For office use only	Team Control Number	For office use only
T1 ________	**89423**	F1 ________
T2 ________		F2 ________
T3 ________	Problem Chosen	F3 ________
T4 ________	**A**	F4 ________

2018
MCM/ICM
Summary Sheet

Radio Hops, Information Spreads

Summary

HF radio, as a principal communication method on the sea, transmits information by multiple reflection off the ionosphere and off the ocean. Our modeling group does research into radio propagation off different ocean surfaces and compare it to different backgrounds. And we successfully solve a sailing problem using our findings.

To meet requirements, we establish a radio propagation model to estimate the transmission loss. The propagation model consists of four parts: free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss.

Since plane-earth reflection loss is the critical issue, we first establish a sub-model concentrating on ocean surface to study the radio reflection off the ocean surface. We successfully simulate the reflection, by using Pierson-Moscowitz spectrum combining double summation model.

Then, we put our propagation model into application. Firstly, we prove that strength of the first reflection off a turbulent ocean is lower than that off a calm ocean by ocean surface model. Additionally, the maximum of hops on a calm ocean is calculated as 6. Secondly, reflection models of mountains, rugged and smooth terrain are built by analogy and compare with ocean surface model. At last, we accommodate our model to a moving ship on a turbulent ocean to calculate the maximum distance of remaining communication by MATLAB.

Last but not least, we apply sensitivity analysis to different turbulence and incidence angles, which shows our model is stable and reliable. Also, we list the overall strengths and weaknesses of our model as well as the future work.

Keywords: HF radio propagation; ocean surface model; propagation model; Pierson- Moscowitz spectrum; double summation model

Synopsis

Up to now, radio takes a significant place in peoples production and life. It is the base of many practical applications, such as international broadcasters, mobile telephone systems, radio navigation and radar systems. In particular, HF (3-30MHz) radio is a principal communication method on the sea. As the changeable ocean surface can disturb the radio propagation, it is of great significance to study the ocean surface. This paper does research into radio propagation off different ocean surfaces and other different backgrounds and makes comparison. On the basis, this paper solves a sailing communication problem in real life.

To estimate the transmission loss during the propagation process, this paper establishes a radio propagation model. The propagation model comprises four parts: free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss. The propagation model is mainly used in the problem solving process.

When establishing the propagation model, plane-earth reflection loss is the critical issue. So a sub-model concentrating on ocean surface is firstly established to study the radio reflection off the ocean. To simulate the reflection off the ocean surface, this paper begins with abstracting the ocean into a regular model in 2-D. By using Pierson- Moscowitz spectrum, the model can be developed to an irregular model in 2-D. At last, this paper takes advantage of double summation model to put the irregular model in 3-D. Using this irregular model in 3-D, reflection off irregular waves can be presented vividly.

Then, the propagation model is put into application. When a 100-watt HF radio, leaves from a source point at the juncture of land and ocean, this paper proves that strength of the first reflection off a turbulent ocean is lower than that off a calm ocean by ocean surface model. Additionally, the maximum of hops on a calm ocean is calculated as 6.

When extending the ocean surface model, reflection models of mountains, rugged terrain and smooth terrain can be built by analogy. Compared with ocean surface model, this paper analyzes the differences between them. The result shows that from the direction of radio transmission, the reflection loss is more than loss on the ocean where the elevation of mountains decreases gradually. On the other direction, the results are opposite. Besides, reflection loss of rugged terrain is higher than that of ocean surface while reflection loss of smooth is lower.

At last, the paper suppose that a ship travelling across a turbulent ocean will use HF for communications and to receiver weather and traffic reports. The propagation model is accommodated to a moving ship on a turbulent ocean to calculate the maximum distance of remaining communication by MATLAB.

With respect to the radio propagation, this paper gives out some findings about calculation of transmission loss. This can contribute to more efficient exploit of radio communication on the sea with less signal loss and long transmis-

sion distance, which is of great meaning.

1 Introduction

1.1 Background

1.1.1 HF Radio Propagation

Radio propagation is the behaviour of radio waves as they travel from one point to another, or into various parts of the atmosphere. Radio propagation is the base of many practical applications, such as international broadcasters, mobile telephone systems, radio navigation and radar systems. HF (High Frequencies) radio is defined to 3-30 MHz and its wavelength ranges from 100 to 10 meters. HF radio waves may travel by any of the following modes: ground waves, direct waves, sky waves. Due to its small path loss, long travel distances and plain installations, sky waves occupy a significant place in the transmission of HF radio. By multiple reflection off the ionosphere and off the earth, sky waves leave one point on the earth surface and are returned to another at a considerable distance, thus information transferred. The limited reflecting capacity of the ionosphere (affected by electron concentration) sets a restriction on the frequencies of radio waves. Only if the frequencies are below the *maximum usable frequency*(MUF) can sky waves reflect off the ionosphere back to the earth. MUF changes with different electron concentration which varies with the season, time of the day and solar conditions. However, HF radio waves, as a form of electromagnetic radiation, will still undergo some loss because of reflection, refraction, diffraction, absorption, polarization and scattering.

1.1.2 Influence of the ocean surface

To this day, HF radio propagation is widely applied to maritime mobile communication. As the changeable ocean surface can disturb the radio propagation, it is of great significance to study the ocean surface. In the propagation process, ocean surface mainly influences the reflection of the radio waves, where turbulent oceans differ from calm oceans in attenuating the signals. The factors of ocean turbulence can be classified into two categories. One is electromagnetic gradient of seawater, local permittivity and permeability of the ocean. The other is wave heights, shapes, frequencies and direction of wave. Both kinds of factors are complex.

1.2 Literature review

Since radio was born in 1888, it has played a vital role in peoples production and lives. Therefore, plenty of researchers have made a number of notable papers to address the problem of radio propagation. Up to now, scientists have established some models focusing on the large-scale decline of propagation path by trial and error. According to the propagation modes and environment, valid propagation models are designed to forecast and estimate the path loss.

