# A Study on the Propagation Characteristics of AIS Signals in the Evaporation Duct Environment

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***Abstract*** **─** The propagation characteristics of signal of the Automatic Identification System (AIS) in the evaporation duct environment over the sea surface are investigated by using the parabolic equation method. The parabolic equation method has excellent stability and accuracy in solving the computational problem of electromagnetic wave propagation under different atmospheric conditions and it is probably the most suitable for the purpose of analyzing AIS signals. The propagation of AIS signals in air is determined by the variation of the refractivity with height. For AIS transmission, ducting propagation may be the most important propagation mechanism. The propagation loss of AIS signals in the evaporation duct is calculated and compared with that for the case of the standard atmosphere. In order to demonstrate the effect of evaporation duct on the propagation of AIS signals more intuitively, propagation loss versus range for three typical AIS links and the receiver height versus propagation loss under different atmospheric conditions are analyzed in details. The simulation results show that the evaporation duct has little influence on the AIS system.

***Index Terms*** **─** AIS, evaporation duct, parabolic equation method, propagation loss.

## I. INTRODUCTION

Automatic Identification System (AIS) is a new navigation aid that operates in the Very High Frequency (VHF) maritime mobile band, and its primary purpose is to facilitate the efficient exchange of navigation and voyage data between ships, and between ships and shore stations [1]. As a maritime navigation safety communication system, it can automatically provide vessel information, including the vessel's identity, type, position, course, speed, navigation status and other safety-related information to other ships and to shore stations in its surroundings. It also receives such information from similarly fitted ships and exchanges data with shore-based facilities automatically. When AIS signals propagate over the sea surface, it is easily affected by various atmospheric conditions. At the beginning of this research, only three papers were found to study the effects of atmospheric conditions on AIS signal propagation over the sea environment. A report by the International Telecommunications Union (ITU) examined some general propagation mechanisms that could enhance the shore-based AIS detection range, but ignores atmospheric conditions behind it [2]. Green et al. [3] analyzed phenomena that could theoretically affect the transmission of AIS signals. In their opinion, the parabolic equation method may be the most suitable for predicting the propagation characteristics of AIS signals in atmospheric duct conditions. Bruin [4] studied the impact of North Sea weather conditions on the performance of AIS, and the Advanced Refractive Effects Prediction System (AREPS) was used to calculate the propagation loss and predict AIS coverage.

Over the sea, evaporation duct is the most common type of anomalous propagation [5,6]. The height of the evaporation duct is usually between 6 m and 30 m, and generally no more than 40 m. When radio waves, especially microwaves, travel near the sea surface, they are easily affected by the evaporation duct. Part of energy is trapped in the duct and propagates beyond the line-of-sight, forming a very important evaporation duct propagation mechanism.

Because the evaporation duct has significant influence on the stability of the communication link and

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the accurate estimation of the target position by radar, analysis of the effect of evaporation duct on radio waves has been the focus of attention. By studying the effects of the evaporation duct on the propagation of AIS signals, it is of profound significance to improve maritime situational awareness. At the same time, it also has important application value for the inversion research of atmospheric ducts.

The parabolic equation method is based on a reduction of the Helmholtz equation and it can be implemented to propagation over sea and land. It can accurately predict the propagation characteristics of electromagnetic waves in a complex environment and is commonly used in the study of wave propagation problems [7-9]. In addition, through the marching method, it can use the fast Fourier transforms technique to obtain solutions. For maritime propagation applications, the parabolic equation method can be solved by running on a laptop for a few seconds. To this end, the parabolic equation method is utilized to model the propagation of AIS signals under ducting conditions. The propagation loss of AIS signals in the standard atmosphere and the evaporation duct is calculated and compared.

