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2018
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Summary Sheet

The Analysis of HF Radio Propagation

Summary

HF radio wave whose frequency is below the MUF could make multiple reflections off the earth and ionosphere. Therefore, they may travel a long distance.

In order to compare the strength of the first reflection off a turbulent ocean and calm ocean, we develop the **PLO** model for determining the energy attenuation. And we decompose the total energy attenuation to the basic energy loss and **the ocean reflection loss** caused by multipath fading. At the same time, the basic energy loss contains **the free-space loss, the ionosphere absorption and the additional loss**.

By means of the simulation of ocean wave and propagation, we can view that the received power of turbulent ocean changes violently over time while calm ocean keeps constant. And reflections on a turbulent ocean are attenuated more than reflections on a calm ocean. As for the maximum number of hops, we find that **if the 30 MHz radio wave is transmitted by 0.65 rad (elevation angle), it has the maximum number of hops-3.58** by Simulated Annealing.

In regard to HF reflections off rugged terrain versus smooth terrain, we believe the only difference reflects in **physical properties**. So we make some corrections to the land reflection loss as well as simulate the process. Also, we make a rank on the energy attenuation degree: **urbulent ocean > calm ocean > rugged terrain > smooth terrain**.

For accommodating a shipboard receiver moving on a turbulent ocean, we consider the impact of **ship motions** on the energy attenuation. Besides, we turn the analysis of ship communication time to the travel time for passing through **the effective reception area**. Also, we define the transfer coefficient to describe the turbulence degree of ocean indirectly. The results show that the ship can remain in communication for **3.93 days** by using the same multi-hop path. We also propose we can set some **radio repeaters** to strengthen the received power.

At last, we make the sensitivity analysis by **altering the turbulence level of ocean** as well as **changing the transfer coefficient** .

Keywords: PLO; Multipath Fading; Computer Simulation; Simulated Annealing

Contents

1 Introduction 2

1.1 Background . . . 2

1.2 Restatement of the Problem . . . 2

1.3 Literature Review . . . 3

2 Assumptions and Justifications 3

3 Notation 4

4 The Power Loss Model for HF Radio Reflection off The Ocean (PLO) 5

4.1 Some Basic Knowledge . . . 5

4.2 The Analysis of HF Radio Transmission Loss . . . 5

4.2.1 The Basic Energy Attenuation . . . 6

4.2.2 The Exploration of Ocean Reflection Loss Based on Multi-path Fading . . . 7

4.2.3 The Total HF Radio Transmission Loss . . . 10

4.3 The Signal-to-noise Ratio . . . 10

4.3.1 Basic discussion about SNR . . . 10

4.3.2 Identify the Maximum Number of Hops by SA . . . 11

4.4 Model Simulation And Results Analysis . . . 11

5 The Modified Power Loss Model for HF Radio Reflection off Land(PLL) 13

5.1 The Exploration of Land Reflection Loss . . . 13

5.2 Model simulation and results analysis . . . 13

6 The Modified Power Loss Model for Ship Travelling(PLS) 15

6.1 The Modified Power Loss Model . . . 15

6.1.1 Ship Motions . . . 15

6.1.2 The New Total Power Loss . . . 16

6.2 The Analysis of Ship Communication . . . 16

6.2.1 The Effective Reception Area . . . 16

6.2.2 The Length of The Effective Reception Area 17
6.2.3 The Travel Time 19
6.3 Some Proposals about Ship Communication 19

7 Sensitivity Analysis 20
7.1 Alter the "Turbulence" of Ocean 20
7.2 Change the transfer coefficient t_p 20

8 Strengths and weaknesses 21
8.1 Strengths 21
8.2 Weaknesses 21

9 Conclusions 21

Appendices 25

Appendix A The detailed proof 25

1 Introduction

1.1 Background

HF radio waves may propagate by the three following modes: **Ground Wave**, **Direct Wave** and **Sky Wave**[1]. However, in this problem, we only consider Sky Wave. In radio communication, sky wave usually refers to the propagation of radio waves refract or reflect back toward earth from the **ionosphere**, an electrically charged layer of the upper atmosphere[2]. To be brief, we can also treat the ionosphere as a vast reflecting surface encompassing the earth.

The ionosphere is a thin layer in the atmosphere, which is formed by ions. And the reflection capability of ionosphere mainly depends on the **ions density**. That's to say, the more ions are, the stronger the reflection becomes. In addition, the reflection ability may also influenced by time of day, season, solar activity and latitude.

1.2 Restatement of the Problem

HF radio waves whose frequencies are below the MUF could make multiple reflections off the earth and ionosphere. Therefore, they may travel a long distance. Generally speaking, the properties of the reflecting surface can identify the waves' strengths and propagation distances. Besides, the MUF varies with the season, time of day and solar conditions. And in particular, owing to the impact on electromagnetic gradient, local permittivity and permeability, reflections off a turbulent ocean are always attenuated more than a calm ocean.

In our main paper, we are required to:

- According to our developed model of signal reflection off the ocean, compare the strength of a first reflection off a turbulent ocean and calm ocean. In addition, caculate the maximum number of hops the signal can take when its strength falls below a usable SNR threshold of 10 dB.
- Analyse the HF radio waves' reflection off mountainous or rugged terrain versus smooth terrain and compare it with the first question.
- HF propagation is also used for ships, especially in communications as well as receiving weather and traffic reports. And then explore how our model change to accommodate a shipboard receiver moving on a turbulent ocean. Besides, determine the time if the ship remain in communication using the same multi-hop path.
- Based on our previous study, write a short synopsis for IEEE Communications Magazine.

1.3 Literature Review

Radio waves can travel a long distance because they can be reflected to the earth's ionosphere, which is called **"hop"**. HF radio waves reflected by the ionosphere can travel back to earth, and then it bounces of the earth's surface back up again into the ionosphere. Thus the **"multi-hop"** propagation is just the multiple bounces and reflections[3].

In addition, the ionosphere consists out of 4 layers: $\boldsymbol{D-Layer}$, $\boldsymbol{E-Layer}$, $\boldsymbol{F_1-Layer}$ and $\boldsymbol{F_2-Layer}$ [4]. And the $F_2 - Layer$ makes the largest sense in ionizing to HF radio waves and reflecting them to earth, while the $D - Layer$ is completely an **attenuator**[5].

