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HF Sky wave hop-propagation on earth’s surfaces in different conditions

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Abstract. HF Radio waves can be reflected by the ionosphere and the earth’s surface and propagate long distance from the transmitter to the receiver with several hops, which is also called sky wave propagation. Path loss of sky wave propagation varies with different conditions of ionosphere and types of the earth’s surfaces. In order to get a deeper insight into the multi-hop sky wave propagation, we establish a model to investigate calculate the propagation losses under certain circumstances. We separate the path loss into three parts, namely the free space propagation loss (FSPL), the ionosphere propagation loss (IPL) and the sea surface reflection loss (SSRL). The FSPL and the IPL are calculated by using the propagation loss equations from ITU (International Telecommunication Union) standard. The SSRL is estimated by Pierson-Moscowitz (PM) sea wave spectrum and Kirchhoff approximation (KA) method. The model results agree well with the existing observations that the strength of the reflection off the turbulent ocean attenuates more than that of the clam ocean.

1. Introduction
Sky wave propagation is the basis of long-distance HF communication and over-the-horizon radar detection. Reflecting on Ionosphere is a necessary part of the propagation. Ionosphere can be divided into three layers called D, E, and F. F layer can be further divided into F1 layer and F2 layer. The F2 layer persists by day and night and is the main region responsible for the radio wave reflection. Sky wave propagation loss is considered to be related to the reflector surfaces’ conditions.

In this paper, we establish a model to determine the strength of a first reflection off the ocean. In the model utilized to determine the SSRL, we use PM Spectrum to demonstrate the energy distribution of the sea wave, from which we can derive the root-mean-square height and the relevant wavelength of the ocean, both determined by the wind speed. Then we get the scattering coefficient via KA method so that the SSRL can be determined by it. Next we calculate the maximum number of hops the signal takes if there is additional reflection off a calm ocean before the strength falls below the SNR threshold of 10 dB. Finally we separate the situation of a calm ocean and a turbulent ocean by using different wind speeds, according to the relationships between the range of the wind speeds and the sea conditions.

The outline of the paper is as follows. We start in section 2 by using the relevant propagation loss equations from ITU standard, PM sea wave spectrum and KA method to build the model of sky wave reflection off the ocean and calculate the maximum number of hops given certain conditions. In
2. The model of the reflection off the ocean

In this section, we establish a model to investigate the sky wave propagation in the condition of sea surfaces. The model focuses on the simulation of sea surfaces. To simplify our models, we make the following assumptions: The ionosphere is reduced to only one layer, which means our model considers only F2 layer and ignores the other two layers’ effect, for the F2 layer is the main region responsible for the refraction and the reflection of the radio waves. The elevation angle is equal to the incident angle of the radio wave. The only difference between a turbulent ocean and a calm ocean is the conditions of the sea surfaces. This assumption is to keep the temperature, salt content and other factors fixed. Additional losses, including polarization loss, absorption loss due to ionosphere bias, abnormal winter absorption, etc. in the process of propagation are ignored because they are difficult to model accurately and have minimal effect.

2.1. The free space propagation loss

First we calculate the FSPL, which mainly results from the divergence of the energy during the propagation. Suppose the earth and the ionosphere are flat, thus there is negative correlation between the energy density and the square of the ray path. \[ D \]

Let \( D \) denote distance of ray path and let \( P \) denote propagate power, then the power flux density equals \( P(4\pi D^2)^{-1} \).

As for the receiving end, the receiving area is \( \lambda^2(4\pi)^{-1} \), so the receiving power equals \( P\lambda^2(4\pi D)^{-2} \).

Define propagation loss as the ratio of the transforming power to the receiving power:

\[
L_{fs} = 10\log\left[\frac{P}{P\lambda^2(4\pi D)^{-2}}\right] = 20\log\frac{4\pi D}{\lambda} \tag{1}
\]

Substitute the frequency of the radio waves \( f \) for \( \lambda \) and obtain the equation. As for \( D \), we suppose the ratio waves’ path is an equivalent triangle, thus \( D \) can be expressed as

\[
D = \frac{2nh}{\sin \theta} \tag{2}
\]

\( h \) represents the height of the ionosphere, \( n \) represents the hop times, \( \theta \) represents the elevation angle.

