Research on the Propagation of Electromagnetic Wave over the Horizon in Maritime Communication in the Atmospheric Duct Environment

Liang Chen¹, Yongxing Jin¹, Qinyou Hu¹, Kecheng Tang², Wanming Gao²

¹Shanghai Maritime University
Merchant Marine College
Shanghai, China
²Donghai Navigation Safety Administration MOT
Shanghai, China

Abstract — With the development of science and technology, modern communication and advanced military equipment system increasingly rely on complex communication, electronic equipment and system technology, which require very high demand for broadband communications. Therefore, the propagation characteristic of electromagnetic wave in the marine atmospheric duct environment is researched in this paper. Based on the introduction of the related basic knowledge of radio in atmospheric environment, the reference earth model and atmospheric structure parameters are determined, then the multipath characteristics of the waveguide transmission are analyzed and modeled with the combination of PE theory and related theories, and the loss performance of the low altitude atmospheric duct in horizontal and vertical space is simulated. In addition, the PE method is used to analyze the field distribution of electromagnetic wave propagation in the waveguide, the simulation results show that the PE analysis has a good effect on the high frequency electromagnetic wave over GHz, and the multipath propagation in waveguide has great advantage in long distance communication. The research in this paper gets the constructive and innovative achievements in the establishment of the multipath model, the loss performance and the visual analysis and other aspects.

Keywords - atmospheric duct; ray tracing; PE equation; multipath characteristics; wave loss

I. INTRODUCTION

Modern communications and advanced military systems increasingly rely on sophisticated communications, electronic equipment and systems technology, which puts forward very high demand for broadband communications, so as to ensure that all kinds of sophisticated weapons systems have strong survival and attack capability in the extremely harsh electromagnetic environment. Atmospheric duct is a special structure that often appears in the troposphere, which generates a special gradient structure of the atmospheric refractive index, this structure can make the propagation path of the electromagnetic wave signal of the normal transmission change. These anomalies will lead that the radar appears blind area, and the accuracy and probability of the detection range and target location decrease severely, but it provides possibility for the realization of marine ultra long distance communication. Atmospheric duct can interrupt the normal communication links, but also can realize the microwave over the horizon communication of large capacity information transmission, so the solution of this problem can greatly enhance the capability of the basic communication of our vast coastal areas and territorial seas. In addition, in the modern war, the advantages and disadvantages of the communication system and the electronic countermeasure capability will directly influence the trend of the war, so it is necessary to increase the investment in the field. At present, researchers in the field have carried out a lot of researches, such as the microwave is used to carry out the visual communication technology and other experiments in the wave guide structure caused by the evaporation of the sea. With the further research of the sea waveguide, the application of the electronic system which is suitable for the environmental communication of the ocean waveguide is being carried out in various countries. The innovation of this paper lies in: The plane earth coordinate is creatively used in the research of the waveguide, the simulation and analysis of the multipath arrival angle, time delay spread, reach height and amplitude are carried out, then the multipath model is established, besides, the initial field is derived and set, and the PE method is used to explore the adaptability of different frequencies and beyond horizon problem. In general, the research in this paper gets the constructive and innovative achievements in the establishment of the multipath model, the loss performance and the visual analysis.

II. RESEARCH STATUSES

Atmospheric duct research started in the 1940's, the national laboratory of the United States of America studied the atmospheric duct, and the anomalous atmospheric distribution structure similar to optical waveguides in the sea is discovered through the meteorological experiment of radio wave. In the 1960's, the western researchers carried out a lot of meteorological data collection, and obtained the meteorological statistical parameters of the evaporation duct. In general, the research in this paper gets the forecast of marine atmospheric
duct and the waveguide structure. In this period, the academic circles put forward a lot of atmospheric waveguide models, such as the JESKE model, it has been applied to the United States weather forecast and other systems. Anderson used 3GHz and 18GHz waves to research the evaporation waveguide, and gave the preliminary theory of the propagation mechanism in the evaporation duct (Anderson et al. 1995) [1]. Sirkova carried out the statistical experiment of the prediction of surface waveguide loss in the south of the United States (Sirkova et al. 2003) [2]. Reza carried out the test of 16.65GHz radio propagation characteristics in the Five Great Lakes region of North America (Reza et al. 2005)[3]. All of these studies have proved the feasibility of the signal over the horizon communication in the evaporation duct. Compared with foreign mature research, domestic research started late. The present research scope of China involves three parts: one is the prediction of the atmospheric duct, including the time, the area, and the structural parameters and so on. Two is the influence of the waveguide to the wireless communication, and the transmission law of the signal in the waveguide. Three is the use of radar in the military to search for suspicious targets. Wu Xiaojin researched over the horizon radar and air defense applications (Wu Xiaojin et al. 2002) [4]. Chen Li studied the weather characteristics of the low altitude atmospheric duct in the coastal waters of China (Chen Li et et al. 2010) [5]. These achievements are more in the direction of the mechanism, formation, prediction and improvement of the atmospheric waveguide. The remainder of this paper is organized as follows. Section 3 describes the related theories and key technologies: such as refractive index, ray tracing theory, refraction theory and so on. Section 4 gives the design and construction process of the architecture model of the multipath characteristics of the waveguide transmission. Section 5 presents a real experiment to evaluate the model. Conclusion is summarized in Section 6.