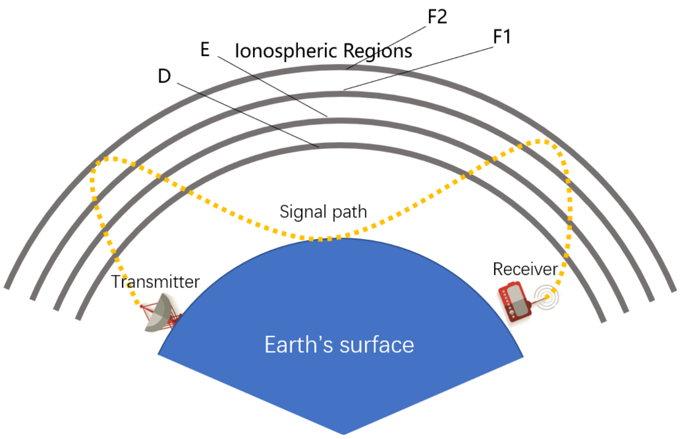


Figure 1: Multi-hop HF radio propagation

2 Assumptions and Justifications

We make the following basic assumptions in order to simplify the problem. Each of our assumptions is justified and consistent with the basic fact.

- **We ignore the energy attenuation in the E-Layer and F-Layer.** Compared with the attenuation occurs in E-Layer and F-Layer, the level of attenuation in D-Layer is much larger. So we only consider the attenuation in D-Layer.
- **We only consider the F_2 reflection mode.** In fact, the overwhelming majority of reflections occur in F_2-Layer, thus we suppose all the reflections off the ionosphere happens in F_2-Layer.
- **The sole difference between ocean reflection and land reflection is physical properties**. When HF radio waves reflect off rugged terrain, it may undergo direct reflection, specular reflection or diffuse reflection, just like the turbulent ocean, as same as smooth terrain and calm ocean. Thus we only

consider the differences in permittivity, electrical conductivity and other physical properties.

- **The height of ionosphere is constant at different areas.** There exists just a few differences in ionosphere(F_2-Layer) height at different areas.

3 Notation

Here we list some important symbols and notations used in our paper, as shown in Table 1. And the others will be illustrated later in the following sections.

Table 1: Notations

Symbols	**Description**	**Unit**
MUF	the maximum usable frequency	MHz
Q	the total HF radio transmission loss	dB
Q_{ia}	the ionosphere absorption loss	dB
Q_{or}	the ocean reflection loss	dB
Q_{al}	the additional loss	dB
Q_{fs}	the free-space path loss	dB
P_t	the transmitted power	watt
P_r	the recieved power	watt
f	the frequency of HF radio wave	MHz
λ	the wavelength of HF radio	m
l	the mean skip distance of a multi-hop propagation	km
N	the number of hops	-
$W(x,y,t)$	the irregular ocean wave	-
A_{ij}	the ocean wave's amplitude	m
ω	the circular frequency of ocean wave	Hz
ρ_i	the specular reflection coefficient	-
ρ_d	the diffuse reflection coefficient	-
ρ_f	fresnel reflection coefficient	-
Q_{lr}	the land reflection loss	dB
Q_{sm}	the power loss caused by ships motion	dB
T	the effective reflection area	-

4 The Power Loss Model for HF Radio Reflection off The Ocean (PLO)

4.1 Some Basic Knowledge

If we transmit HF radio waves straight up towards the ionosphere, the HF radio will be returned to earth only when their frequencies below the critical frequency.

Maximum usable frequency(MUF) (equals to critical frequency divide $\cos\theta$) is the highest radio frequency that can be used for transmission between the transmitter and receiver via reflection off the ionosphere[6]. That's to say, frequencies above the MUF may pass through the ionosphere, but not reflect or refract.

Besides, there exists a region where HF radio transmission can not be received, which is called skip zone or zone of silence. Also, the ionosphere consists of four layers(D-Layer, E-Layer, F_1-Layer, F_2-Layer), and they differ greatly in reflection ability[2].

4.2 The Analysis of HF Radio Transmission Loss

As you know, the attenuation of HF radio energy is a common phenomenon in the transmission procedure. And there are many factors may influence the transmission loss. To simplify our model, we divide the energy attenuation during the whole transmission process into several parts: **the free-space path loss** Q_{fs}, **the ionosphere absorption loss** Q_{ia}, **the additional loss** $Q_{al}$and particularly, **the ocean reflection loss** Q_{or}. And these four losses make up the total HF radio transmission loss Q. Also, we must stress that we employ **dB** to depict the energy loss of HF radio indirectly.

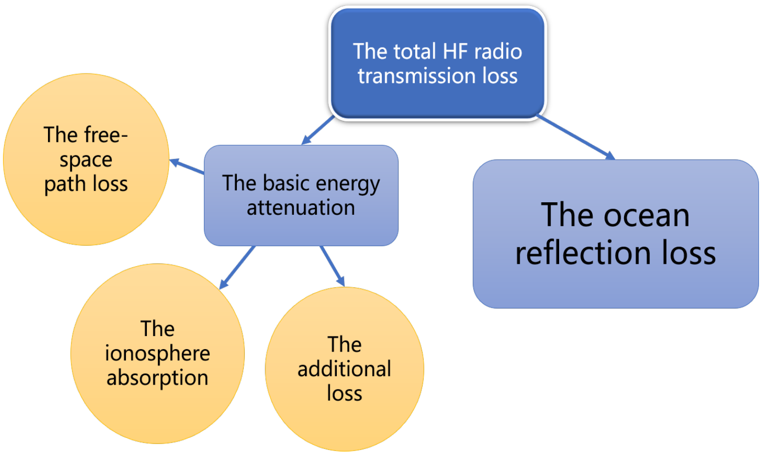


Figure 2: The total HF radio transmission loss

4.2.1 The Basic Energy Attenuation

- **The free-space path loss(FSPL)**

The free-space path loss(FSPL) is the loss in signal strength that occurs when a HF wave propagates over a line of sight path in free space. And it is defined as the ratio of the transmitted power P_t to the received power P_r [7]. In fact, the free-space path loss makes the maximum proportion among all these losses. In other word, the majority of losses take place during the free-space path. FSPL can be calculated as the following empirical formula:

$$Q_{fs} = 10\lg\frac{P_t}{P_r} = 32.4 + 20\lg f + 20\lg d \tag{1}$$

And f denotes the frequency(MHz) of HF radio wave while d shows the virtual slant rang(km).

Besides, the virtual slant rang d is obtained as follow:

$$d = 2R\sum_{i=1}^{N}\frac{\sin(l/2R)}{\cos(\theta + l/2R)} \tag{2}$$

Where R is the radius of earth(6371km), θ denotes the elevation angle(rad) and l represents the mean skip distance(km) of a multi-hop propagation.

According to the given information, the first transmitted power P_t is 100 watt and the frequency range of HF radio is 3-30 MHz. To get the numerical results of total energy loss, we consider 20MHz as HF radio wave's frequency while 2000km as the mean skip distance[1].

