

# Multi-hop Attenuation of HF Radio

Xin Qiao <sup>a)</sup>

North China Electric Power University, Baoding 071000, China

<sup>a)</sup> Corresponding author: 931621593@qq.com

**Abstract.** High frequency (HF) propagation can achieve long distance, low cost communications and it is one of the most important communication methods. The focus of this research is to develop an appropriate mathematical model for HF radio waves to communicate efficiently over various surface of the earth. First of all, the multi-hop attenuation (MHA) model is established which takes free space loss, ionosphere loss and surface reflection loss into account. [1] The effect of the free space loss and the ionosphere loss is simplified, and subsequently the relationship between signal attenuation and frequency variation under different wind speed is revealed. At the same time, the contrast of signal attenuation off a calm ocean and a turbulent one is conducted. [2].

**Key words:** HF; MHA; ionosphere; signal attenuation; low cost communications.

## THE MULTI-HOP ATTENUATION MODEL

In high-frequency wireless communication, the signal will continue to decay during transmission and "transmission loss" is often referred to represent the power loss of radio waves through the transmission line, which can be divided into four basic parts: Free space loss Lbf, Ionization Layer loss La, Surface reflection loss Lg and Additional loss Yp. Due to unpredictable changes in the additional loss, we mainly study the other three losses. Then consider the transmit antenna and receive antenna gain LGT and LGR. The whole channel transmission loss is the sum of these sections.

When we study the signal reflection off the ocean, we should first establish the model of the surface shape of the ocean. The Fourier transform of the correlation function of the height fluctuation in the ocean surface is defined as sea spectrum, which directly gives the distribution of making up various harmonic components in ocean surface relative to spatial frequency and orientation. [3]

The two-dimensional distribution of the PM sea spectrum is shown in the following formula:

$$S_{\zeta}(\omega) = \frac{ag^2}{\omega^5} \exp\left(-\beta\left(\frac{g}{U\omega}\right)^4\right) \quad (1)$$

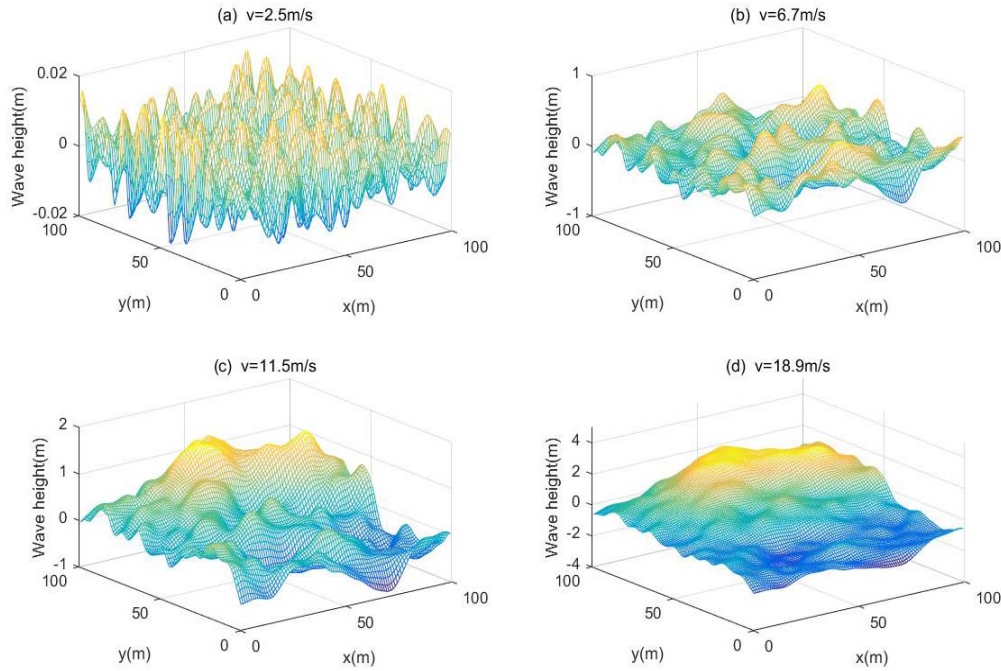
In that formula,  $\alpha=0.0081$ ,  $\beta=0.74$ . U is the wind speed at a distance of 19.5 meters from the sea surface.