III. KEY TECHNOLOGIES

A. Refractive index and refraction theory

The main factors that affect the structural parameters of the low altitude atmosphere are: air temperature, atmospheric humidity, atmospheric pressure, temperature and latitude, altitude, season and so on. These parameters which are closely related to the atmospheric structure are not only large but also random. From the equator to the poles of the earth, the temperature will decrease with the increase of latitude [6]. Vertical height increases 1000 m, the atmospheric temperature reduces about 6.5 ℃. Over the upper troposphere, the temperature is generally stable. The influence of troposphere atmosphere on the transmission is reflected by the refraction index n. Here refractive index N is introduced. The relationship between refractive index and index n is:

\[ N = (n - 1) \times 10^6 \]  

(1)

The refractive index of troposphere air, which is composed of a variety of dry gas and water vapor, can be expressed as:

\[ N = a \frac{P_d}{T} + b \frac{e}{T} + c \frac{e^2}{T^2} \]  

(2)

Where \( P_d \) is the pressure of dry gas, the unit is mbar. The first item is from the contribution of no water gas, second and third are the water vapor factor. In the range of 40-50℃:

\[ a = 77.6 \]
\[ b = 72 \]
\[ c = 3.75 \times 10^6 \]  

(3)

This parameter is used in the simulation of flat earth reference [7].

\[ M = \left[(n-1) + \frac{b}{a}\right] \times 10^6 = N + 6 \times \frac{h}{a} = N + 157 \times h \]

(4)

In the formula, a is the radius of the earth, h is altitude, the unit is km. The concept corresponding to M is the correct refractive index m, the relationship between m and M can be expressed as the following form:

\[ M = (m - 1) \times 10^6 \]

\[ m = 1 + M \times 10^{-6} = n + \frac{h}{a} \]  

(5)

In this paper, M uses the flat earth system, and N uses the spherical earth system [8].

B. Geometrical optics theory in the study of waveguides

Atmospheric refraction is a common phenomenon in nature, and the atmosphere itself is an inhomogeneous medium. So in the atmosphere, the ray path of the radio wave propagation is not a straight line, but a curve or a combination of many segments of the line approximation. In this theory, the form is as follows:

\[ nr \cos \theta = n_0 r_0 \cos \theta_0 \]  

(6)

In the formula, r0 is the distance from the point of departure to the earth's core, and h0 is the height of the starting point, then \( r = R + h \). \( \theta_0 \) is the angle of the ray starting point and the level of the ground, r is the distance from here to the center of the earth, and \( \theta \) is the tangent angle of the beam to the point [9].

C. Equivalent spherical earth reference system

The air structure that only changes with the height of the vertical is the horizontal layer. The gradient of the refraction index is defined as follows:

\[ \frac{dn}{dh} = g \]  

(7)

For the stratified uniform air structure, the refractive index and refractive index can be expressed as:
In the formula, $n_0$ is the refractive index of the ray emission point, $N_0$ is the refractive index of the ray emission point, and $h$ is the altitude of the point antenna [10]. $G$ can be called the refractive index gradient, the unit is N/km. The relationship between the refractive index gradient $g$ and $G$ is:

$$G = 10^6 g (N/km)$$

Due to the height of the antenna and the signal propagation $h$ is less than the earth's radius $r_0$, so the transmission of the signal can be expressed as:

$$\cos \theta_0 = \left[1 + \left(1 + \frac{g}{n_0} h\right) \right] \cos \theta = \left(1 + \frac{h}{r_0}\right) \cos \theta$$

Where

$$r_e = \frac{1}{1 + \frac{g}{n_0}} = k_e r_0$$

$$k_e = \frac{1}{1 + \frac{g}{n_0} \times r_0}$$

$\theta_0$ is the angle between the ray emission point and the horizontal line, $h$ is the height of the point of the ray (unit: km), $k_e$ is spherical equivalent factor, $r_e$ is the radius of the effective earth surface [11].