We search relative resources and find that the reflection of short wave takes place at a height of from about 170km to 300km. So we suppose that \( h \) equals 200 km. Practically, the general incident angle ranges from 20 degrees to 60 degrees. So we determine that \( \theta \) equals 60 degrees. According to the information of the question, \( f \) ranges from 3 to 30 MHz. Then \( f \) is 15 MHz.

The result is that in the first hop, the FSPL \( L_{bf} = 109.2624 \text{ dB} \).

2.2. The ionosphere propagation loss

Let \( f_{ob} \) denote the oblique incident frequency, the absorption loss in F2 layer is:

\[
L(f_{ob}) = \frac{677.2 \times I \times \sec \phi_0}{(f_{ob} + f_{o})^{0.8} + 10.2} \tag{3}
\]

\[
\sec \phi_0 = \frac{1}{\cos(\frac{\pi}{2} - \frac{D}{2R_z} - \beta)} \tag{4}
\]

\[
f_{o} = 2.8 \times 0.347448 \times (\frac{R_z}{R_z + 300})^3 \times (1 + 3(\sin \theta)^2)^{\frac{1}{2}} \tag{5}
\]
\[ \beta = \arctg \left( \frac{\cos D}{2 R_z} - \frac{R_z}{R_z + 110} \sin \frac{D}{2 R_z} \right) \quad (6) \]

\( g_n \) represents geomagnetic latitude of the reflection area, \( \phi_0 \) represents the radio wave’s incidence angle at the altitude of 100 km, \( f_H \) represents magnetic rotation frequency, \( R_z \) represents the earth’s radius.

\[ I = (1 + 0.0037 \times R)[\cos(0.881 \times \psi)]^{1.3} \quad (7) \]

\( I \) represents absorption factor, and \( R \) represents the number of the sunspots. \( \psi \) represents the solar zenith of the reflection area that the radio waves pass through.

We can derive \( \psi \) from the equation below:

\[ \cos \psi = \sin x \sin \delta_x + \cos x \cos \delta_x \cos(\delta_y - y) \quad (8) \]

\( x, y \) represents the longitude and the latitude of the ionosphere reflection area respectively, \( \delta_x \) represents declination, \( \delta_y \) represents the longitude of the subsolar point. We suppose that \( R_z = 6371 \), which is given as the real parameter of the earth. And we choose 150, which is near the mid-value, as the value of \( R \), according to figure 1.

![Figure 1](image.png)

**Figure 1.** Monthly mean and 13-month smoothed number of sunspot.

Here comes the result that the ionosphere propagation loss \( L_f = 4.6560 \) dB.

### 2.3. The propagation loss on the ocean

In this part, we calculate the SSRL, which is the most important part of the model. Owing to the complexity of the relationship between dielectric constant and ocean turbulence, a new method is adopted to measure the propagation loss on the ocean, which is totally different from the method above. [2]

Use PM Spectrum to demonstrate the energy distribution of the sea wave [3]:

\[ W(K, \phi) = \frac{\alpha}{2|K|^4} \exp[-\beta g_0^2] \left( \frac{\cos \phi}{K^2 U^2} \right)^2 \quad (9) \]

\( \phi \) represents the direction of the wind, and \( U \) represents the speed of the wind.

Figure 2 demonstrates the relationship between \( W(K) \) and \( U \).
Root-mean-square height and relevant length of the ocean are given by the formula [4]:

\[ h_{rms} = \frac{\alpha U^2}{4\beta g_0^2} \]  \hspace{1cm} (10)

\[ l_x = l_y = \frac{3\pi U^2}{8 g_0^2} \left( \frac{\pi}{2\beta} \right)^2 \approx 0.175U^2 \]  \hspace{1cm} (11)

Root-mean-square height \( h_{rms} \) and relevant length \( l_x, l_y \) are both only related to \( U \).

