)} \\
L_i &= I \left( \frac{677.2\sec_f f}{(f+f_0)^{1.98} + 10.2} \right) \text{(dB)} \\
I &= (1 + 0.0037R_{12}) (\cos 0.881\chi)^{1.3}
\end{aligned}
\] (17)

**Determination of the Model**

We first determine the launch angle of 45 degrees, the radio frequency of 20MHz, the wind speed of 10m / s. By the model above, we calculate that the signal attenuation of the radio waves on the smooth plane is 2.08 dB, while the signal attenuation on the turbulent sea is 3.97 dB. Then we conclude that the signal attenuation of radio waves on the turbulent sea surface is significantly greater than that on the calm sea surface.

We established the ocean signal reflection attenuation model as a multivariate function optimization model, which is suitable for solving using genetic algorithm. Although the global search ability of genetic algorithm is strong, the local search ability is weak. We can only get the suboptimal solution of the problem, rather than the optimal solution. The classical nonlinear programming algorithm uses the method of gradient descent to solve, whose local search ability is strong, but the global search ability is weak. Therefore, we combine the advantages of the two algorithms. On one hand, we use the genetic algorithm to search the global, on the other hand, we use the non-linear programming algorithm to search locally to obtain the global optimal solution of the problem. Algorithm flow chart is as follows:

![Algorithm flow chart](image)

Figure 7. Nonlinear genetic algorithm flow chart.
Figure 8. Evolutionary process.

The results of the genetic iteration after multiple genetic iterations are as Fig 8. The maximum number of hops that can be used before the signal strength is no lower than 10dB of the available signal-to-noise ratio threshold is three times. At this time the signal transmission frequency of 23.732MHZ, signal launch angle of 50.34°.

Result Analysis

Here, we use the angle of launch to make the sensitivity analysis the ionospheric loss and the sea level reflection loss.

SENSITIVITY ANALYSIS OF EMISSION ANGLE TO IONOSPHERIC LOSSES

\[
S(L_i, \Delta) = \frac{\partial L_i/L_i}{\partial \Delta/\Delta} = \frac{6.772 \sec 100}{(f+f_H)^{1.98} + 10.2} \times \frac{\partial L_i}{\partial \Delta} \quad (18)
\]

When \( \Delta \) is equal to 50.34°, \( S(L_i, \Delta) \approx 0.516 \). That is, when the angle is increased by 1%, the corresponding ionospheric loss will increase by 0.516%, which explains that the change of angle is not sensitive to the influence of ionospheric loss.

2.3.2 SENSITIVITY ANALYSIS OF TRANSMITTING ANGLE TO SEA LEVEL REFLECTION LOSS

\[
S(L_g, \theta) = \frac{\partial L_g/L_g}{\partial \theta/\theta} = \frac{\partial L_g}{\partial \theta} \times \frac{L_g = 10 \log \left[ \frac{|R_V^2| + |R_H^2|}{2} \right]}{\theta} \quad (19)
\]
When $\theta$ is equal to $49.56^0$, $S(L_g, \theta) \approx 1.748$. That is, when the angle is increased by 1%, the corresponding picture loss will increase by 1.748%, which explain that the change of angle is more sensitive to the influence of sea surface loss.

**MODEL II: RUGGED TERRAIN AND SMOOTH TERRAIN SIGNAL REFLECTION LOSS MODEL**

**Model Establishment**

In classical electromagnetic theory applications, the design of mountains or rugged terrain diffraction radio field strength can be expressed as:

$$\frac{E}{E_0} = F e^{i\Delta \phi}$$

(20)

In the formula, $E_0$ is a free-space electromagnetic field when there is no mountains or rugged terrain diffraction, $F$ is the diffraction coefficient, and $\Delta \phi$ is the phase difference with respect to the path of the direct wave. Due to the diffraction loss:

$$\xi = 20\log F$$

(21)

In the formula

$$F = \frac{S + 0.5}{\sqrt{2 \sin(\Delta \phi + \pi / 4)}}$$

(22)

Kirchhoff's theory of diffraction has helped to predict the predicted path loss along mountains and similar obstacles. In the mountains or rugged terrain diffraction, the introduction of a diffraction constant $v$, which is a dimensionless parameter, defined as:

$$v = -h_p \sqrt{\frac{2 (\frac{1}{r_1} + \frac{1}{r_2})}{\lambda}}$$

(23)

In the formula, $r_1$ and $r_2$ are different distances, and $h_p$ is the height of the mountain. Two possible scenarios must be considered in predicting the effect of the mountains or rugged terrain diffraction: the first one is when the radio waves are not obstructed by the obstacle to reflect in the smooth terrain, and the second is when the radio waves are diffracted by the mountains or rugged terrain.
SMOOTH TERRAIN

Figure 9 shows the first case where radio waves are diffracted in a smooth area, so \( h_p \) is a negative value and \( v \) becomes a positive value. When \( v \) is a positive value, the range of the diffraction coefficient \( F \) can be expressed as:

\[
0.5 \leq F
\]  

(24)

MOUNTAINS OR RUGGED TERRAIN

The second case is shown in Figure 10. When the radio wave is diffracted by a mountain, \( h_p \) is therefore a positive value and \( v \) becomes a negative value. In this case, when \( v \) is a negative value, the range of the diffraction coefficient \( F \) can be expressed as:

\[
0 \leq F \leq 0.5
\]  

(25)

The approximate diffraction loss is:

\[
L = \begin{cases} 
0 & \text{if } v \leq -2.4 \\
20\log(0.5 + 0.62v) & -2.4 < v \leq -1 \\
20\log(0.5e^{0.6v}) & -1 < v \leq 0 \\
20\log(0.4 - \sqrt{0.1184 - (0.1v + 0.38)^2}) & 0 < v \leq 1 \\
20\log\left(\frac{0.225}{v}\right) & v > 1
\end{cases}
\]  

