Multi-Hop HF Radio Propagation

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Abstract

The characteristics of the reflecting surface determine the strength of the reflect-ed wave and how far the signal will ultimately travel while maintaining useful signal strength. Determine the loss of strength and multi-hop path during HF signal reflection of the turbulent ocean will be the subject of this paper. By making key assumptions, we reduce the problem to two spatial dimensions. We develop a static geometric model base on the law of reflection to determine multi-hop path. For the reflection off a calm ocean, we only consider the free-space path loss. For the turbulent ocean, we establish the relationship between reflectivity and wave height to determine the reflection loss. Two extreme angles of incidence are considered. Ultimately, we can determine the multi-hop path and the maximum number of hops by assuming that atmospheric noise is the only source of noise and giving a usable signal-to-noise ratio (SNR) threshold of 10dB. We then extend the reflections to off mountainous or rugged terrain versus smooth terrain. Consider the difference of electromagnetic characteristics between the land surface and sea surface, we have revised the reflection coeffi-cient. Our results show that reflection loss on land surface is greater than the that on the sea surface. For a ship dynamically traveling across the ocean using HF for communications. We can determine the minimum number of hops that can cover the spherical distance between the ship and the antenna by the results of the static geomet-ric model. Then the multi-hop path is determined and the signal strength was calculated dynamically. Finally, we obtain the relationship of the ship traveling distance and the signal strength received. Our solution is derived from the two-dimensional model, we have no clear way of evaluating whether the 2D approach limited our model in some important way. However, the model, which is easy to implement, gives us all the infor-mation we want includes a detailed HF traveling multi-hop path and the signal integrity received of any static or dynamic point of the circle (2D earth).

Keywords

Reflection model; HF radio waves; reflection factor; signal-to-noise ratio; modifying factor.

1. Background

In the electromagnetic spectrum, HF Radio Waves whose frequency is 3 30M Hz can travel long distances. Electromagnetic waves used in the fields of interna-tional broadcasting, amateur radio service operations, citizens' band operation, point-to-point military and diplomatic communications, etc., are all within the scope of 3 30M Hz.

In the research of HF Radio Waves, the issue of sky waves (a radio wave reflect-ed back to the earth by the ionosphere from the transmitting antenna) is a hot one. In this issue, many research achievements about the process of sky waves traveling and reflecting in air have been acquired, however, any preferable re-sults about the process of reflection propagation of sky waves on the surface of oceans, especially on the turbulent ones, haven't been achieved by now. The reason is that radio waves reflecting off the turbulent oceans through the iono-sphere will have multiple reflections off the oceans. Both the conditions of the ionosphere and fluctuation of the oceans will have influence on the process of reflection propagation of radio waves.

Modelling appropriately to describe the process of reflection propagation of ra-dio waves both on the oceans and through the ionosphere is of great significance to research radio communication, direct ships’ navigation and ensure the security of seamen.

2. Assumptions

Assuming that the air composition is uniform, the loss of HF radio waves in the air is the propagation loss of free-space radio waves;

Assuming that no signal is attenuated when the ground signal source is transmitting;

Assuming that there is no loss caused by other obstacles such as buildings during the propagation of HF radio waves, that is, only the attenuation is taken into account, irrespective of the blocking.

Assuming that the height of ionosphere is fixed and the component is uni-form, and there has no loss when HF radio waves reflect off the ionosphere.

Assuming that HF radio waves transmitting from the signal source have multiple reflection by the angle of total reflection off the ionosphere and ocean surface.

3. Notations and Descriptions

Symbol	Description	Value
P0	High-frequency radio wave transmission power	Watt
Sav	power density	Watts/square meter
Ac	Antenna effective reception area	m2
P1	Antenna received power	Watt
Pn	Noise power	Watt
SNR	signal-to-noise ratio	dB
RH	horizontal polarized wave Reflection coefficient	
RV	vertically-polarized wave Reflection coefficient	
B	correctionn factor	

4. Models

4.1 Reflection Models of HF Radio Waves on the Ocean Surface

4.1.1 Model Assumptions

Assuming that there has no loss when HF radio waves reflect off the calm ocean;

Assuming that there exists no multi-path disturbance in the process of HF Radio waves propagation.