In the two-dimensional PM sea spectrum, for any wave frequency, if the wave height is specified, the wave comes only from one direction of the sea surface. In fact, waves have three-dimensional irregularity. Not only are the waves different in height and frequency, but they also travel from one direction to another. In addition to the main waves generated along the main wind direction, these harmonics are diffused in the range of  $\pm\pi/2$  angles from each side of the main wave, so we use a double superposition model.

$$\xi(x, y, t) = \sum_{i=1}^n \sum_{j=1}^m \xi_{aij} \cos(k_i x \cos \mu_j + k_i y \sin \mu_j - w_i t + \varepsilon_{ij}) \quad (2)$$

While  $\xi_{aij}$ ,  $k_i$ ,  $\omega_i$ ,  $\mu_j$  are the amplitude, wave number, angular frequency and direction angle of the composing harmonics, respectively.  $\epsilon_{ij}$  is the random initial phase which is a random variable distributed evenly between  $0 \sim 2\pi$ .

According to the above theory, we can obtain the 3D irregular wave simulation at four different wind speeds, shown as in Fig 1.



**FIGURE 1.** Sea waves simulation corresponding when wind speed is (a) $v=2.5\text{m/s}$ , (b) $v=6.7\text{m/s}$ , (c) $v=11.5\text{m/s}$  and (d) $v=18.9\text{m/s}$ .

Then we consider the electromagnetic environment of the ocean. During the propagation of HF radio waves, the reflection, refraction and scattering will occur when passing through the ocean surface, and the electromagnetic environment of the ocean surface will have some effect on these phenomena. [4] Here, we consider that the dielectric constant of seawater is related to the salt content, the frequency of external electric field and the temperature of sea water. The following formula is used to calculate the dielectric constant of seawater.

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{(j2\pi f\tau)^{1-\alpha}} - j \frac{\sigma}{2\pi f \epsilon_0} \quad (3)$$

It can be seen from the upper formula that the dielectric constant is negatively correlated with the temperature, salinity and frequency of the wave.

When the sea surface wind speed is large, the sea surface is covered by foam in a certain extent, and the effect of the foam particles on the sea water scattering also is significant. Therefore, we use the Maxwell-Garnett model to calculate the dielectric constant of the surface covered with foam.

$$\epsilon_e = \epsilon_0 + \frac{3f_b(\epsilon_p - \epsilon_0)\epsilon_0 / (\epsilon_p + 2\epsilon_0)}{1 - f_b(\epsilon_p - \epsilon_0) / (\epsilon_p + 2\epsilon_0)} a \quad (4)$$

Where  $\epsilon_p$  denotes the bubble dielectric constant, and  $f_b$  denotes the empirical formula of the bubble in seawater.

In fact, even when the wind speed is high, there still exists an area without foam covering on the sea surface. Therefore, we modify the above model to obtain the foam coverage rate of the sea surface  $c$  and the corrected dielectric constant  $\epsilon'$ .

$$C = 2.32 \times 10^{-6} V_{10}^{3.4988} \quad (5)$$

$$\varepsilon' = (1 - c)\varepsilon + c\varepsilon_e \quad (6)$$

After that we consider sea surface reflection loss Lg. From the previous analysis, we know that the HF radio waves are reflected, refracted and scattered when they pass through the turbulent sea. Here we mainly consider the reflection of radio wave.

Figure 2 shows the track of one of the signals after it is emitted from a point source on land. In Fig 2,  $\alpha$  is the angle between the signal from the signal transmitter and the horizontal plane.  $\beta$  is the angle between tangent of the reflection point on the wave and the horizontal plane.  $\Delta$  is elevation angle of the ray,  $h$  is the distance from the ionosphere in the horizontal plane and  $R_0$  is the radius of the earth.

