The Reflection of Multi-hop HF Radio Signal

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Abstract

High frequency radio waves below MUF can be applied for long-distance communications by multiple reflections between the ionosphere and the earth's surface. Properties of reflection surface determine the strength and integrity of reflection signal while re-flection off the ocean is the hot topic in wireless transmission field. We establish the reflection model of signal from ocean to resolve the problem about strength decay of small-scale fading successfully, and compare the reflections off the turbulent ocean with the calm ocean. Then we compare reflection model of signal from ocean and land. Finally, combined with actual situation, the model has been corrected to analyze when shipboard receiver is moving on a turbulent ocean.

Keywords

HF; multipath channels; diffuse reflection; reflection modeling.

1. Introduction

1.1 Problem Background

"Voyager Guo lost contact in Hawaii sea area, US", it is the news headline released on November 7, 2016. From the relevant news reports, the news of ships and crew members losing contact can often be seen. Analyzing the reasons, we can find out that whether the ships collide with other objects or the ships are damaged due to wind and waves, the important impact on our rescue is radio signals on board lost communication. As a result, it can be seen that radio transmission at sea, whether in turbulent ocean or in calm ocean, is crucial to ensure the safety of ship and crew members.Further, studying this issue is conducive to improving the development of communication technologies and the quality of communication, especially when the ships encounter bad weather.

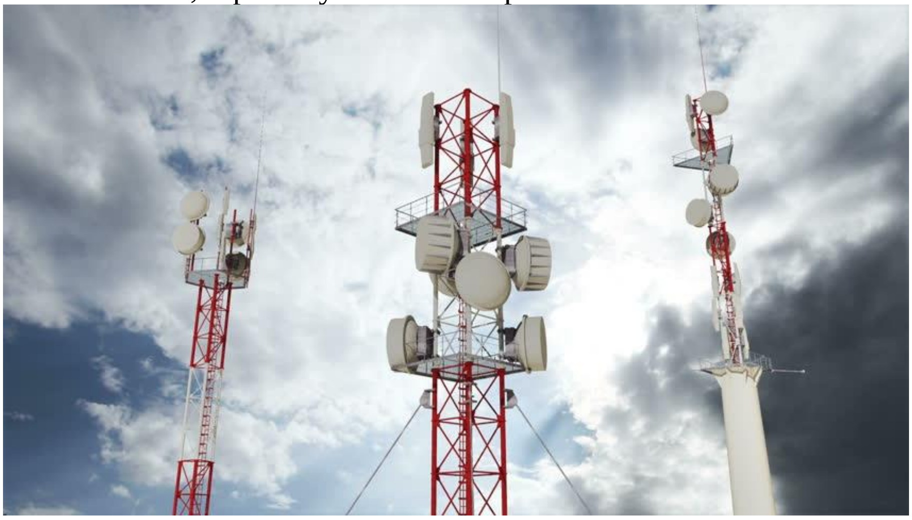


Figure 1: signal receiver

1.2 Literature review

By analyzing previous researches, we find that they only focused on the theoretical part, which lacks of rigidity. For example, Literature [1] studied the effects of turbulence in the sea on high frequency transmission, but it only take few factors into account. On the other hand, they provided theoretical basis and inspiration for our solution to the problem as well. In a word, literature review helps us find new ideas and understand the meaning of problem better

1.3 Our work

After selecting the problem, we firstly studied the meaning of problem and understand the requirements of it. Our work is listed as follows:

Make significant assumptions.

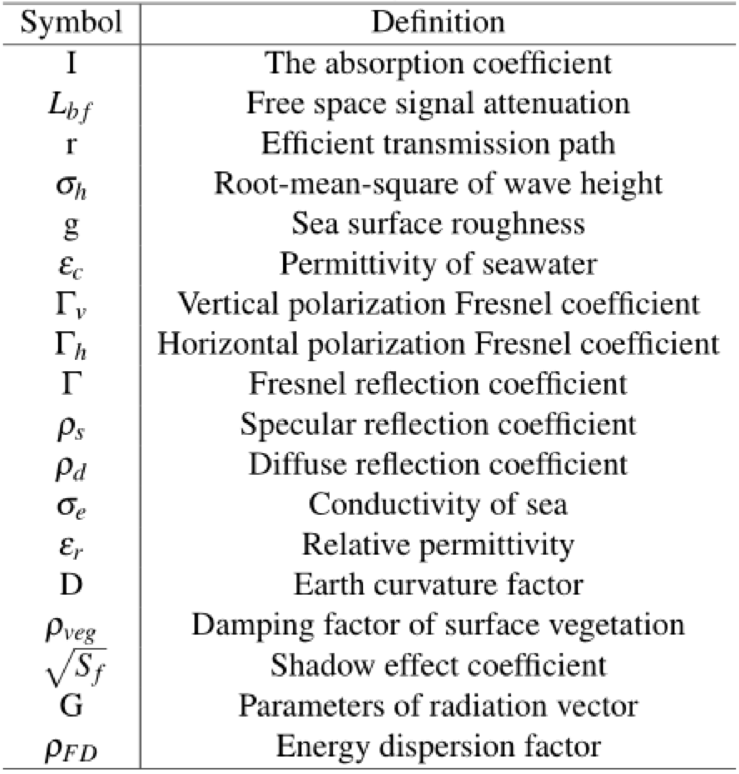
Build ocean reflection model considering diffuse reflection, which determines the strength of the first reflection off a turbulent ocean. Then we compare it with the strength of a first reflection off a calm ocean.

By simulating and comparing, we obtain important conclusions about findings above compare with high frequency reflections off mountainous or rugged terrain versus smooth terrain

Develop ocean reflection model considering ship shaking to accommodate a shipboard receiver moving on a turbulent ocean.

2. Notation

Table 1: Symbols



Symbol	Definition
I	The absorption coefficient
L_{bf}	Free space signal attenuation
r	Efficient transmission path
σ_h	Root-mean-square of wave height
g	Sea surface roughness
ε_c	Permittivity of seawater
Γ_v	Vertical polarization Fresnel coefficient
Γ_h	Horizontal polarization Fresnel coefficient
Γ	Fresnel reflection coefficient
ρ_s	Specular reflection coefficient
ρ_d	Diffuse reflection coefficient
σ_e	Conductivity of sea
ε_r	Relative permittivity
D	Earth curvature factor
ρ_{veg}	Damping factor of surface vegetation
$\sqrt{S_f}$	Shadow effect coefficient
G	Parameters of radiation vector
ρ_{FD}	Energy dispersion factor

3. Assumptions and Justifications

Assumption: Sea state is constant.

Justification: When ocean is calm, the sea state is certainly zero; however, when ocean is turbulent, it’s difficult to determine sea state. In order to calculate, we assume that sea state is constant so that we can determine root-mean-square waves height.

Assumption: We employ omnidirectional dipole antenna. Justification: The assumption is easy to calculate.

Assumption: Free space parameters in the propagation path are constant. Justification: We can get meaningful data by making assumption.