## II. AUTOMATIC IDENTIFICATION SYSTEM

In 2000, the AIS system was introduced by the International Maritime Organization (IMO) as a part of the Safety of Life at Sea (SOLAS) regulations, which require AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size [10]. International regulations came into full force on December 31, 2004, and this system is known as Class A AIS system. After this date, all ships in service have installed an AIS system must operate it continuously except for international agreements, rules, or standards allow navigational information to be protected. In 2007, Class B AIS system was introduced for small vessels, including pleasure boats. Class A and Class B AIS systems are fully compatible and they can receive and decode each other’s messages. Class A system’s messages generally contain more information than Class B system’s messages. However, they all provide essential safety information. In this paper, we only consider the Class A AIS system.

Two international channels have been allocated for AIS use and both frequencies are in the maritime VHF mobile band [11]. AIS 1 (161.975 MHz) and AIS 2 (162.025 MHz) are designated for long-range AIS systems. At all time, messages can be received on both channels, whilst messages should be transmitted alternately from AIS 1 and AIS 2 channels. Class A AIS system parameters are given in Table 1.

Table 1: AIS system parameters

| Parameter | Value |
|---|---|
| Transmitter Power (W) | 12.5 |
| Frequency (MHz) | 161.975/162.025 |
| Antenna Gain (dBi) | 2~5 |
| Wavelength (m) | 1.86 |
| Receiver Sensitivity (dBW) | –137.0 |

## III. AIS SIGNAL PROPAGATION MODELLING

### A. Atmospheric refractivity model

Evaporation duct is a kind of duct with the highest frequency over the surface of the sea. It is formed by the evaporation of sea surface water vapour, which causes the atmospheric humidity to decrease sharply with height in a small height range. At a certain height, the modified atmospheric refractivity is minimized, which is defined as the evaporation duct height (Fig. 1).

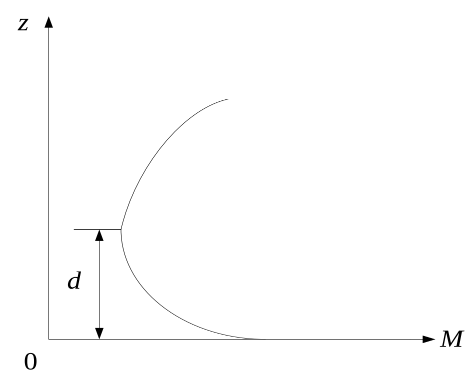


Fig. 1. Modified atmospheric refractivity profile for an evaporation duct.

The evaporation duct is usually described using a logarithmic model, which is defined as [12]:

$$M(z) = M(0) + 0.125z - 0.125d \ln\left(\frac{z + 0.00015}{0.00015}\right), \quad (1)$$

where $M(0) = 339$ is the modified atmospheric refractivity at the sea surface, $z$ is the vertical height, and $d$ is the evaporation duct height.

### B. Parabolic equation method

The two-dimensional Helmholtz equation in Cartesian coordinates is given by [13]:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} + k_0^2 m^2 \phi = 0, \quad (2)$$

where $\phi$ is the electric or magnetic field in the horizontal or vertical polarization, respectively, $x$ is the range and $z$ is the height, $k_0 = 2\pi/\lambda$ is the free space wave number, $\lambda$ is the wavelength, and $m = 1 + M \times 10^{-6}$ is the height and range dependent modified refractive index.

A wave function is introduced to derive the parabolic equation:

$$\phi(\mathrm{x}, z) = u(\mathrm{x}, z) e^{ik_0 x}. \tag{3}$$

Substituting (3) into (2), yields:

$$\frac{\partial^2 u}{\partial x^2} + 2ik_0 \frac{\partial u}{\partial x} + \frac{\partial^2 u}{\partial z^2} + k_0^2 \left(m^2 - 1\right) u = 0. \tag{4}$$

Ignoring backward propagation waves, the standard narrow angle parabolic equation (SPE) can be written as:

$$\frac{\partial u(x,z)}{\partial x} = \frac{ik_0}{2} \left[ \frac{1}{k_0^2} \frac{\partial^2}{\partial z^2} + m^2 - 1 \right] u(x,z). \tag{5}$$