D. Equivalent plane of the earth reference system

In order to simplify the study of the characteristics of the radio wave ray, the actual earth can be transformed into a plane reference system in the theory [13]. On the actual earth, when the atmospheric refraction index in the spherical layered structure is uniform, the refractive index $n$ is only related to altitude $h$. Snell's law can be expressed as:

$$n_0 \cos \theta_0 = n(h) \left(1 + \frac{h}{r_0}\right) \cos \theta$$

$$m(z) = n(z) \left(1 + \frac{h}{r_0}\right) \approx n(h) + \frac{h}{r_0}$$

Where $m(z)$ is the modified refraction index which determined by the high degree, $m(0) = n(0) = m_0 = n_0$, so Snell's law is rewritten as:

$$m_0 = \cos \theta_0 = m(z) \cos \theta$$

$$\sin \theta_0 = \frac{1}{\cos \theta_0} = \frac{1}{m_0}$$

$S$ is the actual earth, $S'$ is the equivalent plane earth surface, $S$ and $S'$ is a concentric circle, circle is O. T is the launch point, TG is the horizon, O, T, K are in a straight line, which is perpendicular to TG, the length of TK, namely, the radius difference of the two circle is $h$. P is the intersection of $S'$ and actual ray $TP$, $P'$ is the intersection of $S'$ and equivalent ray $TP'$. The tangent elevation is $\theta_0$. The emission angle of $P$ is $\theta$, the emission angle of $P'$ is the supplementary angle of $\theta'$. The elevation angles of $P$ and $P'$ are equal. The common external tangent of $TP$ and $TP'$ is $TE$. $TE$ is perpendicular to $CC'$. In the flat earth model, the value of the $m$ ($h$) is equal to the refractive index $n$ ($h$) of the layered earth in the real world. So the actual earth is converted into a flat reference system, and the corrected refractive index is used to replace the atmospheric refraction index.

E. Ray tracing theory

The ray tracing and parabolic equation are used to research the atmospheric duct in this paper. The effect of the frequency spectrum is neglected by the approximation of the ray tracing method, and the method is used to abstract the
motion track of a lot of radio rays. This paper sets the frequency is infinite, and the atmospheric density distribution is irregular for the same altitude, the ray method will lead to a longer simulation time, and the superiority of the method will drop. When the frequency is very high, the electric field of the radio signal can be expressed as follows:

$$\vec{E} = \sqrt{\frac{\mu}{\varepsilon} \times \frac{\nabla \Theta}{n}}$$

In the electromagnetism theory:

$$\nabla \Theta \left( \nabla \Theta \times \vec{E} \right) = -n^2 \vec{E}$$

In this paper, the height of the atmospheric parameters is same, that is, n is the same. The atmospheric environment is the only factor that influences the radio wave.

Figure 3 is the pictorial representation tracking techniques of radio wave propagation, the journey of the curve from the starting point to a position is l, and the distance in a very short period of time is ΔL. θ is the angle to the center of the earth. The atmospheric refractive index is n, θs is launching elevation. The refractive index of the new position is n + Δn, θs’ is the launching elevation.

According to the above Figure:

$$ndl = n\sqrt{R^2 \Delta \theta^2 + \Delta R^2} \Rightarrow ndl = \sqrt{R^2 + \frac{\Delta R^2}{\Delta \theta}}$$

It can be obtained by the Fermi principle:

$$\frac{\Delta R}{\Delta \theta} \sqrt{\frac{\Delta R}{\Delta \theta}} \frac{\Delta R}{\Delta \theta} + R^2 \frac{\Delta \theta}{\Delta \theta} = n \sqrt{\frac{\Delta R}{\Delta \theta}} + R^2 = \xi$$

Then

$$nR \sin \theta_s = (n + \Delta n)(\Delta R + R) \sin \theta_s'$$

That is

$$nR \sin \theta_s = (n + \Delta n)(\Delta R + R) \sin(\theta_s + \Delta \theta_s)$$

This is the theoretical premise of the study of atmospheric waveguide with the method of ray.

