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T4 ________________	**A**	F4 ________________

2018
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Summary Sheet

Modeling a Cooperated Sea Communication based on Multipath HF Radio Propagation

We analyze the **propagation** of **multi-hop HF radio** waves on the **ocean surface** by establishing several mathematical models. Our efforts in building these models are showed as followed.

In Part I, there are two problems. The first problem requires us to find a 100-watt HF's **signal strength**. The HF radio is launched from the land and reflects off the ionosphere and the ocean respectively. The second one is to find the maximum number of **hops** in the calm ocean under the condition that the signal strength is not less than 10 dB during the propagation. We first use the **field strength** at the receiving point to measure the signal strength. After that, we use the maximum propagation distance of the signal to measure the number of hops. Clearly, the distance is greatly affected by the signal strength.

Therefore, how to calculate the field strength becomes the key point to establish our models. The first model we set up is **Ocean-Wave Model**, which divides a turbulent ocean and a calm ocean by the standard deviation of sea wave height. The **reflection coefficient** of different ocean surfaces determines signal transmission loss. Then, by considering free space propagation loss, ionospheric absorption loss, ocean surface reflection loss and additional systematic loss, we can establish **Skywave-Field-Strength Model**. Based on these models, we can calculate the value of field strength at the reflecting point on the ocean surface.

In Part II, we use modified Ocean-Wave Model which divides a rugged terrain and a smooth terrain by the altitude of the ground. Then we use Skywave-Field-Strength Model to calculate the strength of the reflection off different ground surface.

Compared with Part I, we found that the reflection loss of a rugged terrain is larger than the reflection loss of a turbulent ocean. However, the reflection loss of a smooth terrain is the same as the reflection loss of a calm ocean.

In Part III, we take the diffuse reflection into consideration, because the ocean surface is not always calm. Additionally, some factors that we ignore above such as the interference caused by other ships are taken into consideration. What's more, we introduce glistening surface to describe the time remains in communication using the same mult-hop path.

Finally we make sensitivity analysis on the range of radio frequency which proves our models to be feasible and applicable. We discuss the strengths and weaknesses based on our model. Besides, our team put forward the further improvement of these models.

Keywords: propagation, multi-hop, ocean surface, reflection coefficient, field strength

Modeling a cooperated sea communication based on multipath HF radio propagation

***Abstract*—As is known to us all, a ship travelling across the ocean use HF radio to communicate. We can analyze the multipath HF radio propagation on the ocean surface by establishing several mathematical models. We first set up Ocean-Wave Model to describe the reflecting surface. Then, we establish the Skywave-Field-Strength Model to calculate the signal strength at the receiving point. This model is based on the ideal situation. The signal transmission loss on the ocean surface is determined by a specular reflection coefficient. Further, we take the diffuse propagation into account because the ocean isnt always calm in reality.**

Keywords: reflection coefficient, signal strength, multipath HF radio, specular reflection, diffuse reflection

I. Introduction

HF radio waves can be transmitted to the distant by the back-and-forth reflections off the ionosphere and the earth's surface. The ionosphere can change the radio wave propagation direction, introducing refraction, reflection, scattering and so on. In addition, radio waves will be absorbed in varying degrees while reflecting off the ionosphere.

The reflection on the earths surface is divided into ground reflection and ocean reflection. The characteristics of different reflection surfaces determine the signal transmission loss by the reflection coefficient and other factors.

We focus particularly on the reflection of HL waves reflected off the ocean surface. When the initial power of HF radio waves is constant, the strength of the signal and the distance of the propagation mainly depend on the signal transmission loss, which mainly includes the transmission loss of the signal in the air, the absorption loss of the ionosphere, the reflection loss of the Earth's surface and other systematic losses. Therefore, whether radio waves can propagate forward or not depends on whether the remaining signal intensity can support the occurrence of the next reflection.

In actual life, ships traveling across the ocean communicate by receiving wireless signals to obtain corresponding weather and traffic information. The signal is propagated not only by reflection but also by scattering and other factors.

II. MODELS

A. Ocean-Wave Model

We assume that the ocean waves are mainly superimposed by certain number of sine waves and its probability density function is a random distribution function on the wave height δ_H. Function(1)(7)(8) are based on the essay [3]

$$D(\eta) = \frac{1}{2\pi^{\frac{3}{2}}\delta_H} exp(-\frac{-\eta^2}{8\delta_H^2} \cdot K_0(\frac{\eta^2}{8\delta_H^2})) \tag{1}$$

Where K_0 is the second-order zero-order Bessel function.

B. Skywave-Field-Strength Model

Our team establish Skywave-Field-Strength Model for the propagation of radio waves on the ocean surface. Under the ideal circumstance, We only consider specular reflection off the ocean surface. The formula is displayed as followed :

$$E = 137.2 + 20lgf(MHz) + 20lgP_0 + G_t - L_b \tag{2}$$

Where f is Range of the high frequencies radio waves, P_0 is initial transmitted power, G_t is the amplitude gain of transmitting antenna in the direction of launching elevation angle, L_b is the basic transmission loss of skywave. Basic transmission loss of skywave L_b always consists of four parts, that is Basic transmission loss in free space L_{bf} , absorption loss in ionosphere L_i, reflection loss from sea surface L_g and additional systematic loss Y_p.

Basic transmission loss in free space can be calculated as followed

$$L_{bf} = 32.45 + 20lgf(MHz) + 20lgd(km) \tag{3}$$

Where d is the distance of effective route of the radio propagation.

We simplify that the loss of HF radio waves in ocean is only related to their reflection coefficient $_rho$. The relevant calculating formula is:

$$L_g = -10lg|\rho| \tag{4}$$

Where $0 < |\rho| < 1$.

$$\rho = \rho_0 \cdot r \tag{5}$$

Where θ is the grazing incidence angle and is equal to the size of the launching elevation angle irrespective of the change of the reflection angle. ρ_0 is the reflection coefficient of the smooth sea surface. From the essay [1] , we know its value is

$$\rho_0 = \frac{sin\theta - \sqrt{\epsilon - cos^2\theta/\epsilon^b}}{sin\theta + \sqrt{\epsilon - cos^2\theta/\epsilon^b}} \tag{6}$$

Where ϵ is the permittivity of seawater.

Put the wave model into

$$r = \int_{-\infty}^{+\infty} exp(\frac{4\pi fi}{c}\eta sin\theta)D(\eta)d\eta \tag{7}$$

we can get

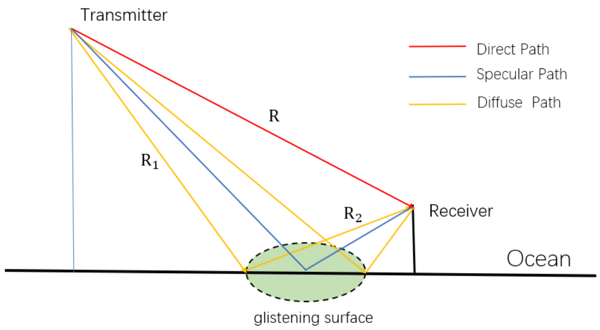

Fig. 1. Diffuse reflection process

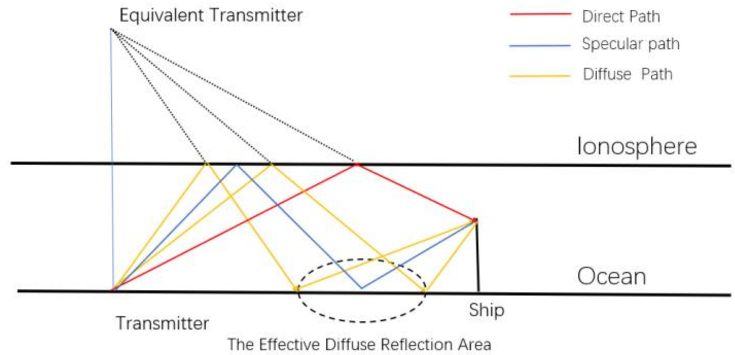

Fig. 2. Improvement of diffuse reflection transmission

$$r = \frac{\sqrt{2}}{\pi^{\frac{3}{2}}} \int_0^{+\infty} x^{-\frac{1}{2}} exp(-x) cos(\frac{8\sqrt{2}\pi f \delta_H}{c}\sqrt{x}) K_0(x) dx \tag{8}$$

Among them, c is light speed, which is 299792458 m / s, δ_H is the root mean square(RMS) wave height, f is the frequency of HF radio wave.