- **The ionosphere absorption loss**

We have indicated that ionospheric absorption is one of the major contributors to the reduction in strength of HF radio waves previously. And compared with the attenuation occurs in the E-Layer and F-Layer, the level of attenuation in D-Layer is much larger. As a result, we **neglect** the energy attenuation in the E-Layer and F-Layer[8]. The Q_{ia}(dB) can be obtained as the following empirical formula:

$$Q_{ia} = \frac{677.2N\cdot\sec\alpha}{(f+f_e)^{1.98}+10.2}\frac{1}{M}\cdot\sum_{i=1}^{M}[(1+0.0037C)(\cos 0.88\beta)^{1.3}] \tag{3}$$

Where α denotes the angle(rad) of incidence at 120 km, f_e is the mean value of electron gyrofrequency(MHz), M shows the number of control points, C represents the absorption factor at local noon and β is the solar zenith angle(rad).

- **The additional loss**

The additional loss(Q_{al}) denotes other elements that may cause energy attenuation, such as defocusing effect, polarization loss and so on. And the present recommended value is 8 dB [9].

4.2.2 The Exploration of Ocean Reflection Loss Based on Multipath Fading

- **The ocean wave simulation model**

As we all know, the ocean waves are irregular. And in fact, ocean waves are made up of the short crested waves from all directions:

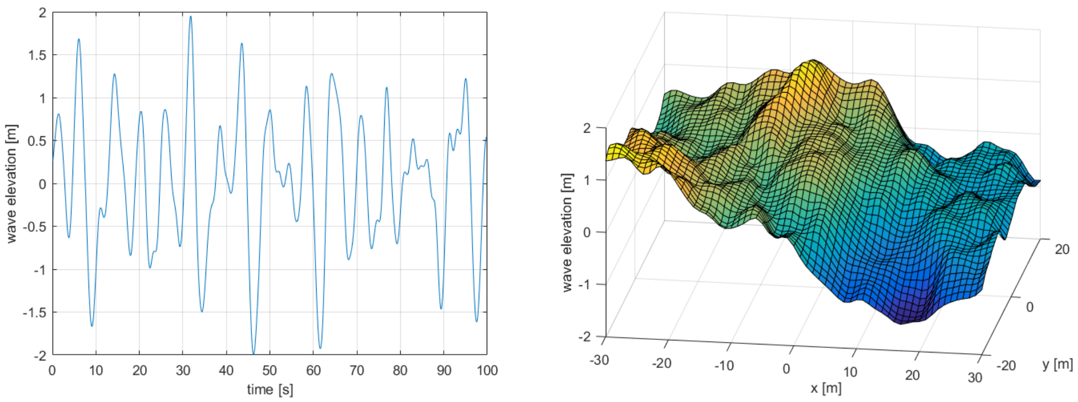
$$W(x,y,t) = \sum_{i=1}^{p}\sum_{j=1}^{q} A_{ij}\cos(r_i x\cos\eta_j + r_i y\sin\eta_j - \omega_i t + \varphi_{ij}) \tag{4}$$

And A_{ij}, r_i , ω_i and η_j represent the wave amplitude(m), wave number, circular frequency(Hz) and random phase angle(rad) of wave component j. Also, the random phase angle φ_{ij} is uniformly distributed between 0 and 2π and constant with time.

Besides, the wave amplitude A_{ij} can be calculated as follow:

$$A_{ij} = \sqrt{2f(\omega_{ij})\Delta\omega} = \sqrt{0.0162\omega_{ij}^{-5}\exp(-0.74(\frac{g}{\omega_{ij}})^4)\Delta\omega} \tag{5}$$

And now we apply this algorithm to simulate ocean waves by MATLAB and set the wind speed at the height of 19.4 m as 13 m/s.



(a) The wave elevation (b) The ocean wave

Figure 3: The simulation of ocean wave

- **Multipath fading**

Generally speaking, multipath means that a single signal can travel multiple paths to arrive at a receiving antenna. More specifically, the multipath reflection waves mainly contain three parts: **the direct waves**, **the specular reflection waves** as well as **the diffuse reflection waves**[10]. However, we must stress that if reflections occur on a calm ocean, the diffuse reflection path won't exist.

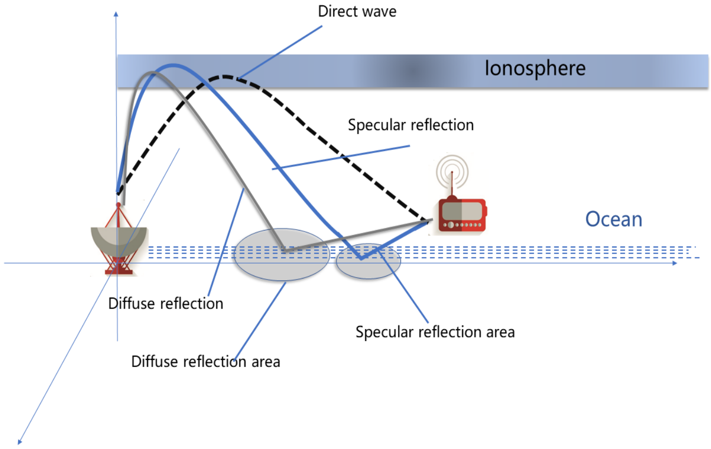


Figure 4: The multipath reflection

Just as Figure 5 shows, different areas of ocean surface make small or great contributions to reflection, but we only consider the area that plays a great role, which is also called **the effective reflection area**. And the ocean reflection loss can be shown as follow:

$$Q_{or} = -147.56 + 20\lg l + 20\lg f - 20\lg|1 + \sum_{i=1}^{T} \rho_i e^{j\Delta\phi_i} + \rho_d e^{j\Delta\phi_d}| \tag{6}$$

Where ρ_i is the specular reflection coefficient, ρ_d denotes the diffuse reflection coefficient, T represents the effective reflection area, $\Delta\phi_i$ shows the phase difference(rad) between specular reflection wave and direct wave while $\Delta\phi_d$ shows the phase difference(rad) between diffuse reflection wave and direct wave.

- **Determine the effective reflection area**

As you know, most of the reflections occur in the effective reflection area. To make the calculation of ocean reflection loss more simple, we try to identify the effective reflection area T.