Assumption: Ionosphere parameters in the propagation path are constant. Justification: We do this in order to calculate.

4. Secondary signal attenuation

4.1 Ionospheric signal attenuation

Atmosphere with the height below 50km has no effect on the propagation of radio waves. Air in the atmosphere with the height between 50km and 500km rarely flows. The electrons in the gas molecules get rid of the bondage of atoms under intense ultraviolet light and form free electrons and ions, which is ionosphere. After the high-frequency signal reaches the ionosphere at a suitable angle of incidence, it leaves at the same angle and produces power loss. Calculate the ionosphere absorption loss using the following semi-empirical formula[2].

$$L_i = I \frac{6772 \sec i_{236.12}}{\left(f + f_H \right)^{1.98} + 10.2}$$

$$I = (1 + 0.0037 \bar{R}_{12}) \left(\cos 0.881 x \right)^{1.3}$$

$$i_{236.12} = \arcsin \left(0.985 \cos \Delta \right)$$

$i_{236.12}$ is the incident angle of electric wave at a height of 236.12km； Δ is the elevation angle of the ray； f_H is the frequency of the magnetic rotation at a height of 100km. Take a precise data: reflection point is located at latitude 22° 35’,and f_H equals to 1.3MHz. $\bar{R}_{12}$ is the average of sunspots in December, which can be retrieved.In addition, we can know that x is the sun angle. Finally, we calculate that L_i equals to 2.66364dB.

4.2 Free space signal attenuation

Free space loss is energy loss caused by the geometric diffusion after radio wave leaves the transmitting antenna.The expression of L_{bf} is:

$$L_{bf} = 32.44 + 20 \lg f + 20 \lg d$$

5. Reflection model of ocean considering diffuse reflection

To multi-hop high frequency radio signals from the transmitter，when they reach the receiver by land and ocean channels, the power will attenuate obviously, which performs as follows: average pathloss, large scale fading and small scale fading. Small scale fading is determined by a combination of factors: multipath propagation, the speed of the surrounding objects, and so on, which are closely related to the problem, thus the following part focuses on analyzing small scale fading when signals are reflected by the ocean, while discussions about large scale fading would be mentioned in the Part Ⅲ. Given to this, we build related reflection models.

5.1 Assumptions

The slope of ocean obeys the normal distribution.

Parameters of seawater are stable and equal.

5.2 Statement

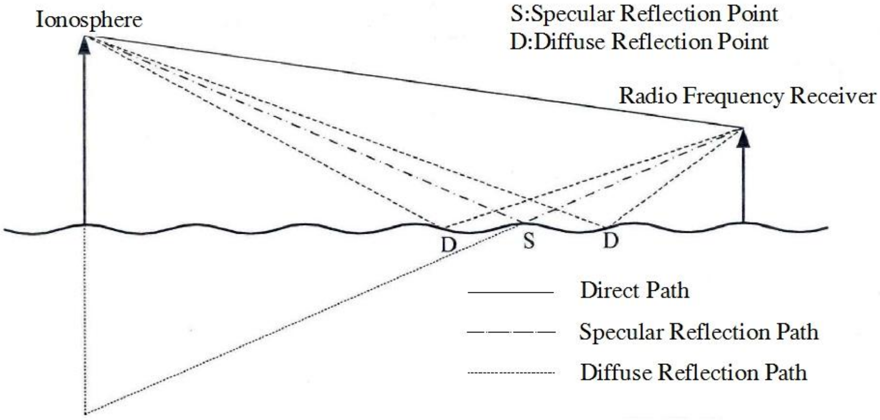


Figure 2: Diffuse multipath model producing by sea surface

At most of times, surface of ocean is rough.When the radio waves are reflected by the ocean, there are two different reflection ways: specular reflection and diffuse reflection[3] . Therefore, there are three kinds transmission path in the complete maritime wireless signal transmission path (as shown in figure). That is, direct path, specular path and diffuse path.

5.2.1 Key terminology

Direct path refers to the visible path between the transmitter and the receiver.

Specular reflection path refers to the path by one specular reflection.

Diffuse reflection path refers to the diffuse reflection path through rough ocean.

5.2.2Data Source

Our data originate from actual situation of a certain place at 10:00 am on January 1, 2018 , and coordinate of transmitter is (41:09 W,8:37 N) ,and coordinates of receiver is (29:35 W,30:50 N).

5.3 Parameters

Climate change at ocean is frequent, so radio waves are affected by many factors when they propagate on the ocean. Before developing reflection model of ocean considering diffuse reflection model, we introduce six important model parameters, they are root-mean-square waves height, permittivity of seawater, sea surface roughness, Fresnel reflection coefficient, specular reflection coefficient and diffuse reflection coefficient.

Root-mean-square waves height

The state of ocean, namely sea state, is the general condition of ocean wit respect to wind waves and swell at a certain location and moment . A sea state is characterized by statistics, including the wave height,period, and power spectrum. In this paper, the wave height recommended by the World Meteorological Organization (WMO) (shown in Table) and Douglas is chosen to characterize the sea state . Where, which demonstrates rms(root mean square) value of wave height. In this paper, the sea state is chosen as fourth level and root-mean-square waves height is two meters.

Permittivity of seawater

Permittivity of seawater ε_c is a function concerning carrier signal wavelength λ , sea conductivity σ_e and permittivity ε_r . It can be expressed as:

$$\varepsilon_c = \varepsilon_r - j60\lambda\sigma_e$$

Sea surface roughness

Sea surface roughness g can be used to describe extent of fluctuation, which is:

$$g=\frac{\sigma_h \sin\varphi}{\lambda}$$

Where, λ is wavelength of carrier signal. σ_h is root-mean-square waves height. φ is incident angle of carrier signal.

Fresnel reflection coefficient

Fresnel reflection coefficient can be applied to calculate received signal energy, concerning permittivity of seawater ε_c and incident angle of carrier signal φ .

Expression of Vertical polarization Fresnel coefficient is:

Expression of Horizontal polarization Fresnel coefficient Γ_V is:

$$\Gamma_V=\frac{\varepsilon_c \sin\varphi-\sqrt{\varepsilon_c-\cos^2\varphi}}{\varepsilon_c \sin\varphi+\sqrt{\varepsilon_c-\cos^2\varphi}}$$

Expression of Horizontal polarization Fresnel coefficient Γ_H is:

$$\Gamma_V=\frac{\varepsilon_c \sin\varphi-\sqrt{\varepsilon_c-\cos^2\varphi}}{\varepsilon_c \sin\varphi+\sqrt{\varepsilon_c-\cos^2\varphi}}$$

Fresnel coefficient Γ is:

$$\Gamma=\sqrt{\Gamma_V^2+\Gamma_H^2}$$

Specular reflection coefficient

Specular reflection[4] coefficient in the model is modified by the zero-order Bessel function $I_0\left(P_s\right)$,which shows:

$$P_S=2\left(\frac{2\pi\sigma_h \sin\varphi}{\lambda}\right)^2$$

$$\rho_s=\exp\left[-P_s\right]I_0\left(P_s\right)$$

The measured data prove that above formula is more suitable for actuality on the ocean.