4.1.2 HF Radio Waves Reflection Process Model

The HF radio waves transmitted from a point source propagate in space and will have multiple reflection off the ocean surface and the ionosphere. If the angle of incidence of the radio wave is greater than its angle of total reflection in the ionosphere, at the time of reflection, this radio wave will also refract. For radio waves that emit at angles greater than the total reflection angle, after multiple reflection and refraction, the attenuation will be too high to considerate. In Fig-ure1, represents the angle of total reflection, represents the included angle between the angle of total reflection and the critical angle.Combined with the above diagram, the angle of total reflection of the HF radio wave transmitted by the ground signal source can be determined by the following formula:

$$\theta = \arcsin\frac{n_1}{n_0} \tag{1}$$

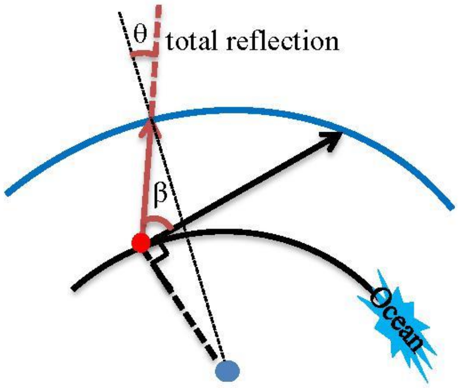

Figure 1. The Schematic Diagram of the Total Reflection of the HF Radio Wave off the Ionosphere

In formula 1 , N0 represents the refractive index of the air, N1 represents the re-fractive index of the ionosphere. The propagation of HF radio waves in the iono-sphere mainly involves the level F of the ionosphere, whose height is between 241 km to 402 km. In the following discussion, we assume that the ionosphere is a uniform sphere with the height of 322 km (200 miles).

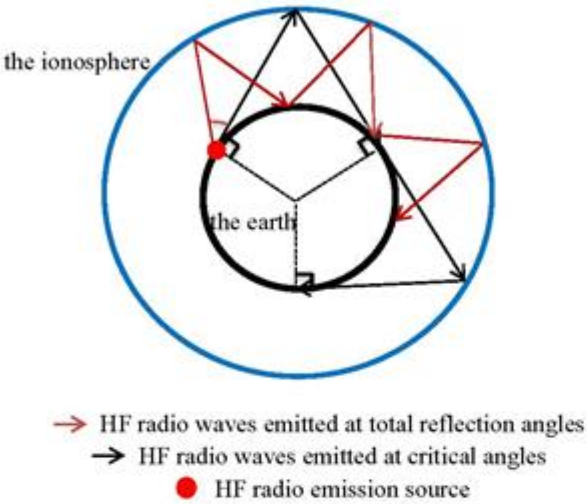

Figure 2. The Schematic Diagram of the Process of HF Radio Waves Reflect off the Earth and off the Ionosphere

The HF radio waves emitted from the point signal source spread around in the form of spherical waves. The distance of the HF radio wave whose emission angle is , propagated once in the ionosphere meets the following formula:

$$R^2 + l^2 - (R+h)^2 = 2Rl\cos(\pi - \theta) \tag{2}$$

In formula 2 , R represents the radius of the Earth, h represents the height of the ionosphere, and l represents the distance traveled during one reflection.P0 represents the transmission power of the HF radio wave. In the process of prop-agation, the power density of the HF radio wave can be expressed as:

$$S_{av} = \frac{P_0}{4\pi s^2} \quad (3)$$

Where s represents the propagation distance of the HF radio wave; P0 repre-sents the transmission power of the HF radio wave. The effective receiving area of the HF radio wave receiving antenna located in the distance can be expressed as:

$$A_e = \frac{\lambda^2}{4\pi} \quad (4)$$

The received power of the receiving antenna can be obtained is: Pl = Sav Ae When the frequency of the radio wave is below 30 M Hz, the noise of the atmo-sphere and the environment is dominant, and is determined by the following equation:

$$P_n = KTB \quad (5)$$

In this equation, Pn represents the noise power, K represents the Boltzmann constant,T represents the Kelvin temperature,B represents the bandwidth. At a standard ambient temperature of 17 C, the noise power is typically -174 dBm per 1Hz bandwidth.

Signal-to-Noise Ratio is:

$$SNR = \frac{P_1}{P_n} \quad (6)$$

The loss of the radio wave in the process of propagation can be expressed as:

$$L = L_b + L_a + L_s + L_p \quad (7)$$

In this equation,Lb represents the loss of propagation in free space, La represents the absorption loss of the ionosphere, LS represents the reflection loss of the o-cean surface, Lp represents the other losses.

4.1.3 HF Radio Waves Reflection Model on the Calm Ocean

The Calculation of the First Reflection Strength on the Calm Ocean

After the first reflection off ionosphere and the first reflection off the ocean, the propagation distance of the HF radio wave is 2l, the initial frequency of the HF radio wave transmitted from the ground source is 100W . Substitute the dif-ferent frequencies and different angles into the HF radio waves reflection model and program by using MATLAB to get the strength of the first reflection off the calm ocean in different frequencies and different angles. The results are shown in the following graph.