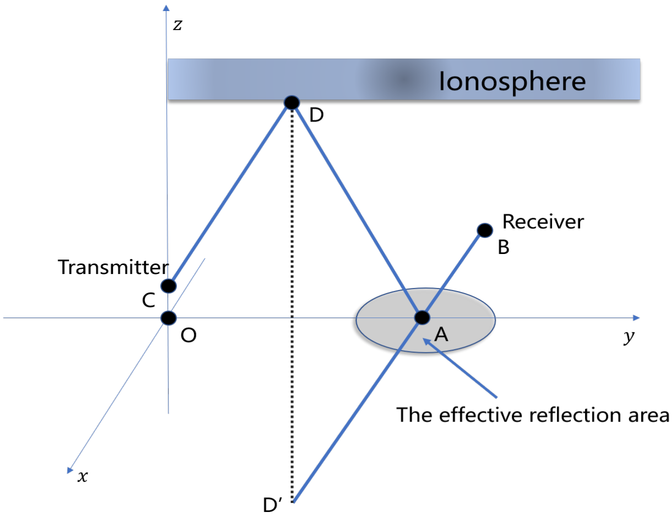


Figure 5: The multipath reflection

For a point G in the effective reflection area, it must satisfy the following formula(as shown in Figure 5):

$$|\overrightarrow{BG}| + |\overrightarrow{GD}| < |\overrightarrow{BD'}| + \frac{\lambda}{2} \tag{7}$$

- **The impact of ocean wave on the parameters change**

To quantizate the incidence of the first reflection off a turbulent ocean, we turn the impact of ocean wave on multipath fading into the influence on the parameters in E.q (6).

The specular reflection coefficient ρ_i is the product of fresnel reflection coefficient ρ_f , scattering factor on rough surface F_s and diffusion factor D_f.

$$\rho_i = \rho_f F_s D_f \tag{8}$$

And the fresnel reflection coefficient ρ_f can be gotten as follow:

$$\rho_f = \begin{cases} \rho_{fv} = \frac{\cos\gamma - \sqrt{\varepsilon_0 - (\sin\gamma/\varepsilon_0)^2}}{\cos\gamma + \sqrt{\varepsilon_0 - (\sin\gamma/\varepsilon_0)^2}} \\ \rho_{fh} = \frac{\cos\gamma - \sqrt{\varepsilon_0 - (\sin\gamma)^2}}{\cos\gamma + \sqrt{\varepsilon_0 - (\sin\gamma)^2}} \end{cases} \tag{9}$$

Thereinto, ε_0 equals to $\varepsilon - j60\sigma\frac{c}{f}$. Where γ shows the angle(rad) of incidence when HF wave reflect off the ocean surface, ε_s is the **local permittivity** and σ_s denotes the **electrical conductivity** of seawater.

The scattering factor on rough surface F_s:

$$F_s = \exp(-2(2\pi S)^2)I_0((2\pi S)^2) \tag{10}$$

And $S(\delta\cos\gamma/\lambda)$ is the Rayleigh criterion while I_0 denotes the modified Bessel function of the first kindand order zero.

The diffusion factor D_f:

$$D_f = \frac{1}{\sqrt{1 + \frac{2r_i r_j}{R(r_i+r_j)\cos\gamma}}} \tag{11}$$

In which r_i and r_j are the distances(km) between the transmitter and reflecting point as well as the receiver and reflecting point.

In addition, the diffuse reflection coefficient ρ_d is the product of the fresnel reflection coefficient ρ_f and the correction factor ρ_c .

$$\rho_d = \rho_f \rho_c \tag{12}$$

Where the correction factor ρ_c:

$$\rho_c = \begin{cases} 3.75S, & 0 \le S \le 0.1 \\ 0.4625 - 0.875S, & 0.1 < S \le 0.5 \\ 0.025, & S > 0.5 \end{cases} \tag{13}$$

4.2.3 The Total HF Radio Transmission Loss

On the basis of the previous analyse, we can get the total energy attenuation Q (dB):

$$Q = 10\lg\frac{P_t}{P_r} = Q_{fs} + Q_{ia} + Q_{al} + Q_{or} \tag{14}$$

However, we must emphasize that Q doesn't show the attenuated energy directly, but the the ratio of the transmitted power P_t to the received power P_r. **That's to say, the larger Q is, the more energy attenuates.**

4.3 The Signal-to-noise Ratio

4.3.1 Basic discussion about SNR

Signal-to-noise ratio is defined as the ratio of the power of a signal (meaningful information) and the power of background noise (unwanted signal).

$$SNR = 10\lg\frac{P_{signal}}{P_{noise}} \tag{15}$$

From the formula we can view that the larger SNR shows the signal has more meaningful information. And the usable (SNR) threshold is 10 dB, which means the signal is ten times the power of the noise. Besides, we can evaluate the power of noise as follow[11]:

$$P_{noise} = -0.0019f^4 + 0.098f^3 - 1.8f^2 + 13f - 13 \tag{16}$$

4.3.2 Identify the Maximum Number of Hops by SA

To identify the maximum number of hops, we employ the Simulated annealing algorithm. And it can be decomposed into several steps:

- Step 1: choose a random value (eg $U(0) = U_0$) as the original state, and then initialize it ($T = T_0, i = 0$).
- Step 2: let $T = T_i$, and employ Metropolis-Hastings algorithm to deal with U and T. Next, make T equals to $T_{i+1}(T_{i+1} < T_i)$.
- Step 3: check whether T is the optimal. If so, the algorithm finishes. Otherwise turn to Step 2.

In the above expression, U is the solution space, which shows the number of hops under the given frequency and elevation angle. And T denotes the temperature.

Eventually, we find that if the 30 MHz radio wave is transmitted by 0.65 rad (elevation angle), it has the maximum number of hops 3.58 (Just as shown in Figure 7). It demonstrates that the wave can finish three hops and its power will attenuate to zero during the fourth hop.

4.4 Model Simulation And Results Analysis

We make a simulation of HF radio propagation as well as ocean waves based on the previous discussions . And the parameters are shown as follow:

Table 2: The simulated parameters

parameter	value
the frequency of HF radio wave f	20 MHz
the mean skip distance l	2000 km
the radius of earth R	6371km
the elevation angle θ	$\pi/6$
the additional loss Q_{al}	8 dB
the amplitude of ocean wave A_{ij}	19.4 m
the wind speed	13m/s
the local permittivity ε_s	80
the electrical conductivity of seawater σ_s	4
the simulation time	100s

After setting all these parameters, we compare the strength of the first reflection off a turbulent ocean as well as calm ocean. Also, we simulate some HF radio wave propagations on the basis of the specific frequencies and elevation angles.

