Reflection of the Multi-hop HF Radio on the Rough Ocean Surface

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Abstract. The HF radio waves can travel long distances using the multi-hop paths between ionosphere and the earth. When the radio waves reflect from the surface of ocean, they are sometimes affected greatly due to the turbulent ocean surface. In this article, we study the impact of the turbulent ocean on multi-hop radio propagation, analyzing different effects of every parameter on the reflection of radio waves from the surface of ocean. We analyze the reflection process from the ionosphere and the effective factors to the ionospheric transmission loss. We find that in the high frequency band, the value of Li stays at a relatively low level. Then, the calculation formulas about the reflection coefficient are shown, which are obtained in the bibliographies. We use MATLAB to simulate the fluctuation of the turbulent ocean surface according to the two-dimensional wave equation. Then we add the light equation into the model, and calculate the reflected direction. With a pre-set screening conditions, we get the proportion of beams that can keep travel forward. As a simplified model, we regard the ratio of these beams as the reflection coefficient. The coefficients in different situations of turbulent are shown respectively.

Keywords: reflection, ocean surface, multi-hop.

1. Background

With the development of high frequency (HF) radio communication, the information exchange between long distance has become easier than ever before. But the transmission loss during the propagation of the radio wave is a severe problem, which may reduce the quality of the information. What’s more, because of the multipath effect, the receiver set in the communication chain may receive several signals which arrive with a different time-lag, and this phenomenon will generate undesirable error codes. Study the process in the multi-hop propagation is an essential subject in today’s wireless communication field, and the reflection occurring on the turbulent ocean is an important section. Our task is to build a model to simulate the motion of the ocean wave, and predict the HF radio reflection on the surface of the turbulence.

2. Analysis of the Reflection Loss in the Ionosphere

Due to the ability of ionized atmospheric gases to refract high frequency (HF, or shortwave) radio waves, the ionosphere can reflect radio waves directed into the sky back toward the Earth. The returning radio waves can reflect off the Earth's surface into the sky again, allowing greater ranges to be achieved with multiple hops.*

Figure 1. Radio waves (black) reflecting off the ionosphere (red) during skywave propagation.
We use the equation to calculate the ionospheric loss coefficient:

\[
L_I = I \frac{677.2 \sec{i_{100}}}{(f + f_0)^{1.98} + 10.2}
\]

\[
I = (1 + 0.0037f_12)(\cos{0.881})^{1.3}
\]

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

Where: \(I\) denotes for the absorption coefficient, \(i_{100}\) denotes for the wave incident angle at a height of 100km, \(\Delta\) denotes for the ray elevation. Other parameters can be found in the chart (Liu Maochun, 1988). Figure 2 shows the trend of \(I\) varied with \(\Delta\).

![Figure 2. The absorption loss curve](image)

From Figure 2, we notice that the absorption loss drops with the increase of ray elevation angle. And higher frequencies means lower absorption. We set the ray elevation angle as 20 degree, and get the value of \(I\) equal to 4.3879 dB.

3. The Determination of the Reflection Coefficient

When reflecting from the ionosphere, the radio wave will travel down to the surface of the ocean and make a reflection. The reflecting characteristics are determined by sea condition, where the calm ocean shows better optical features compared with the rough one. In order to distinguish the smooth and rough ocean surface, the Rayleigh Criterion is introduced:

\[
\rho_h < \frac{\lambda}{8 \sin{\theta_t}}
\]

Where =: \(\rho_h\) is the mean square wave height, \(\lambda\) is the wavelength of the incident wave, \(\theta_t\) is the satellite elevation angle. Using this criterion, we can decide whether an ocean surface of different wave height ought to be regarded as a smooth or a rough one. It is worth noting that the radio wave itself also participate in the judgment between different styles of ocean surface.

In the context of our current problem, the value of parameters can be estimated according to our assumption. We have listed the value range of these parameters in Table 1 and Table 2:

| Table 1. Value estimation of relevant parameters |
|-----------------|-----------------|
| \(\lambda/m\)   | \(\theta_t/\circ\) |
| 10 - 100        | 0 - 20          |
Table 2. Mean square wave height

| wind force scale | The sea level of Douglas |
|------------------|--------------------------|
|                  | Mean square wave height (m) | Description of roughness length |
| 0                | no wave                   | Calm (Glassy)                     |
| 1                | 0–0.10                    | Calm (rippled)                     |
| 2                | 0.10–0.50                 | Smooth                             |
| 3                | 0.50–1.25                 | Slight                             |
| 4                | 1.25–2.50                 | Moderate                           |
| 5                | 2.50–4.00                 | Rough                              |
| 6                | 4.00–6.00                 | Very rough                         |
| 7                | 6.00–9.00                 | High                               |
| 8                | 9.00–14.00                | Very high                          |
| 9                | 14.00+                    | Phenomenal                         |