Among these models, models of land are maturer than those of ocean. Now the general land model commonly adopted is Okumura-Hata Model and it has been tested and verified successfully in practice (Yanjun Zeng, 2003). However, when it is put into radio propagation on ocean surface, its outcome shows great deviation. Additionally, many complicated factors, for example, permeability of the ocean, wave directions, frequencies and so on, need to be taken into consideration. Consequently, many models cannot fit the conditions of ocean surface appropriately.

2 Model overview

We are required to provide a model to simulate the process of HF radio propagation over the ocean. Then we need to apply the model to determine the strength of a first reflection off both turbulent and calm ocean and make a comparison, followed by our discussion of multi-hop propagation off a clam ocean. In addition, we should compare our findings with HF reflection off mountainous areas, rugged terrain and smooth terrain. At last, we are going to accommodate our model to a moving ship receiver, so that we can give out our strategy and put it into practice.

In order to solve these problems, we will proceed as follows:

- Make quantitative evaluations to transmission loss in HF propagation, including free-space path loss, plane-earth reflection loss, ionospheric absorption loss, etc. in order to build a HF propagation model.
- Establish ocean surface model to analyze plane-earth loss for improving the HF propagation model.
- Design mountain model and compare with ocean surface model.
- Apply the HF propagation to a shipboard receiver moving on a turbulent ocean.
- Make analysis and assessment of our models, find the strengths and weaknesses of them and make future predictions.

A mind map of our analysis of the problem is shown as below:

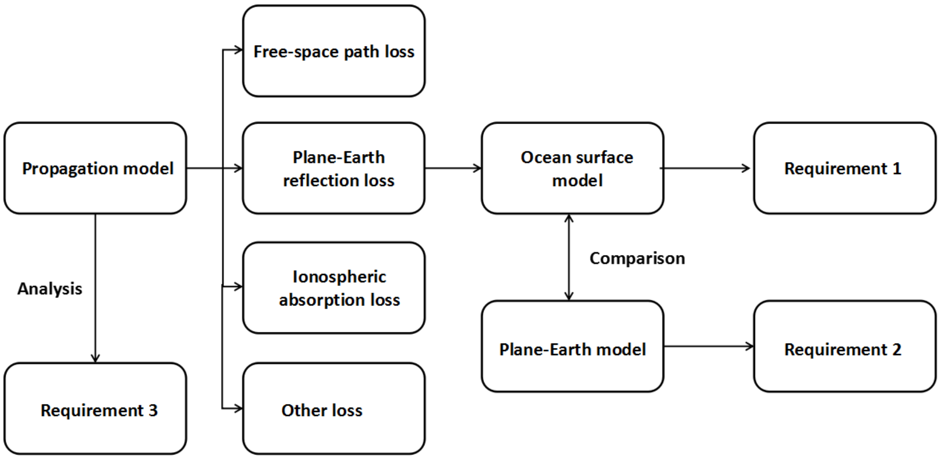

Figure 1: Mind map of analysis of the problem

3 General assumptions

To simplify our problems, we will make the following basic assumptions. Further improvements of these simplified assumptions will be achieved later with more reliable data.

- **HF propagation over the ocean obeys the free-space propagation model.** If not, it will make the solving process more complex due to reflection, refraction, diffraction, absorption, polarization and scattering in the propagation process.
- **Ionosphere is relatively parallel to the earth.**
- **The parameters of ionosphere will not change with time and space, which means MUF is constant.**Without the variety of MUF, the research can be simplified.
- **Turbulence will not affect the nature of seawater, such as electromagnetic gradient, local permittivity and permeability of the ocean.** Since too many variables will complicate the solving process, we do not take them into consideration.
- **Time of radio propagation is not considered.** As the speed of light is $3 \times 10^8 m/s$, the time of radio travel is so short that it can be negligible.
- **Incident angle θ ranges from 0 to 30 degrees.** As generally radio waves leave the transmitting antenna at such angles in practice.

4 Notions and symbol description

we will define the following variables here as they are widely used throughout our paper. Additional variables may be defined later, but will be confined to a particular section.

Table 1: Table 1 Notations

Symbols	Definition
L_b	Transmission loss
L_{bf}	Free-space path loss
L_g	Plane-earth reflection loss
L_a	Ionospheric absorption loss
Y_p	Other loss
R	reflectance
P_0	radio transmit power
P_1	radio received power
G_0	transmitting gain
G_1	received gain
f	radio frequency
SNR	signal-to-noise ratio
E_1	signal strength of receiver point
E_2	noise field intensity of receiver point
r	the distance of radio propagation
s	travel distance of ship
θ	angle of incidence
λ	wavelength

5 Sub-model: Ocean surface model

In order to provide an overview of radio propagation over the ocean, we need to study transmission loss in HF propagation, including free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss. Among these, plane-earth reflection loss is critical issue. So we first establish a sub-model concentrating on ocean surface model to study the radio reflection off the ocean.

5.1 Local assumptions

We will make similar simplifying assumptions as follow:

- Suppose MUF is $30MHz$ and the frequency of radio is also $30MHz$.
- Assume that the reflectance of land equals that of ocean to simplify the calculation.
- Radio obeys the law of reflection when it reflects off the turbulent ocean, giving no considering to scattering.

5.2 Calm ocean model

Since ocean can be calm or turbulent, we should take both situations into account. To begin with the calm ocean model, we regard the calm ocean as a smooth horizontal surface. The illustration is presented in **Figure 2**.