The split-step Fourier transform solution of the SPE is given by:

$$u(x_0 + \Delta x, z) = \exp\left( ik_0 \left(m^2 - 1\right) \frac{\Delta x}{2} \right) \bullet \mathrm{F}^{-1} \left( \exp\left( -ip^2 \frac{\Delta x}{2k_0} \right) \mathrm{F}\left( u(x_0, z) \right) \right), \tag{6}$$

where F and $\mathrm{F}^{-1}$ represent the forward and inverse Fourier transforms respectively, $p = k_0 \sin\theta$ with $\theta$ being the propagation angle referenced from the paraxial direction, $\Delta x$ is the range step, and $u(x_0, z)$ is the initial field distribution.

Split-step Fourier transform method is a stepping algorithm that calculates the field distribution of the next step based on the field distribution of the previous step. Given the initial field distribution $u(x_0, z)$, $u(x_0 + \Delta x, z)$ can be calculated using the split-step Fourier transform method. Thus, all numerical solutions can be determined by an iterative process.

It should be noted that in order to ensure accuracy of the SPE solution, propagation angles should be less than 15˚. For maritime evaporation duct propagation, the propagation elevation angle of electromagnetic waves is generally less than 1˚. Thus, the SPE is chosen to model the propagation characteristics of AIS signals in the atmospheric duct environment.

### C. AIS signal model

Since AIS is a one-way communication system, according to the radio wave propagation theory, received AIS signal level is [4]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} F^2, \tag{7}$$

where $P_t$ is the transmitted power, $G_t$ is the gain of the transmitter antenna, $G_r$ is the gain of the receiver antenna, $\lambda$ is the wavelength, $R$ is the distance from the transmitter to the receiver, and $F = \sqrt{x}\left|u(x,z)\right|$ is the propagation factor.

The propagation loss $PL$ of AIS signals is defined as [14]:

$$PL = 20\log\left(\frac{4\pi R}{\lambda}\right) - 20\log(F). \tag{8}$$

### D. Rough sea surface effect

A flat sea surface is usually used in electromagnetic waves propagation modeling. However, in reality this is not the truth [15,16]. Since the wavelength of the AIS signal is 1.86 m, which is of the same order as the root mean square sea height variations under strong wind, the influence of sea surface roughness must be taken into account. Therefore, the effective reflection coefficient $\Gamma_{eff}$ is introduced to account for the rough sea surface effect, which is defined as [17]:

$$\Gamma_{eff} = \rho\Gamma_e, \tag{9}$$

where $\Gamma_e$ is the reflection coefficient of a flat sea surface, $\rho$ is the roughness reduction factor, which is defined as:

$$\rho = \exp\left(-\frac{\gamma^2}{2}\right) I_0\left(\frac{\gamma^2}{2}\right), \tag{10}$$

where $I_0$ is the modified Bessel function of the first kind of order zero, $\gamma$ is the Rayleigh roughness parameter, which is defined as:

$$\gamma = 4\pi\sigma \sin\alpha / \lambda, \tag{11}$$

where $\sigma = 0.0051\omega^2$ is the root mean square sea height, $\omega$ is the wind speed, $\alpha$ is the grazing incidence angle, and $\lambda$ is the wavelength.

## IV. NUMERICAL SIMULATION AND DISCUSSION

### A. Comparison of propagation loss pattern

In this section, we present the simulation results of the propagation loss of AIS signals under different atmospheric conditions. The simulation parameters are: the AIS signal frequency is 162 MHz, the transmitter antenna is an omnidirectional antenna with a height of 10 m, the elevation angle is 0˚, and vertical polarization is adopted. Figure 2 contains the propagation loss for the standard atmosphere generated with the parabolic equation method. Figure 3 contains the propagation loss results for an ideal 30 m evaporation duct with the same simulation parameters.