Based on the PM model, we use KA method [5] and scalar approximation method [6] to calculate the scattering coefficient.

\[ \sigma_{pq} = 10 \times \log \left( \frac{S_0}{S_i} \right) \]  \hspace{1cm} (12)

\[ S_2 = S_i \times 10^{\frac{1}{10}\sigma_{pq}} \]  \hspace{1cm} (13)

\[ S_1 = S_0 - L_{df} - L(f_{ob}) \]  \hspace{1cm} (14)

So, the final model is:

\[ S_2 = \left[ S_0 - L_{df} - L(f_{ob}) \right] \times 10^{\frac{1}{10}\sigma_{pq}} \]  \hspace{1cm} (15)

2.5. The maximum number of hops

The model established above can be used to calculate the maximum number of hops in real circumstances. Take the calm ocean for example. Noise is taken into consideration in the study of radio wave propagation. It can be divided into three categories: [7] the noise of electronic equipment itself, Cosmic noise and Atmospheric noise. The noise generated in the process of radio wave propagation relatively has little to do with the cosmic noise, and the noise of electronic equipment itself is also ignored in our model. According to the ITU-R P.372-9 proposal, the galactic noise should be mainly considered in the atmospheric noise at the frequency of 3-30MHz. Therefore, the effective antenna noise of radio wave \( F_a \) can be set at 30 db. When \( SNR=10dB \), the minimum power of the received signal is:

\[ P_e = F_a + B + SNR - 204 \]  \hspace{1cm} (16)
$B$ represents the bandwidth of the receiver’s equivalent noise. Based on practice, we let it equal to 3 kHz.
The transmitted signal power $P$ is 100 W, so:

$$10 \log_{10} \frac{P}{P_0} = 150 \text{ dB} \quad (17)$$

In practical application, the elevation angle ranges from 20 degrees to 60 degrees, and with the increasing of the angle, the propagation loss tend to be larger. Therefore, we set $\theta$ equal to 60 degrees and transmitted signal’s frequency $f$ equal to 10 MHz.

According to the result of propagation loss calculated above, the maximum number of the hops the signal can take is about 2 after calculation. And in different situations, the number can also be 1 or 3.

3. Comparison among sky wave reflection on different surfaces

The feature of sky wave reflection off the calm sea and the turbulent sea is compared. The core of this part is the difference of the scattering coefficient of the turbulent ocean and the calm ocean.

Since root-mean-square height $h_{rms}$ and relevant length $l_x, l_y$ are both only related to $U$ (the speed of the wind):

$$h_{rms} = \frac{\alpha U^2}{4 \beta g_0^2} \quad (18)$$

$$l_x = l_y = \frac{3\pi U^2}{8 g_0^2} \left( \frac{\pi}{2\beta} \right)^{\frac{1}{2}} \approx 0.175 U^2 \quad (19)$$

At the meantime, root-mean-square height and relevant length are related to the scattering coefficient. Therefore, the problem can be simplified as a functional relationship between scattering coefficient and speed of the wind. The turbulent ocean can be explained that the sea surface wind speed is high, while that of the calm ocean is very low approaching zero. As for the relationships among scattering coefficient, incident angle and frequency of incident wave, they are shown in figure 3 and figure 4.

![Figure 3](image)

**Figure 3.** Relationship among $\sigma_{pq}^\theta$, $\theta$ and $f$ (two-dimensional).
To distinguish the turbulent ocean and the calm ocean, we suppose the speed of the wind on the calm ocean is 0.1 m/s, and the speed of the wind on the turbulent ocean is 9 m/s. This allows us to calculate the scattering coefficient of the rough sea surface and the smooth sea surface respectively. The relationships among total propagation loss, incident angle and frequency of incident wave are shown in Figure 5.

4. Conclusion
By using the aforementioned three models, we estimate quantitatively the three parts of the propagation loss and obtain the total propagation loss. Our numerical results indicate that there is a negative correlation between the loss and the incident angle and a positive correlation between the loss and frequency of radio waves.

By the comparison between the results of turbulent ocean and the calm ocean, we conclude that the former generates more losses than the latter, which is consistent with the observations.

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