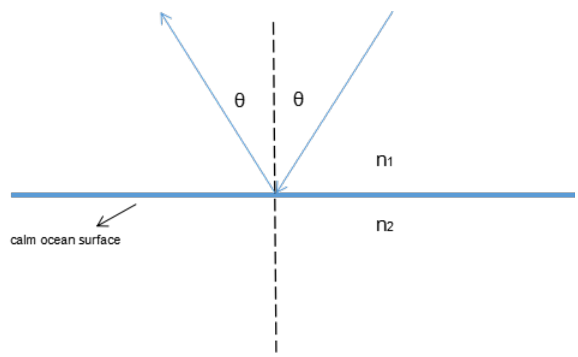

Figure 2: Reflection over calm ocean

Referring to relative materials, we get the formula of reflectance as below:

$$R_1 = \frac{1}{2}\left[\left(\frac{\sin\theta - \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2\theta}}{\sin\theta + \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2\theta}}\right)^2 + \left(\frac{(\varepsilon_r - j60\lambda\sigma)\sin\theta - \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2\theta}}{(\varepsilon_r - j60\lambda\sigma)\sin\theta + \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2\theta}}\right)^2\right] \quad (1)$$

where:

R_1 : reflectance

θ : angle of incidence

σ : Conductivity

λ : wavelength

ε_r : Relative dielectric constant

To simplify the calculation, we assume that the reflectance of land equals that of ocean. We assign 0.001 to conductivity ,4 to relative dielectric constant and $30MHz$ to wavelength. As θ ranges from 0 to 30 degrees, we can adopt the average value for simplifying.

After calculation, we can get that $R_1 = 0.398$.

5.3 Basic turbulence ocean model

When it comes to turbulent ocean, we bring waves into the establishment of model. On the basis of waves shapes, we compare waves of ocean to sinusoidal wave in 2-D.

As turbulent waves are different from calm ocean, we must take the turbulence impact on the reflection of radio into consideration. For quantitative calcu-

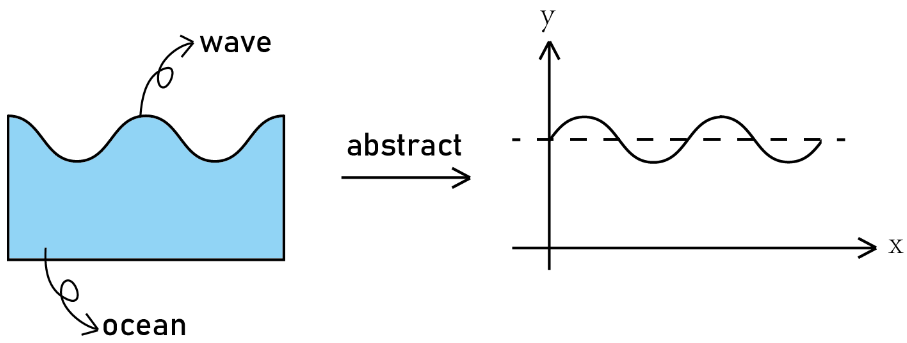

Figure 3: Analogy between waves and sinusoidal wave

lation, we find statistics of Station 46059 in Northern Pacific Ocean from 1994 to 2008, including wave heights, wave period and wind speed. In order to correct the reflectance, we successfully simulate the process of radio reflection off the ocean with multiple calculations complied by MATLAB in a two-dimensional image. The fitness outcome is shown in **Figure 4**.

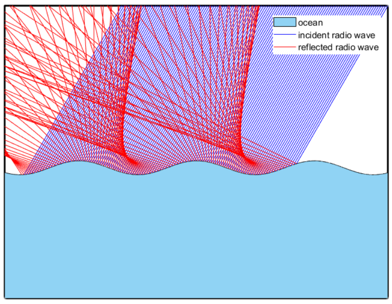

Figure 4: Fitness of radio reflection off the ocean in 2-D

From fitness of MATLAB, we can correct the reflectance to:

$$R = a * R_1 \tag{2}$$

$$a = m/n \tag{3}$$

a represents the coefficient of correction, while m is the number of radio waves basically follow Fresnel Formula and n is the number of incident radio waves. After calculation, we can find that $a = 0.75$.

5.4 Improvement of basic turbulence ocean model

In basic turbulence ocean model, we briefly abstract waves into sinusoidal wave. However, a turbulent ocean is one where wave heights, shapes, frequencies and direction of wave are changing all the time. Thus, in this section, we will make some improvements to the basic model to describe the reflection off turbulent ocean more precisely.

5.4.1 Simulation of irregular ocean waves in 2-D

Since various factors contribute to the irregular change of ocean waves, we further analyse the sinusoidal waves in 2-D and build a model of irregular ocean waves in 2-D by the method of *Pierson-Moscowitz spectrum*. The result is presented in **Figure 5**.

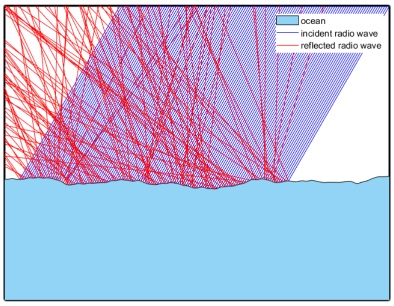

Figure 5: Fitness of irregular ocean waves in 2-D

Using MATLAB, we can calculate that a=0.62

5.4.2 Stimulation of irregular ocean waves in 3-D

When we consider to expand two dimensions to three dimensions, *double summation model* is adopted to simulate irregular ocean waves in 3-D by using MATLAB. The result is presented in **Figure 6**.

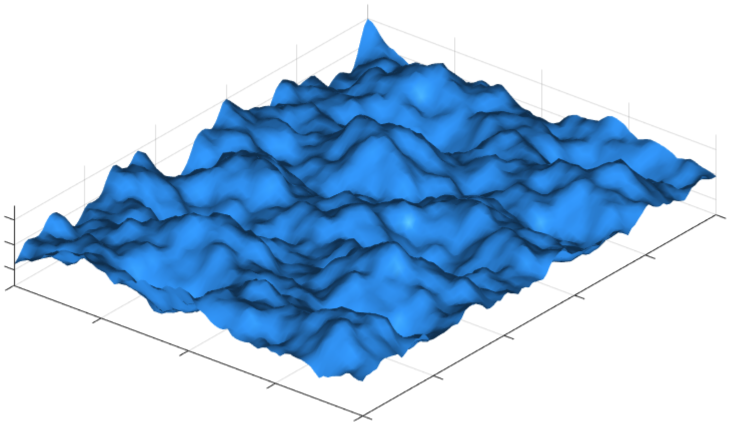

Figure 6: Fitness of irregular ocean waves in 3-D

5.4.3 Further simulation of irregular ocean waves in 2-D

In order to determine the value of a in irregular conditions, we intercept sections of **Figure 6** in all directions to get simulation of irregular ocean waves in 2-D.

