Research on the propagation of radio waves in the marine environment

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Abstract: Since the marine environment is more complex than the terrestrial environment, a Multi-parameters model of Reflection Coefficient (ORPM) is established to study the propagation of radio waves in the marine environment. By comparing reflection coefficients off a turbulent ocean and a calm ocean, it is found that the turbulent and reflection coefficient are inversely related and the finding is correspond with actual situation. Then do research on the propagation of high frequencies (HF) radio in the atmosphere. By combining it with ORPM, the Model for the Maximum Number of Hops (NOHF) is established to figure out the maximum number of hops the signal can take before its strength falls below a usable signal-to noise ratio (SNR). Finally the sensitivity analysis of ORPM and NOHF is performed, and the results are clear.

1. Introduction

Wireless Communication, the common way that we use to transmit information today, depends on multiple reflections of HF radio. For HF radio which frequencies range from 3-30MHz transmits by skywave, it means HF radio reflect successively between ionosphere and reflecting surface until it can’t keep useful signal integrity. During the complicated radio propagation, lots of factors would affected the strength of the reflected wave, including the water vapor aerosol and suspended solid particles in troposphere, Atmospheric Refractive Index (ARI) and the characteristics of the reflecting surface [1]. During exist researches of electromagnetic wave transmission, there are two important conclusions: Helmholtz equation and Skin Effect. Helmholtz equation indicates that the propagation of electromagnetic fields in a lossless medium is not attenuated [2]. Skin Effect indicates that HF radio could only exits on the thin surface of good conductor while there are none HF radio inside the good conductor [3].

This research builds ORPM with 100-watt HF constant-carrier signal which is transmitted from the ground and has a frequency below the maximum usable frequency to determine its first reflection intensity in the turbulent ocean. Then establishes NOHF to determine the propagation distance of the HF radio.

2. Establishment of ORPM

2.1. The boundary conditions of time-varying electromagnetic field

The differential form of Maxwell's equations describes the variation of an electromagnetic field in one
medium. However, in actual problems, there are often interfaces of different media. Assuming the permittivity, magnetic permeability and conductivity of medium 1 and medium 2 are $\varepsilon_1, \mu_1, \sigma_1$ and $\varepsilon_2, \mu_2, \sigma_2$ respectively. The field components are $E_1, D_1, H_1, B_1, J_1$ and $E_2, D_2, H_2, B_2, J_2$ respectively. And the normal vector of interface is expressed as $n$.

If both media are ideal, there is no surface charge or surface current on the interface. Under this situation, the conditions of interface are:

$$n \times (E_1 - E_2) = 0$$
$$n \times (D_1 - D_2) = 0$$
$$n \cdot (B_1 - B_2) = 0$$
$$n \cdot (H_1 - H_2) = 0$$

If medium 1 is ideal and medium 2 is the ideal conductor, the conditions of interface are:

$$n \times E_1 = 0,$$
$$n \times H_1 = 0,$$
$$n \cdot D_1 = 0,$$
$$n \cdot B_1 = 0$$

These equations show that for ideal conductors in time-varying field, the electric field always perpendicular to the ideal conductor while the magnetic field always tangent to the ideal conductor [4]. There is neither an electric field nor a magnetic field inside the conductor.

2.2. The oblique incidence of interface

When the electromagnetic wave propagates to the surface in $\alpha^t$ direction, some part is reflected in $\alpha^r$ direction, the other part is transmitted into medium 2 in direction $\alpha^t$, and the angle $\theta^t$ between the transmission line and the normal of the reflecting surface calls transmission angle.

The Angular Frequency is represented by $\omega$ which can represent the propagation constants $K_1$ and $K_2$ in the medium 1 and the medium 2.

$$k_1 = \omega \sqrt{\mu_1 \varepsilon_1}$$
$$k_2 = \omega \sqrt{\mu_2 \varepsilon_2}$$

Normally, magnetic permeability of general medium is close to free space which is $\mu_1 = \mu_2 = \mu_0$ [5]. Combing Snell’s Law, could get the following conclusion [6]:
\[
\frac{\sin \theta_t}{\sin \theta_i} = \sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \tag{1}
\]

2.3. Creation and Result of the ORPM

To study the loss of reflections off the ocean surface, building a multi parameters model based on Matlab — Ocean Reflection Parameter Model (ORPM). According to previous studies, these following parameters are choosen: the permeability of the ocean \(\varepsilon_1\), the permeability of the air \(\varepsilon_2\), the angle \(\alpha\) between the incident wave and the horizontal plane, the angle \(\beta\) of the reflection surface and the height of the reflection surface and electromagnetic gradient of seawater \(\eta_2\).

The permeability of general medium is close to that of free space \(^7\), therefore we assume that \(\varepsilon_1\) and \(\varepsilon_2\) are constant values. However, ocean turbulence alters \(\varepsilon_2\), therefore a quantitative relationship is established between ocean turbulence and \(\varepsilon_2\), and using the angle \(\beta\) to quantify the ocean turbulence, it means the bigger \(\beta\) is, the more turbulent the ocean is.