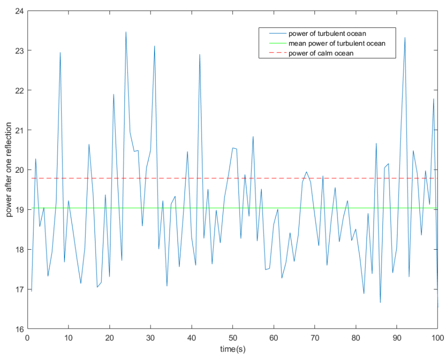


Figure 6: The strength of the first reflection off the ocean

Frequency f (MHz)	Elevation angle θ(rad)	Number of hops
25	0.62	3.35（3）
30	0.48	3.42（3）
15	0.87	2.83（2）
30	0.65	3.58（3）
27	0.68	3.32（3）

Figure 7: Simulate the propagation of some specific HF radios

Figure 6 shows us how the received power changes with respect to time. We can view that the received power of turbulent ocean changes violently while calm ocean keeps constant. In fact, it's reasonable. **Because the diffuse reflection path doesn't exist when reflection occurs on a calm ocean.** To compare the strength better, we calculate the mean power of turbulent ocean(the green line). **And it's obvious that reflections on a turbulent ocean are attenuated more than reflections on a calm ocean.**

5 The Modified Power Loss Model for HF Radio Reflection off Land(PLL)

Compared with the PLO model, we can view that no matter HF reflections off land or ocean surface, the basic energy attenuation calculation method is absolutley identical. That is to say, what we only consider is the land reflection loss Q_{lr}.

$$Q = 10\lg\frac{P_t}{P_r} = Q_{fs} + Q_{ia} + Q_{al} + Q_{lr} \tag{17}$$

5.1 The Exploration of Land Reflection Loss

As we all know, the HF reflections off rugged terrain versus smooth terrain are really similar with the reflections off ocean. When HF radio waves reflect off rugged terrain, it may undergo direct reflection, specular reflection or diffuse reflection, just as the turbulent ocean. And if HF radio reflect off smooth terrain, it may undergo direct reflection or specular reflection, just as the calm ocean. And the primary differences are reflected in their own properties, such as permittivity, electrical conductivity and so on.

Besides, in PLO model, we mainly simulate the change of received power with respect to time on a specific reflecting point. As for this model, we want to simulate the change of received power with respect to geographic positions. Also, we make some corrections to the land reflection loss Q_{lr} on the basis of the ocean reflection loss.

$$Q_{lr} = -50.27 + 20\lg l + 20\lg f - 20\lg\left|\sum_{i=1}^{T}\varepsilon_l e^{j\Delta\phi_i} + \sigma_l e^{j\Delta\phi_d}\right| \tag{18}$$

Where ε_l denotes the permittivity and σ_l shows the electrical conductivity of soil.

5.2 Model simulation and results analysis

Similarly, we set the parameters' value first. In order to make a comparison with ocean, we choose the identical value for most of parameters[12].

Table 3: The simulated parameters

parameter	value
the frequency of HF radio wave f	20 MHz
the mean skip distance l	2000 km
the radius of earth R	6371km
the elevation angle θ	$\pi/6$
the additional loss Q_{al}	8 dB
the local permittivity ε_l	5
the electrical conductivity of soil σ_l	0.001
the simulation points	80

At first, we simulate the terrain , as shown in Figure 8. And then we simulate the propagation process for analysing how the received power changes with respect to geographic positions baesd on the simulated terrain.

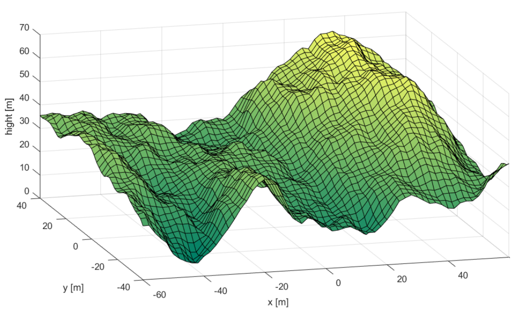


Figure 8: Simulated terrain

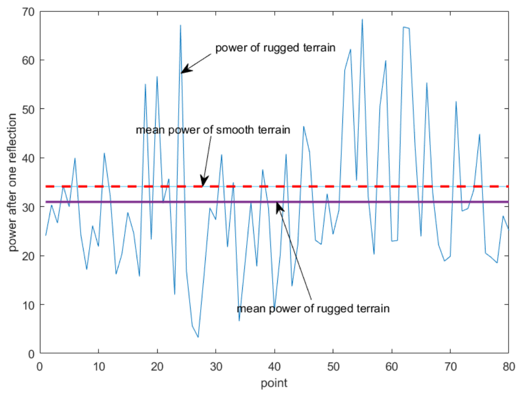


Figure 9: Simulate the propagation of the given HF radios

From Figure 9, we can view that the received power of rugged terrain varies in 80 different positions(in a continuous area) while the received power of smooth terrain keeps constant. Also, we apply mean value to measure the degree of attenuation. As a consequence, we can draw the conclusion that reflections on a rugged terrain are attenuated more than reflections on a smooth terrain. However, both of them are much less than reflections on the ocean. As a result, we can make a rank on the energy attenuation degree: **urbulent ocean** > **calm ocean** > **rugged terrain** > **smooth terrain**.

6 The Modified Power Loss Model for Ship Travelling(PLS)

6.1 The Modified Power Loss Model

6.1.1 Ship Motions

As we know it, when a ship travels across a turbulent ocean, it may motion violently, which causes the power loss to an extent[13]. And then we study this process concretely.

- **Maximum angular deviation**

In fact, the ship motions are decomposed to three parts: Heave is a linear vertical (up/down) motion along z axis. Sway is a linear lateral (side-to-side or port-starboard) motion along x axis. And surge is a linear longitudinal (front/back or bow/stern) motion along y axis.

To describe the motion degree of one ship, we employ maximum angular deviation. Knowing the wave height(m) h_s and the ocean wave's length(m) λ_s, the maximum angular deviation μ can be evaluated:

$$\mu = \arcsin(\frac{\pi h_s}{\sqrt{\lambda_s^2 + \pi^2 h_s^2}}) \tag{19}$$

- **The radiation vector function**

Generally speaking, the radiation vector function is an important index to measure the degree of energy attenuation. And it relys on the practical gain for a given set of incidence and arrival angles:

$$M = \sqrt{M(\theta, \tau)} Y = \sqrt{M(\theta, \tau)} \begin{pmatrix} Y_\theta(\theta, \tau) \\ Y_\tau(\theta, \tau) \end{pmatrix} \tag{20}$$

And θ is the elevation angle while τ is the azimuth angle. Also, Y denotes the normalized unit vector(as shown in Figure10).

