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Original Paper

Atmospheric Ducts Inversion with Over-the-Horizon Propagation of Automatic Identification System Signals

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ABSTRACT

Automatic identification system (AIS) is a maritime navigation safety communication system that operates in the very high frequency (VHF) mobile band and was developed primarily for collision avoidance. Since the height of the antenna cannot be extended indefinitely, communication distance of the AIS is usually within the horizon. However, with the increasing importance of the AIS traffic, this line-of-sight propagation mechanism cannot meet the need to monitor shipping at a longer distance. When AIS signal is propagating in the atmospheric duct, the trapping effect allows it to propagate over-the-horizon. In this work, the parabolic equation method is utilized to calculate the propagation loss of AIS signals in ducting channel and the simulation results show that AIS can perform over-the-horizon propagation. In order to obtain the distribution of atmospheric refractivity profile over the sea surface, a new inversion method based on the AIS signal level is proposed. The particle swarm optimization (PSO) algorithm is selected to minimize the objective function for obtaining the atmospheric refractivity profile in the maritime environment. Numerical simulations are presented to validate this method for refractivity profile estimation, which provides a theoretical basis and effective

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support for the applications of over-the-horizon communication and radar over-the-horizon detection.

Keywords: Atmospheric Ducts Inversion, Atmospheric Duct, Automatic Identification System.

1 Introduction

Automatic identification system (AIS) is a new type of marine navigation equipment that operates in the VHF mobile band, mainly used in ship safety navigation and communication between ships, and between ships and shore stations [4]. As AIS is normally governed by the line-of-sight propagation mechanism, the maximum communication range of AIS is about 20 NM, depending on antenna height above mean sea level. However, this cannot meet the need to monitor shipping at longer distance because of the increasing importance of the AIS traffic. When AIS signals propagate over the sea surface, the propagation path of AIS signals will be influenced by the atmospheric conditions. Because of the widespread existence of various types of atmospheric ducts over the sea surface, when the AIS signal is trapped in the duct layer, its propagation loss falls off with distance much less rapidly, thus leads to propagation of AIS signals over very long distances to extend the communication range of the AIS. The International Telecommunication Union (ITU) has studied the effect of some propagation mechanisms of AIS and analysed the reasons for extended detection ranges, but the effects of atmospheric conditions are ignored [20]. AIS is also utilized to monitor coastal vessels [21]. According to their results, the detection range of AIS could reach several hundred kilometres in ducts propagation, and surface ducts propagation may be the best choice. Factors that influence AIS performances in maritime propagation were theoretically analysed, and ducts resulting from the varying refractivity of air was determined to most likely extend the range of AIS transmission [9]. The impact of North Sea weather on AIS and coastal radar wave propagation was examined and the Advanced Refractive Effects Prediction System (AREPS) was used to predict coverage and propagation loss for both AIS and coastal radar [1]. According to their results, elevated ducts and surface ducts could extend both AIS and radar detection ranges, whereas evaporation ducts only to extend radar detection ranges. Minimum detection ranges were achieved under standard atmospheric conditions for both systems. To this end, the ducting layer is a promising propagation medium for over-the-horizon applications of AIS.

Automatic identification system is not just highly reliable in communications, but also less affected by meteorological conditions and sea surface conditions. As a new maritime communication technology, AIS not only have a wide range of application prospects, but it also enables the exchange of information between ships into a new era of digital communications. The use of existing information resources and technologies will be an important means to improve and enhance the communications capabilities of AIS. Therefore, it is important to study the propagation characteristics of AIS signals under different atmospheric conditions.

There are many ways to calculate the propagation loss of radio waves [5, 13], but for the purpose of analysing AIS signals, only the parabolic equation method is considered in this work. The parabolic equation method is a result of the paraxial approximation of the electromagnetic wave Helmholtz equation. It can not only model complex boundary conditions and horizontal inhomogeneous atmospheric environment, but also the solution method based on the split-step Fourier transform (SSFT) is very simple, and it has good stability and accuracy, so it is widely applied to electromagnetic wave propagation problems under atmospheric duct conditions [2]. Therefore, the parabolic equation method is utilized to calculate the propagation loss of AIS signals in ducting channels.

For the over-the-horizon communication application of AIS, it is critical to obtain the current refractivity profile of atmospheric ducts over the sea surface. Refractivity from clutter (RFC) techniques estimate the lower atmospheric refractivity structure by using sea clutter return and find the refractivity profile associated with the best modelled clutter match to the observed clutter power [10, 11, 23]. Although RFC has some advantages, it actually has the following limitations: In order to estimate the refractivity structure, radar need to transmit high power signals for active detection, which easily interferes with the normal operation of electronic equipment in the relevant area. In addition, the uncertainty of the normalized radar cross section of the sea surface will severely limit the accuracy of the inversion. Therefore, referring to the idea of RFC, this article proposes a new refractivity estimation method based on the AIS signal level. Using existing shipboard and shore-based AIS equipment and AIS networks not only does not require an increase in the burden on ships, but also has good security performance. It can accurately and efficiently invert the distribution of atmospheric ducts over the entire sea surface.