C. Diffuse Reflection Attenuation Model

In reality, the ocean surface is not always calm. So we assume that the propagation of radio waves on the ocean surface should consider diffuse propagation in addition to the specular reflections discussed above. Therefore, we establish a diffuse model of radio waves on the ocean surface in this section. According to related literature [2], we can get the general diffuse reflection formula, which is stated as:

$$L(t_d) = \frac{P_R(t = (r_{TS} + r_{SR})/c)}{P_T(t = 0)} = \frac{\lambda^2 \sigma}{(4\pi)^3 r_{TS}^2 r_{SR}^2} \tag{9}$$

where
λ is the wavelength. σ is scattering cross section of the target. P_T, P_R are transmitted and received powers respectively r_{TS}, r_{SR}, r_{TR} transmitter/scatter, scatter/receiver, transmitter/receiver path lengths respectively.

We generally think that the path of the specular reflection comes from a point on a surface, and the diffuse one comes from a region nearby. Therefore, how to calculate the area and position of the glistering surface becomes the key point to establish the diffuse reflection model.

As Haspert explained to us in his studyHaspert,2010,we can simplify this glistening surface to a flat oval,Fig.1 . This will provide the great convenience on modeling diffuse reflection. In the meantime, Haspert explains in his paper how to calculate the location and extent of effective glistening surface area.

Hence, we can figure out the value of the diffuse reflection cost at sea surface diffuse model.

III. Conclusion

Because the skywave transmission works through the reflection of ionosphere layer, which is different from the multipath propagation model (i.e. figure). The model established in this paper is improved to apply the diffuse reflection model off sea surface. We assume the ionosphere as a mirror, and then we can create an equivalent transmitter. This equivalent transmitter does not exit in the real world but it's very practical on our numerical valuation.

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1 Introduction

1.1 Background

HF radio waves can be transmitted to the distant by the back-and-forth reflections off the ionosphere and the Earth's surface. The ionosphere is the part of the Earth's atmosphere that is ionized by solar rays and is the inner boundary of the Earth's magnetosphere. [3] It can change the radio wave propagation direction, introducing refraction, reflection, scattering and resulting in polarization plane rotation. In addition, radio waves will be absorbed in varying degrees while reflecting off the ionosphere. [3] As the radio frequency increases, there exists a critical frequency that allows the radio waves to penetrate the outer space just beyond the ionosphere. This frequency is known as the maximum available frequency (MUF). Only frequencies below MUF can be reflected off the ionosphere back to Earth's surface. The reflection on the ground surface is divided into ground reflection and ocean reflection. The characteristics of different reflection surfaces determine the signal transmission loss by the reflection coefficient and other factors.

We focus particularly on the reflection of HF waves reflected off the ocean surface. When the initial power of HF radio waves is constant, the strength of the signal and the distance of the propagation mainly depend on the signal transmission loss. In order to simplify the model, we do not consider the Earth's curvature, scattering, refraction, diffraction and so on. At this moment, the signal loss mainly includes the transmission loss of the signal in the air, the absorption loss of the ionosphere, the reflection loss of the Earth's surface and other system losses. Therefore, whether radio waves can propagate forward or not depends on whether the remaining signal intensity can support the occurrence of the next reflection.

In actual life, ships traveling across the ocean communicate by receiving wireless signals to obtain corresponding weather and traffic information. The signal is propagated not only by reflection but also by scattering and other factors.

1.2 Restatement

1.2.1 Part I

The problems that we need to solve are shown as followed:

- Determine the first reflection strength off a turbulent ocean and a calm ocean and compare them. The problem is under the circumstance that a 100-watt HF radio wave is launched from a ground-based transmitting station.
- Determine the maximum number of hops of the HF radio wave while maintaining the reflection intensity not less than 10 dB . And the reflection strength is measured by signal-to-noise ratio (SNR).

To solve the problem , we establish two mathematical models based on the propagation of the radio signal on the surface of oceans. Using these models, some variables and standards need to be explained more precisely to facilitate further analysis.

- The characteristics of different ocean surfaces determine the strength of the reflected wave and the effective propagation distance, which is based on the integrity of the signal. We employ the field strength detected at the receiving station to measure the strength of the reflected wave. We also define the effective propagation distance of the signal as the horizontal distance between the transmitting station and the receiving station.

- We interpret the strength of the first reflection off different ocean surface as the field strength at the first reflecting point.
- A hop of the signal includes only one reflection off the ionosphere and off the ocean surface . For example, the first hop of the signal happens when it reflects off the ionosphere and the surface of the ocean in turns.
- Rapid changes may occur in the shape, height, frequency and forwarding direction of a turbulent ocean. To simplify the analysis of the problem and make it easier to understand, we introduce the standard deviation of the sea wave height to distinguish between a turbulent ocean and a calm ocean. In addition, we assume that the radio waves reflected off these ocean surfaces have different reflection coefficient while other factors remain the same.
- The HF radio wave propagation includes the groundwave propagation and the skywave propagation. The former spreads along the ground while the latter spreads after the ionospheric reflections. In this problem, our focus is particularly on the skywave propagation and ignore the effects of the groundwave propagation.

1.2.2 Part II

The problem that we need to solve is to consider the HF radio reflections off mountainous or rugged terrain and smooth terrain by using the models described above, and to compare the results with Part I. According to the characteristics of the reflecting surfaces, we mainly focus on the intensity of the reflected wave and the effective propagation distance of the signal.

1.2.3 Part III

The problem we need to solve is to make a modification of our model, making it satisfy the reality. Actually, the ocean surface is not always calm, so we cannot regard the ocean surface as the ideal reflecting surface and ignore the diffuse reflection. What's more, we assume that the time remains in communication using the same multi-hop path can be measured by the related distance.

1.3 Our Approach

1.3.1 Part I

Our model measures the magnitude of the reflecting strength by detecting the magnitude of the field strength at the signal receiving point. Radio waves launched from a land transmitting station have a certain loss during propagation. The signal strength remaining after the first reflection off the ocean is the first reflection strength of the ocean.

First of all, we establish Ocean-Wave model which use the standard deviation of sea wave height to divide a turbulent ocean and a calm ocean. Secondly, we introduce the reflection coefficient of a rough surface and a smooth surface, which determines the reflection loss from sea surface. Thirdly, we introduce Skywave-Field-Strength model, which mainly considers the basic transmission loss in free space, the ionospheric absorption loss, the reflection loss from the sea surface and other systematic losses.

1.3.2 Part II

After making a careful analysis between mountains and waves, our team find that both of them have a variable related to height. So we use the analogy method to modified the initial Ocean-Wave model. We use the altitude of the ground to divide the rugged terrain and the smooth terrain by using the analogy method. Then, the strength of the reflected wave and the effective propagation distance of the signal are compared with Part I.

1.3.3 Part III

In reality, the ocean surface is not always calm. So we introduce the diffuse reflection to meet the actual needs. To calculate the effective time the ship can receive signal, we define the effective area of diffuse reflection as glistening surface.