- **The power loss**

According to the previous discussion, the propagation path are always divided into direct path as well as reflected path. Thus we try to obtain their channel matrix. The direct path channel matrix:

$$K_d = \frac{1}{r} \sqrt{M^A} \sqrt{M^B} (Y_\theta^B, Y_\tau^B) \tag{21}$$

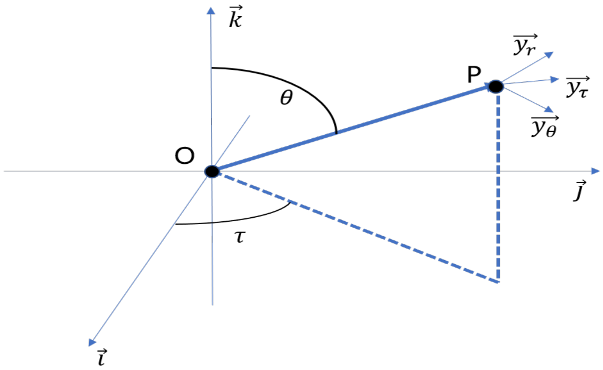


Figure 10: Antenna coordinate system with unit vectors

And the reflected path matrix:

$$K_r = \frac{1}{r_1 + r_2}\sqrt{M^A}\sqrt{M^B}(Y_\theta^B, Y_\tau^B) \tag{22}$$

Finally, we can evaluate the power loss(dB) caused by ships motion:

$$Q_{sm} = -20\lg(\frac{\lambda}{4\pi}|K_d + K_r|) \tag{23}$$

6.1.2 The New Total Power Loss

On the basis of the PLO model, we can obtain the new tatal power loss.

$$Q = 10\lg\frac{P_t}{P_r} = Q_{fs} + Q_{ia} + Q_{al} + Q_{or} + Q_{sm} \tag{24}$$

6.2 The Analysis of Ship Communication

6.2.1 The Effective Reception Area

At first, we define the effective reception area, just as Figure 11 shows. The left area is the **zone of silence**, where HF radio transmission can not be received limited by elevation angle θ and MUF. And the right area is defined as the **invalid area**. As you know, the energy decreases with the increase of hops number. Therefore, if SNR is less than the threshold 10 dB, we think the signal can not be used for ship communication any more. Obviously, the area between the zone of silence and invalid area is the **effective reception area**.

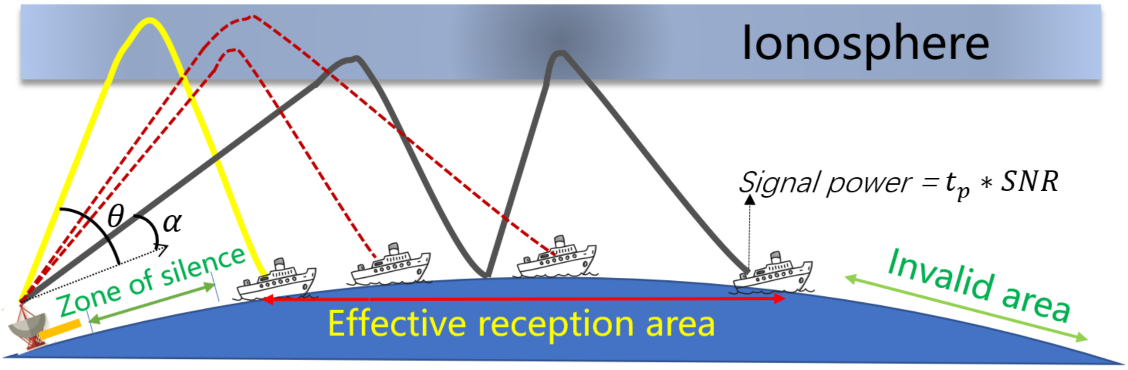


Figure 11: The effective reception area

And the key is to calculate how long can the ship travel across the effective reception area.

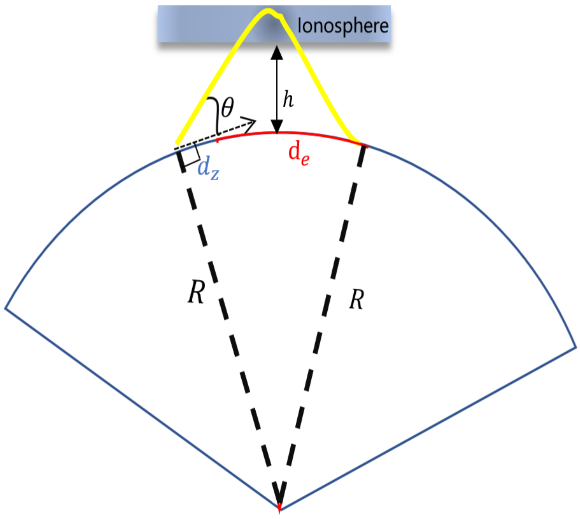


Figure 12: The calculation of d_z

Just as Figure 12 shows, the length of the zone of silence d_z can be calculated as follow(there is detailed proof in appendix):

$$d_z = 2R\left[\frac{\pi}{2} - \theta - \arcsin\frac{R\cos\theta}{R+h}\right] \tag{25}$$

6.2.2 The Length of The Effective Reception Area

- **The transfer coefficient** t_p

As you know, ocean waves are random, which may also cause the random multipath fading and ship motions. All of these factors may cause the uncertainty of the effective reception area. In order to identify the effective reception area, we consider the changes of multipath fading and ship motions over a period of time. And the larger the variance of the received power is, the more negative impacts exsit(Just as Figure 6, 9 shows). Thus we define a transfer coefficient t_p for describing the turbulence of ocean indirectly, which is also proportional to the variance. More specificly, t_p is the product of the variance caused by multipath fading and ship motions.

Besides, the transfer coefficient t_p can also demonstrate the continuity of information. That's to say, too large transfer coefficient may cause information absence(Just as shown in Figure 13).

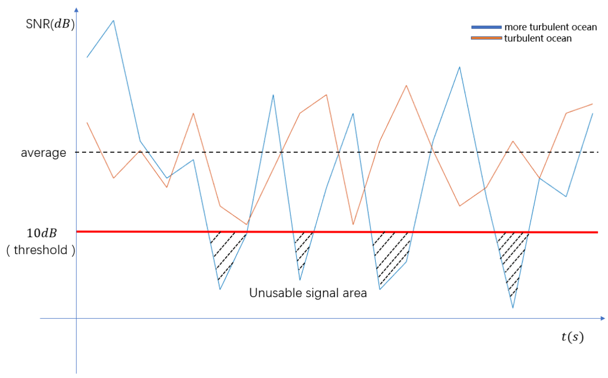


Figure 13: The information absence described by t_p

Specifically, we can make an example. If the information carried by signal is" Tomorrow morning from 9:00 to 9:30, there will be a force ten storm. Please be prepared".

If t_p equals to 2, people may hear "XXX morning from 9:00 to 9:30, there will be a force ten storm. Please be prepared".

But if t_p equals to 5, people may hear "XXX morning from 9:00 to 9:30, there will be a XXX XXX XXX. Please be prepared".