Because incident angle \(\theta_i\) and refraction angle \(\theta_t\) affect the reflection coefficient, it is necessary to find a way to express \(\theta_i\) and \(\theta_t\). When \(\theta_i\) is known, \(\theta_t\) could be calculated by equation (1). Also, by building flat model which is shown in picture 3, it is found that \(\theta_t\) could be expressed by \(\alpha\) and \(\beta\):

\[\theta_t = \frac{\pi}{2} - \alpha - \beta.\]

By reading documents, it is found that the permeability of ocean has little effect on the reflection of HF radio \(^8\). To simplify the model, this parameter is neglected.

By referring to previous studies, the reflection coefficient and the projection coefficient could be expressed as following where \(\Pi_1\) and \(\Pi_2\) indicate wave impedance of the air and the ocean respectively:

\[
R = \frac{\Pi_2 \cos \theta_t - \Pi_1 \cos \theta_i}{\Pi_2 \cos \theta_i + \Pi_1 \cos \theta_t} \tag{2}
\]

\[
T = \frac{2 \Pi_2 \cos \theta_i}{\Pi_2 \cos \theta_i + \Pi_1 \cos \theta_i} \tag{3}
\]

When the ocean becomes more turbulent, \(\varepsilon_2\) would become smaller while \(\varepsilon_1\) keep same. And \(\varepsilon_2\) would affect \(\Pi_2\), according formula (2), the reflection coefficient would change finally.

With the help of MATLAB, the strength of the first reflection off ocean which is expressed by reflection coefficient \(R\) is calculated and shown in table 1 and picture 4.

| Turbulence | \(\varepsilon_1\) | \(\varepsilon_2\) | \(\beta\) | \(R\) |
|-----------|-----------------|-----------------|--------|------|
| 0%        | 1.000585\(\varepsilon_0\) | 81.5\(\varepsilon_0\) | 0      | 0.8666 |
### Table 1: Relationship between R and turbulence

| Percentage | C₀ | α₀ | β₀ | γ₀ | ε₀ | Δε₀ | μ₀ | θ₀ | ρ₀ | σ₀ | ε₀ | Δε₀ | μ₀ | θ₀ |
|-----------|----|----|----|----|----|-----|----|----|----|----|----|-----|----|----|
| 10%       | 1.000585ε₀ | 0.9 × 81.5ε₀ | π/6 | 0.8021 |
| 20%       | 1.000585ε₀ | 0.8 × 81.5ε₀ | 2π/9 | 0.7825 |
| 30%       | 1.000585ε₀ | 0.7 × 81.5ε₀ | 5π/18 | 0.7661 |
| 40%       | 1.000585ε₀ | 0.6 × 81.5ε₀ | π/3  | 0.7530 |
| 50%       | 1.000585ε₀ | 0.5 × 81.5ε₀ | 7π/18 | 0.7430 |

Figure 4: The relationship between R and turbulence

### 3. Establishment of NOHF

#### 3.1. The Attenuation of HF Radio in Troposphere

It is found that when HF radio propagate through troposphere, the free space loss would happen which caused by the increase of propagation and medium transmission loss caused by various obstacles in the troposphere. To simplify the model, just consider the attenuation of HF radio when it propagate through loss-free medium — Free Space Loss:

\[
L_0 = 3.24 + 20 \log_{10} d + 20 \log_{10} f
\]  

(4)

Where \( L_0 \) means Free Space Loss, \( d \) means the distance of propagation and \( f \) means the frequency of HF radio.

#### 3.2. The Calculation of Initial Values

When the strength of signal falls below a usable signal-to-noise ratio (SNR) threshold of 10 dB, it would be useless, therefore it is necessary to calculate the maximum number of hops.

Assuming that \( \alpha = 40^\circ, f = 16.9 \text{MHz}, D = 50 \text{km} \) where \( D \) represents the distance between the reflection surface and the ionosphere, then \( d \) would be calculated as 155.5274 km. So the attenuation of HF radio during one reflection of this signal off the ionosphere \( S_1 \) could be calculated out by equation (4): 100.7964 dBm.

As for a 100-watt HF constant-carrier signal, its strength could be measured by dBm using the following formula.

\[
x \text{ dBm} = 10 \times \log_{10} y \text{ mW}
\]  

(5)

Therefore, the initial power of HF radio could by calculated out: 99657.8428 dBm.