In addition, multi-hop high-frequency radio signal used in this model has a larger span than that of ordinary signal, so influence of earth curvature[5] should be taken into account. Therefore, we introduce earth curvature factor（D）, and the expression is:

$$D=\left(1+\frac{2G_1G_2}{R_e\left(G_1+G_2\right)\sin\varphi}\right)^{-\frac{1}{2}}$$

Where, G_1 is the distance between the first ionosphere reflection point and specular reflection point. G_2 is the distance between the next ionosphere reflection point and specular reflection point. R_e is radius of the earth, determining that it is 6400km.

Therefore, specular reflection coefficient after modified by earth curvature factor （D）can be expressed as:

$$\rho_s'=\rho_s D$$

Correspondingly, diffuse reflection coefficient can be expressed as:

Finally, model about reflection and direct irradiation of wireless carrier signal after considering earth curvature[6] is shown as following.

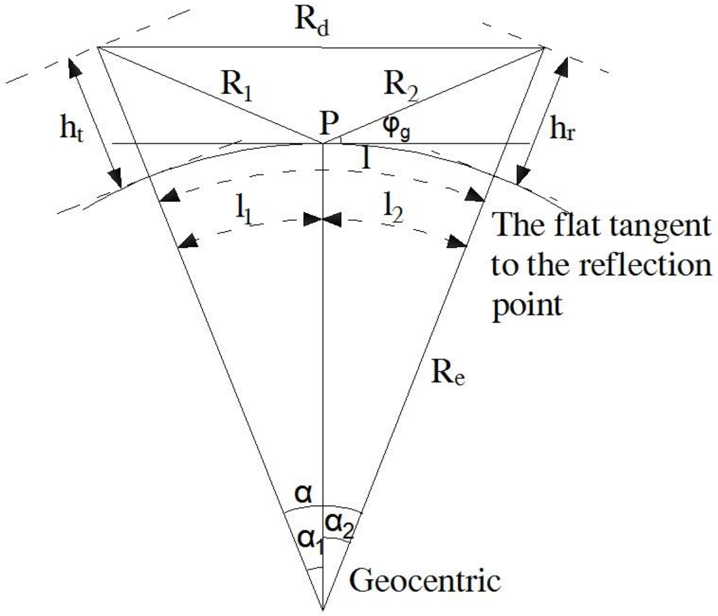


Figure 3: Two-ray model by considering the earth curvature

$$\frac{h_l + R_e}{\sin\left(90^\circ + \varphi_g\right)} = \frac{R_1}{\sin\alpha_1} = \frac{R_2}{\sin\alpha_2} = \frac{R_e}{\sin\beta}$$

$$2R_1R_2\cos\left(180^\circ - 2\varphi_g\right) = R_1^2 + R_2^2 - R_d^2$$

In the picture, P is specular reflection point. ϕ_g is incidence grazing angle h_t is height of reflection point, and h_r is height of receiving point. R_1 、 R_2 is reflection path. R_d is direct path.

R_e is radius of the earth. a is included angle between the transmitter and the receiver and the center of earth. $l = R_e\alpha$ is horizontal distance between the transmitter and the receiver.Through the sine and cosine theorems, we can get the value of R_1 、 R_2 and R_d .

5.4 Specular reflection energy

The loss of specular reflection energy component compared to direct signal energy component is expressed as follows:

$$\frac{v_{specular}}{v_{Direct}} = \rho_s\sqrt{Gant}\left|\Gamma_V\right|\rho_{veg}$$

Where, ρ_s' is corrected specular coefficient. Γ is Fresnel reflection coefficient. rveg is damping factor of surface vegetation. Since background of the model is ocean, influence of vegetation is neglected. ρ_{veg} is taken as 1 and Gant is ratio about antenna gain from specular reflection point to the receiver compared to antenna gain along the direct path to the receiver.

5.5 Diffuse reflection energy

5.5.1 Effective diffuse reflection area

When the carrier signal is diffusely reflected near specular reflection point, radio waves reflected by some of diffuse reflection surfaces can reach the receiver. The area consisted of these surfaces is called effective diffuse reflection area. The range and location of effective diffuse reflection area can affect the reach of maximum additional time delay of signal at the receiver, thereby affecting extraction of the effective signal. Therefore, the model needs to determine range and position of effective diffuse reflection area[7].

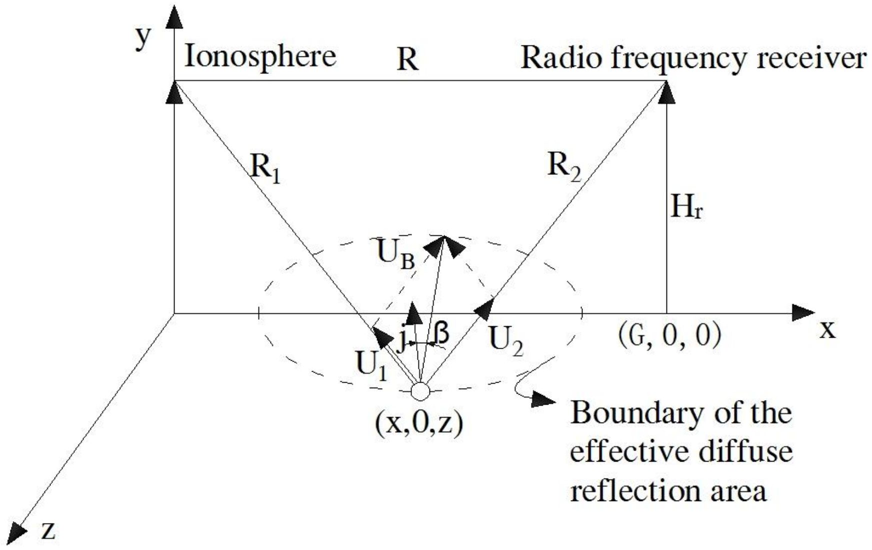


Figure 4: Geometric extent of the effective diffuse reflection area

After the carrier signal is reflected by several infinitely small reflecting surfaces (excluding specular reflection point) in the effective diffuse reflection area, in order to make reflected signal reach the receiver, the reflecting surfaces must have a certain slope, which is expressed as β . According to geometric relationship, we can get that β is the radian angle between the sum vector of U_1 and U_2 and normal vector of the ocean surface.

$$U_B = (U_1 + U_2) / |U_1 + U_2|$$

$$\beta = \cos^{-1}(U_B \cdot j)$$

Where, U_1 is unit vector in R_1 direction, and U_2 is unit vector in R_2 direction.