Both the reflection from the rough and smooth ocean surface are effected by their optical characteristics, so we will start with searching the relation between reflection coefficient and some variances. On the surface of a smooth ocean, which can be seen approximatively as a specular surface, Fresnel reflection coefficient is ascertained by electromagnetic wave frequency, polarization mode, satellite elevation angle and surface type. The vertical polarization and Horizontal polarization is given by:

\[
\rho_v = \frac{\varepsilon \sin \theta_t - \sqrt{\varepsilon - \cos^2 \theta_t}}{\varepsilon \sin \theta_t + \sqrt{\varepsilon - \cos^2 \theta_t}}
\]

\[
\rho_H = \frac{\sin \theta_t - \sqrt{\varepsilon - \cos^2 \theta_t}}{\sin \theta_t + \sqrt{\varepsilon - \cos^2 \theta_t}}
\]

Where, \(\varepsilon\) is the water complex permittivity. The computational formula of \(\varepsilon\) is shown as bellows:

\[
\varepsilon = \varepsilon' - i\varepsilon''
\]

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

\[
\varepsilon'' = \frac{2\pi f\tau}{1 + \left(2\pi f\tau\right)^2} + \frac{\sigma_s}{2\pi \varepsilon_0 f}
\]

Where, \(f\) is frequency of electromagnetic wave and its unit is Hz, \(\varepsilon_0\) is the permittivity of free space and \(\varepsilon_{ir} = 8.854 \times 10^{12} \text{F/m}\). \(\varepsilon_{ir}\) is the sea water dielectric permittivity and \(\varepsilon_{ir} = 4.9\). \(\tau\) is the relaxation time of sea water, \(\sigma_s\) and \(\varepsilon_s\) are the ionic conductivity and the static permittivity of sea water. According to the*****, when the water temperature \(T\) is taken as 28°C and the global average value of salinity \(S\) is 3.254%, \(\varepsilon, \varepsilon', \varepsilon''\) are respectively equal to 77.1404, 7.5177e-12 and 55.1151e-4.

Now we can further discuss the reflection coefficient of the smooth ocean surface. When the \(\rho\) is small enough and satisfy the Rayleigh Criterion, the following equation can be used to calculate specular reflection coefficient:

\[
\rho = \rho_o \rho_s
\]

\[
\rho_s^2 = \begin{cases} 
    \exp(-2(2\pi f)^2) & 0 < f < 0.1 \\
    0.812537 & f > 0.1 
\end{cases}
\]

\[
\Gamma = \frac{\sigma_s \sin \theta_t}{\lambda}
\]

Using formulas above, we can get a general description of the reflection properties of different kinds of ocean surface. After calculating the value of \(\rho\) based on the \(\lambda\) and \(\theta\) given above, we draw the following curve:
Likewise, we use a series of similar equations to describe the characteristics of a rough ocean surface. The diffuse reflection coefficient of rough surface is defined by the following formulas:

\[ \beta = \rho_o \rho_d \]

\[ \rho_d = \begin{cases} \sqrt{2} |\rho_o| 3.68 \Gamma, & 0 < \Gamma < 0.1 \\ \sqrt{2} |\rho_o|(0.454 - 0.858 \Gamma), & 0.1 < \Gamma < 0.5 \\ \sqrt{2} |\rho_o| 0.025, & \Gamma > 0.5 \end{cases} \]

The total transmission loss is equal to the loss in the process of reflecting from the ionosphere and from the ocean surface. So, we get two equations as follows:

\[ L_{\text{total}} = L_i + L_s \]
\[ L_s = 10 \log \tau^2 \]

When the radio off the calm ocean takes additional hops, we assume that it will repeat the process identical to the first one which contains a reflection from the ionosphere and another from the calm ocean surface.
4. Model of Rough Ocean Surface

Though we have made a general impression on the reflection characteristics of the ocean surface through the existing formula, the model is not specific enough and we seek to find a persuasive way to demonstrate the reflective condition on the rough ocean surface.

In order to simulate the fluctuation of real wave in a turbulent ocean, we first introduce the two dimensional dynamic wave equation. It conforms to the definition of Fourier spectrum, the data base is good, the calculation is relatively simple, and the analysis and processing is very detailed, so we use the P-M spectrum to simulate the waves.

\[
S(\omega) = \alpha \frac{g^2}{\omega^2} \exp \left\{ -\beta \left( \frac{g}{U\omega} \right)^4 \right\}
\]

The peak frequency of the P-M spectrum is:

\[
\omega_p = 0.877 \frac{g}{U}
\]

The corresponding period is:

\[
T_0 = 2.28\pi U/g
\]

The displacement of wave surface in fixed point is expressed as the following random process:

\[
\zeta(t) = \sum_{n=1}^{\infty} a_n \cos(\omega_n t + \epsilon_n)
\]

The relation between amplitude and spectrum is:

\[
S(\omega)\Delta \omega = \sum_{\omega} \frac{1}{2} a_n^2 \delta(\omega - \omega_n)
\]

Based on the wave equation given above, we plot the curve of wave in the MATLAB. While the roughness of the turbulent ocean can be affected by the wind speed on the surface of turbulent ocean and the radio frequency, we can change these parameters to simulate different states of it.