2 General Assumptions

- Regardless of the height of the transmitting station and the receiving station. So the route between them can be approximated as a straight line.
- Regardless of the influence of earth curvature. So the ionosphere and the ocean surface can be seemed as parallel.
- Regardless of the altitude difference between the sea level and the ground level . If there exists a large gap between them, the results might be affected by these unrelated variables.
- Regardless of the influences of some irrelevant factors such as the temperature difference and the density difference. The temperature difference and uneven distribution of sea density will introduce deviations.[4]
- Regardless of the scattering phenomenon when the wave encounters with the particles in the air.
- Regardless of the interference caused by the atmospheric noise to the radio wave propagation.
- We assume that the radio waves dont fluctuate randomly during the propagation.
- We assume that the radio waves experience a specular reflection off the ionosphere, because we particularly focus on the reflection off the ocean surface in our research.
- We assume that the ideal receiving and transmitting antenna gain $G_i = G_r = 1$

3 Symbols and Definitions

Symbol	Definition
f	Range of the high frequencies radio waves
δ_h	Standard deviation of the ocean surfaces wave height
ρ	Reflection coefficient of the rough surface(turbulent ocean surface)
ρ_0	Reflection coefficient of the smooth surface(calm ocean surface)
r_0	Correction coefficient of the surface roughness
ϵ	Permittivity of sea water(set as 82 as a constant)
P_0	Initial transmitted power
G_t	Amplitude gain of transmitting antenna in the direction of elevation angle
G_r	Amplitude gain of receiving antenna in the direction of elevation angle
L_{bf}	Basic transmission loss in free space
L_i	Absorption loss in ionosphere
L_b	Basic transmission loss of skywave
L_g	Reflection loss from sea surface
Y_p	Additional systematic loss
E	Field strength of skywave
E_i	Field strength of skywave at the receiving point after the ith hop
d	Distance of effective path of the wave propagation
θ	Launching elevation angle(between launching direction and horizontal ground)
f_H	Magnetic frequency, ranging from 1.21.5MHz

4 Model Construction

4.1 Ocean-Wave Model

In order to simulate the ocean's impact on the propagation of HF radio waves, we introduce a variable called reflection coefficient and approximate it by idealizing the actual surfaces. The reflection coefficient of the ocean surface includes the following three parts, that is the reflection coefficient of the smooth surface, the diffusion coefficient corresponding to the earth curvature, and the correction coefficient of the ocean surface roughness. For simplicity, we do not consider the influence of earth curvature, so the ocean surface reflection coefficient is the product of the reflection coefficient of the smooth surface and the correction coefficient of the ocean surface, which is

$$\rho = \rho_0 \cdot r \tag{1}$$

Where ρ_0 is the reflection coefficient of the smooth sea surface, and its value is

$$\rho_0 = \frac{sin\theta - \sqrt{\epsilon - cos^2\theta/\epsilon^b}}{sin\theta + \sqrt{\epsilon - cos^2\theta/\epsilon^b}} \tag{2}$$

Where ϵ is the permittivity of seawater and θ is the launching elevation angle.

Index $b = 1$ is used for vertical polarization and index $b = 0$ is used for horizontal polarization. Since the skywave we studied is a vertically polarized wave, we take $b = 1$.

We assume that the ocean waves are mainly superimposed by certain number of sine waves and its probability density function is a random distribution function on the wave height δ_H. Equations (3)(4)(5) are based on an essay [6]:

$$D(\eta) = \frac{1}{2\pi^{\frac{3}{2}}\delta_H} exp(-\frac{-\eta^2}{8\delta_H^2} \cdot K_0(\frac{\eta^2}{8\delta_H^2})) \tag{3}$$

Where K_0 is the second-order zero-order Bessel function. Put the wave model into the following formula

$$r = \int_{-\infty}^{+\infty} exp(\frac{4\pi f i}{c}\eta sin\theta)D(\eta)d\eta \tag{4}$$

Then we get

$$r = \frac{\sqrt{2}}{\pi^{\frac{3}{2}}} \int_{0}^{+\infty} x^{-\frac{1}{2}} exp(-x) cos(\frac{8\sqrt{2}\pi f \delta_H}{c}\sqrt{x}) K_0(x)dx \tag{5}$$

Where
c is light speed, whose value is 299792458 m/s;
δ_H is the root mean square(RMS) wave height;
f is the frequency of HF radio wave.

The RMS height of the waves is used to measure the calmness or turbulence of the ocean. Figure 1 is shown below to illustrate the relation between the RMS height of the waves and the state of sea.

According to the above wave height distribution model, we only need to select a specific root mean square height to simulate the wave height distribution model of different waves. Therefore, we can obtain the propagation loss generated by rough surface on HF radio wave reflection. In addition, when the root mean square height is large enough, we can approximate the distribution model of the rugged mountain by Equation (3).

4.2 Skywave-Field-Strength Model

The ionosphere can reflect and absorb radio waves. However, it absorbs very little radio waves at high frequencies. Shortwave (ie, HF radio waves) is the highest effective band in the propagation of radio waves via ionospheric reflections. When the shortwave reflects off the ionosphere back to the earth, it may reflects back to the ionosphere and then back to the earth by the ionosphere. After multiple round trips, the radio waves can spread further and further.

According to the definition, we assume that skywave is the one reflects from the ionosphere back to the earth. Besides, we also assume that skywave propagation is the one that transmits using ionospheric reflection. The high-frequency radio wave propagation we mentioned above belongs to skywave propagation, so we establish the corresponding Skywave-Field-Strength model.

The actual propagation distance of skywaves is closely related to the propagation mode. And the propagation mode of skywaves is determined by many factors such as

State of the sea (wind sea) [edit]

Degree	Height (m)	Description
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

Figure 1:

operating frequency, ionospheric state as well as the distance between the transmitting station and the receiving station. After reading related literature, We can divide the ionosphere into D layer, E layer, F1 layer and F2 layer based on their electronic density. On average, the one-hop distance reflected from layer E is about 2000km while the one-hop distance reflected from layer F is about 4000km. For the further communication distance, it must be a few hops to reach. F2 layer is the main reflection layer of shortwave skywave, whose height is of the range from 225km to 450km. To simplify the model analysis, we choose the F2 layer as the reflecting surface for HF radio waves, using an ionospheric height of 225 km. We also don't take the frequency changes of the HF radio when reflecting off the ionosphere into account.

Skywave-Field-Strength model can be defined as

$$E = 137.2 + 20lgf + 20lgP_0 + G_t - L_b \tag{6}$$

Where

f is range of the high frequencies radio waves in Unit MHz;

P_0 is initial transmitted power;

L_b is the basic transmission loss of skywave;

G_t is the amplitude gain of transmitting antenna in the direction of launching elevation angle.

Basic transmission loss of skywave L_b always consists of four parts, that is Basic transmission loss in free space L_{bf} , absorption loss in ionosphere L_i, reflection loss from sea surface L_g and additional systematic loss Y_p. Therefore, basic transmission loss of skywave L_b can be calculated as followed:

$$L_b = L_{bf} + L_i + L_g + Y_p \tag{7}$$

In free space, there is no energy loss in the shortwave propagation. The loss of the shortwave in propagation is only related to the propagation distance, that is, it increases with the propagation distance . Basic transmission loss in free space can be calculated as followed:

$$L_{bf} = 32.45 + 20lgf(MHz) + 20lgd(km) \tag{8}$$

During the skywave propagation, the high-frequency radio waves introduces transmission loss when reflecting off the ionosphere back to the Earth's surface and then reflecting back to the ionosphere. The loss is called the reflection loss of the earth surface. Its value is in corresponding with the polarization of electric waves, operating frequencies, launching elevation angle and characteristics of the surface. According to the background of the problem, we consider that reflections of the Earth's surface is equivalent to reflections of the ocean surface. And we simplify that the loss of HF radio waves in ocean is only related to their reflection coefficient $_rho$. The relevant calculating formula is

$$L_g = -10lg|\rho| \tag{9}$$

Where $0 < |\rho| < 1$.

Ionospheric absorption loss L_i is relevant with sunspots, the sun zenith angle, frequency, amplitude elevation angle. The semi-empirical formula of L_i is:

$$L_i = \frac{677.2sec(\frac{\pi}{2} - \theta)}{(f + f_H)^{1.98} + 10.2} \sum_{j=1}^{n} I_j \tag{10}$$

Where

n is the number of hops;

f is the frequency of high-frequency radio waves;

f_H is magnetic frequency, at the range between 1.2MHz and 1.5MHz;

θ is the launching elevation angle.

I_j is the ionospheric absorption coefficient and it was defined as

$$I_j = (1 + 0.0037\overline{R_{12}})(cos0.881\psi_j)^{1.3} \tag{11}$$

Where $\overline{R_{12}}$ is the average number of 12-month sunspot changes, ψ_j is the sun zenith angle.