We get the relationship between the first reflection strength and the frequency of the HF radio wave on the calm ocean with the constant emissive angle. The first reflection strength on the calm ocean surface decreases with the increasing of the frequency. The decreasing tendency is obvious and the reduction rate is faster. The reflected power is in the order of 10 10W ; Meanwhile, the reflection strength and the loss change in the opposite direction.

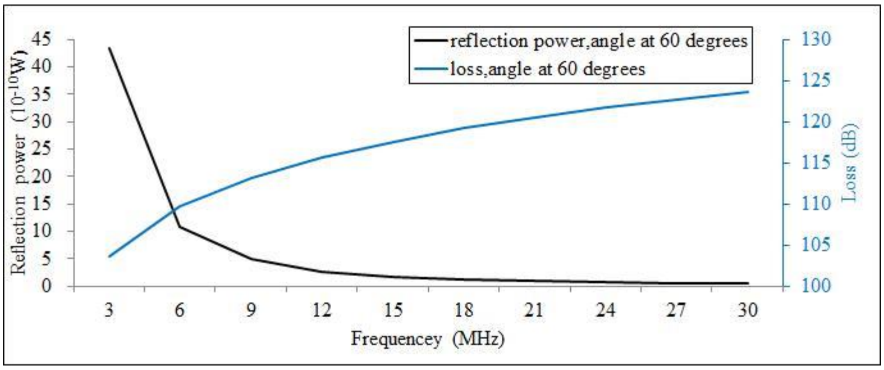

Figure 3. When the emissive angle is 60 degrees, changes of the the first reflection strength on the calm ocean with the varying of frequency

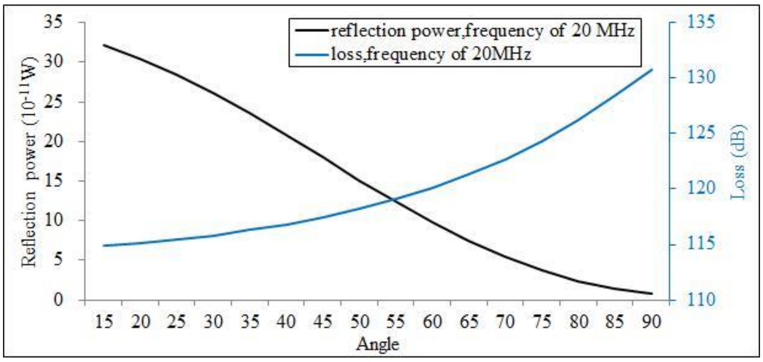

Figure 4. When the emission frequency is 20MHz, changes of the strength of one reflection off the calm ocean with the varying of emission angle

We obtain the relationship between the first reflection strength of the HF ra-dio wave on the calm ocean and the frequency when the transmitting frequency is constant. The first reflection strength on the calm ocean decreases with the increasing of the emissive angle, the rate of descent has a tendency to decrease, and the loss tends to be infinite with the increasing of the angle. Thus, the choice of the angle is of great importance when transmitting the HF radio waves. By calculation, the first reflection strength of the HF radio wave on the calm ocean decreases with the increasing of the emissive angle and the emissive frequency. However, since the study assumes that there is no reflection loss on the calm o-cean and no disturbance loss of the multi-path, which can not be neglected in the real situation, the value of the first reflection strength on the real calm ocean should be less than the value calculated in this paper.

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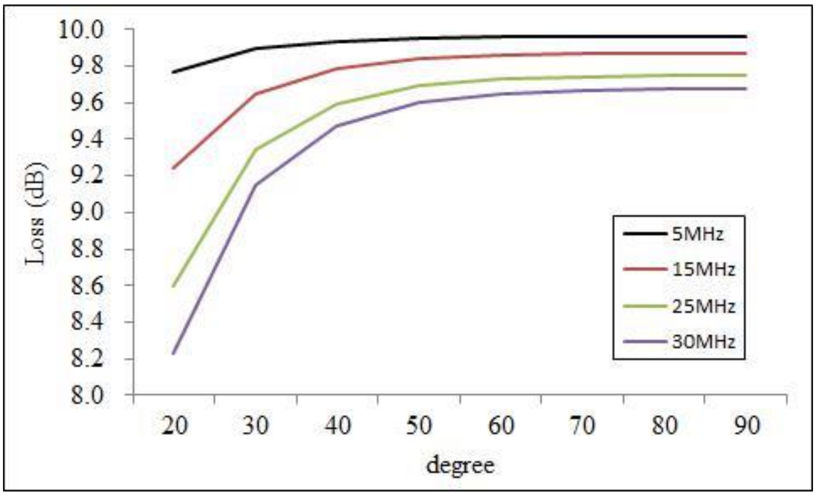

Figure 5. When the emission frequency is 20MHz, changes of the strength of one reflection off the calm ocean with the varying of emissive angle

Calculation of the Maximum Number of Hops on the Calm Ocean.