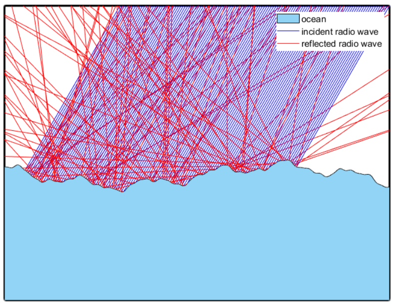

Figure 7: Further fitness of irregular ocean waves in 2-D

From fitness of MATLAB, we can correct the coefficient of correction a.

After calculation, we can find that $a = 0.5$.

6 Master model: Propagation model

The aim of propagation model is to study transmission loss in HF propagation. A multi-hop radio propagation can be seen in Figure 8. The transmission loss consists of four sections: free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss. As a result, total transmission loss can be represented as follows:

$$L_b = L_{bf} + L_a + L_g + Y_p \quad (dB) \tag{4}$$

where:

L_b : transmission loss

L_{bf} : free-space path loss

L_g : plane-earth reflection loss

L_a : ionospheric absorption loss

Y_p : other loss

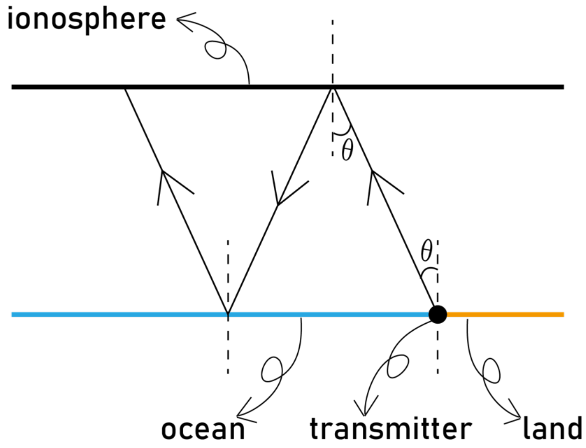

Figure 8: Diagram of a multi-hop radio propagation

6.1 Free-space path loss

When radio waves travel in free space, path loss is attributed to energy diffusion of radiation. Free-space path loss is primary loss of transmission. The formula of free-space path loss is stated as follows:

$$L_{bf} = 32.45 + 20lgf(MHz) + 20lgr(km) \quad (dB) \tag{5}$$

where:

f : radio frequency

r : the distance of radio propagation

The distance of radio propagation each hop can be calculated as below:

$$r = n \times 2h/\cos(\theta) \tag{6}$$

h : the distance between earth and ionosphere

n : the number of hops

θ : angle of incidence

6.2 Ionospheric absorption loss

When radio waves come into contact with ionosphere, absorption loss takes place. However, its theoretical calculation is very complicated. Therefore, semi-empirical formula is commonly adopted to determine ionospheric absorption loss. In general, absorption loss is less than $1dB$. In this paper, the value of absorption loss each reflection is stated as below:

$$L_a = 1dB \tag{7}$$

6.3 Plane-earth reflection loss

Reflection off the earth is also accounted for transmission loss, which is related to reflectance. The reflection loss each hop is shown below:

$$L_g = -10lgR \tag{8}$$

According to the discussion of sub-model ocean surface model above, the calculation of R can be formulated as below:

$$\begin{cases} R_1 = 0.398 \\ R = a \times R_1 \end{cases} \tag{9}$$

6.4 Other loss

Apart from three types of loss above, loss caused by other reasons like antenna transmitting and receiving can be classified as other loss. Because various conditions of transmission will affect the amount of other loss, we here define other loss as below:

$$Y_p = 8dB \tag{10}$$

6.5 Propagation model

According discussion above, we can find that signal undergoes loss when transmitted. As a result, signal could be useless if its signal-to-noise ratio (SNR) is below 10 dB. For this sake, we introduce signal strength E1 to evaluate whether signal is usable. The definition of SNR is given as follows:

$$\begin{aligned} SNR &= 10lg(P_1/P_2) \\ &= 10lg(E_1^2/R_0)/(E_2^2/R_0) \\ &= 10lgE_1^2/E_2^2 \\ &= 2E_1(dB) - 2E_2(dB) \end{aligned} \tag{11}$$

where:

P_1 : radio received power

P_2 : noise power

E_1 : signal strength of receiver point

E_2 : noise field intensity of receiver point

R_0 : impedance

According to the law of conservation of energy, we can get an expression below:

$$P_1 = P_0 + G_0 + G_1 - L_b \quad (dB) \tag{12}$$

According to the antenna theory, we can get an expression below:

$$P_1 = \frac{E_1^2}{120\pi} \times \frac{G_1\lambda^2}{4} \tag{13}$$

$$P_1(dB) = -107.2 - 20lgf(MHz) + G_1(dB) + 20lgE \tag{14}$$

Combine two expressions above, we can calculate:

$$E_1(dB) = 107.2 + 20lgf(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \tag{15}$$

where: P_0 : radio transmit power

G_0 : transmitting gain

G_1 : received gain

L_b : transmission loss

λ : wavelength

If the signal is usable, the restraint of E_1 is given as follows:

$$2E_1 - 2E_2 > 10dB \tag{16}$$

It can be simplified as :

$$E_1 > E_2 + 5dB \tag{17}$$

When radio reflects off the surface, we define n as the number of hops. If the receiving signal is usable, the restraint of n is given as follow:

$$\begin{cases} L_b = L_{bf} + n(L_a + L_g) + Y_p \quad (dB) \\ L_{bf} = 32.45 + 20lgf(MHz) + 20lgr(km) \quad (dB) \\ r = \dfrac{h}{\cos(\theta)} * 2n \\ L_g = -10lgR \\ E_1(dB) = 107.2 + 20lgf(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \\ E_1 > E_2 + 5dB \\ n \geq 1 \end{cases} \tag{18}$$

7 Solutions of Requirement 1

In this part, a 100-watt HF radio, below the MUF, is transmitted from a point source on land. We are required to work out the strength of the first reflection off a turbulent ocean and a calm ocean. In addition, we need to determine the maximum number of hops the signal can take before its SNR falls below $10dB$.