We define the system extra loss as the one except for the above three kinds of losses, including ionospheric spherical focusing, multipath interference, polarization loss and an unstable parameter which stands for other not yet clear losses. This parameter is related to geomagnetic latitudes, seasons, local time, the traveling path and other factors. However, its value is difficult to estimate. Therefore, we ignore it in practical application and use it as a fault tolerant coefficient in our study. In our study, we set Y_q as follows:

$$Y_p = 1(dB) \tag{12}$$

4.3 Diffuse-Reflection-Attenuation Model

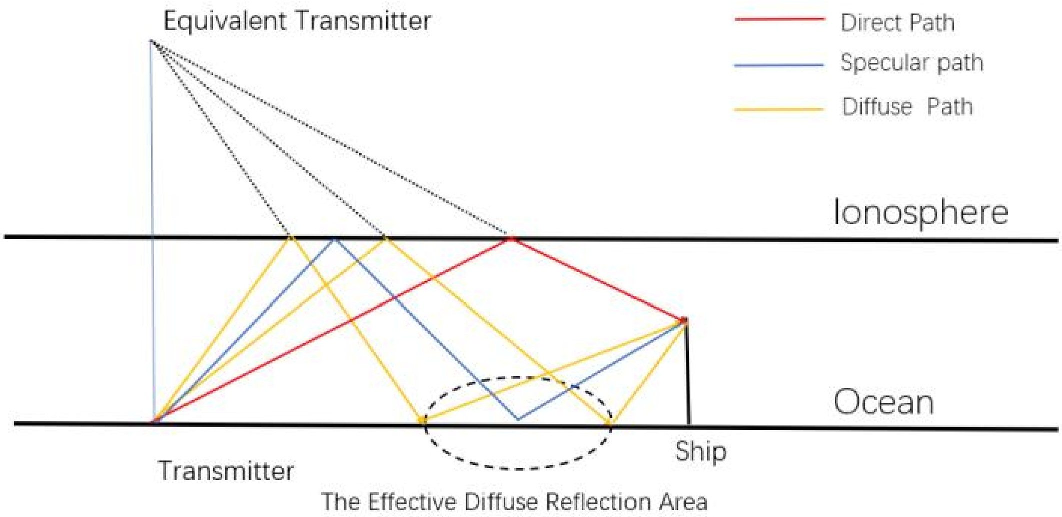

Figure 2: Improvement of diffuse reflection transmission

Because the skywave transmission works through the reflection of ionosphere layer, which is different from the multipath propagation model (i.e. figure). The model established in this paper is improved to apply the diffuse reflection model off sea surface. We assume the ionosphere as a mirror, and then we can create an equivalent transmitter. This equivalent transmitter does not exit in the real world but it's very practical on our numerical valuation.

In reality, the ocean surface is not always calm. So we assume that the propagation of radio waves on the ocean surface should consider diffuse propagation in addition to the specular reflections discussed above. Therefore, we establish a diffuse model of radio waves on the ocean surface in this section.

According to related literature[7], we can get the general diffuse reflection formula, which is stated as:

$$L(t_d) = \frac{P_R(t = (r_{TS} + r_{SR})/c)}{P_T(t = 0)} = \frac{\lambda^2 \sigma}{(4\pi)^3 r_{TS}^2 r_{SR}^2} \tag{13}$$

where

λ is the wavelength;

σ is scattering cross section of the target;

P_T, P_R are transmitted and received powers respectively;

r_{TS}, r_{SR}, r_{TR} transmitter/scatter, scatter/receiver, transmitter/receiver path lengths respectively.

We generally think that the path of the specular reflection comes from a point on a surface, and the diffuse one comes from a region nearby.

Therefore, how to calculate the area and position of the glistering surface becomes the key point to establish the diffuse reflection model.

We generally think that the path of the specular reflection comes from a point on a surface, and the diffuse one comes from a region nearby. Thus, we define the region as the glister surface. The receiver cannot receive the radio wave signal that outside this area. Our team use a schematic diagram to describe the diffuse multi-path propagation principle.

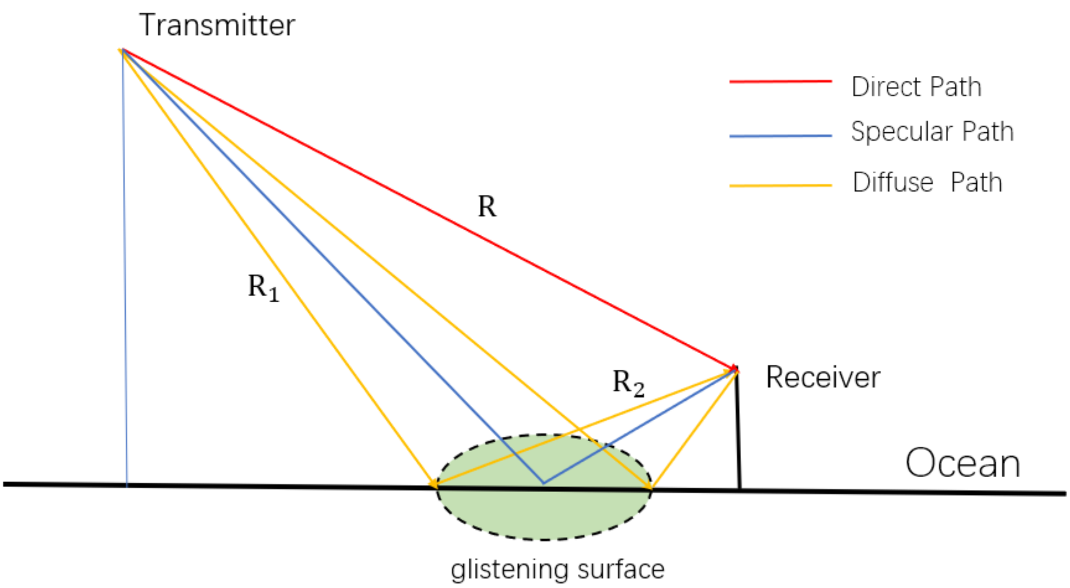

Figure 3: A Diffuse-Reflection-Attenuation Model on Glistening Surface

As Haspert explained to us in his study [5],we can simplify this glistening surface to a flat oval in Figure 2. This will provide the great convenience on modeling diffuse reflection. In the meantime, Haspert explains in his paper how to calculate the location and extent of effective glistening surface area.

Hence, we can figure out the value of the diffuse reflection cost at sea surface diffuse model. The sky-wave propagation with the diffuse reflection is

$$\begin{aligned}\rho_m &= P_R - P_N \\ &= E + 20lgL(t_d) + G_r \\ &= 137.2 + 20lgf + 20lgp_0 + G_t + G_r + 20lg(\frac{\lambda^2\sigma}{(4\pi)^3 r_{TS}^2 r_{SR}^2})\end{aligned} \tag{14}$$

5 Analysis and Results

5.1 Part I

5.1.1 Analysis

In Model One, we set up the skywave field strength model and the transmission loss model. In Model Two, we established the wave height distribution model to influence the correction factor of the roughness reflection coefficient. Based on these two models, we can solve the problem in Part I. First of all, in order to simulate the reflection of HF radio waves on the turbulent oceans, we need to select the appropriate root mean square height ϵ_H to simulate the wave height distribution of the sea surface. We first examine the distribution of the formula (3) at different root-mean-square height ϵ_H. For this purpose, we write the corresponding functions and test codes in Matlab and select the cases of $\epsilon_H = 1$, 2, and 4 for analysis. The result is shown in Figure 3:

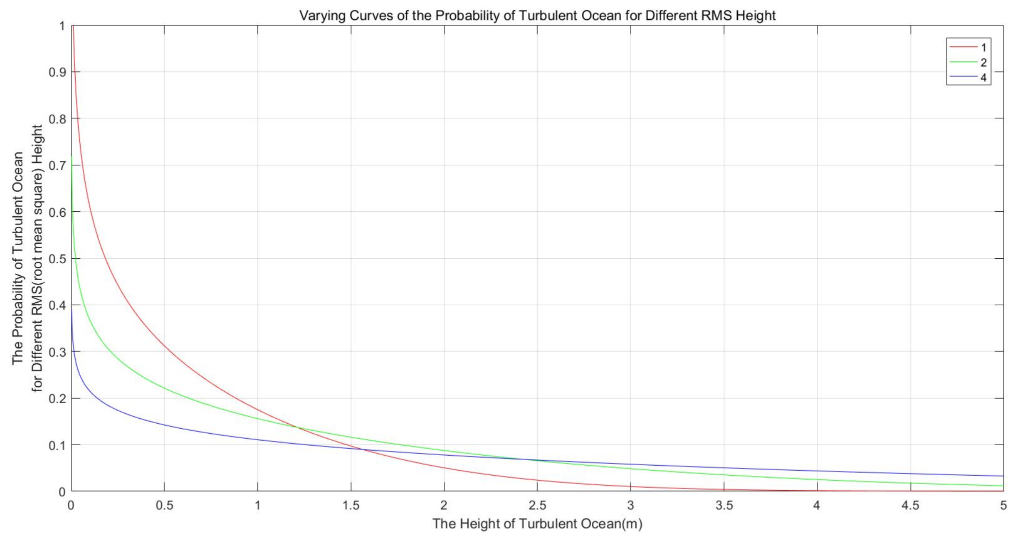

Figure 4: Curves of the Probability of Turbulent Ocean for Different RMS Height

By observing the Figure 3, we can find that using different value of ϵ_H can simulate the wave distribution in different situations. When $\epsilon_H = 1$, the wave height is mostly distributed in the range of 1-3 meters and belongs to the slightly fluctuating sea surface. When $\epsilon_H = 2$, the wave number of 3-5 meters increases, which belongs to the sea surface with greater turbulence. When $\epsilon_H = 4$, waves in the 3-5 meters will be much more than the normal level.

In order to study the influence of turbulent sea surface on the reflection loss of HF radio waves and consider the wave height in reality, we choose the root mean square height ϵ_H as 2 and the permittivity as 82.

In order to facilitate the study of the ionospheric absorption loss L_i, we need to select a specific place and time to study the ionospheric absorption coefficient I_j, we selected 2017 in New York as the research site, and write the corresponding code to study wireless high-frequency Reflection and the loss during the process. According to the observations provided by the site SILS [2], the average number of changes on the sunspots of the earth in 2017 is 21.7. According to the data provided by the Solar Position Calculator website [1], the sun zenith angle of New York, USA is 29.95 degrees. Therefore, we can find the ionospheric absorption coefficient I_j, and then find the ionospheric absorption loss L_i.

Part I requires the initial HF radio signal power is 100 Watt, but it do not determine the specific signal frequency and angle of launching elevation (measured by the launch elevation angle), so we selected three specific sets of signal frequency and angle of launching elevation to analyze the attenuations of HF radio-wave SNR.

(1) $f = 3$ MHz, $\theta = 60$ degrees

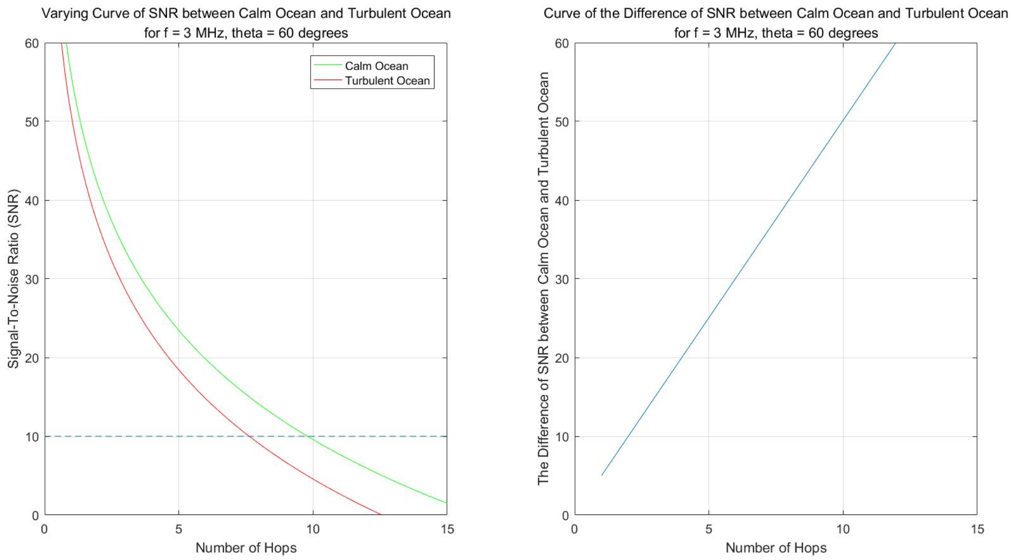

Figure 5: The Attenuations of HF Radio-Wave SNR for $f = 3$ MHz, $\theta = 60$ degrees

According to the image in Figure 4 on the left, we can initially find that the energy of HF radio signals decays differently as the hop count increases in calm sea surface and turbulent sea surface. On turbulent seas, the HF radio signal SNR declines more rapidly, dropping below 10 dB after the 8th hop; on the calm sea, the loss after HF radio signal reflections is small and falls below 10dB only after the 10th hop.

According to the image in Figure 4 on the right, after the 8th hop of the HF radio signal, the difference of the signal attenuation between the calm sea surface and the turbulent sea surface is about 40 dB.

(2) $f = 30$ MHz, $\theta = 60$ degrees

According to the image in Figure 5 on the left, on turbulent seas, the SNR of the HF radio signal whose frequency increased to 30MHz declines more rapidly than that in Figure 4 dropping below 10 dB after the 3rd hop; on the calm sea, the loss after HF radio signal reflections falls below 10dB until the 10th hop.

According to the image in Figure 5 on the right, after the 4th hop of the HF radio signal, the difference of the signal attenuation between the calm sea surface and the turbulent sea surface has been already about 100 dB.

(3) $f = 30$ MHz, $\theta = 30$ degrees

According to the image in Figure 6 on the left, on turbulent seas, the SNR of the HF radio signal whose launching elevation angle is 30 degrees declines far more slowly