According to the formula 6 and 7 , calculate the additional reflections off the calm ocean and the the maximum propagation distance when the signal-to-noise is lowered to 10dB. The maximum number of hops has been deduced from the formula 3. As the frequency of HF radio waves changes, the maximum hops and maximum distances that can be transmitted on the calm ocean surface are shown in the Table 1.

Table 1: Receiving from different emission frequencies

frequency(MHz)	3	6	9	12	15	18	21	24	27	30
Noise power(10 -14W)	1.2	2.4	3.6	4.8	6.01	7.21	8.41	9.61	10.81	12.01
propagation distance (10^7m)	22.96	8.12	4.42	2.87	2.05	1.56	1.24	1.01	0.85	0.73
Hops	93	33	18	11	8	6	5	4	3	2

As can be seen from Table 1, when the signal-noise ratio is reduced to 10dB, the noise power generated is in the order of 10 -14.The propagation distance decreases as the emission frequency increases. When the emission frequency is 18M Hz, the maximum number of hops is 6.

As can be seen from Figure 6, the maximum number of hops decreases with the increasing of frequency, which is consistent with the description of the first reflection strength on the calm ocean. The maximum number of hops in the real situation should be smaller than the computation in this paper.

4.1.4 HF Radio Waves Reflection Model on the Turbulent Ocean

In the above calculation, we ignore the loss of HF radio waves reflected off the calm ocean, but in fact, there does exist loss of reflection of the radio waves on the calm ocean. The reflection characteristics of radio waves on a calm ocean are mainly characterized by the reflection coefficient on the ocean surface of radio waves. The reflection coefficient of the ocean is related to the grazing incident angle of radio waves on the sea, the size of the sea wave and the electromagnetic parameters of the sea surface. On disturbed rough seas, radio waves, in addition to reflections, will scatter and transmit, which all impair the reflection strength of radio waves.

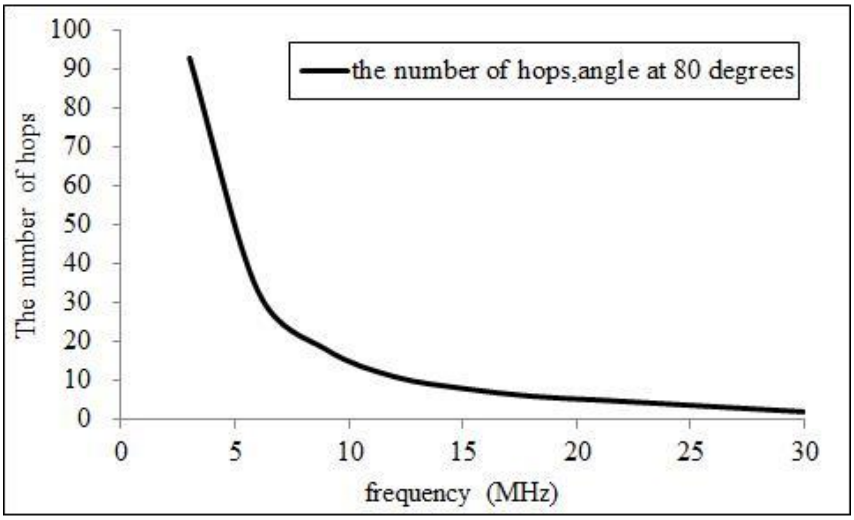

Figure 6. When the emission angle is 80 degrees, changes of the maximum number of hops on the calm ocean with the varying of frequency

The reflection strength of radio waves on the ocean is affected by the electro-magnetic properties of the ocean surface. The electromagnetic properties of the ocean surface are related to many factors such as seawater temperature, salinity and electromagnetic wave frequency. The complex permittivity of the sea can characterize the electromagnetic properties of the sea surface.

$$\varepsilon(S, T, W) = \varepsilon_\infty(S, T) + \frac{\varepsilon_1(S, T) - \varepsilon_\infty}{1 - i\omega\tau} - \frac{i\sigma(S,T)}{\omega\varepsilon_0} \tag{8}$$

In formula (8) ε_0 represents free space permittivity, $\varepsilon_\infty = 4.9$, $\omega = 2\pi$f , which are the angular frequency of radio waves. In the above equations, ω, τ, σ are all the functions about the temperature and sea salinity.Considering the complexity of seawater , we introduce two variables, temperature and seawater salinity, so that the computations are close to reality. See Appendix for details.