7.1 Local assumptions

We will make similar simplifying assumptions as follow:

- The point source is located at the juncture of land and ocean.
- Suppose MUF is 30 MHz and the frequency of radio is also $30MHz$.
- Suppose noise field intensity E_2 is $5dB$ and transmitting gain G_0 is $15dB$. The values are basically in accordance with the actual case.
- The distance between earth and ionosphere h is defined as $60km$, as we take the average distance between earth and lower layer of ionosphere.

7.2 Strength of the first reflection

7.2.1 Calm ocean

Firstly, we study the strength of the first reflection off calm ocean and on the basis of our propagation model problem can be described as such:

$$\begin{cases} n = 1 \\ L_b = L_{bf} + n(L_a + Lg) + Yp \quad (dB) \\ L_{bf} = 32.45 + 20\lg f(MHz) + 20\lg r(km) \quad (dB) \\ r = n \times 2h/\cos(\theta) \\ L_g = -10\lg R \\ R = a \times R_1 \\ a = 1 \\ E_1(dB) = 107.2 + 20\lg f(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \end{cases} \tag{19}$$

Because calm ocean is regarded as smooth horizontal surface, the coefficient of correction a is 1. By calculation, the results are given below in **Figure 9**.

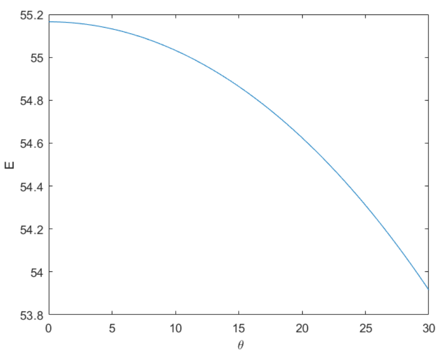

Figure 9: Strength of the first reflection off calm ocean

7.2.2 Turbulent ocean

Then we study the strength of the first reflection off turbulent ocean and process of problem solving is the same as clam ocean.

However, the coefficient of correction a is different. According to the further simulation of irregular ocean waves in 2-D in 5.4.3, coefficient of correction a is 0.5. By calculation, the results are given below in **Figure 10**.

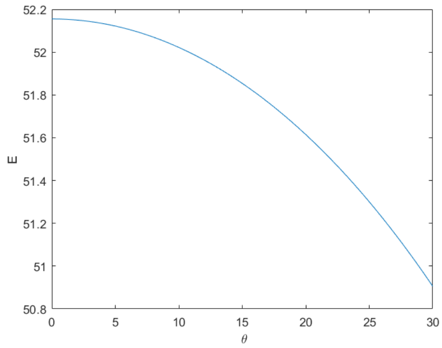

Figure 10: Strength of the first reflection off turbulent ocean

7.2.3 Comparison

As can be seen from Figure 9 and 10, the strength of the first reflection off turbulent ocean is smaller than that off calm ocean. The reason of the difference is that the reflectance of turbulent ocean is smaller than that of calm ocean, thus reflection loss is more.

7.3 Maximum number of hops

When considering multi-hops reflection off the calm ocean, we will determine the maximum number of hops the signal can take before its SNR falls below

$10dB$. From the propagation model, the problem can be expressed as follow:

$$\begin{cases} L_b = L_{bf} + n(L_a + L_g) + Y_p \quad (dB) \\ L_{bf} = 32.45 + 20\lg f(MHz) + 20\lg r(km) \quad (dB) \\ r = n \times 2h/\cos\theta \\ L_g = -10\lg R \\ R = a \times R_1 \\ E_1(dB) = 107.2 + 20\lg f(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \\ E_1 > E_2 + 5dB \\ n \geq 1 \\ a = 1 \\ 0 \leq \theta \leq 30 \end{cases} \tag{20}$$

Using MATLAB, we can achieve the results which is shown below:

$$n = 6 \tag{21}$$

This means the signal can take six hops at most before its SNR falls below **10 dB**.

8 Solutions of Requirement 2

In this task, we are asked to compare our findings from requirement 1 with reflection off mountainous areas, rugged terrain and smooth terrain. The models of mountainous areas, rugged terrain and smooth terrain can be drawn from the ocean surface model by analogy.

8.1 Local assumptions

We will make similar simplifying assumptions as follow:

- Assume that the reflectance of land equals that of ocean in order to simplify the calculation.
- Models of rugged terrain and smooth terrain is basically in accordance with irregular ocean waves model

8.2 Mountainous areas

In mountainous areas, there is always a peak from which elevation decreases progressively to the foot in general. Different from ocean surface model, mountainous areas are high in the middle and low on the edge on the whole. Whats more, mountainous areas drop is much larger than ocean waves which is calculated by kilometre. Here is the simulated diagram of mountainous areas in 3-D by MATLAB.

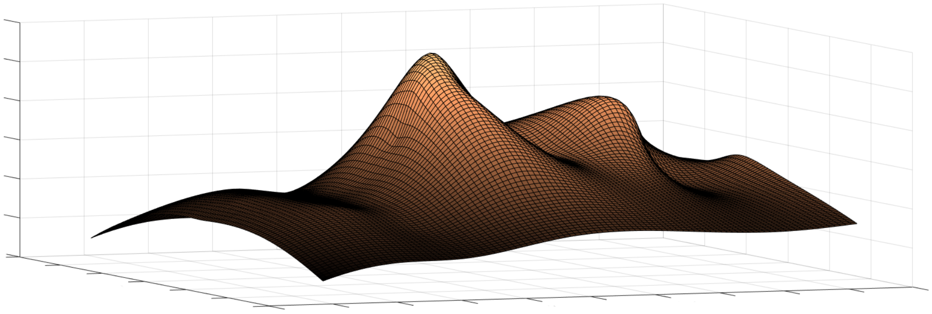

Figure 11: Simulation of mountainous areas in 3-D

In order to discuss the radio reflection off mountainous areas, we intercept sections of **Figure 11** in all directions to get simulation of mountains in 2-D. By means of MATLAB, we can study the radio reflection off mountains.