(26)
Determination of the Model

Due to the random nature of sea surface movement similar to the mountainous area, we use the sea reflection simulation established by Problem 1. The figure below shows the surface reflection simulation results:

We maintain the dielectric constant of the medium, the conductivity constant, only change the roughness, and compare field strength. We found that the electric field intensity after the smooth scene reflection is obviously higher than the field intensity after the rough scene reflection by the results, and the electric field density is relatively concentrated. The relationship between roughness and electric field loss is as follows:

| Table IV. Roughness Effect. |
|-----------------------------|
| $\gamma = 1$ | $\gamma = 0.7$ | $\gamma = 0.4$ | $\gamma = 0.1$ |
|----------------|
| 0.967 | 0.984 | 0.991 | 1.027 |
| 0.974 | 0.996 | 1.013 | 1.029 |
| 0.993 | 1.027 | 1.036 | 1.048 |
We only change the angle of incidence:

Through the figure we can see, the larger the angle of incidence, the more pronounced attenuation for radio transmission. This is due to roughness and angle of incidence. We only change the height of the mountain, comparative analysis of the intensity.

Figure 13. Angle of incidence: $15^0$.
Figure 14. Angle of incidence: $45^0$.

Figure 15. Roughness $\gamma = 0.4$.
Figure 16. Roughness $\gamma = 0.1$. 
TABLE V. ANGLE EFFECT.

|   | $\theta = 15^0$ | $\theta = 45^0$ | $\theta = 75^0$ |
|---|----------------|----------------|----------------|
| 0.904 | 0.973 | 1.025 |
| 0.934 | 0.994 | 1.137 |
| 0.968 | 1.014 | 1.051 |

The larger the angle, the rougher the surface, the more energy radio transmission losses. Angle of incidence and radio transmission loss are as follows:

We can see from the graph, the color of the middle part of the smooth topography is higher than the reflection after the mountain reflection. This is due to the terrain caused by the uneven surface, radio transmission energy loss and more.

Result Analysis

By comparing the sea-reflected signal attenuation with the land-reflected signal attenuation, we find that the mountain signal attenuation is more stable than the turbulent ocean signal attenuation, facilitating the calculation and study. And the difference in signal attenuation between high mountains and smooth surfaces is much greater than the signal attenuation gap between turbulent and calm seas.

From the Figure 15 and 16, the higher the ground relative altitude, the higher the roughness of the ground, the lower the roughness coefficient, the stronger the absorption loss to the electromagnetic wave.

CONCLUSIONS

This paper fully considers the whole process of signal loss caused by multi-hop propagation of high-frequency radio waves in the ocean. The model of ocean signal reflection loss is established by Fresnel reflection coefficient and three-dimensional ocean wave PM spectrum modeling, and the roughness correction coefficient is used to apply the model to the turbulent ocean. By genetic algorithm based on classical nonlinear optimization to solve the model, the maximum number of hops without distortion signal is obtained, which has the advantage of ensuring excellent global search ability and greatly improving the local search ability of the algorithm. Due to the time, we does not study the impact of electromagnetic field changes caused by radio frequency waves reflected by the ocean on the signal loss. In the next study, we will further consider the electromagnetic field changes in this factor.
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REFERENCES

1. Zhong Ren, Chi Xu, Haiyong Zhang. Simulation of Signal to Noise Ratio and Signal to Interference Ratio in Shortwave Communication [J]. Communication Confrontation, 2010(03):29-33.
2. Yajun Bai. Influence of Ionosphere on High Frequency Radio Waves [D]. Xi'an University of Electronic Science and Technology, 2014.
3. Tao Feng. Influence of Ionosphere on MF/HF and Satellite Communication and Navigation and its Solutions: The Fourteenth Session of China Association for Science and Technology the 20th Meeting: Transformational Innovation, New Forum for the Development of Telecommunication Industry, Shijiazhuang, Hebei, China, 2012[C].
4. Qingdi Yi. Study on Electromagnetic Wave Propagation Model in Sea Area [D]. Hainan University, 2015.
5. Hang Dong, Chi Xu, Tao Yi. Research on Auxiliary Decision Model of Shortwave Communication Based on SNR Estimation [J]. Communication Technology, 2014(11):1313-1317.
6. Yin Wang, Jian Gu. Research and Simulation Analysis on Sea Surface Wave Reflectance [J]. Electronic Design Engineering, 2016(05):113-115.
7. Xuelian Yang. Research on Modeling of Ocean Surface Wireless Channel Based on Ray Tracing [D]. Xiamen University, 2014.
8. Dockery D, Kuttler J R. An Improved Impedance-Boundary Algorithm for Fourier Split-step Solutions of the Parabolic Wave Equation[J]. IEEE Transactions on Antennas and Propagation, 1996, 44; 44(12; 12):1592-1599.
9. Gouliang Zhou, Jiancheng Ye. Design and Simulation of Polar Shortwave Communication in Earth [J]. Computer Simulation, 2015(05):226-229.
10. Wei Yang. Modeling and Characteristic Analysis of Three Dimensional Complex Rough Sea Surface Electromagnetic Scattering [D]. University of Electronic Science and Technology, 2012.
11. Min Zhu. Radio Channel Propagation Prediction Based on Electronic Map [D]. Xi'an University of Electronic Science and Technology, 2009.
12. Z Yun, Wanting M, Qiming G, Etal. Detection of Bohai Bay Sea Ice Using GPS-Reflected Signals[J]. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2015, 8; 8(1; 1):39-46.