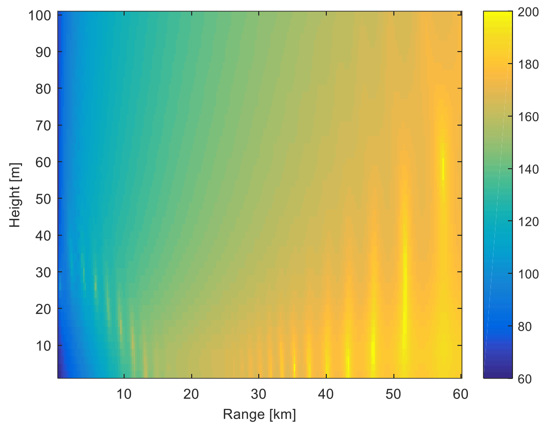


Fig. 2. Propagation loss for the standard atmosphere.

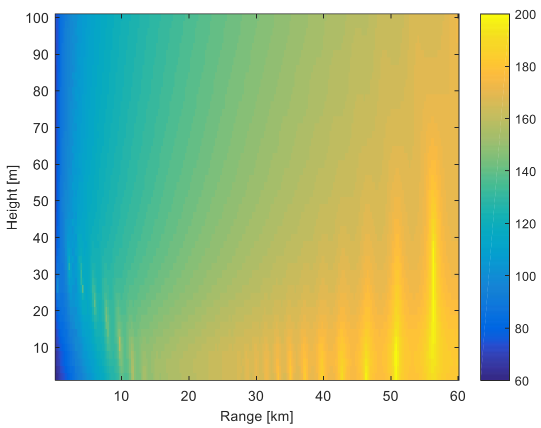


Fig. 3. Propagation loss for an ideal 30 m evaporation duct.

Comparing Fig. 2 with Fig. 3, we can see that the propagation loss pattern of the evaporation duct and the standard atmosphere are basically the same, indicating that the evaporation duct has almost no effect on the propagation of AIS signals.

## B. Propagation loss versus range for three types of AIS links

In order to better reveal the influence of the evaporation duct on the propagation of the AIS signal, propagation loss at different duct height is given. Figure 4 shows propagation loss versus range for the AIS ship-to-ship link under the standard atmosphere and the 5 m, 15 m, 25 m, and 35 m height evaporation duct conditions. The receiver is located 10 m above mean sea level, which is a typical ship antenna height.

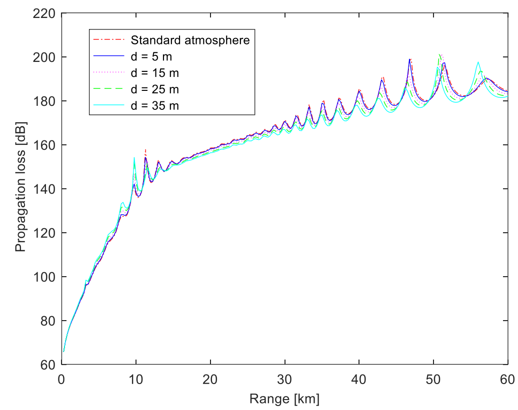


Fig. 4. Propagation loss under different evaporation duct height conditions at a receiver height of 10 m.

As can be seen from Fig. 4, as the distance increases, the propagation loss gradually increases. However, although the propagation loss generally decreases slightly as the height of the evaporation duct increases, the propagation loss curve is basically coincident with the propagation loss curve under standard atmospheric conditions, indicating that the evaporation duct has little effect on the propagation of the AIS signal.

For the AIS ship-to-shore link, the shore station usually has high antenna, typically 30 m. Figure 5 shows propagation loss versus range for the AIS ship-to-shore link under the standard atmosphere and different evaporation duct conditions.