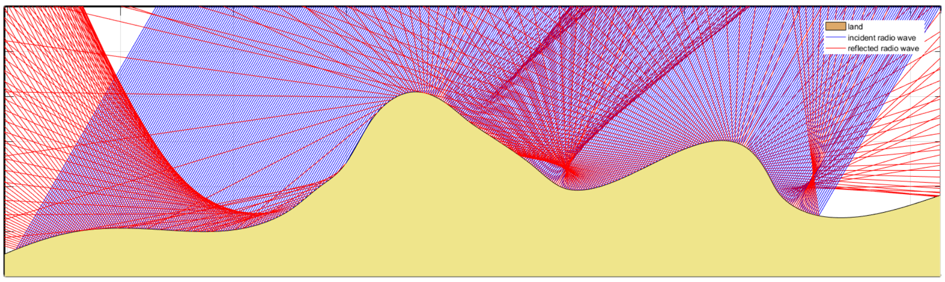

Figure 12: Simulation of mountains in 2-D

In **Figure 12**, we set the highest peak as our baseline and radio is transmitted from the right side. From the direction of radio transmission, the elevation of mountains firstly ascend to the top and then decrease gradually. On the right side of the baseline, the coefficient of correction a is less than 0.5, while the coefficient of correction a is more than 0.5 on the left side. Therefore, the reflection loss on the right is more than loss on the ocean while the reflection loss on the left is less than loss on the ocean.

8.3 Rugged terrain

By analogy, the abstract model of rugged terrain is similar to turbulent ocean model. However, rugged terrains drop is larger than ocean waves which is calculated by hundred-metre and its wave curve is steeper. According to sub-model: ocean surface model, we can produce the simulated diagram of rugged terrain in 2-D by MATLAB.

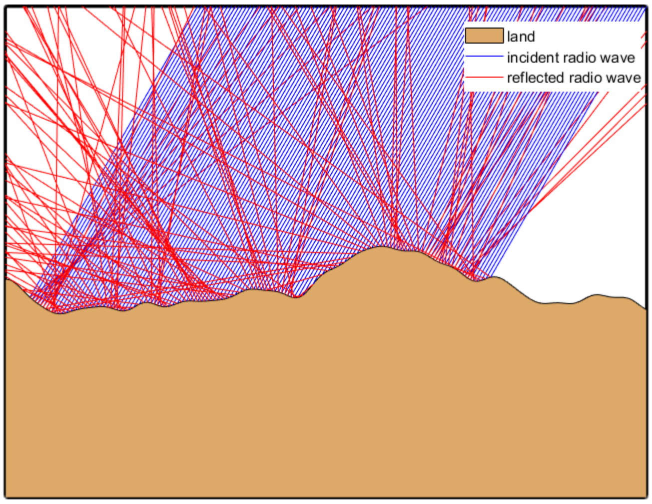

Figure 13: Simulation of rugged terrain in 2-D

Using MATLAB calculation, we can find that the coefficient of correction a is less than 0.5. Therefore, the reflection loss off the rugged terrain is more than loss on the ocean.

8.4 Smooth terrain

Similarly, the abstract model of smooth terrain can be compared to turbulent ocean model. However, smooth terrains drop is smaller than ocean waves and it is about 1 metre. According to sub-model ocean surface model, we can produce the simulated diagram of smooth terrain in 2-D by MATLAB.

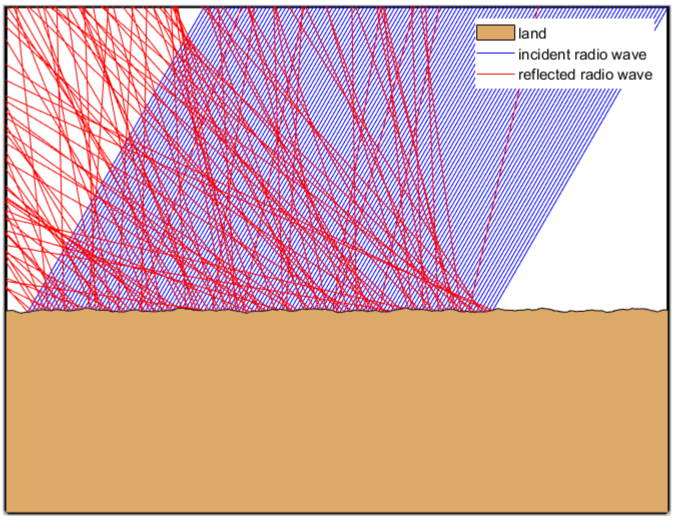

Figure 14: Simulation of smooth terrain in 2-D

After calculation, the coefficient of correction a is more than 0.5. Therefore, the reflection loss off the rugged terrain is more than loss on the turbulent ocean.

9 Solutions of Requirement 3

In this task, a ship is travelling across a turbulent ocean using HF radio for communication. We need accommodate our propagation model to this shipboard receiver and figure out how long the ship can remain contact using the same multi-hop path.

9.1 Local assumptions

We will make similar simplifying assumptions as follow:

- The ship sets off from the transmitting point and travels in a straight line.
- The ship is viewed as a point, as its size will have a negligible impact.

9.2 Adjustment of propagation model

In our propagation model, there are two types of receiving modes of the ship, which are shown in **Figure 15** and **Figure 16**. In Figure 15, the ship receives signal which is reflected off the ocean. In Figure 16, the radio reflects off the ionosphere and is received by ship directly.