According to the snell's law of reflection, the Fresnel reflection coefficient of a calm ocean surface can be obtained:

$$R_H = \frac{\sin\theta - \sqrt{\tilde{\varepsilon} - \cos^2\theta}}{\sin\theta + \sqrt{\tilde{\varepsilon} - \cos^2\theta}}$$
$$R_V = \frac{\tilde{\varepsilon}\sin\theta - \sqrt{\tilde{\varepsilon} - \cos^2\theta}}{\tilde{\varepsilon}\sin\theta + \sqrt{\tilde{\varepsilon} - \cos^2\theta}} \quad (9)$$

R_H is the reflection coefficient of the horizontal polarized wave and RV is the reflection coefficient of the vertical polarized wave. The reflection coefficient of the horizontal polarized wave changes little with frequency and is close to 1.

Therefore, we assume that the horizontal polarized wave reflection coefficient is 1. To study the reflection of radio waves on the rough ocean, we modified the reflection coefficient of the calm ocean and the set the modifying factor as , which is the function of radio frequency, incident angle and the height of the waves.

$$\rho = \frac{1}{\sqrt{3.2g - 2 + \sqrt{(3.2)^2 - 7g + 9}}} \quad (10)$$

In equation (10), $g = 0.5\left(\frac{4\pi hf \sin\theta}{c}\right)^2$, $h = 0.005 l\omega^2$, c is the speed of light, f is the radio frequency, h is the root mean square height of the ocean surface, and!is the wind speed near the height of the ocean.

Thus, the corrected reflection coefficient of radio waves on the rough ocean can be obtained, which is $R' = \rho R_V$.

Combined with Equations 8 - 10, the reflection coefficient of the rough ocean surface is as follows:

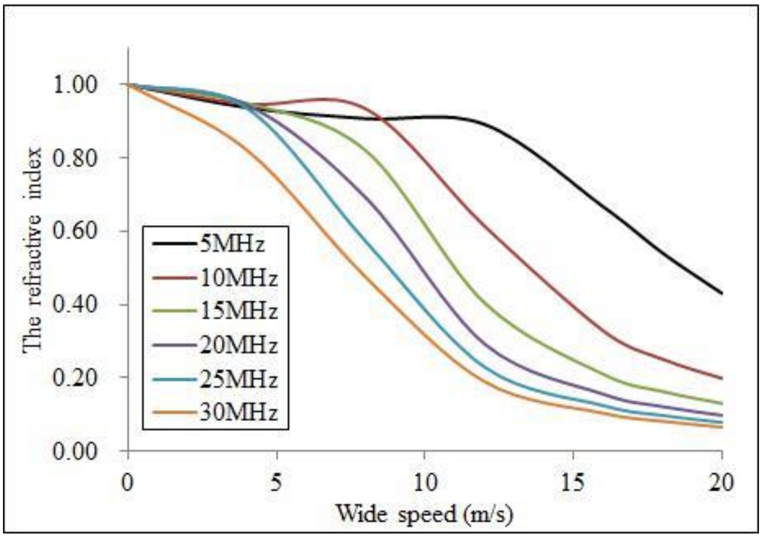

Figure 7. Changes of the reflection coefficient varying with the ocean surface wind speed at different frequencies

It can be seen from the diagram figure in Figure 7 that the reflection coefficient of radio waves on fluctuating rough ocean level decreases with the increasing of wind speed. When the wind speed near ocean surface is close to 0, the reflection coefficient of ocean surface is close to 1, so we can assume that the reflection coefficient of the calm ocean is 1. When the wind speed increases to 20m/s, the reflection coefficient decreases near 0.1; the reflection coefficient decreases with the increasing of the emission frequency.

The reflectivity of HF radio waves in the turbulent ocean surface is $n = R'^2$, so when the radio wave is at the point of $P' = P_l' \cdot n$, the first reflection strength the at the wind speed of 18 m/s is:

Table 2: When the wind speed is 18m=s, the reflection intensity of the radio waves of different frequencies

frequency(MHz)	5	10	15	20	25	30
Reflection intensity (10 -10W)	29.21	6.29	2.65	1.48	0.95	0.67

4.2 The Reflection of Radio Waves on the Smooth Terrain

4.2.1 Model Assumption

Assuming that the height of the smooth terrain is uniform and the electromagnetic characteristics of everywhere are the same;

4.2.2 The Reflection Model of Radio Waves on the Smooth Terrain

When the radio waves are reflected on the ground, the basic propagation loss is $L = L_b + L_a + L_P$. Lb represents the propagation loss in free space, $L_b = 32.45 + 20\lg d(\mathrm{km}) + 20\lg f(MHz)$, Lg represents the loss caused by the reflection of radio waves on the ground,Lp is not only related to the polarization of radio waves, frequency, elevation of radiation and geological conditions and other factors, but also related to the signal interference and temperature. Its approximate value can be taken as 16dB. If the incident wave is a circularly polarized wave, then the ground reflection loss is:

$$L_g = 10\lg\left[\frac{|R_v|^2 + |R_H|^2}{2}\right](dB) \tag{11}$$

Respectively, Rv and RH are the ground reflection coefficients of the vertical po-larized wave and the horizontal polarized wave. The reflection coefficient will vary with the electromagnetic properties of the ground.