In this work, the parabolic equation method is utilized to calculate the propagation loss of AIS signals under various atmospheric ducting conditions, and verify the possibility of AIS for over-the-horizon communication. Thus, areas of reliable AIS coverage can be predicted based on current atmospheric conditions. Using knowledge of the reliable AIS reception, surveillance officers can recognize the area that broadcast AIS messages are being received reliably and whether broadcasting ships in the area will be identified using AIS or not. Thereby, surveillance officer's situation awareness and the safety and security within the area are strongly increased. In addition, an atmospheric refractivity inversion method based on the AIS signal level is proposed, and a specific inversion flow is given. Since AIS is a one-way communication system, unlike the RFC inversion technique, this new inversion method does not need to consider backscatter from the sea surface. Thereby, complexities associated with uncertainties in surface reflection coefficients are removed. Through this method, the distribution of atmospheric ducts over the sea surface can be constructed more accurately, which provides a theoretical basis and effective support for the applications of over-the-horizon communication and radar over-the-horizon detection.

2 Automatic Identification System and Atmospheric Ducts

2.1 Automatic Identification System

In 2000, as a part of the Safety Of Life At Sea (SOLAS) regulations [16], the International Maritime Organization (IMO) 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. It came into full force on December 31, 2004, and this system is known as Class A AIS, which 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. In 2007, Class B AIS was introduced for small vessels, including pleasure boats. Class B messages generally contain less information than Class A messages. However, they all provide essential safety information.

The main function of AIS is to achieve collision avoidance by using Self-Organization Time-Division Multiple Access (SOTDMA) technology for effective communication between ships, and between ships and shore stations. Two international channels have been allocated for AIS use and both frequencies are in the maritime VHF band. The general parameters for Class A and Class B AIS are provided in Table 1 [14].

Table 1: General AIS parameter values for both classes.

Characteristic	Class A AIS	Class B AIS
Power (W)	12.5	2
Frequency (MHz)	161.975/162.025	161.975/162.025
Antenna gain (dBi)	2∼5	2∼5
System loss (dB)	3.6	3.6
Receiver sensitivity (dBW)	−137	−137

2.2 Atmospheric Duct

Atmospheric duct is an anomalous propagation phenomenon that is caused by abnormal atmospheric conditions, such as temperature rises with altitude and forms an atmospheric inversion layer or water vapour density decreases rapidly with height to form an atmospheric moisture reduction layer. It can occur for days or weeks at a time. The formation and properties of atmospheric ducts depend on the refractivity (N). Refractivity is defined by [15]:

$$N = (n - 1) \times 10^6 \tag{1}$$

where n is the refractivity index.

In order to take into account the influence of the curvature of the earth, the modified refractivity (M) is introduced and defined as:

$$M = N + \left(\frac{z}{R_0}\right) \times 10^6 = N + 0.157z \tag{2}$$

where $R_0 = 6370$ km is the radius of the earth, and z is the height above sea level in m.

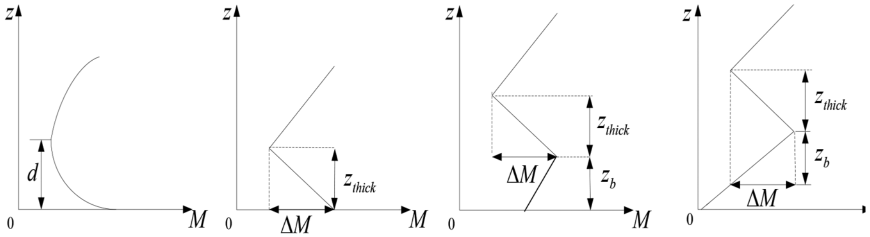
According to the distribution of the atmospheric refractivity structure, there are generally four atmospheric refraction types: sub-refraction, normal refraction, super refraction and trapping (ducting), which are stated in Table 2.

Table 2: Atmospheric refraction types and formation conditions.

Refraction types	$dN/dz(\mathrm{m}^{-1})$	$dM/dz(\mathrm{m}^{-1})$
Sub-refraction	>0	>0.157
Normal refraction	$-0.079 \sim 0$	$0.079 \sim 0.157$
Super refraction	$-0.157 \sim -0.079$	$0 \sim 0.079$
Trapping (Ducting)	< -0.157	<0

The propagation characteristics of electromagnetic waves in the troposphere mainly depend on the modified refractivity gradient (dM/dz). When the modified refractivity gradient dM/dz is less than zero, the curvature of the electromagnetic wave propagation path will exceed the curvature of the earth's surface, that is, there is an atmospheric duct phenomenon. Four kinds of ducts usually appear in the lower atmosphere: evaporation duct, standard surface duct, surface-based duct, and elevated duct, which are presented in Figure 1.