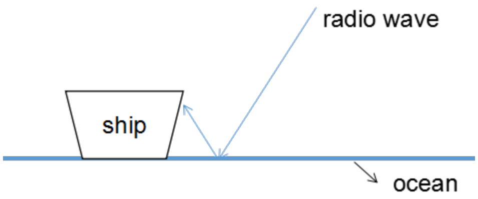

Figure 15: Receiving mode A

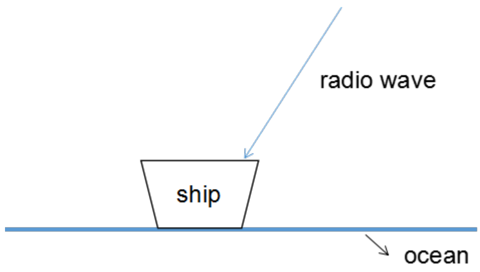

Figure 16: Receiving mode B

Comparing two receiving modes, we think mode B is more optimal, for it goes through less path loss if the ship is in the same position. With mode B, the ship can remain longer communication. So we will choose mode B as the receiving mode in our propagation model.

9.3 Maximum distance of remaining communication

According to the propagation model, the maximum distance of remaining communication is related to maximum number of hops and the angle of incidence. In the first place, we calculate the maximum number of hops on the turbulent ocean using our propagation model.

$$\begin{cases} Maxn \\ \quad L_b = L_{bf} + n(L_a + L_g) + Y_p \quad (dB) \\ \quad L_{bf} = 32.45 + 20\lg f(MHz) + 20\lg r(km) \quad (dB) \\ \quad r = n \times 2h/\cos\theta \\ \quad L_g = -10\lg R \\ \quad R = a \times R_1 \\ E_1(dB) = 107.2 + 20\lg f(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \\ \quad E_1 > E_2 + 5dB \\ \quad n \geq 1 \\ \quad 0 \geq \theta \geq 30 \end{cases} \tag{22}$$

In last section, we have discussed two receiving modes and chosen mode B to optimize our model. Here we are going to calculate the maximum distance of remaining communication using mode B. The problem can be described as such:

$$\begin{cases} n = n_{max} + 1 \\ L_b = L_{bf} + n(L_a + L_g) + Y_p \quad (dB) \\ L_{bf} = 32.45 + 20\lg f(MHz) + 20\lg r(km) \quad (dB) \\ r = n \times 2h/\cos\theta \\ L_g = -10\lg R \\ R = a \times R_1 \\ a = 0.5 \\ E_1(dB) = 107.2 + 20\lg f(MHz) + P_0(dB) + G_0(dB) - L_b(dB) \\ 0 \leq \theta \leq 30 \end{cases} \tag{23}$$

$$\begin{cases} S = 2 \times n \times 60 \times \sin\theta/\cos\theta & , E_1 > E_2 + 5dB \\ S = 2 \times n_{max} \times 60 \times \sin\theta/\cos\theta & , E_1 < E_2 + 5dB \end{cases} \tag{24}$$

Using MATLAB, we can achieve the correlation between incidence angle and maximum distance.

As is seen from **Figure 17**, the maximum distance is in proportion to the incidence angle. When the angle is 30 degrees, the maximum distance reaches the limit.

10 Sensitivity Analysis

In this part, we manually increase the turbulence of ocean and the angle of incidence and analyse the changes in maximum number of multi-hops and maximum distance of remaining communication.

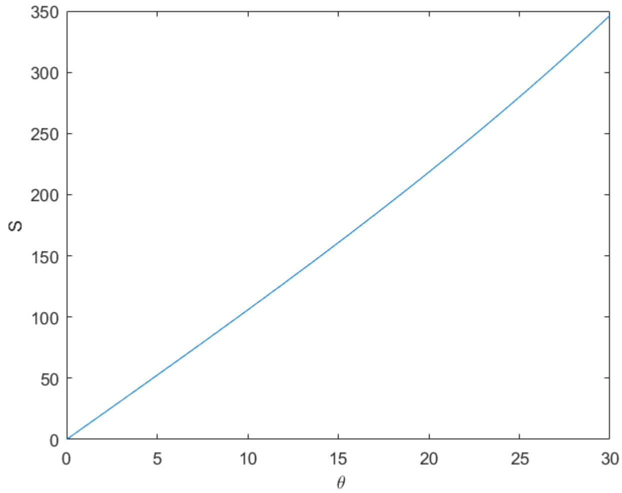

Figure 17: Maximum distance of different angles

10.1 Sensitivity to ocean turbulence

According to the study above, we have already known that the coefficient of correction a has a relation with ocean turbulence: a decreases with ocean turbulence increasing. When the ocean is calm, a is 1. We decrease the value of a from 1 to the limit of 0 to check the maximum number of multi-hops. The changes in the maximum number are depicted in **Figure 18**:

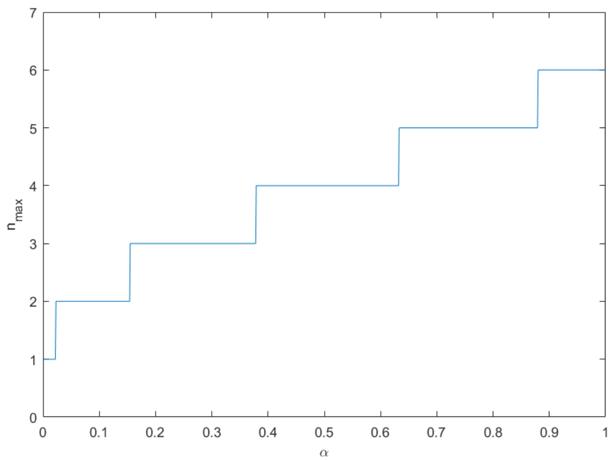

Figure 18: Changes in the maximum number

With the value of a decreases, the number of multi-hops also decreases, which is line with the actual cases. When a decreases, the reflection loss increases leading to smaller number of hops. The number of hops reaches its limit of 1 when a approaches the limit of 0.