The conductivity of the soil σ is between 1.4×10 -4- 5×10-2 $\mathrm{ms} \cdot m^{-1}$, the relative dielectric constant, ε_r is between 2.6 -40: Here we suppose that the electromagnetic properties are the same everywhere on the smooth terrain. Taking the conductiv-ity as 3× 10-3 $\mathrm{ms} \cdot m^{-1}$ and the relative dielectric constant which is 30, substitute them into the reflection coefficient formula (10). The reflection coefficient of the radio waves on the smooth terrain can be obtained, that is R'.

As can be seen from the above graph, with the increasing of the grazing incident angle, the reflection coefficient of the smooth terrain gradually increases to a fixed value; when the grazing incident angle is constant, the reflection coefficient decreases with the increasing of frequency and the ground loss increases.

4.2.3 The Propagation Model of Radio Waves on the Mountainous or Rugged Terrain

Compared with the smooth terrain, the situation of radio waves becomes more complex when propagating through the mountainous or rugged terrain. In the rugged terrain, the propagating methods of radio waves mainly involve the visual distance propagation, diffraction propagation and scattering propagation. When the distance between the transmitter and the receiver is far enough, the radius of the earth can not be ignored. At this time, the diffraction can not reach the receiver and the radio waves propagate mainly by atmospheric scattering (reflection) propagation.

Reflection Propagation.

When radio waves reflect into the rugged terrain through the atmosphere, they can reflect multiple times in rugged terrain due to altitude effects. Therefore, when radio waves are reflected in the rugged terrain, the loss is greater than the that of the smooth terrain.

Based on the reflection coefficient of the smooth terrain , a modifying factor 0 is added to show the influence of the height of the rugged terrain on the reflection of radio waves. Compared with the modifying factor of the turbulent ocean, this one does not need to consider the effect of wind speed on the altitude.

$$\rho = \frac{1}{\sqrt{3.2g' - 2 + \sqrt{(3.2)^2 - 7g' + 9}}} \quad g' = 0.5\left(\frac{4\pi h' f \sin\theta}{c}\right)^2 \tag{12}$$

ρ' represents the modifying factor of the rugged terrain, g' represents the function related to the altitude. The reflection coefficient of radio waves in the rugged terrain after being modified can be expressed as: $R'' = \rho' R'$.

Diffraction Propagation.

Diffraction, that is the phenomenon of propagation of radio waves encountering and diffracting the obstacles whose size is much larger than the size of radio waves in its propagation process. For example, radio waves will have diffraction phenomenon when traveling around the mountain.

The calculation of the diffraction loss of the multi-edged peak is based on the algorithm of the diffraction loss of the double-edged peak , as shown in Figure9:

Making the double-edged peak be equivalent to two single-edged peaks and calculate respectively, a, b, h1 and b, c, h2 constitute a single-edged peak respectively. According to the formula (appendix) of calculating the single-edged peak: calculate the diffraction loss L1 and L2, on the basis of which, add a modifying factor Lc.