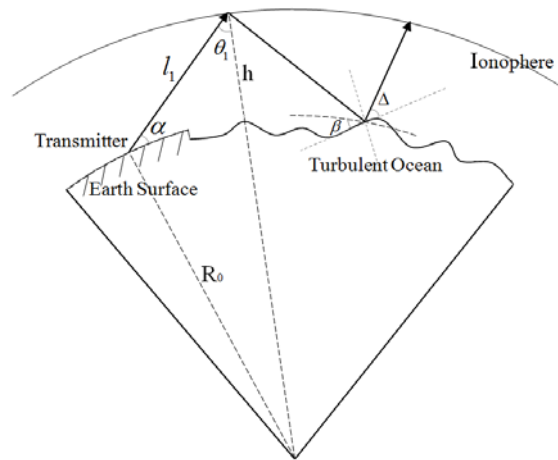


FIGURE 2. Diagram of Signal propagation

The geometric analysis of the above figure shows that the three lengths of the sides of the left triangle are  $L_1$ ,  $R_0$ ,  $R_0+h$ . By applying sinusoidal theorem to the triangle, it can be obtained the reflection angle  $\theta_1$  when the signal passes through the ionosphere for the first time, then the length  $l_1$  is solved by the cosine theorem.

$$\theta_1 = \arcsin \frac{R_0 \sin(\alpha + \pi/2)}{h + R_0} \quad (7)$$

And it is easy to get that the path length  $r$  of one hop is  $r=2l_1$ .

Under the condition of HF radio Propagation, the reflection of the radio wave through the sea surface will cause the power loss of the signal. The sea surface reflection loss is related to the polarization, frequency, ray elevation angle and geological conditions of the wave which is complicated, so we calculate the circularity polarized wave.

The energy of a circularly polarized wave is equally distributed between horizontal polarization and vertical polarization and can be decomposed into a vertical polarized wave and a horizontal polarized wave. From the knowledge of the electromagnetic field, the reflection coefficients of the two kinds of polarized waves can be obtained, which are as follows:

$$R_H = \frac{\sin \Delta - \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2 \Delta}}{\sin \Delta + \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2 \Delta}} \quad (8)$$

$$R_v = \frac{(\varepsilon_r - j60\lambda\sigma) \sin \Delta - \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2 \Delta}}{(\varepsilon_r - j60\lambda\sigma) \sin \Delta + \sqrt{(\varepsilon_r - j60\lambda\sigma) - \cos^2 \Delta}} \quad (9)$$

Where,  $\sigma$  is the ground conductivity,  $\lambda$  is the radio wave wavelength. And the corresponding reflection loss  $L_g$  can be calculated as

$$L_g = -10 \lg \left( \frac{|R_v|^2 + |R_H|^2}{2} \right) \quad (10)$$

## RESULTS FROM THE MHA MODEL

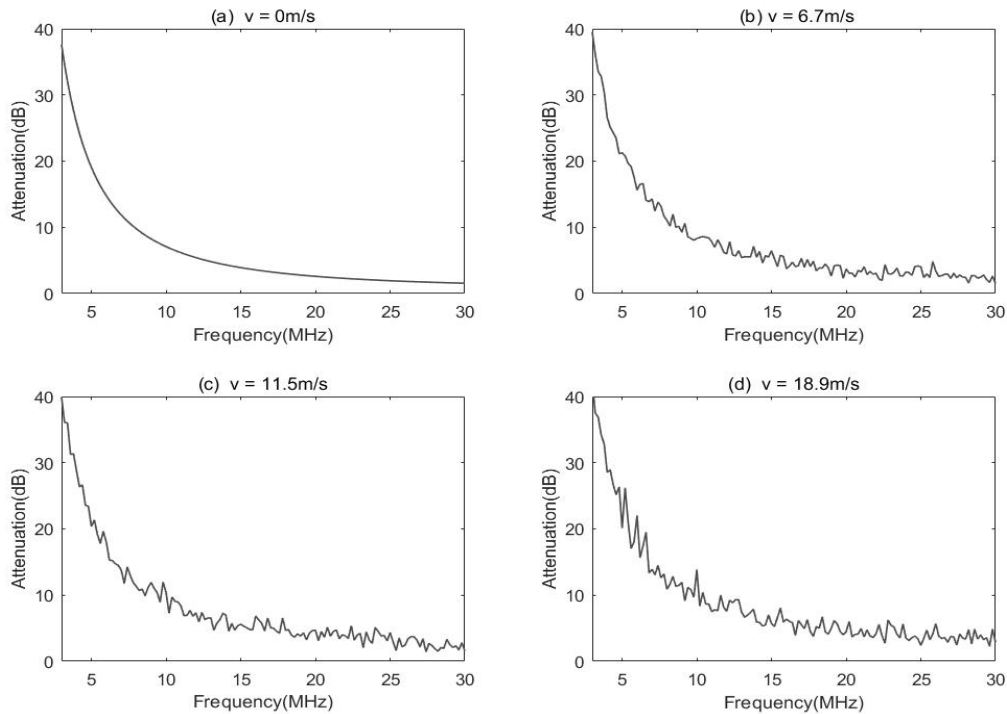
### Simulation and Analysis

We decompose the transmitted signal into  $n$  beams from  $0$  to  $\pi/2$  according to the launch angle and simulate the energy attenuation of the signal at different turbulences degree under the four different wind speeds. Thus, the hops of the signal in propagation are further confirmed. The launch angle and the signal intensity of each beam are