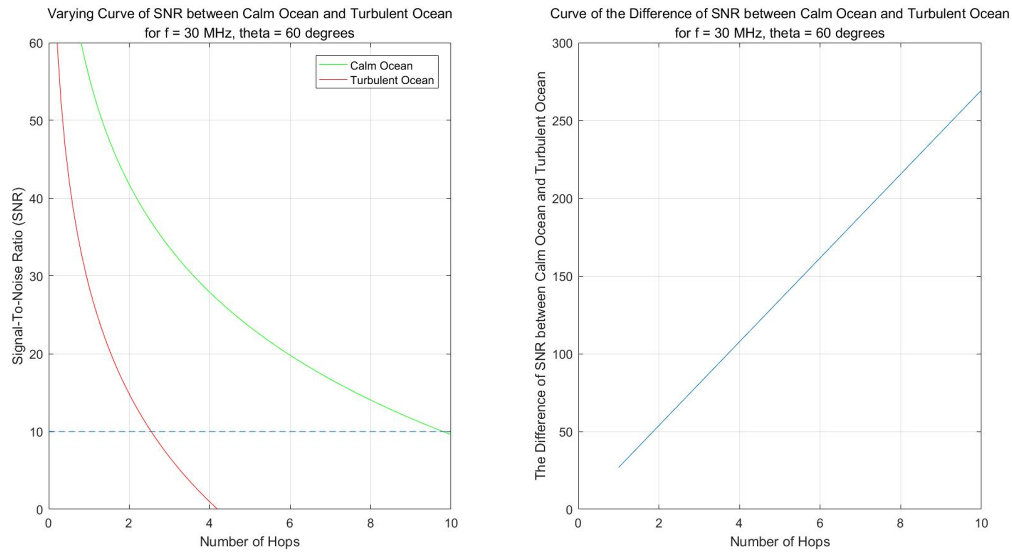

Figure 6: The Attenuations of HF Radio-Wave SNR for f = 30 MHz, θ = 60 degrees

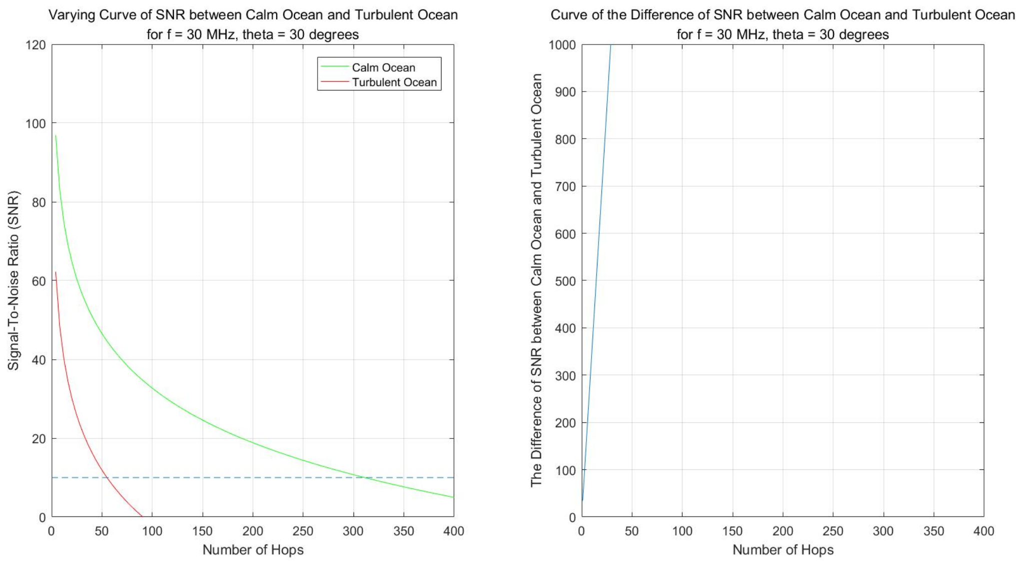

Figure 7: The Attenuations of HF Radio-Wave SNR for f = 30 MHz, θ = 30 degrees

than that in Figure 5, dropping below 10 dB until the 55th hop; on the calm sea, the loss after HF radio signal reflections falls below 10dB until the 310th hop.

According to the image in Figure 6 on the right, after the 30th hop of the HF radio signal, the difference of the signal attenuation between the calm sea surface and the turbulent sea surface has been already about 1000 dB.

5.1.2 Conclusion

The attenuations of HF radio signal energy in turbulent ocean and calm ocean are different, and the HF radio signal energy drops more slowly in the calm ocean, indicating that the reflection loss of HF radio signal in turbulent ocean is larger.

With different frequencies and launching elevation angles, the required number of hops in turbulent ocean and calm ocean are not the same. Thus, we conduct sensitivity analysis on these factors.

5.2 Part II

5.2.1 Analysis

By observing the distribution of root mean square heights, we selected 75 as the root mean square height to simulate the mountain model. The reflection coefficient of the smooth land is related to the dielectric constant of the land. Since the land is composed of rocks whose permittivity is between 5-8 by referring to the data, we choose 8 as the dielectric constant of the land. Therefore, we can easily determine the similar model of short ware loss on the land.

In our study, we consider the rugged mountain model with a height of 0-300m. We choose the three cases of h = 10,75,150 to analyze. The result is shown in Figure 7

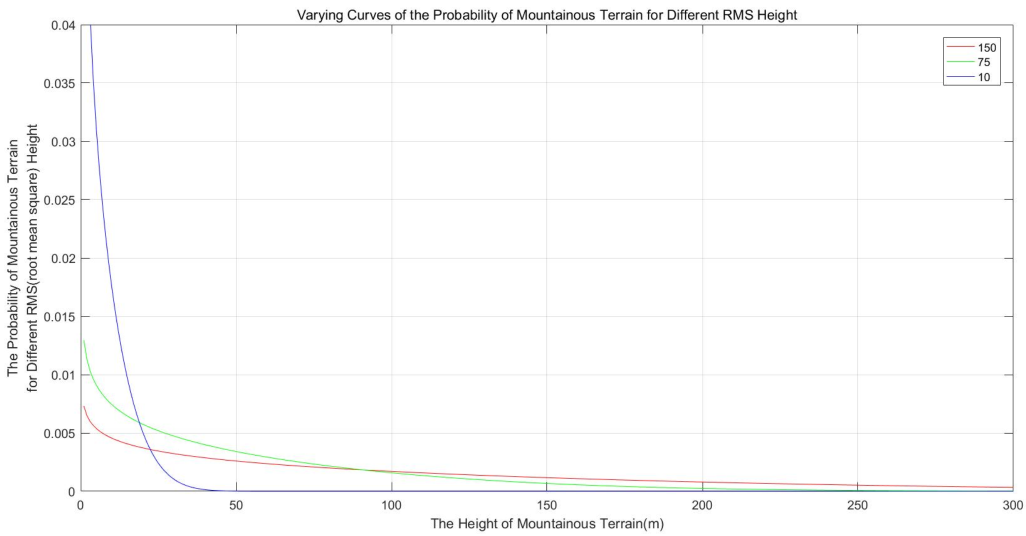

Figure 8: Curves of the Probability of Mountainous Terrain for Different RMS Height

Observing the image of the function, we can see that when $delta_H = 10$, the height of the mountain ranges mostly from 0 to 50 meters and these areas belongs to the plain landscape. When $delta_H = 75$, the number of the mountain with a height of 100-300 meters increases and these mountains are more rugged. When $delta_H = 150$, the number of mountains in the 100-300 meters is larger and these mountains are of high ups and downs.

In order to study the influence of rugged mountain on HF radio-wave reflection loss and near-realistic mountain distribution better, we choose a root mean square height $delta_H$ of 75. As for the ionospheric absorption loss L_i, our team use the same 2017 New York data as stated above. Additionally, we selected the same three specific sets of signal frequency and angle of launching elevation to analyze the attenuations of HF radio-wave SNR.

(1) $f = 3$ MHz, $\theta = 60$ degrees

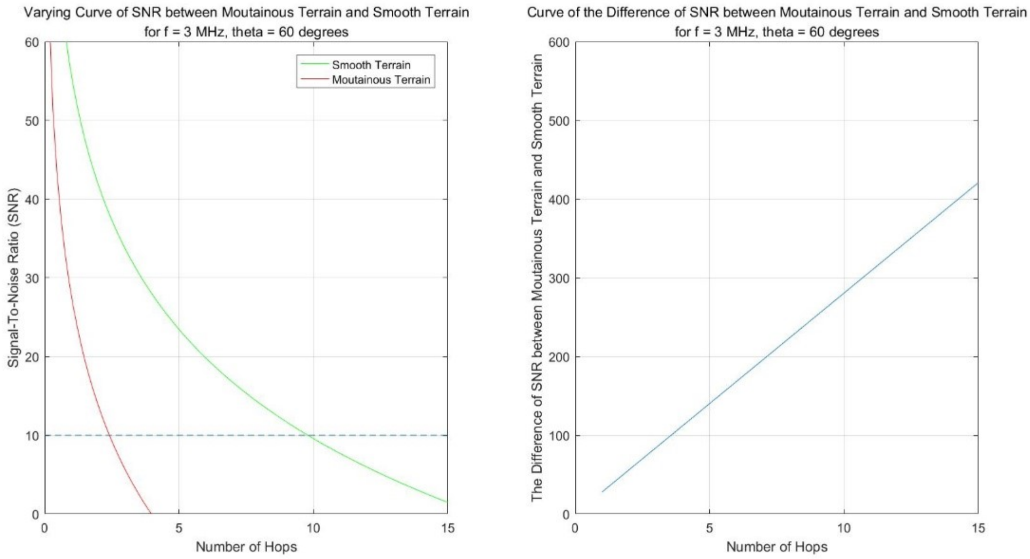

Figure 9: The Attenuations of HF Radio-Wave SNR for $f = 3$ MHz, $\theta = 60$ degrees

According to the image in Figure 8 on the left, we can initially find that the energy of HF radio signals decays differently as the hop count increases in rugged terrain and smooth terrain. In rugged terrain, the HF radio signal SNR declines more rapidly, dropping below 10 dB after the 3th hop; in the smooth terrain, the loss after HF radio signal reflections is small and falls below 10dB only after the 10th hop.

According to the image in Figure 8 on the right, after the 3th hop of the HF radio signal, the difference of the signal attenuation is about 100 dB between the rugged terrain and smooth terrain.

From Figure 8 and Figure 4, we can see that with the same frequencies and launching elevation angles, the required number of hops in rugged terrain and smooth terrain are different. The former decays rapidly than the latter. Whats more, the required number of hops in smooth terrain and calm ocean are approximately the same.

(2) $f = 30$ MHz, $\theta = 60$ degrees

According to the image in Figure 4 on the left, on rugged terrain, the SNR of the HF radio signal whose frequency increased to 30MHz declines more rapidly than that in Figure 8, dropping below 10 dB after the 10th hop; on the smooth terrain, the loss after HF radio signal reflections falls below 10dB until the 10th hop.