#### 3.3. The Calculation of Initial Values

The strength of wave after reflection could be calculated by multiplying the initial strength of wave with \( R \). Generally, there just exists addition and subtraction between dBms which quantify power. By inquiring information, it is known that the subtraction between dBms represents division between two powers. Therefore the signal to SNR could be represented by subtraction between powers of wave. After calculation, the maximum number of hops could be calculated as 34.
Table 2: The Maximum Number of Hops

| The Number of Hops | The Power of Wave before Reflection(dBm) | The Power of Wave after Reflection(dBm) | SNR(dB) |
|--------------------|------------------------------------------|----------------------------------------|---------|
| 0                  | 99657.84                                 | 99657.84                               |         |
| 1                  | 99557.05                                 | 85276.14                               | 13280.91|
| 2                  | 86175.34                                 | 74679.55                               | 11475.79|
| ...                | ...                                      | ...                                    | ...     |
| 18                 | 8040.16                                  | 6967.61                                | 1072.56 |
| 19                 | 6866.81                                  | 5950.78                                | 916.03  |
| 20                 | 5849.98                                  | 5069.59                                | 780.39  |
| ...                | ...                                      | ...                                    | ...     |
| 33                 | 8040.16                                  | 235.16                                 | 36.20   |
| 34                 | 6866.81                                  | 116.44                                 | 17.92   |
| 35                 | 15.65                                    | 13.56                                  | 2.09    |

4. Sensitivity Analysis

4.1. Sensitivity Analysis of ORPM
As mentioned before, the turbulence affects reflection coefficient obviously. In the further discussion of ORPM, the angle $\alpha$ between incident wave and horizontal plane is chosen to evaluate ORPM. By setting $\beta$ equals $0^\circ$ and $30^\circ$ respectively and altering $\alpha$ from $30^\circ$ to $50^\circ$, $R$ could be calculated and shown as following. It is found that $\alpha$ has little effect on $R$.

Table 2: The Change of R Caused by $\alpha$ (when $\beta = 0^\circ$)

| $\alpha$ | $\beta$ | R    |
|----------|---------|------|
| 30°      | 0°      | 0.8946|
| 35°      | 0°      | 0.8800|
| 40°      | 0°      | 0.8666|
| 45°      | 0°      | 0.8543|
| 50°      | 0°      | 0.8432|

Table 3: The Change of R Caused by $\alpha$ (when $\beta = 60^\circ$)

| $\alpha$ | $\beta$ | R    |
|----------|---------|------|
| 30°      | 60°     | 0.8005|
| 35°      | 60°     | 0.8012|
| 40°      | 60°     | 0.8032|
| 45°      | 60°     | 0.8066|
| 50°      | 60°     | 0.8113|

4.2. Sensitivity Analysis of NOHF
By changing frequency and $\alpha$ respectively, the maximum number of hops is calculated and shown as following. It is found that $\alpha$ has great effect on the maximum number of hops while the frequency of HF radio has little effect.

Table 4: The Change of the Maximum number of Hops by Frequency ($\alpha = 40^\circ$)

| Frequency of HF Radio (mHz) | Attenuation during Atmosphere (dBm) | Maximum Number of Hops |
|-----------------------------|-------------------------------------|------------------------|
| 3                           | 85.78                               | 35                     |
| 12                          | 97.82                               | 34                     |
Table 5: The Change of the Maximum number of Hops by $\alpha$

| $\alpha$ | Attenuation during Atmosphere (dBm) | R     | Maximum of Hops | Number |
|---------|------------------------------------|-------|-----------------|--------|
| 30°     | 102.98                             | 0.8945| 41              |        |
| 40°     | 100.80                             | 0.8666| 34              |        |
| 50°     | 99.27                              | 0.8432| 30              |        |
| 60°     | 98.21                              | 0.8246| 27              |        |
| 70°     | 97.50                              | 0.8113| 25              |        |

5. Conclusion

With the help of electromagnetic theory, a multi-parameter model of reflection coefficient of high-frequency electromagnetic waves propagating on the sea surface is established. Based on the multi-parameter model of reflection coefficient, a multi-hop model of electromagnetic wave propagation is established by combining usable signal-to-noise radio threshold of electromagnetic wave, and the maximum number of hops can be obtained. By Sensitivity Analysis, it is found that the angle $\alpha$ between incident wave and horizontal plane has little effect on ORPM and $\alpha$ has great effect on the NOHF while the frequency of HF radio has little effect on it.

References:

[1] Yan JianHao, Fu Yang, Hong ZhenJie. Introduction to Modern Atmospheric Refraction [M].ShangHai: Shanghai Science and Technology Education Press, 2006.

[2] Wang MinJuan. The Research on Electromagnetic Response Characteristics of Cross-hole Formation Resistivity [D]. Xi’an Shiyou University, 2014.

[3] Zhong CaiChi, Zhang DongBi, Zhong KeWu, etc. Electromagnetism [M]. ShangHai: Scientific Literature Press, 1990. 352-354.

[4] Guo HuiPing, Liu XueGuan. Electromagnetic Field and Electromagnetic Wave [M]. Xi’an: Xidian University Press, 2014.

[5] Xiao xiao, Fu HongLiu, Tang JingTian and etc. Apparent resistivity of electromagnetic waves at oblique incident plane and its influence [J]. Chinese Journal of Geophysics, 2015.

[6] Guo HuiPing, Liu XueGuan. Electromagnetic Field and Electromagnetic Wave [M]. Xi’an: Xidian University Press, 2014.

[7] Wang MinJuan. The Research on Electromagnetic Response Characteristics of Cross-hole Formation Resistivity [D]. Xi’an Shiyou University, 2014.

[8] Yao JiHuan. Study on Electromagnetic Scattering from Rough Sea Surface [D]. Xidian University, 2000.