As the geometrical optics theory cannot be satisfied in the macroscopic perspective, which means the reflected angle can travel in all directions, and it is not possible to establish geometrical relationship with the direct wave, we try to study the microscopic reflection conditions and analyze the proportion of radio wave still traveling forward. However, it is not easy to figure out the real reflected beams considering the properties of seawater, and the scattered radio wave also brings a lot of troubles. To simplify our model, we make some local assumptions:

- We assume that the majority of the radio wave propagates in a certain multi-hop path and can be seen as a light beam, because we only consider the signal that can be received by the antenna.
- The refraction from the ocean surface is very little, so we only consider the reflection process. This means there will be no power absorption by the ocean, and the beam can go on with its path at its initial strength.
- The secondary or multiple reflection is ignored for simplicity.

Now, we add a beam of radio wave to the surface of turbulent ocean. We get the slopes of some points on the turbulent surface in the two-dimensional wave curve and calculate the reflected direction of every beam. Among these reflected beams, only those with a proper reflected angle can keep travelling forward (see the illustration of Figure 6), and we set the range of reflected angle from 5 degrees to 35 degrees. Figure 7 shows the slopes of reflected radio waves. The result has taken the roughness of the surface into consideration.
Figure 6. Illustration

This is a three-dimensional illustration, the yellow arrows represent the light beams, the green part is the sea surface. The black box is displayed to judge whether a light beam can keep traveling forward according to whether it travels through the box.

Figure 7. The calculation of reflected light slopes

Since it is apparent that only a small part of the incident radio wave can meet our criterion, we figure up the ratio of reflected beam forward. This can be viewed as the two-dimensional reflection coefficient in this simplified model. Though the single simulation of the turbulent surface is random, it can show some certain features after many times of repetition.

5. Model Application in Different Types of Terrain

We know that there is a big difference between the physical characteristics of the land and ocean. Here we list the relative permittivity and conductivity of land and ocean in Table 3:

|       | $\varepsilon$ | $\sigma$ |
|-------|---------------|----------|
| land  | 4             | 1.00E-03 |
| sea   | 80            | 4        |

When waves diffuse from air to soil, the interface between air and ground produces reflection and transmission. Therefore, the electromagnetic waves on the ground are the combined effect of the incident waves and the reflected waves, and it is obviously not the same as that of the incident waves. The following is the reflection coefficient of the soil:

$$R_b = \frac{\sin(\varphi) - [\varepsilon_r \left( 1 + \frac{\sigma}{j\omega \varepsilon} \right) - \cos^2 \varphi]^{1/2}}{\sin(\varphi) + [\varepsilon_r \left( 1 + \frac{\sigma}{j\omega \varepsilon} \right) - \cos^2 \varphi]^{1/2}}$$

Where $\sigma$ denotes electric conductivity of soil, $\varepsilon$ denotes soil permittivity constant of soil and $\varepsilon=\varepsilon_r$. $\varepsilon_r$ denotes relative permittivity constant of soil. We take $z=0$, $\sigma=0.01S/m$, $\varepsilon_r=10$, $\varphi=30$ degrees.

Then figure 8 shows that the ground reflection coefficient changes with the incident wave frequency within the range of 5-30MHz. From the curve we can know that the reflection coefficient of mountain ground is still below 0.0353, but the reflection coefficient of the flat ground remains in
the neighborhood of 0.52, which is far more bigger than the reflection coefficient of mountain. Therefore, we can draw the conclusion that the mountain electromagnetic wave has no reflection in the range of allowable error and the flat ground electromagnetic wave reflects part of all. This conclusion is different from the reflection on sea surface and the calm sea surface.

![Figure 8. Ground reflection coefficient changes with the incident wave frequency Within the range of 5-30MHz](image)

**References**

[1]. Huang Fang, Research on Characteristics of Maritime Wireless Radio Propagation and Channel Modeling [D], Hainan University, 2015.

[2]. Ding Y, Sun J, Wang X. Sea Surface Reflection and Power Attenuation Analysis of Radio Wave in UHF Satellite Communications [J]. Telkomnika Indonesian Journal of Electrical Engineering, 2014, 12(4).

[3]. REN Zhong, XU Chi, ZHANG Hai-yong, HUANG Xiao-fei, Modeling and Simulation of SNR and SIR in HF Communication System [J], Communication Countermeasures, 2010 (3): 29-33.

[4]. Si Lihong, Ao Faliang, He Ning, Study of upward transmission characteristics in submarine laser communication [J]. Optical Technique, 2007, 33 (s1): 234-236.

[5]. Liu Maochun, Radio Interference Calculation [M], National Defence Industry Press, 1988.

[6]. Wang Caiyun, Channel Simulation of Wireless Optical Communication across the Air-sea Interface [J], Guilin University of Electronic Technology, 2007, 33 (s1): 234-236.

[7]. Han Peng, Modeling and Simulation of electromagnetic wave propagation at short and medium ranges [D]. Harbin Engineering University, 2013.