Suppose: coordinate of reflection point is (x, 0, z), then

$$U_1 = (-xi + H_t j - zk) / R_1$$

$$U_2 = ((G - x)i + H_r j - zk) / R_2$$

Suppose β obey normal distribution and define β_0 as RMS(Root Mean Square) of ocean surface slope in any small patch of diffuse reflection area[8]. The expression is :

$$\beta_0 = \frac{4\sigma_h}{l^2}$$

Where, σ_H is root-mean-square height of waves of ocean, and l is relevant length of correlation coefficient about wave height of any two points on the ocean.

Therefore, stipulate that the boundary of effective diffuse reflection area satisfies the equation:

$$\beta_{\lim} = \frac{k\beta_0}{\sqrt{2}}$$

Where, k is the coefficient of standard deviation

When $\beta = \beta_{\lim}$, we can calculate range of effective diffuse reflection area.

$$C_B = \cos(\beta_{\lim}) = \cos\left(\frac{k\beta_0}{\sqrt{2}}\right) = U_B \cdot j$$

$$= \frac{H_t/R + H_r/R_2}{\sqrt{\left(\frac{-x}{R_1}+\frac{G-x}{R_2}\right)^2 + \left(\frac{H_t}{R_1}+\frac{H_r}{R_2}\right)^2 + \left(\frac{-z}{R_1}+\frac{-z}{R_2}\right)^2}}$$

When z equals to 0, we can get range of x and 6 x values .While value of x is at transceivers， it is meaningful, so we can obtain the maximum and minimum values of x after filtering. Then take n numbers in the range of x, solve the corresponding value of z according to value of x, and each value of x can solve two values of z that are opposite each other. We suppose that sea state is fourth, then get value of β_0 is 0.5. Taking k = 3， that height of reflection ionosphere is 236km, and horizontal distance between two reflection points on the ionosphere is 2236 km. Then location and scope of effective diffuse reflection area can be obtained. Using MATLAB to draw schematic diagram, which is approximately an ellipse as shown in the figure.

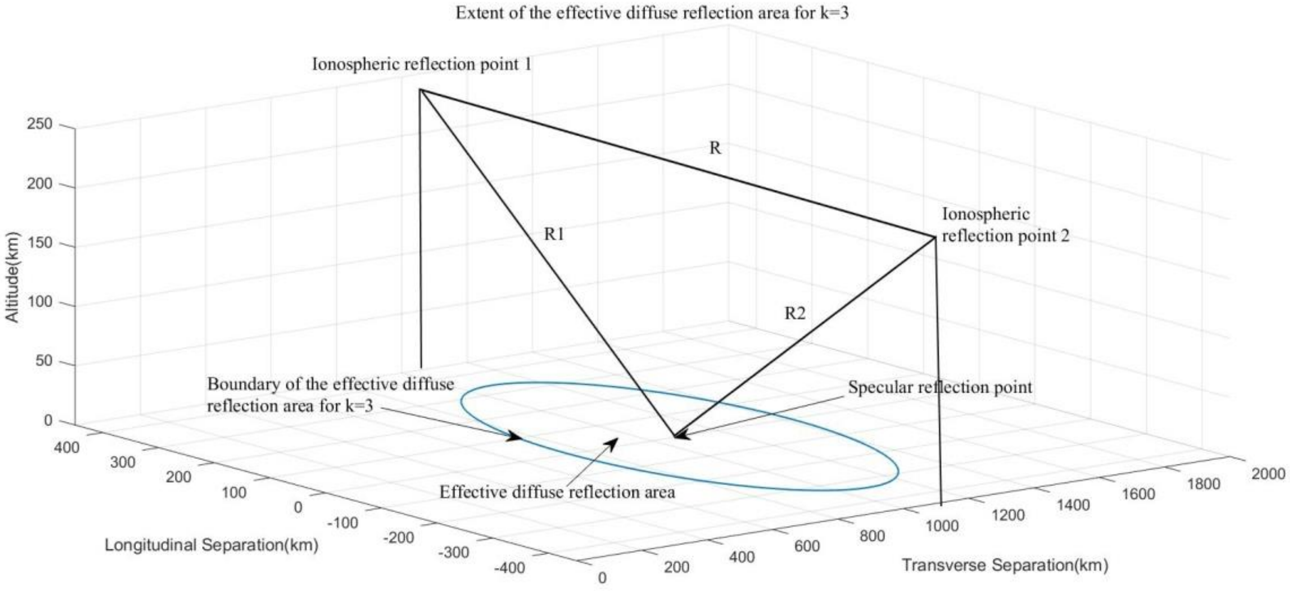


Figure 5: Extent of the effective diffuse reflection area

5.5.2 Diffuse reflection energy

The diffuse reflection points gathering around specular reflection points form effective diffuse reflection area, the shape of which is approximately an ellipse. Diffuse reflection energy[9] component in the received signal can be seen as the sum of energy components after reflection in any small area ,dA, in the effective diffuse reflection area. The voltage loss calculation formula of the diffuse reflection path from dA relative to the direct path signal is:

$$\frac{v_{Diffuse}}{v_{Direct}} = \sqrt{\frac{1}{4\pi}\left(\frac{R}{R_1 R_2}\right)^2 \frac{1}{\beta_0^2}\exp\left(-\frac{\beta^2}{\beta_0^2}\right) dA} \cdot \left|\Gamma_V\right| \cdot \rho_{roughness} \cdot \sqrt{S_f}$$

Where, R、R_1、R_2 is direct path length and reflection path length. dA represents area of any small area in the effective diffuse area. $\rho_{roughness}$ is diffuse reflection coefficient. Diffuse reflection coefficient on dA should be a function of the specular reflection coefficient ρ_s at this location. φ_1 is incident angle, and φ_2 is Angle of reflection. The expression is :

$$\rho_{roughness} = \sqrt{\rho_d(\varphi_1)\cdot\rho_d(\varphi_2)} = \sqrt[4]{\left(1-\rho_s(\varphi_1)^2\right)\cdot\left(1-\rho_s(\varphi_2)^2\right)}$$

$\sqrt{S_f}$ is shadow effect coefficient, which indicates the probability of the carrier signal being received by the receiver after scattered by ocean surface[10]. The formula is:

$$S_f = S_{f_1} \cdot S_{f_2}$$

$$S_{f_1} = \left[1-\frac{1}{2}erfc\left(\frac{\tan\varphi_i}{\beta_0}\right)\right] \Big/ \left(L_i+1\right)$$

$$L_i = \beta_0 \cdot \exp\left[-\left(\frac{\tan\varphi_i}{\beta_0}\right)\right] \Big/ \sqrt{\pi}\cdot\tan\varphi_i - erfc\left(\frac{\tan\varphi_i}{\beta_0}\right)$$

5.5.3 Selection of dA

The selection of dA’s shape and size has a great impact on the prediction of the model. In this part, ensure that time delay of signal from scattering point in any small area is as equal as possible, that is to say, reflection path difference is close. According to geometric relation, points with the same path difference form an ellipse, whose focuses are transmitting point and receiving point. The point of the ellipse intersecting xoz plane is reflection point, whose path difference is constant. Owing to the intersecting parts of ellipse and effective diffuse reflection area can be approximated seen as a straight line, dA selected in this model is a narrow strip-like area that is nearly parallel to the z-axis.