$$L_c = 10\lg\left[\frac{(a+b)(b+c)}{b(a+b+c)}\right] \tag{13}$$

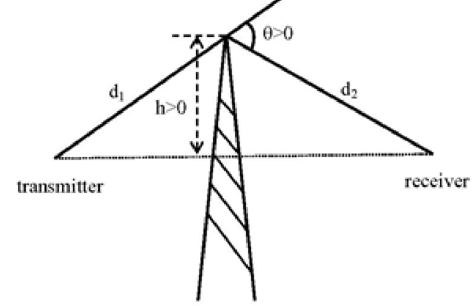

Figure 8. the diffraction schematic of the single-edged peak

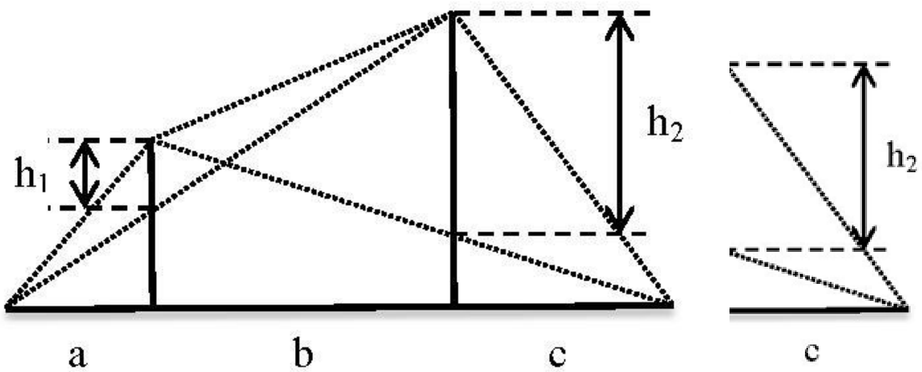

Figure 9. the diffraction schematic of the double-edged peak

The total diffraction loss is:Pl = L 1 + L 2 + L c, Assuming that: a = 80m, b =40m, c = 120m, h1 = 80m, h2 = 120m.

Table 3: When the wind speed is 18m=s, the reflection intensity of the radio waves of different frequencies

frequency(MHz)	5	10	15	20	25	30
Loss(dB)	169.22	175.24	178.76	181.26	183.2	184.78

It can be calculated that in the double-edged peak model, due to diffraction, the loss of HF radio waves is between 169-184dB. And the loss increases with the increasing of frequency. The data show that, the loss of HF radio waves in the rugged terrain is between 90-220dB, which indicates that in rugged terrain, the loss caused by diffraction is not negligible and the discussion of the diffraction of HF radio waves is necessary.

4.3 Ocean-Traveling Shipboard Receiver Communication Model

In order to solve the problem of the maximum communication distance of a ship in a multi-hop path, considering the loss of ocean surface and air, the following ship communication model is established :

If the signal-to-noise ratio of the signal is less than 10dB, the on-board receiver cannot receive a valid signal. At this time, set the signal tower as 100 meters.

Situation 1: When the ligature between the ship's position and the signal source doesn't pass through the Earth, the signal doesn't need to propagate through the reflection of the ionosphere and the ocean surface. Meanwhile, the signal source directly transmits the signal to the position of the ship as shown in the Figure 10.

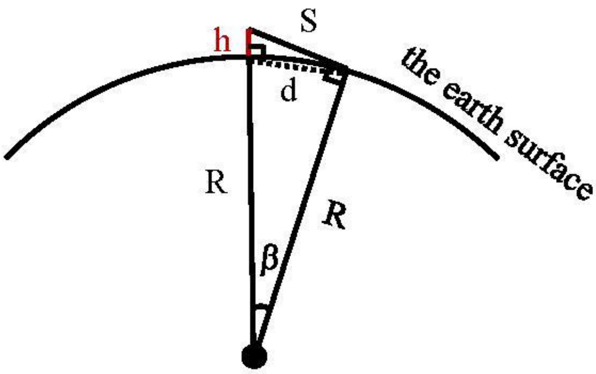

Figure 10. Signal receiving schematic

$$s = \sqrt{(h+R)^2 - R^2}$$
$$d = s \cdot arccos\beta \quad (14)$$

Situation 2: When the ship travels farther, it needs to depend on the reflection of the ocean surface and the ionosphere to propagate the signal. Taking into account the air and ocean loss, programming by using MATLAB , calculate the the travel distance of the ship and the number of radio waves hops when the noise dropped to 10dB to get the maximum distance of the ship. Programmed to calculate the process of the following signal-to-noise ratio (SN B) decreasing with the increasing of the propagation distance.

The four figures in Figure 11 discuss the breeze (5m/s), strong wind (12m/s), squally wind (26m/s) and typhoon (38m/s) on the ocean surface respectively. As can be seen from the graph, the signal-to-noise ratio of the signal received by the shipboard receiver generally shows a weakening trend as the propagation distance increases. In the very small range of the distant, the receiver directly obtains information from the signal source, resulting in rapid SNR attenuation. The SNR then decays slowly, then there is a sudden drop at some distance which indicates that the significant loss of radio waves occurs after each ocean-surface reflection.

The four figures in Figure 12 respectively correspond to the maximum num-ber of hops of the radio waves which can be received by a traveling ship in the case of breeze (5m/s), strong wind (12m/s), squally wind (26m/s) and typhoon (38m/s). And the numbers of hops are 6, 6, 4, 3 (The radio wave was received the last time it was close to the ocean surface. No losses occurred to the ocean surface and that time was not counted as a hop).