According to the image on the right, after the 2nd hop of the HF radio signal, the difference of the signal attenuation between the smooth terrain and the mountainous terrain has been already about 100 dB.

In comparison with the results in Part I, we can see that with the same frequencies and launching elevation angles, the signals require roughly the same number of hops for attenuation below 10 dB on both smooth terrains and calm seas, decay more rapidly in the mountainous terrains than in turbulent oceans. The number of hops decayed below 10 dB in mountainous terrains is 2, while the number of hops decaying below 10 dB in turbulent oceans is 3.

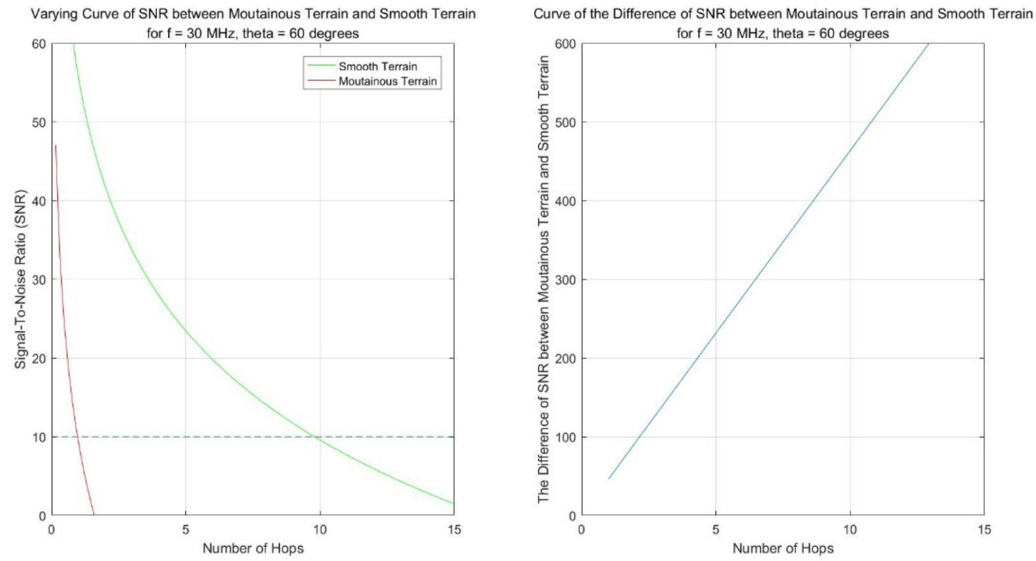

Figure 10: The Attenuations of HF Radio-Wave SNR for f = 30 MHz, θ = 60 degrees

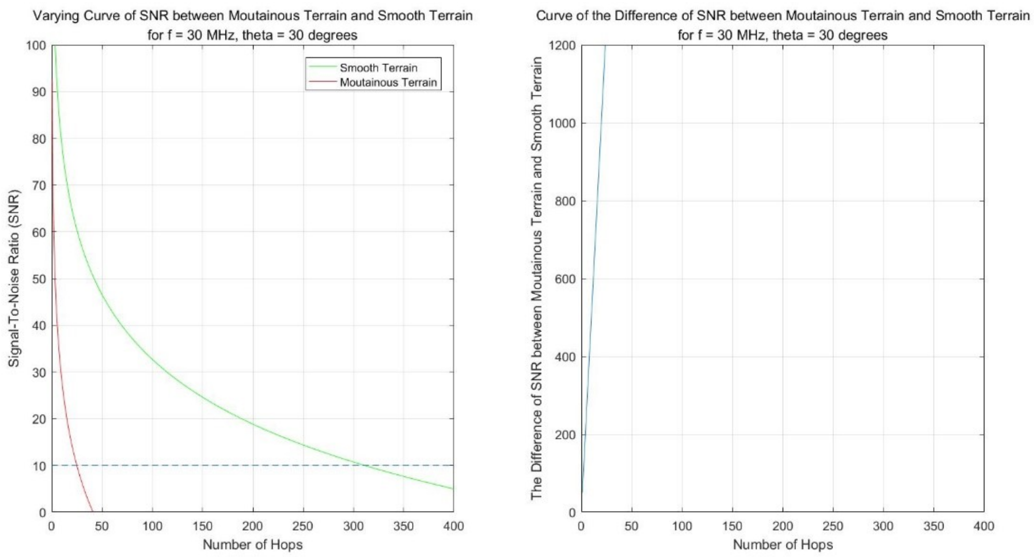

Figure 11: The Attenuations of HF Radio-Wave SNR for f = 30 MHz, θ = 30 degrees

(3) f = 30 MHz, θ = 30 degrees

According to the figure in Figure 10 on the left, the HF radio signal SNR at a launching elevation angle of 30 degrees in mountainous terrains is decreasing much more slowly than that in Figure 9, and drops below 10 dB at about the 25th hop; On smooth terrains, HF radio signal energy does not drop to below 10dB until about 310 hops.

According to the figure in Figure 10 on the right, after the 30th hop of the launched HF radio signal, the signal has already been attenuated in smooth and mountainous terrains by more than 1200 dB. At the same frequency and launching elevation angle, the signals require approximately the same number of hops below 10 dB for both smooth terrains and calm seas, decay more rapidly in the mountainous terrains than in turbulent oceans, and fall below 10 dB in mountainous conditions. The number of hops is around 25 and the number of hops decaying below 10 dB under turbulent sea conditions is at least 60.

5.2.2 Conclusion

The attenuation of HF radio signal energy in rugged terrain and smooth terrain increases with hops, and the HF radio signal energy drops more slowly in the smooth terrain, indicating that the reflection loss of HF radio signal in rugged terrain is larger. In addition, comparing with Part I's ocean surface loss results with the same frequency and angle of launching elevation, we found that the loss of electric wave energy on the mountains is larger than the loss of electric wave energy in the turbulent ocean surface. The SNR attenuation requires fewer steps to reach 10dB. What's more, flat and calm ocean surface losses are roughly the same because the required number of hops is almost the same.

With different frequencies and launching elevation angles, the required number of hops in rugged terrain and smooth terrain are not the same. Thus, we conduct sensitivity analysis on these factors.

6 Sensitivity Analysis

We will focus on the influences of some parameters on our models. First we select the frequency the HF radio wave f in a range of 3-30 MHz and drawing a 3D figure to analyze its influences on the decrease of the loss.

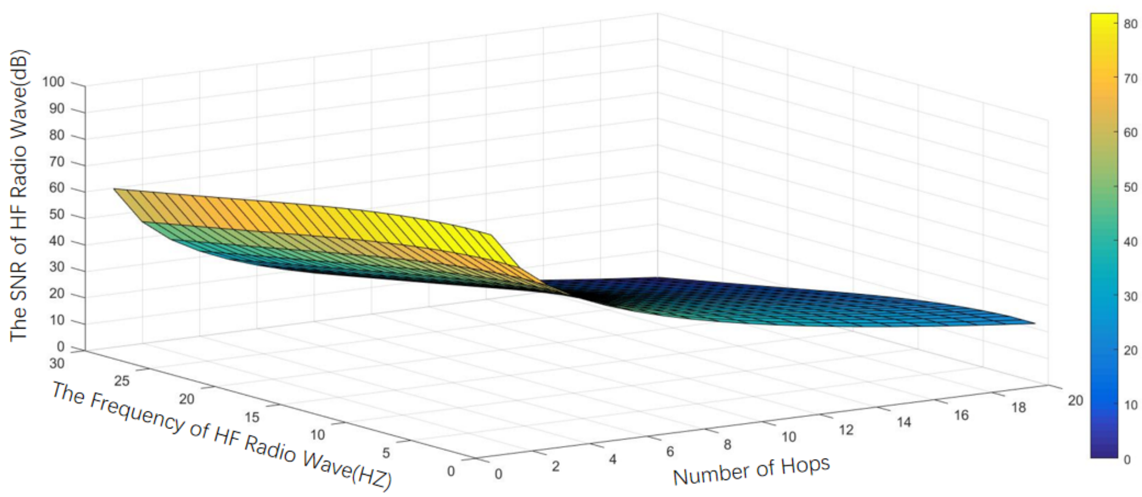

Figure 12: Sensitivity Analysis of the Frequency f in the range of 3-30 MHz

From the figure, we can find that with the larger frequency, the energy of HF radio signals decays more rapidly as the number of hops increases.