Even if t_p equals to 10, people may hear "XXX morning from XXX to XXX, there will be a XXX XXX XXX. Please be prepared".

Obviously, if people lose some keywords in a sentence, they can't get the full information. That means, the greater the variance is, the worse the signal becomes.

- **The critical power for communication**

Just as formule (15) shows, SNR is defined as the ratio of the power of a signal (meaningful information) and background noise (unwanted signal). According to the given information, the SNR threshold is 10dB. It suggests that the signal is ten times the power of noise for turbulent ocean, which is also called the critical power. However, for calm ocean, we employ the transfer coefficient to modify it.

$$P_{calm} = 10P_{noise}, P_{turbulent} = t_p P_{calm} \tag{26}$$

- **The calculation of propagation distance**

According to our results in section 4.3.2, if the 30 MHz radio wave is transmitted by 0.65 rad (elevation angle), it has the maximum number of hops. And to guarantee the same multi-hop path, we use the same 30 MHz radio. On the basis of the total power loss Q in PLO model, we obtain the propagation distance before its strength falls below the usable SNR threshold. In fact, the propagation distance equals to $d_z + d_e$.

6.2.3 The Travel Time

Above all, the travel time t can be gotten as follow:

$$t = \frac{d_e}{v_s} \tag{27}$$

And v_s denotes the velocity of ships. In general, v_s equals to 28-35 km/h[14]. But in consideration of the turbulent ocean, we set v_s as 25 km/h.

Finally, we can draw a conclusion that the ship can remain in communication for 3.93 days by using the same multi-hop path.

6.3 Some Proposals about Ship Communication

On the basis of the previous analysis, we find that the shipboard receiver may not receive the signal at some areas. So we propose that we can set some radio repeaters to elimate the phenomenon(Just as Figure 14 shows). In addition, we can transmit the signal for several times.

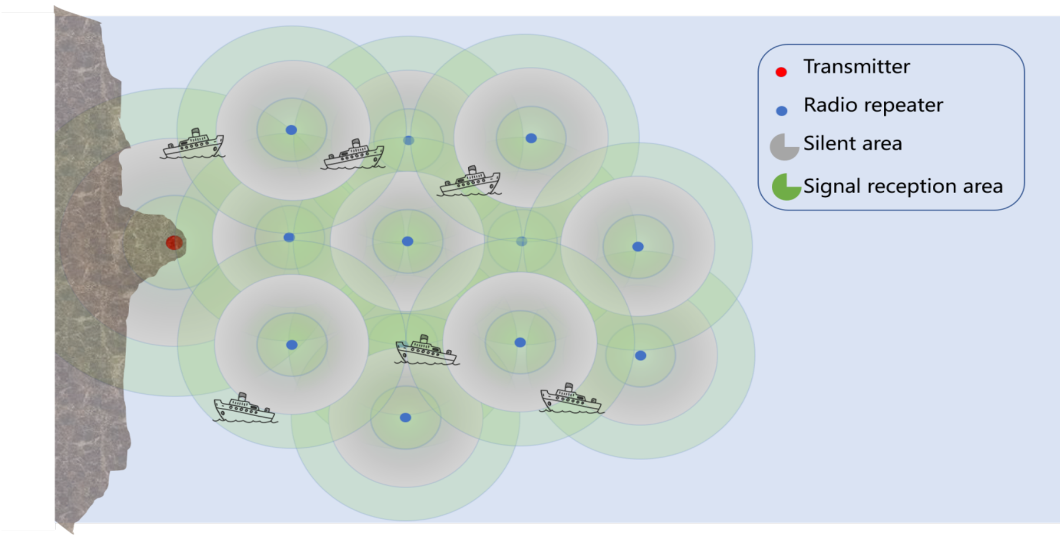


Figure 14: Set some radio repeaters

7 Sensitivity Analysis

7.1 Alter the "Turbulence" of Ocean

In our PLO model, we simulate the ocean wave by setting the wind speed at the height of 19.4m as 13m/s. And now we try to get the strength of a first reflection off a turbulent ocean under different turbulence level of ocean. Here we select some wind speeds to depict different turbulent ocean and make another several simulations.

At the same time, we must emphasize that the simulation result is the change of first received power with respect to time. So in order to compare the energy attenuation degree under different turbulence level, we use **variance** to describe it. And the larger variance shows the more violent changes on received power.

Table 4: The variance of received power under different turbulence level

wind speed(m/s)	10	11	12	12.5	13	14
the variance of received power	145	169	183	208	230	267

Table 4 demonstrates that the variance of received power is proportional to wind speed. Because the faster the wind speed is, the more turbulent the ocean becomes. And the high degree of turbulence may cause the more violent changes on received power. At the same time, it also suggests that our model is stable.

7.2 Change the transfer coefficient t_p

In the PLS model, we define the transfer coefficient t_p to determine the effective reception area. And it is proportional to the variance of the received power. Different turbulent ocean may make a great sense to the transfer coefficient as well as the communication time. As a result, we try to discuss the communication time under different turbulence level. Likewise, we employ the wind speed to depict different turbulent ocean.

Table 5: The communication under different turbulence level

wind speed(m/s)	10	11	12	12.5	13	14
the communication time(day)	4.40	4.32	4.08	4.05	3.93	3.86

From Table 5 we can view that the communication decrease with the increase of wind speed. Because the larger transfer coefficient shows the high turbulence level, which also causes more energy attenuation. At the same time, it suggests that our model is robust.

8 Strengths and weaknesses

8.1 Strengths

- **Robust** We have analysed the variance of received power under different turbulence level in the sensitivity analysis, and the results suggest that our model is robust.
- **Applicable** Our model can be applied widely to both ocean and land. Besides, various kinds of HF radio waves are also applicable.

8.2 Weaknesses

- **Use some empirical formulas** For calculate the energy attenuation, we employ some empirical formulas, which may be inaccurate.
- **The simple calculation of t_p** Owing to lack of related literatures, we simplify t_p as the product of the variance caused by multipath fading and ship motions.
- **Only consider the physical properties difference between** Q_{or} and Q_{lr}.

9 Conclusions

To compare the strength of the first reflection off a turbulent ocean and clam ocean, we build the PLO model to divide the total power loss into four parts: the free-space path loss Q_{fs}, the ionosphere absorption loss Q_{ia}, the additional loss Q_{al} and particularly, the ocean reflection loss Q_{or}. By means of the simulation of HF radio propagation and ocean wave, **we draw a conclusion that reflections on a turbulent ocean are attenuated more than reflections on a calm ocean**. As for the maximum number of hops, we find that **if the 30 MHz radio wave is transmitted by 0.65 rad (elevation angle), it has the maximum number of hops-3.58**.