$$\alpha_i = \frac{\pi i}{2n}, \quad P_s(i) = \frac{P_s}{n} \quad (11)$$

Considering that some of the signal beams are likely to reflect in exactly the opposite direction, we define the critical reflection angle  $\psi = \pi/4 - \alpha/2$ , and when the signal beam encounters a dip angle greater than  $\psi$  when reflected on the sea, the signal is reflected in the opposite direction and therefore it should be discarded.

According to some restrictions and attenuation formula of HF radio wave, we determine the final signal energy attenuation and obtain the simulation results in Fig 3.



**FIGURE 3.** The relationship between attenuation and frequency of signal when wind speeds are (a) $v=2.5\text{m/s}$ , (b) $v=6.7\text{m/s}$ , (c) $v=11.5\text{m/s}$  and (d) $v=18.9\text{m/s}$ .

By analyzing the relationship between attenuation and frequency at different wind speeds, we can draw the following conclusions.

When the wind speed is not zero, the energy loss of the signal decreases with the increase of frequency, but due to the stochastic volatility of the waves, the energy will oscillate in the process of attenuation.

With the increase of wind speed, the amplitude of oscillation in the process of signal energy attenuation will gradually increase. When the wind speed is  $v=18.9\text{m/s}$ , the signal attenuation oscillation in low-frequency range is very large, which will have a great influence on the communication of receiver.

### The Maximum Number of Hops

From the above simulation results, we can see that the maximum number of hops that can be achieved will be affected by many factors when a certain HF radio propagation occurs.

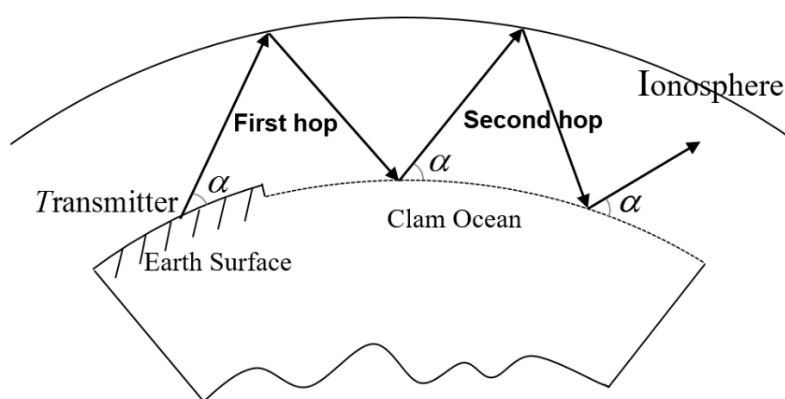


FIGURE 4. Multi-hop transmission diagram

It can be seen from Fig 4 that on a calm sea, the incident angle  $\alpha$  of each hop of the signal is the same, so the transmission loss of each hop  $L_b$  is the same, to obtain the maximum number of hops during signal transmission:

$$n = \frac{SNR_{\max} - SNR_{\min}}{L_b} \quad (12)$$

$SNR_{\max}$  is the signal-to-noise ratio of the signal at the initial time,  $SNR_{\min}$  is the minimum signal-to-noise ratio required in the communication process.

Based on the analysis above, the maximum number of hops in the signal propagation process is calculated and the result is shown in the following table.

TABLE 1. The Max number of hops at different signal frequency

Frequency(MHz)	5	10	15	20	25	30
Max number of hops	1	2	5	7	10	12

The table above shows that as the frequency increases, the maximum number of hops of the signal increases as well, which is advantageous for communication. In view of MUF limitations, it is possible to determine the appropriate communication frequency. The simulation results are in good agreement with our previous analysis, which indirectly proves the accuracy of the model we set up.

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