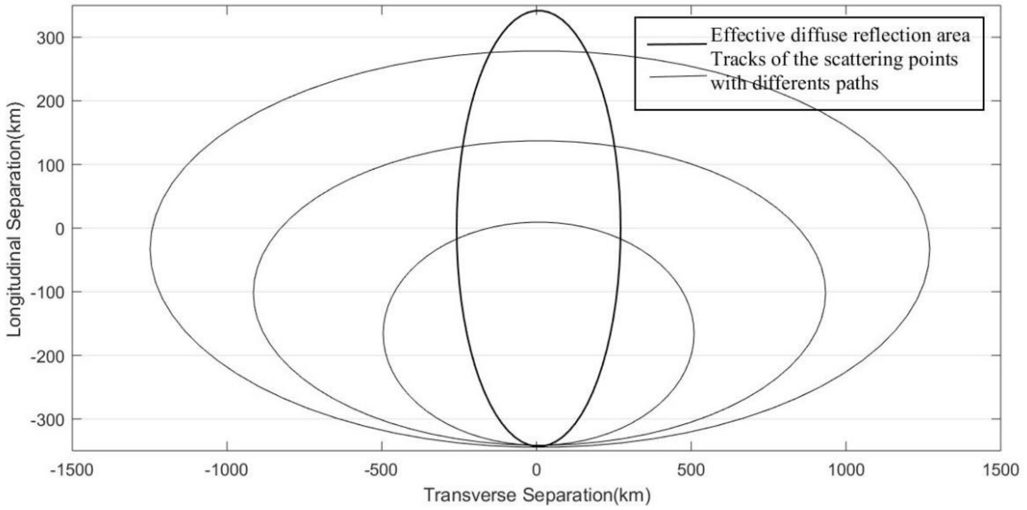


Figure 6: The effective diffuse reflection area and the ellipses with fixed path differences

5.6 Results of part I

In the premise of the launch and receiving has been set, we make reasonable assumptions:noise power=-175dB, SNR=10dB, antenna gain=11dBi, signal frequency=22.554Hz.

We calculate with model 1 and get the relevant data:

On the turbulent sea, the mirror reflection attenuation is 0.08dB, the diffuse reflection attenuation is 2.08dB and the ionospheric reflection decay is 3.017dB.

On the calm sea, the mirror reflection attenuation is 1.27dB, the diffuse reflection attenuation is 0dB and the ionospheric reflection decay is 3.017dB.

The maximum number of hops the signal can achieve before it reaches the available signal-to-noise threshold below 10 dB is 18 hops.

By comparison we can find the diffuse attenuation of calm sea surface is neglected approximately, and the specular reflection attenuation on turbulence sea is larger.

6. Comparision model of ocean versus land

6.1 Statement

Data Source:

Our data originate from actual situation of eight places at 10:00 am on January 1, 2018 .

First place is at ocean, and its coordinate is (29:35 W,30:5 N) .

Second place is at ocean, and its coordinate is (10 E,50:39 N) .

Third place is at offshore, and its coordinate is (1:16 W,45:39 N) .

Fourth place is at offshore, and its coordinate is (10:05 E,40:45 N) .

Fifth place is on the flat ground, and its coordinate is (2:02 E,48:52 N) .

Sixth place is on the flat ground, and its coordinate is (2:05 E,48:55 N) .

Seventh place is on the mountains, and its coordinate is (2:41 E,45:05 N) .

Eighth place is on the mountains, and its coordinate is (5:92 E,45:68 N) .

Table 2: Parameters of ocean

Parameters	ocean 1	ocean 2	offshore 1	offshore 2
Tangle(°)	3.69	26.50	29.78	19.72
Fot(MHZ)	23.468	11.010	11.101	10.881
Delay(ms)	9.40	3.30	3.01	4.10
Virtual Height(km)	242.38	233.84	233.50	233.74
Loss(dB)	130.65	111.01	110.01	115.00
Signal power(dBw)	-73.50	-54.00	-52.95	-58.04
Noise power(dBw)	-174.42	-165.19	-165.06	-164.88
SNR(dB)	100.40	111.18	112.01	110.98
required power(dB)	-11.00	-24.83	-26.84	-24.95

Table 3: Parameters of land

Parameters	smooth terrain 1	smooth terrain 2	mountains 1	mountains 2
Tangle(°)	29.91	31.57	44.52	30.15
Fot(MHZ)	10.491	10.230	9.316	11.537
Delay(ms)	3.00	2.90	2.33	3.00
Virtual Height(km)	234.68	234.45	248.59	238.60
Loss(dB)	109.50	109.01	106.43	110.01
Signal power(dBw)	-52.60	-52.00	-49.37	-53.01
Noise power(dBw)	-164.45	-164.27	-163.36	-165.45
SNR(dB)	111.58	112.18	112.99	112.55
required power(dB)	-25.54	-25.98	-28.71	-25.98

Figure 7: Parameters trend charts

In order to find differences between reflections off mountainous or rugged terrain versus smooth terrain easily and compare it with reflections off oceans, we use VOCAP in the ITS HF Propagation and Global Mapper, select several areas with typical topographical features in Europe as transmitter and receiver, then study some parameters in the receiver area: ionosphere radiation angle, virtual height of ionosphere, signal strength, noise strength, time delay, signal-to-noise ratio, median loss during propagation and antenna gain.Comparison figure is shown as:

By contrast, following conclusions can be concluded.

6.2 Similarities

When the signal is reflected on the land, energy loss reflected in the mountainous or hilly area is larger than that of flat area, which is consistent with the fact that energy loss reflected in the turbulent oceans is larger than that of calm oceans when the signal is reflected on the ocean.

When it comes to roughness, according to Rayleigh criterion, both mountainous and turbulent areas can be regarded as rough, while flat areas and calm oceans can be regarded as smooth.

6.3 Differences

On the land, the difference between energy loss reflected in a mountainous or hilly area and flat areas is greater than that between energy loss reflected in turbulent oceans and calm oceans, which means that mountainous areas absorb signals more strongly than turbulent oceans.

In most cases, ups and downs of mountains is greater than that of oceans. However, ocean waves are changing continuously, while it would not happen in the mountains.

Surface of ocean is more complex compared with land, since land is usually covered by vege-tation and more easily affected by human activities.

In most cases, noise of oceans is smaller than that of land, so signals reflected by land can reach a signal-to-noise ratio earlier when compared with signals reflected by oceans, namely the signal can travel farther.

7. Reflection model of ocean considering ship shaking

7.1 Assumptions

When incidence grazing angle is small and sea state is from third to seventh, specular reflection has the absolute advantage, and diffuse reflection can be ignored.

There is no ship nearby.

7.2 Statement

Our data originate from actual situation of a certain place at 10:00 am on January 1, 2018, and coordinate of transmitter is (41:09 W,8:37 N) ,and coordinates of receiver is (29:35 W,30:50 N).