7 Strengths and Weaknesses

7.1 Strengths

- The results is reliable to predict the results of more complicated models.
- The models are fit for the complex problem of the true HF radio propagation. These models greatly reduce the difficulty of solving the problems, and can get the results that agree well with the reality.
- For the sensitivity of the model, we discuss two key parameters. Sensitivity analysis results show that our models have a wide range of application and good robustness

7.2 Weaknesses

- Limited to time, some model parametersthe RMS wave height δ_H still needs to be determined accurately by more experiments.
- The values of some parameters are determined subjectively, whose values may not be reasonable in reality.

8 Conclusions and Future Works

8.1 Conclusions

From Part I and Part II, we can reach the conclusion that the attenuation of HF radio signal energy in rugged terrain and smooth terrain increases with hops, and the HF radio signal energy drops more slowly in the smooth terrain, indicating that the reflection loss of HF radio signal in rugged terrain is larger. In addition, comparing with Part I's ocean surface loss results with the same frequency and angle of launching elevation, we found that the loss of electric wave energy on the mountains is larger than the loss of electric wave energy in the turbulent ocean surface. The SNR attenuation requires fewer steps to reach 10dB. What's more, flat and calm ocean surface losses are roughly the same because the required number of hops is almost the same.

From Part III, if a ship travels on the ocean, we cannot ignore the effects of diffuse reflection. When discussing the ship which remains communication using the same multi-hop paths, we can get the conclusion that the time delay increases with the distance.

8.2 Future Works

Limited to time, some of our models' parameters still need to be determined by experiment. Therefore, if we take more variables such as the earth curvature and interference caused by the atmosphere noise into account, our results will be more accurate and flexible.

References

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[2] Sunspot index and long-term solar observations, feb 2018.

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[4] Wikipedia contributors. Ocean current — wikipedia, the free encyclopedia, 2018. [Online; accessed 12-February-2018].

[5] K. Haspert and M. Tuley. Comparison of predicted and measured multipath impulse responses. *IEEE Transactions on Aerospace and Electronic Systems*, 47(3):1696–1709, July 2011.

[6] A. R. Miller, R. M. Brown, and E. Vegh. New derivation for the rough-surface reflection coefficient and for the distribution of sea-wave elevations. *Microwaves, Optics and Antennas, IEE Proceedings H*, 131(2):114–116, April 1984.

[7] J. Shapira. Terscat - a model for prediction of terrain scattered interference in microwave cmmunication. In *The Sixteenth Conference of Electrical and Electronics Engineers in Israel,*, pages 1–4, Mar 1989.

Appendices

Here are programmes we used in our model.

Input MATLAB source:

```matlab
%% A function to calculate the propagation loss of HF radio waves in
%% free space, ionosphere and the ocean surface.
function E = shortwave_reflection(f, theta, Yp, n, Lg)
    % Calculate the loss in ionosphere at the location of New York, USA
    Ij = (1 + 0.0037 * 21.7) * (cos(0.881 * (29.95 * pi / 180)))^1.3;
    Li = 667.2 * sec(pi/2 - theta) * Ij * n / ((f * 1e6 + 1.2e6).^1.98 + 10.2);
    % Calculate the loss in free space
    Lbf = 32.45 + 20 * log(f) + 20 * log(225 * tan(pi/2 - theta) * 2 * n);
    % Sum up the losses
    Lb  = Lbf + Li + Yp + Lg;
    E = 137.2 + 20 * log(f) + 20 * log(100) + 1 - Lb;
end
```

```
%% A function to calculate the propagation loss of HF radio waves in
%% the calm ocean surface or smooth terrain by the determing the
%% permitivity of surface epsilon.
function Lg = calm_ocean(theta, epsilon)
    RV = (sin(theta) - (epsilon - cos(theta)^2 / epsilon)^0.5) / ...
        (sin(theta) + (epsilon - cos(theta)^2 / epsilon) ^0.5);
    RC = RV;
    % Reflection Coefficient
    Lg = -10 * log(RC);
end
```

```
%% A function to calculate the propagation loss of HF radio waves in
%% the turbulent ocean surface or moutainous terrain by the determing the
%% permitivity of surface epsilon and the root mean square height deltaH .
function Lg = turbulent_ocean(theta, epsilon, f, deltaH)
    % Reflection Coefficient on smooth surface
    RV = (sin(theta) - (epsilon - cos(theta)^2 / epsilon)^0.5) / ...
        (sin(theta) + (epsilon - cos(theta)^2 / epsilon) ^0.5);
    % Light speed
    c = 299792458;
    lamda = c / (f * 1e6);
    % Calculate the correction coefficient of the surface roughness
    syms x;
    inte = double(int(x^-0.5 * exp(-x) * cos(8 * (2)^0.5 * pi * deltaH * x^0.5 / lamda)* besselk(0, x),x,0.001,1e5));
    factor = (2)^0.5 * inte / pi^1.5;
    % Reflection Coefficient
    RC = abs(RV) * abs(factor);
    Lg = -10 * log(RC);
end
```

```
%% Code for test and plot
n = linspace(0,50);
f = [input('Please input the frequency of the HF radio   ')];
theta = [input('Please input the degree of the launching elevation angle   ')]* pi / 180;
deltaH = [input('Please input the root mean square height   ')];
% Calculate the SNR of smooth surface after nth hops
Lg1 = calm_ocean(theta, 3);
E1 = real(shortwave_reflection(f,theta,1, n, Lg1));
```

```
% Calculate the SNR of rough surface after nth hops
Lg2 = turbulent_ocean(theta, 82, f, deltaH);
E2 = real(shortwave_reflection(f,theta,1, n, Lg2));
% Calculate the difference of SNR between smooth surface and rough surface
% after nth hops
Difference(1) = abs(E1(2) - E2(2));
for i = 2:99
    Difference(i) = Difference(i - 1) + abs(E1(i + 1) - E2(i + 1));
end
% Plot the SNR curve of smooth surface and rough surface with the variation
% of n
figure;
subplot(1,2,1);
plot(n,E1,'g',n,E2,'r');
hold on
line([0 50],[10 10],'LineStyle','--');
axis([0 50 0 100]);
xlabel('Number of Hops');
ylabel('Signal-To-Noise Ratio (SNR)');
title({'Varying Curve of SNR between Calm Oceans and Turbulent Oceans';'for f = 3 MHz, theta = 60 degrees'});
legend('Calm Oceans','Turbulent Oceans')
grid on;
% Plot the difference of SNR between smooth surface and rough surface with
% the variation of n
subplot(1,2,2);
plot(Difference);
axis([0 50  0 1200]);
xlabel('Number of Hops');
ylabel('The Difference of SNR between Calm Oceans and Turbulent Oceans');
grid on;
title({'Curve of the Difference of SNR between Calm Oceans and Turbulent Oceans';'for f = 3 MHz, theta = 60 degrees'});
```

```
%% Determine suitable the the root mean square height deltaH of the
%% turbulent ocean surface or moutainous terrain
n = linspace(0,20,10000);
for i = 1:10000
    D1(i) = wave_height_distribution(n(i), 1);
    D2(i) = wave_height_distribution(n(i), 2);
```

```
    D3(i) = wave_height_distribution(n(i), 4);
end
plot(n, D1, 'r');
hold on;
plot(n, D2, 'g');
hold on;
plot(n, D3, 'b');
legend('1','2','4');
axis([0 5 0 1]);
grid on;
xlabel('The Height of Turbulent Ocean(m)');
ylabel({'The Probability of Turbulent Ocean';'for Different RMS(
    root mean square) Height'});
title('Varying Curves of the Probability of Turbulent Ocean for
    Different RMS Height');
```

```
%% A function to calculate the distribution of wave height or
    altitude
%% of terrain
function D =  wave_height_distribution(n, h)
    D = (1/(2 * pi^1.5 * h)) * exp(-1 * n * n / (8 * h^2)) *
        besselk(0, n * n / (8 * h^2));
end
```