10.2 Sensitivity to incidence angle

We increase the angle of incidence from 0 to 30 degrees to analyse maximum number of multi-hops and maximum distance of remaining communication. The changes in maximum number and maximum distance are depicted in the following figures:

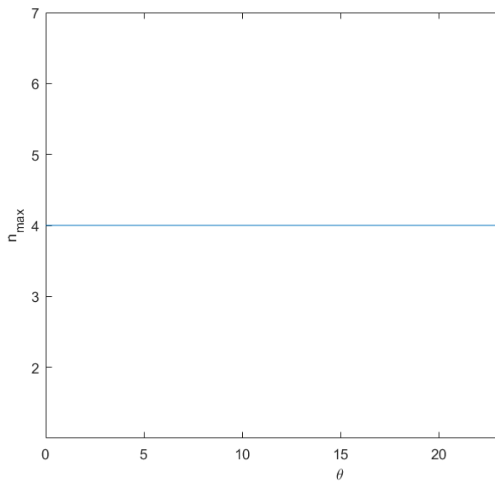

Figure 19: Changes in maximum number

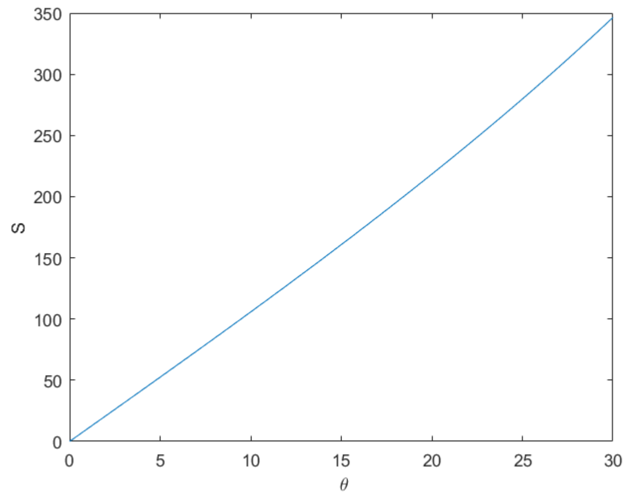

Figure 20: Changes in maximum distance

From **Figure 19**, we can come to the conclusion that the incidence angle has negligible impact on maximum number of hops. In **Figure 20**, the maximum distance is in proportion to the incidence angle.

11 Strengths and Weaknesses

11.1 Strengths

- **Our ocean surface model has simulated irregular movement of ocean waves.**We begin with the establishment of calm ocean model and then develop the ocean model progressively from sinusoidal ocean waves to irregular waves.
- **We compare reflection off the ocean with that off mountains, rugged and smooth terrain.** Based on irregular ocean waves model, we develop models of mountains, rugged terrain and smooth terrain and compare the differences of radio reflection in these models.
- **Our propagation model can estimate the transmission loss of radio propagation.** We specifically analyze four main types of loss in propagation: free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss.

11.2 Weaknesses

- **The data we obtained is limited.** Owing to the time limit, we are unable to search for more comprehensive and accurate data. Therefore, our model is restricted comparatively.
- **We neglect some factors that play a role in propagation model.** For instance, refraction, diffraction, absorption, polarization and scattering also have influence on radio propagation.

12 Future Work

Since the limitations on time and data, there are several factors missing in our model. In the near future, we will make the following adjustments:

- Collect more comprehensive and accurate data to optimize our models of ocean surface, mountains, rugged terrain and smooth terrain.
- Have deeper insights into the theory of ionosphere. The absorption loss of radio propagation should be recalculated.

13 Conclusion

In this paper, we mainly develop a HF radio propagation model. In order to estimate the transmission loss, the propagation model can be divided into four parts: free-space path loss, plane-earth reflection loss, ionospheric absorption loss, and other loss. We calculate four types of loss respectively and especially focus on reflection loss. We build an ocean surface model progressively to simulate the reflection off the ocean. In practice, we firstly prove that strength of the first reflection off a turbulent ocean is lower than that off a calm ocean by ocean surface model. Additionally, we find that the maximum of hops on a calm ocean is 6.

Secondly, we build reflection models of mountains, rugged terrain and smooth terrain by analogy. And with ocean surface model, we compare the differences between them. At last, we accommodate our model to a moving ship on a turbulent ocean. Using MATLAB, we calculate the maximum distance of remaining communication.

References

[1] Yuankun Wang. Introduction to Radio Wave Propagation[M]Beijing: National Defense Industry Press, 1984: 51-72

[2] Hainan Wang. The Comparative Analysis and Application of the Common Wireless Radio Transmittal Model[D], 2011

[3] Qingdi Yi. Research on electromagnetic wave propagation model of sea area[D],2015

[4] Xianghai Wang, Tingting Li. Wave simulation based on geometric modeling[J]Computer Science, 2011(10)

[5] Marc C. Tarplee. Radio wave propagation[Z]

[6] Xiaoping Tian, Jihua Lu. Shortwave propagation over oceans and HF propagation prediction model[J]IEEE Communication Magazine, 2009

[7] Hui Li, Chen Guo, Xiaofang Li. 3-D visual simulation of irregular ocean waves based on Matlab[J]Journal of system simulation, 2003(6)

[8] Ning Qi, Tian Xia, Wenyan Li, Liguang Zhao. Simulation of the mathmetical model of 3-D irregular wave based on Matlab[J]Computer knowledge and technology, 2013(25)

[9] National Data Buoy Center. Station 46059 in Northern Pacific Ocean. Available at http://www.ndbc.noaa.gov/station_history.php?station=46059

[10] Wikipedia contributors. List of mountain peaks of North America. Available at https://en.wikipedia.org/wiki/List_of_mountain_peaks_of_North_America

Appendices

Table 1. Statistics of Station 46059 in Northern Pacific Ocean

month	Jan	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
meters	3.8	3.9	3.3	3	2.5	2.5	2.4	2.3	2.7	3.1	3.7	4
wind	62.45	63.63	56.88	48.76	43.15	43.72	40.75	40.49	48.96	55.13	57.68	64.41

Source: National Data Buoy Center