F. PE parabolic equation

The parabolic equation (PE) method can describe the field distribution and loss model of the whole space of the ocean evaporation duct. The space field of the evaporation duct is expressed as β, and the wave scalar equation of the β is listed under the electromagnetic field theory:

$$\frac{\partial^2 \beta}{\partial x^2} + \frac{\partial^2 \beta}{\partial z^2} + \frac{2\pi fn(x, z)}{c} \beta = 0$$

N(x, z) is the atmospheric refractive index, is the function of the horizontal distance and the vertical height, abbreviated as n. f is the frequency of the radio, C is the speed of light. In order to eliminate the influence of the horizontal phase shift on the radio wave propagation, the phase shift factor can be separated into the following form:

$$u(x, z) = \beta(x, z) \exp \left( -i \frac{2\pi fx}{c} \right)$$

The u(x, z) without the use of phase information is used to replace the β(x, z) to describe the amount of evaporation duct, abbreviated as u. The earth’s radius is much larger than that of the sea wave guide, and the earth model is used to make the earth a flat surface:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} + i2k \frac{\partial u}{\partial x} + k^2 (n-1) u = 0$$

The \( \frac{\partial u}{\partial x} \) can be drawn as follows:

$$\frac{\partial u}{\partial x} = -ik \left( 1 - \frac{1}{\sqrt{k^2 \frac{\partial^2}{\partial z^2} + n^2}} \right) u$$

$$\frac{\partial u}{\partial x} = -ik \left( 1 + \frac{1}{\sqrt{k^2 \frac{\partial^2}{\partial z^2} + n^2}} \right) u$$

When the emission angle is very small, the method can accurately describe the parameters of the waveguide space field if the energy of the backward emission is excluded. Taylor approximation can be replaced by the following:

$$\frac{1}{k^2 \frac{\partial^2}{\partial z^2} + n^2} = \frac{1}{2k^2 \frac{\partial^2}{\partial z^2}} + \frac{n^2 + 1}{2}$$

The scalar equation can be transformed into:

$$\frac{\partial^2 u}{\partial z^2} + i2k \frac{\partial u}{\partial x} + k^2 (n-1) = 0$$

$$\frac{\partial^2 u}{\partial z^2} + \frac{1}{2k^2 \frac{\partial^2}{\partial z^2}} u + \frac{n^2 + 1}{2} = 0$$
IV. MULTIPATH MODEL OF RADIO WAVE PROPAGATION IN OCEAN WAVEGUIDE

A. Ray trace of the propagation of the wave in the sea

In this paper, the waveguide strength is -1M/meters. The 3dB width of the transmitter antenna transmit power is ±0.3 degrees, and the waveguide structure model is used to trace. The premise of low altitude waveguide transmission signal is that the waves are bound by the waveguide, which requires that the launch elevation angle is less than the critical angle. The maximum angle corresponding to the corresponding strength guide can be calculated.

$$s, E_1^2 = s, E_2^2$$  \hspace{1cm} (25)

This paper uses the plane earth reference coordinates, the reflection of the diffusion coefficient of spherical reflection is ignored. Radio wave propagation in space wave has the following equation:

$$\frac{d ln (nE)}{ds} = \frac{1}{n \sqrt{nL_1L_2}}$$  \hspace{1cm} (27)

Where $|E|$ is the integral increase in the wave, $L_1L_2$ is the ray path. In the simulation, the transmission distance is 100 kilometers, the relationship between the absolute value of the signal intensity and the transmission distance is:

$$\zeta = \frac{E_2}{E_1} = \sqrt{s_1 s_2} n_1 n_2$$  \hspace{1cm} (28)

It shows that the distribution information of atmospheric density and the mileage of electric waves will determine the attenuation value of electromagnetic energy expansion [15].

The reflection coefficient model is calculated:

$$Re_{fer} = J_0 \left( -i 8 \pi \frac{x}{\sin \gamma \lambda} \right) e^{-x \sqrt{\frac{\sin^2 \gamma}{\sin \gamma \lambda}} \sqrt{3.2 - 2 + \sqrt{3.2^2 - 2 \gamma + 9}}}$$  \hspace{1cm} (29)

In the formula, $J_0$ is the Bessel function, $\gamma$ is the grazing angle of the ray, and $\lambda$ is the radio wave length. $x$s shows that the model considers the complex sea conditions of wave attenuation. In the simulation, the wave frequency and wind speed are considered, the modified formula is:

$$Re_{fer} = \frac{Re_{fer}}{\sqrt{3.2r - 2 + \sqrt{3.2^2 - 2r + 9}}}$$  \hspace{1cm} (30)