On the basis of PLO model, we modify it as PLL model. By simulating the terrain and propagation of the specific HF radios, **we make a rank on the energy attenuation degree: urbulent ocean > calm ocean > rugged terrain > smooth terrain.**

In order to accommodate a shipboard receiver moving on a turbulent ocean, we take the ships motion into account for calculating the total power loss. Besides, we define the effective reception area. And then turn the analysis of ship communication time to the travel time for passing through the effective reception area. **Eventually, we find that the ship can remain in communication for 3.93 days by using the same multi-hop path.**

A SHORT NOTE ON MULTI-HOP HF RADIO PROPAGATION

MCM Team 84368

Abstract: We develop the PLO model to determine the strength of the first reflection off a turbulent ocean as well as the calm ocean. In fact, we decompose the total power loss into four parts(the free space path loss, the ionosphere absorption loss, the additional loss and the ocean reflection loss) and calculate them respectively. As for rugged terrain versus smooth terrain, we consider the physical properties with ocean and modify it as PLL model. In order to accommodate a shipboard receiver moving on a turbulent ocean, we mainly care about ship motions. At last, we turn the analysis of ship communication time to the travel time for passing through the effective reception area.

Key words: PLO; PLL; PLS; The Effective Reception Area

1 Introduction

Generally speaking, the attenuation of HF radio energy can be decomposed as the basic energy attenuation as well as other attenuation caused by media property or propagation modes. The basic energy attenuation mainly contains the free-space loss Q_{fs}, the ionosphere absorption Q_{ia} and the additional loss Q_{al}.

In fact, the free-space path loss Q_{fs} makes the maximum propagation among all these losses[1].

$$Q_{fs} = 32.4 + 20 \lg f + 20 \lg d \tag{1}$$

Where f denotes the frequency(MHz) of HF radio wave while d shows the virtual slant rang(km).

And the ionospheric absorption loss Q_{ia} is one of the major contributors to the reduction in strength of HF radio waves, too[2].

$$Q_{ia} = \frac{677.2N \cdot \sec \alpha}{(f + f_e)^{1.98} + 10.2} \frac{1}{M} X \tag{2}$$

Where α denotes the angle(rad) of incidence at 120 km, f_e is the mean value of electron gyrofrequency(MHz).

As for the additional loss, we set it as 8 dB[3].

2 The Power Loss Model for Ocean(PLO)

When the signal reflection off the ocean, we should analyse the Ocean Reflection Loss Q_{rl}. Based on the multipath fading theory, we know that the direct wave, specular reflection wave and diffuse reflection wave make up of the multipath reflection waves. But the diffuse reflection path won't exist if reflections occur on a clam ocean. The ocean reflection loss Q_{rl} can be obtained as follow:

$$Q_{or} = -148 + 20 \lg l + 20 \lg f - 20 \lg |Y| \tag{4}$$

Where ρ_i is the specular reflection coefficient, ρ_d denotes the diffuse reflection coefficient.

And now we can calculate the total power loss Q.

$$Q = Q_{fs} + Q_{ia} + Q_{al} + Q_{or} \tag{5}$$

At last we make a simulation of HF radio propagation as well as ocean waves for comparing the strength of a first reflection off a turbulent or calm ocean.

3 The Modified Power Loss Model for Land(PLL)

Compared with the PLO model, HF reflections off rugged terrain versus smooth terrain are really similar with the reflections off ocean. In consideration of the difference between the physical properties, we make some corrections to the land reflection loss Q_{lr}.

$$Q_{lr} = -50 + 20\lg l + 20\lg f - 20\lg|Y| \tag{7}$$

Simarly, we simulate the terain and the propagation process.

4 The Modified Power Loss Model for Ship travelling(PLS)

In this model, we mainly consider the ship motions, which may cause the power loss[4]. In addition, we turn the analysis of ship communication time to the travel time for passing through the effective reception area by the definition of the effective reception area.

5 Conclusion

Based on the previous analysis and simulation results, we draw the following conclusions:

- Reflections on a turbulent ocean are attenuated more than reflections on a calm ocean.
- If the 30 MHz radio wave is transmitted by 0.65 rad (elevation angle), it has the maximum number of hops-3.58.
- The rank on the energy attenuation degree: urbulent ocean > calm ocean > rugged terrain > smooth terrain.
- The ship can remain in communication for 3.93 days by using the same multi-hop path.

Besides, we propose that we can set some radio repeaters to enhance the communication of ships.

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Appendices

Appendix A The detailed proof

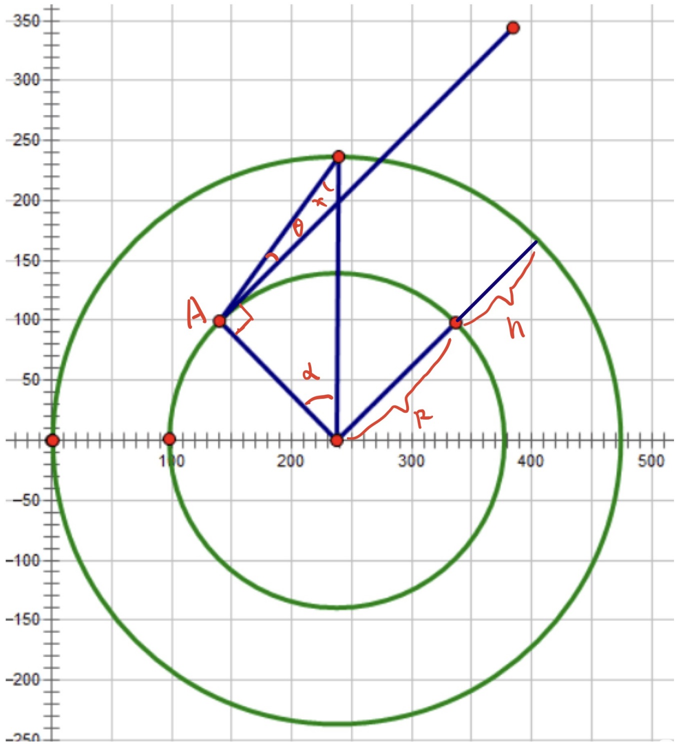

Figure 15

According to Figure 15, the detailed proof are shown as follow:

$$\frac{\sin(x)}{R} = \frac{\sin(\pi/2+\theta)}{h+R}$$
$$\frac{\sin(x)}{\cos\theta} = \frac{R}{R+h}$$
$$x = \arcsin(\frac{R\cos\theta}{R+h})$$
$$\alpha = \pi/2 - \theta - x$$
$$d = 2R\left[\pi/2 - \theta - \arcsin(\frac{R\cos\theta}{R+h})\right]$$