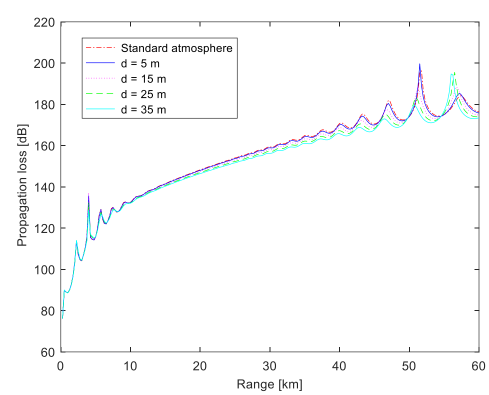


Fig. 5. Propagation loss under different evaporation duct height conditions at a receiver height of 30 m.

As noticed from Fig. 5, although the propagation loss is smaller than that of Fig. 4, the overall variation trend is consistent with Fig. 4, which indicates that the evaporation duct has little effect on the AIS ship-to-shore link.

In addition to ship-to-ship link and ship-to-shore link, AIS receivers can also be installed on weather buoys throughout many coastal areas to form ship-to-weather buoy link. However, as the size of the weather buoy is much smaller, it can significantly limit the antenna height, which is typically 3 m. Propagation loss versus range for the AIS ship-to-weather buoy link under the standard atmosphere and different evaporation duct conditions is shown in Fig. 6.

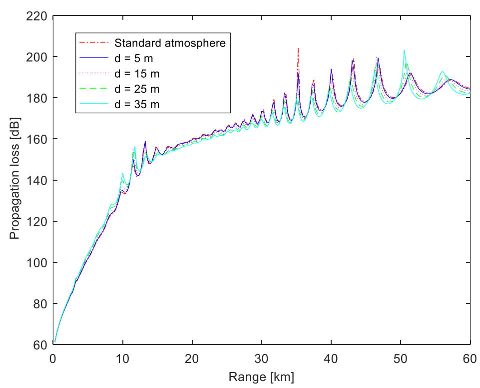


Fig. 6. Propagation loss under different evaporation duct height conditions at a receiver height of 3 m.

Compared with Fig. 4 and Fig. 5, since the receiving height is relatively low, the propagation loss is relatively large. Like the ship-to-ship link and the ship-to-shore link, the propagation loss curves in different atmospheric environments are basically coincident, indicating that the ship-to-weather buoy link is also less affected by the evaporation duct.

### C. Receiver height versus propagation loss for AIS

Figure 7 shows the receiver height versus propagation loss at 20 km distance for a standard atmosphere and evaporation duct height of 5 m, 15 m, 25 m, and 35 m.

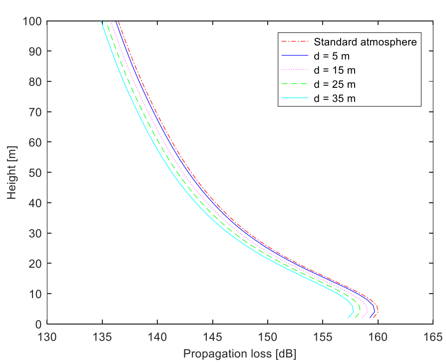


Fig. 7. Propagation loss under different evaporation duct height conditions at 20km distance.

It can be observed in Fig. 7 that as the height increases, the propagation loss first increases and then decreases, which is caused by diffraction mode propagation effect. In general, propagation loss under evaporation duct conditions is slightly reduced compared to the standard atmosphere, and the loss is also smaller as the duct height increases. However, the propagation loss of the standard atmosphere and the evaporation duct are almost the same, indicating that the evaporation duct has a certain influence on the propagation of the AIS signal, but it is very small.

## V. CONCLUSION

In this work, the parabolic equation method is utilized to study the propagation characteristics of AIS signals in the evaporation duct environment over the sea surface. The propagation loss for the standard atmosphere and the evaporation duct is calculated and compared. The simulation results show that the propagation of AIS signals is hardly affected by the evaporation duct. It should be noted that this work mainly theoretically analyzes the problem of AIS signals propagation in the evaporation duct condition, and the simulation results need to be further verified by experiments, which will be investigated in the near future.

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