In the formula, $\gamma$ is the grazing angle of electromagnetic wave with respect to the sea, $\beta$ is 0.0051 $v^2$, $v$ is the wind speed (close to sea level). Refers is the water reflection coefficient, in the setting of the 4 wind speed, the parameters are calculated in the following table:

<table>
<thead>
<tr>
<th>wind speed</th>
<th>1m/s</th>
<th>4m/s</th>
<th>7m/s</th>
<th>10m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>0.0051</td>
<td>0.0816</td>
<td>0.2499</td>
<td>0.51</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>2.601e-5</td>
<td>6.6586e-3</td>
<td>0.06245</td>
<td>0.2601</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>9.12741</td>
<td>2336.631</td>
<td>21914.908</td>
<td>91274.10</td>
</tr>
</tbody>
</table>

In conclusion, for the wave propagation in the waveguide, the loss is mainly composed of energy diffusion and sea loss. Simulation results show that the predictability of the signal transmitted in the waveguide structure can be reduced rapidly because of the deterioration of the sea conditions.
C. Simulation of the arrival angle of each radial waveguide

The smaller the angle between the signal relative to the maximum gain direction of the antenna, the greater the gain of the antenna. Figure 5 is the simulation results of the arrival angle:

![Figure 5. Arrival angle of each path and the probability distribution of the arrival angle of the receiver.](image)

In Figure 5, (a) represents the arrival angle of each path at the receiving point, (b) represents the comparison of the evaporation duct receives end angle of arrival probability distribution and approximate normal model. Experimental results show that the distribution of the arrival angle of the electric wave can be approximated by a normal distribution with a variance of 0.0738.

D. Establishment of the multipath propagation model of the offshore evaporation duct

In this paper, the multipath characteristic response of the transmission signal in ocean waveguide is established:

$$ Duct(t) = \sum_{j=0}^{n} \Gamma(\theta_{j,\text{aoa}}, \Psi, \delta) e^{i(n-j)\omega} $$

The physical quantity $\Gamma$ is the gain graph function of receiving antenna in all directions, $E_i$ is the signal amplitude at the receiving antenna interval, $\Psi$ is the wave phase. $\delta$ is the impulse response function. $n$ will increase and decrease with the change of the horizontal distance, vertical height, and antenna type of the receiving antenna, and $n$ is the time function of $t$.

V. Experimental analyses

In this paper, the PE parabolic method is used to simulate the distribution of different frequency electric field. The simulation conditions: the antenna is 10 meters, the distance from the initial field is 50 meters, the height of the evaporation duct is 20 meters, and the waveguide gradient $\Delta M$ is 20. The simulation of the 2 wave frequency is: $f = 300$ MHz, $f = 30$ GHz, the following simulation distance is 100 km, the capture height is 20 m.

![Figure 6. Simulation experiment results.](image)
is not suitable for the description of the waveguide transmission characteristics of low frequency signal.

VI. CONCLUSION

The appearance of atmospheric duct propagation can not only cause the electromagnetic wave to deviate from the original direction of propagation, but also can make the electromagnetic wave propagate along the waveguide to the outside of the line of sight, which seriously affects the radar, communications, reconnaissance and other radio weapon systems based on electromagnetic transmission. How to make full use of atmospheric duct propagation to improve the working efficiency of the electronic system has important theoretical significance and practical value. Therefore, based on the introduction of the related basic knowledge of radio in atmospheric environment, this paper determines the reference earth model and atmospheric structure parameters, and the multipath characteristics of the waveguide transmission are analyzed and modeled with the combination of PE theory and related theories, and the loss performance of the low altitude atmospheric duct in horizontal and vertical space is simulated. In addition, this paper uses the PE method to analyze the field distribution of electromagnetic wave propagation in the waveguide, the simulation results show that the PE analysis has a good effect on the high frequency electromagnetic wave over GHz, and the multipath propagation in waveguide has great advantage in long distance communication. Generally speaking, the innovation of this paper lies in: The plane earth coordinate is creatively used in the research of the waveguide, the simulation and analysis of the multipath arrival angle, time delay spread, reach height and amplitude are carried out. However, there are some shortcomings. This paper doesn’t study the wave phase, emission angle, Doppler Effect of the waveguide, and there is no in-depth study of the performance of various frequency band radio waves in the realization of waveguide communication. These all are very good new directions and it can be explored later.

REFERENCES