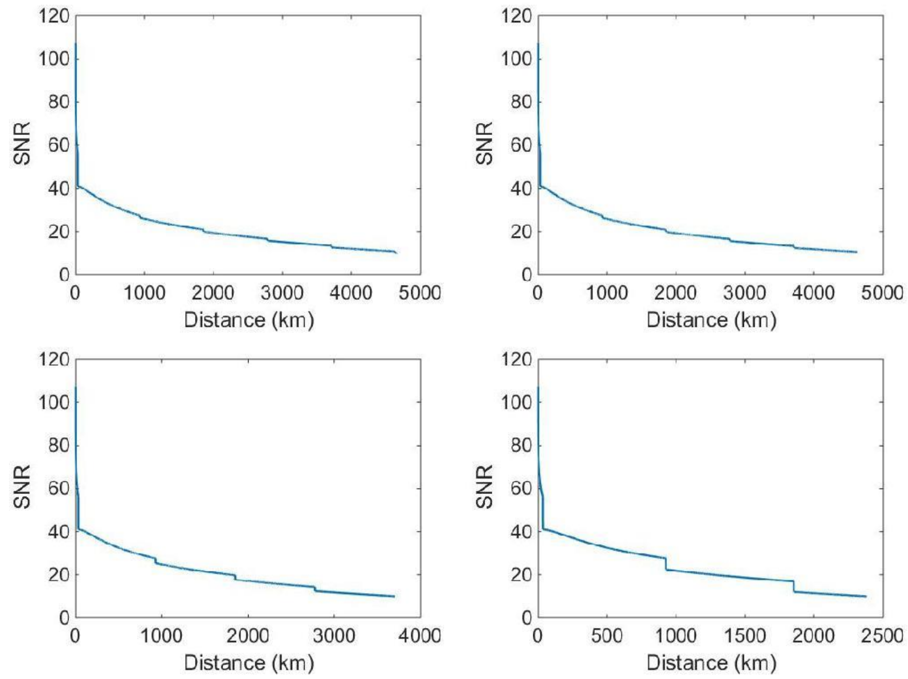

Figure 11. The change of SNR with distance

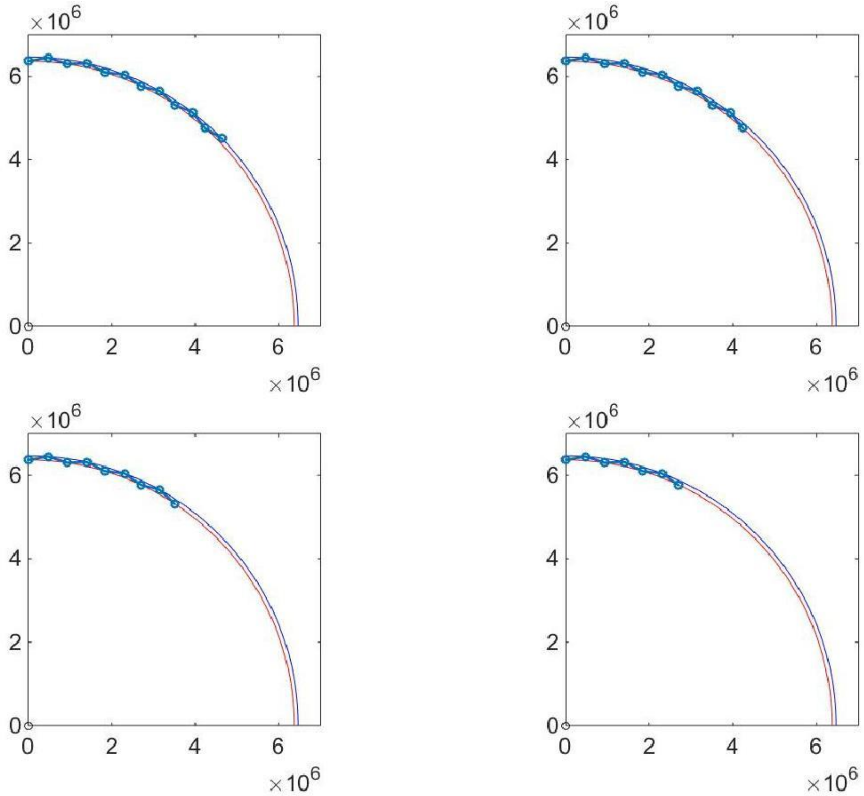

Figure 12. The change of the number of hops with wind speed

Table 4: The furthest distance under different wind speeds

wind types	wind speed(m/s)	hops	total distance(km)	arc distance(km)
breeze	5	6	5273.3	4665.7
gale	12	5	4773.5	4632.4
fierce wind	26	4	3819	3706.1
typhoon	38	3	2846	2378.5

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