7.3 Ship shaking model

Build a 6-DOF(Degrees of Freedom) model of ship movement (x, y, z, α , β , γ). As shown in the figure, a spherical coordinate system (o, x, y, z) is established based on the earth while o is the center of the earth.

So, ship’s movement can be roughly described as:

height change in the Z-axis direction ;

sway in the X-axis direction;

tilt in the Y-axis direction

Considering the shipborne antenna versus ship is relatively static, we can also use this spherical coordinate system to describe the position and receiving angle of the antenna.

The maximum angle ship swaying($\theta_{\max}$) can be obtained by approximately using geometric relationships.

$$\theta_{\max} = \arcsin\left(\frac{\pi H_{\max}}{\sqrt{\lambda_{sea}^2 + \pi^2 H_{\max}^2}}\right)$$

Where, $H_{\max}$ is length of waves. λ_{sea} is maximum height of waves.

7.4 Reflection model considering ship shaking

When a ship shakes, the tilt angle and sway angle of the antenna will change, which can cause changes of the antenna gain in different directions. The model uses $G(\theta,\phi)$ radiation vector G to represent the antenna gain along different directions and the state of their respective components[11].

$$G = \sqrt{G(\theta,\phi)}\begin{pmatrix} U_\theta(\theta,\phi) \\ U_\phi(\theta,\phi) \end{pmatrix}$$

Where, U is unit vector. θ is elevation of antenna. ϕ is azimuth angle of antenna. U_ϕ and U_θ represents the distribution proportion of antenna gain along its direction.

So, we can get the expression of direct path channel matrix C_D:

Where, u_φ and u_θ is the unit vector in the direction with angle φ and θ.

$$C_D = \frac{1}{R_d}\sqrt{G^A}\sqrt{G^B}\begin{pmatrix} U_\theta^B & U_\phi^B \end{pmatrix}\cdot\begin{pmatrix} u_\theta^A \cdot u_\theta^B & u_\phi^A \cdot u_\theta^B \\ u_\theta^A \cdot u_\phi^B & u_\phi^A \cdot u_\phi^B \end{pmatrix}\cdot\begin{pmatrix} U_\theta^A \\ U_\phi^A \end{pmatrix} e^{-j2\pi R_d/\lambda}$$

In addition, channel matrix C_R expression of specular path is:

$$C_R = \frac{1}{R_1 + R_2}\sqrt{G^A}\sqrt{G^B}\begin{pmatrix} U_\theta^B & U_\phi^B \end{pmatrix}\cdots$$

$$\cdot\begin{pmatrix} u_\theta^B \cdot u_{\|}^r & u_\theta^B \cdot u_{\perp}^r \\ u_\phi^B \cdot u_{\|}^r & u_\phi^B \cdot u_{\perp}^r \end{pmatrix}\cdot \rho_{FD} \cdot \rho_r \cdot \begin{pmatrix} \rho_{\|} & 0 \\ 0 & \rho_{\perp} \end{pmatrix}\cdots$$

$$\cdot\begin{pmatrix} u_\theta^A \cdot u_{\|}^r & u_\phi^A \cdot u_{\|}^r \\ u_\theta^A \cdot u_{\perp}^r & u_\phi^A \cdot u_{\perp}^r \end{pmatrix}\cdot\begin{pmatrix} U_\theta^A \\ U_\phi^A \end{pmatrix}\cdot e^{-j2\pi(R_1R_2)/\lambda}$$

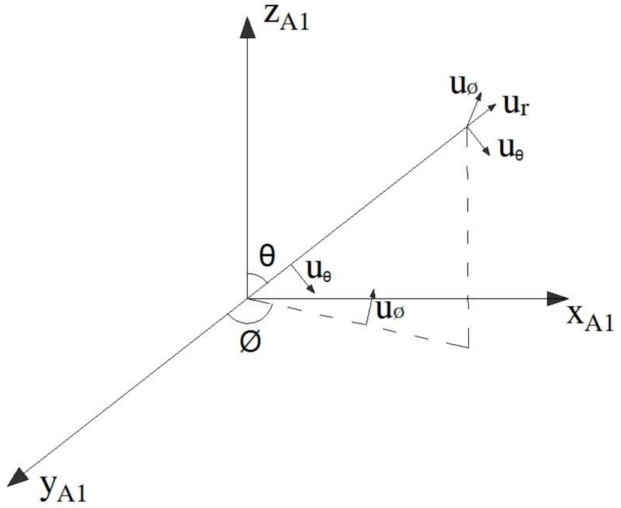


Figure 8: Unit vector under antenna coordinate system

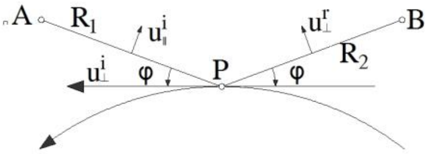


Figure 9: Unit vector definition for specular reflection

$u_\perp^r$ == and $u_\parallel^r$ is shown on the figure.

$$\rho_{FD}=\left(1+\frac{2R_1R_2}{R_e\left(R_1+R_2\right)\sin\varphi_g}\right)^{-\frac{1}{2}}\left(1+\frac{2R_1R_2}{R_e\left(R_1+R_2\right)}\right)$$

Where, ρ_r the specular reflection coefficient[12] corrected by the zero-order Bessel function; ρ_{FD} is energy dispersion coefficient[13], which represents the degree of energy loss after the carrier signal is reflected by the reflection point.

$$\rho_r=\exp\left(-2\left(2\pi g\right)^2\right)\cdot I_0\left(2\left(2\pi g\right)^2\right)$$

$$g=\left(\sigma_h\sin\varphi_g\right)/\lambda$$

Therefore, the propagation path gain of final signal is：

$$P\left(dB\right)=10\log_{10}\frac{P_r}{P_t}=10\log_{10}\left(\left(\frac{\lambda}{4\pi}\right)^2\left|C_D+C_R\right|^2\right)=20\log_{10}\left(\left(\frac{\lambda}{4\pi}\right)\left|C_D+C_R\right|\right)$$

The expression of path loss in propagation described by the dual-path model considering ship shaking is:

$$L_a=147.5582-20\lg f+\beta\left(f,d\right)=147.5582-20\lg f+20\lg\left|C_{DP}+C_{RP}\right|$$

7.5 Result of part III

After considering the path gain caused by the changes of the antenna angle, the maximum num-ber of hops the signal can experience is 16 before the signal reaches the SNR threshold of 10 dB under the premise of part 1. Supposing the ship speed is 25 knots, then it can maintain communication for about a month with the same multi-path.

8. Sensitivity Analysis

In our model,some inputs are not precise enough for the lack of actual data and parameters are difficult to obtain directly.Those inputs or parameters may influence the result of our calculation, so we implement a sensitive analysis to test the robustness of our model.

In fact, the parameters of ionosphere and free space are continuously changing and the sea con-dition level is not a invariable figure, so sensitivity analysis is primarily conducted on these inputs and parameters.

8.1 Sensitivity Analysis for parameters of ionosphere and free space

All the curves have the same trends and they are roughly equal. So the parameters of ionosphere and free space are not sensitive to the results of our models.

8.2 Sensitivity Analysis for different kinds of antennas

The path loss of different types of antennas based on model III are:

Omnidirectional antenna(11dBi): 194dB

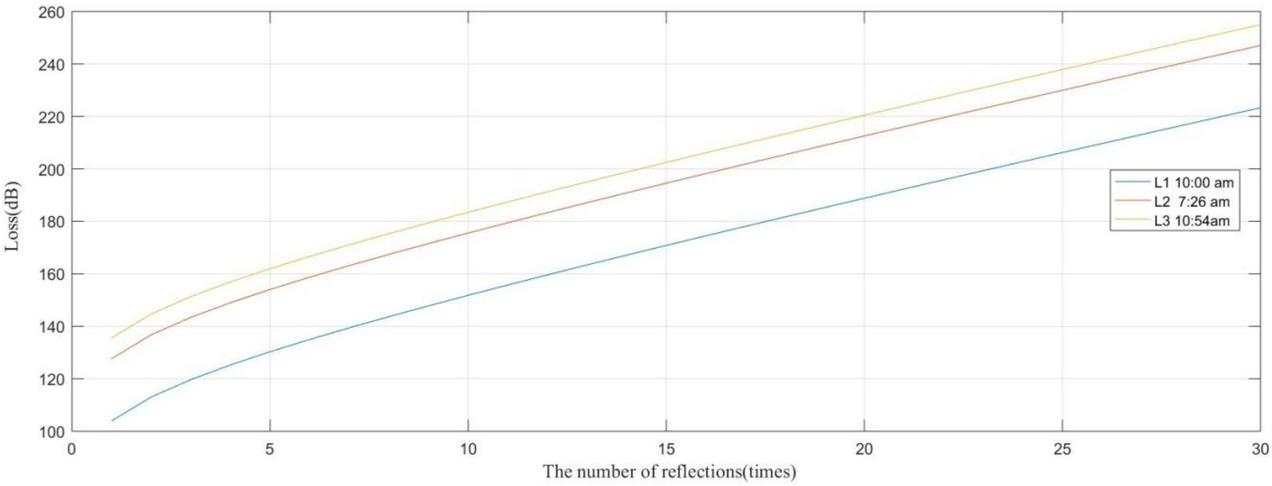


Figure 10: Figure of path loss at different times

Directional antenna(18dBi): 201dB

Under the premise of -173dBw noise power and 10db signal to noise ratio ,by contrast, we can easily figure out that different types of antennas have little effect on path loss so it will not affects our results obviously.

9. Strengths and Weaknesses

9.1 Strengths

Slight changes of parameters will not cause a significant change of the results. That is to say, our models are stable.

Our models can be well applied in other fields and we just need to change some specific conditions.

For different situations, we develop the corresponding modulating strategies and make relative and comprehensive plans, which can provide specific guidance for the ships using HF to communicate and receive weather or traffic information.

Our data come from the database of ITS HF Propagation and Global Mapper, which is believable.

9.2 Weaknesses

Our models don’t consider atmospheric wave guide effect and Doppler effect. We mainly focus on the losses caused by reflections and antenna gain changes caused by angle. But in fact, factors that we did not take into account are important for more accurate forecast. So we discuss them in the future and hope we can solve it in the future.

The data of some parameters is presumptive because we don’t carry out the actual test. How-ever, in view of ensitivity analysis, they will not make a obvious difference.

10. A short note

10.1 Introduction

Radio waves, ranging from 3 Hz to 30 MHz, are called as high frequency radio or short wave. The shortwave is usually reflected by the ionosphere to reach the surface. Radio waves can be ap-plied for long-distance communications by ionosphere reflection or multiple reflections between ionosphere and ground. Due to the different characteristics of the reflecting surface, the loss and reflection strength of high-frequency radio waves during transmission would vary.

10.2 Assumptions

Sea state is constant.

We employ omnidirectional dipole antenna.

Free space parameters in the propagation path are constant.

Ionosphere parameters in the propagation path are constant.

Task 1:

Establishment: Use some parameters, like specular reflection energy, effective diffuse reflection area and diffuse reflection energy, to formulate reflection model of ocean considering diffuse reflection model.

Task 2:

Process: We use VOCAP in the ITS HF Propagation and Global Mapper, select several areas with typical topographical features in Europe as transmitter and receiver, then study some parameters in the receiver area.

Conclusions: Energy loss reflected in the mountainous or hilly area is larger than that of flat area. The difference between energy loss reflected in a mountainous or hilly area and flat areas is greater than that between energy loss reflected in turbulent oceans and calm oceans.

Task 3:

Process

Step1: Build a 6-DOF(Degrees of Freedom) model of ship movement.

Step2: Develop reflection model of ocean considering ship shaking model.

Step3: Describe path loss in propagation by dual-path model considering ship shaking.

10.3 Strengths and Weaknesses

Strengths

1.Slight changes of parameters will not cause a significant change of the results. That is to say, our models are stable.

2.Our models can be well applied in other fields and we just need to change some specific conditions.

Weaknesses

1.Our models don't consider atmospheric wave guide effect and Doppler effect. We mainly focus on the losses caused by reflections and antenna gain changes caused by angle. But in fact, factors that we did not take into account are important for more accurate forecast. So we discuss them in the future and hope we can solve it in the future.

2. The data of some parameters is presumptive because we don't carry out the actual test. However, in view of ensitivity analysis, they will not make a obvious difference.

10.4 Overlook

Though our model is a integral one considering many factors, there are still improvements that can be made. We hope that we'll improve it further in the future.

11. Summary

With regard to task1, we first introduce the maritime wireless multipath channel and list some important parameters. Then, we calculate the loss of reflections off the ocean including specular and diffuse reflection loss. For the specular reflection loss, we consider the effect of earth curvature factor in the model due to the large scale of multi-hop path. For the diffuse reflection loss, we introduce the concept of effective diffuse reflection area and calculate its location and range according to boundary conditions. Finally, the value of diffuse reflection loss can be obtained by integrating the effective diffuse reflection area.We compare the reflection off calm ocean and turbulent ocean, then get the maximum number of hops which reflect off calm ocean.

With regard to task 2, we use ITS HF Propagation to select several areas with typical topographical features as receivers of the signal, and analyze a lot of parameters about sig-nal reflection. Then we figure out the differences between the reflections off mountainous or rugged terrain versus smooth terrain and compare it with the ocean.

With regard to task 3, we consider the swaying of ships combining the specific con-ditions of the ships navigating in the turbulent ocean. Next we use vectors to represent the channel matrix of direct and specular paths and get the corresponding path gain con-sidering the free space propagation and ionospheric reflection loss. Finally we calculate and get the maximum time that the ship can maintain the communication.

In fact, the parameters of the ionosphere will change at different times and seasons, so we focus on it in the sensitivity tests. By studying the signal path loss in different time periods and making comparison, we draw the conclusion and test the effect of different antennas on model results.

Last but not least, our model can reflect the actual situation better and the conclusions drawn are more accurate that can provide some convenience for maritime communications. Also, we list the overall strengths and weaknesses of our model as well as the concrete data.

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Appendices

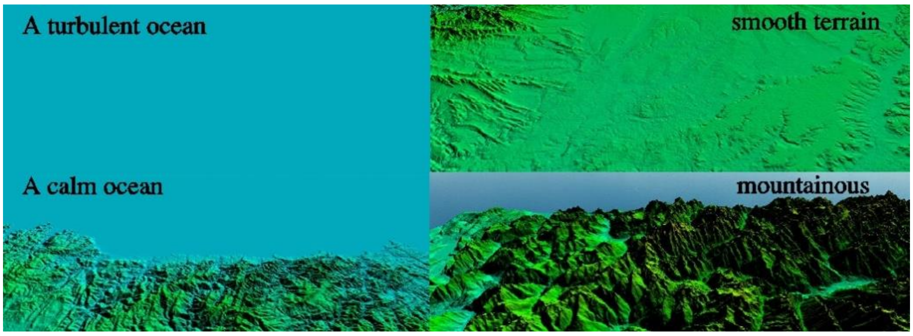

Figure 11: Two-ray model by considering the earth curvature

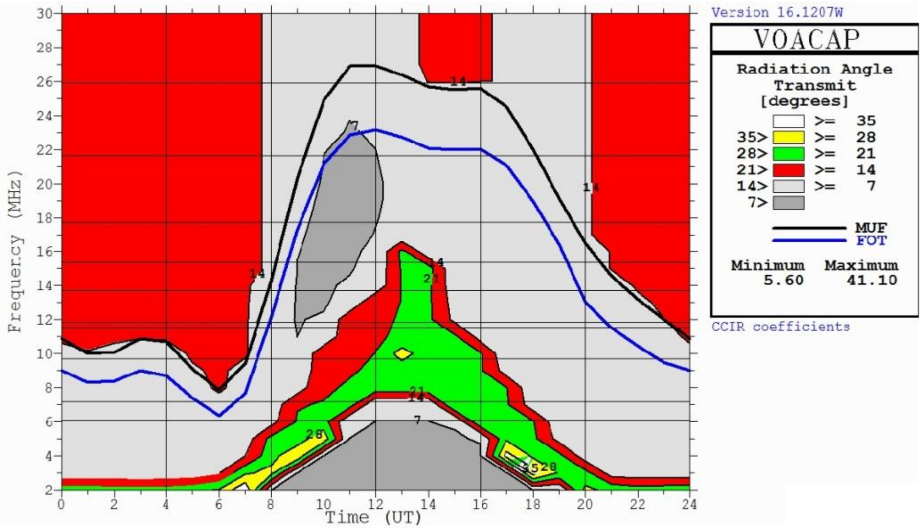

Figure 12: Radiation angle transmit

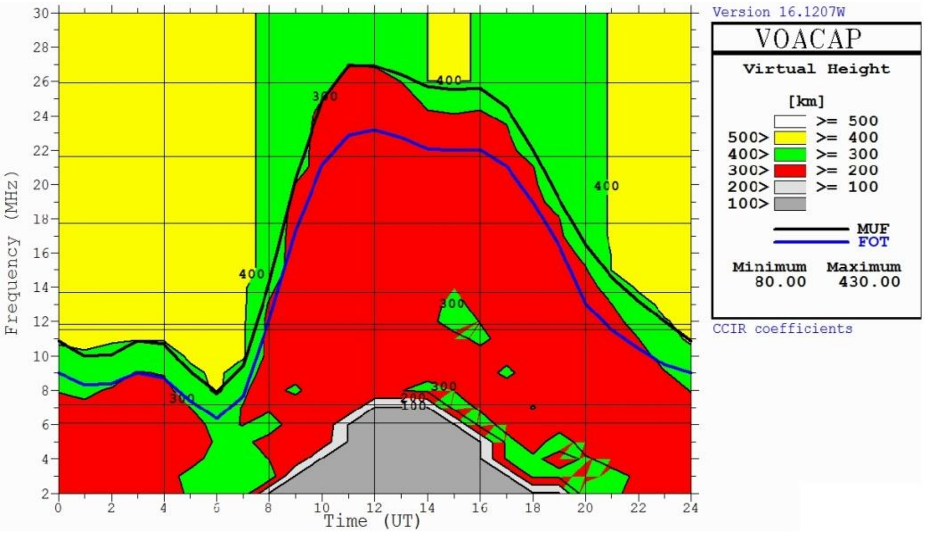

Figure 13: Virtual height

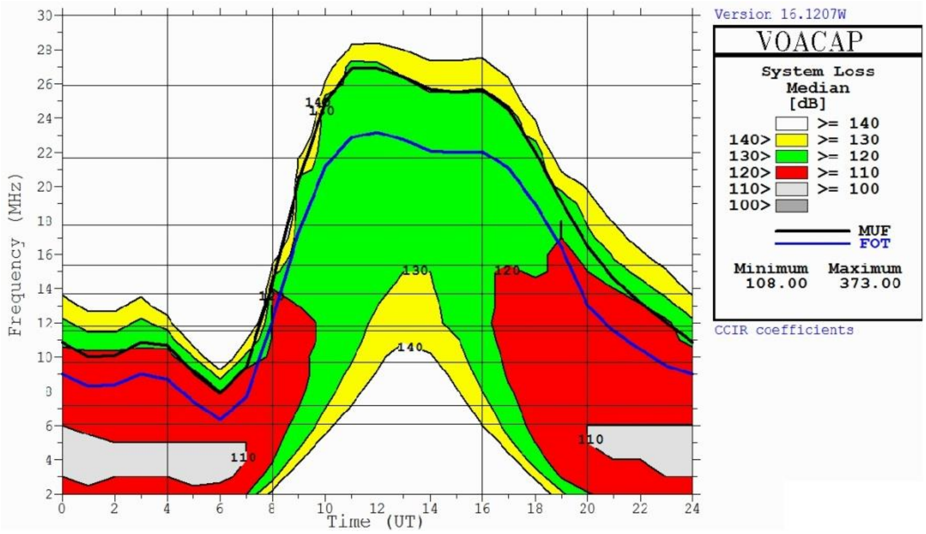

Figure 14: System loss median

Table 4: Parameters at different times

Parameters	max	min	reference value
Tangle(°)	11.04(7:26AM)	6.77(10:54AM)	7.20(10:00AM)
Virtual Height(km)	329.81(7:34AM)	236.02(10:40AM)	236.12(10:00AM)
Freq(MHZ)	9.751(7:34AM)	22.467(10:40AM)	22.554(10:00AM)