Since evaporation ducts have little effect on AIS transmission, this paper only considers surface ducts. As in Figure 1c, the modified refractivity profile



(a) Evaporation duct **(b)** Standard surface duct **(c)** Surface-based duct **(d)** Elevated duct

Figure 1: Modified refractivity profiles of atmospheric ducts.

of surface-based ducts can be modeled with a tri-linear curve [22]:

$$M(z) = M_0 + \begin{cases} c_1 z & z \le z_b \\ c_1 z_b - \Delta M \frac{z - z_b}{z_{thick}} & z_b < z < z_b + z_{thick} \\ c_1 z_b - \Delta M + c_2 (z - z_b - z_{thick}) & z \ge z_b + z_{thick} \end{cases} \tag{3}$$

where $M(z)$ is the modified refractivity, M_0 is the value of modified refractivity at the sea level surface, z is the vertical height, z_b is the base height, z_{thick} is the duct layer thickness, and ΔM is the duct strength, c_1 is the slope of the duct bottom layer and $c_2 = 0.118$ is the slope of the duct top layer. When the base height z_b is zero, Eq. (3) can be used to model the modified refractivity profile of standard surface duct in Figure 1b.

3 Ducting Channel Modelling and a New Inversion Method

As a kind of widely used maritime surveillance and communication equipment and technology, it is necessary to study the influence of environment on the propagation of AIS. Generally speaking, AIS can only perform line-of-light propagation due to the influence of the transmission path, which greatly limits the effectiveness of AIS. However, when there is atmospheric duct over the sea surface, electromagnetic wave will be trapped in the duct layer, and the propagation loss will be greatly reduced, making it possible to perform over-the-horizon propagation [6]. The AIS signal power carries the atmospheric duct environment information along the propagation path, so it can be used to invert the atmospheric modified refractivity profile.

3.1 Parabolic Equation Method

The propagation of electromagnetic waves under atmospheric duct conditions depends on many factors: antenna height, duct height, duct strength, carrier frequency, polarization, and sea surface conditions, and the parabolic equation method can take all of these factors into considerations [7]. The solution of the parabolic equation method can be achieved by a marching technique for Fast Fourier transform technique, and can be implemented on a personal computer in seconds for propagation over a sea surface. For the purpose of analysing the propagation of AIS signals under atmospheric duct conditions, the parabolic equation method may be the best choice. Therefore, the parabolic equation method is utilized to calculate the propagation loss of AIS signals in ducting channel.

In the study of electromagnetic wave propagation in troposphere, the forward narrow-angle parabolic equation is usually adopted. Ignoring backscattering effect of electromagnetic waves, the standard parabolic equation (SPE) is defined as [18]:

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

where $u\left(x,z\right)$ is the reduced function, x is the horizontal range, $k_0=2\pi/\lambda$ is the free-space wave number, λ is the wavelength, $m\left(x,z\right)=1+M\times 10^{-6}$ is the range and height dependent modified atmospheric refractive index.

$u\left(x,z\right)$ can be solved by the split-step Fourier transform method [2]:

$$\begin{aligned} u\left(x,z\right)=\exp&\left(ik_0\left(m^2\left(x,z\right)-1\right)\frac{\left(x-x_0\right)}{2}\right)\\ &\times\Im^{-1}\left[\exp\left(-ip^2\frac{\left(x-x_0\right)}{2k_0}\right)\Im\left(u\left(x_0,z\right)\right)\right] \end{aligned} \tag{5}$$

where $u\left(x_0,z\right)$ is the initial field, $p=k_0\sin\theta$ is the transform variable and θ is the angle from the horizontal. $\Im$ and $\Im^{-1}$ are the Fourier transform and the inverse Fourier transform, respectively.

3.2 Propagation Loss Model

Since AIS is a one-way communication system, it does not need to consider the target echo signal, thus the received signal power is [1]:

$$P_r=\frac{P_tG_tG_r\lambda^2}{\left(4\pi R\right)^2}F^2 \tag{6}$$

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, R is the path length, $F=\sqrt{x}\left|u\left(x,z\right)\right|$ is the propagation factor.

Propagation loss can be expressed as [19]:

$$PL=\frac{\left(4\pi R\right)^2}{\lambda^2}\frac{1}{F^2} \tag{7}$$

Therefore, the propagation loss of AIS signals can be expressed in dB by:

$$PL(x,\mathbf{m}) = 20\log\left(4\pi\right) + 10\log(x) - 20\log(\lambda) - 20\log\left(\left|u\left(x,z\right)\right|\right) \tag{8}$$

where x is the range from the transmitter to the receiver, $\mathbf{m}$ is the unknown environmental parameter vector, λ is the wavelength of AIS signals.

Therefore, the received AIS signal power can be expressed in dB by:

$$P_r = C - PL(x,\mathbf{m}) \tag{9}$$

where C is a constant related to AIS.

3.3 Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) algorithm is a global optimization algorithm proposed by Kennedy and Eberhart, inspired by the foraging process of birds [8, 12, 17]. It is an efficient optimization algorithm based on swarm intelligence. The basic principle of the PSO algorithm is that every particle (bird) in the solution space has direction and speed, and each adjusts its flight direction according to its own experience and the current optimal value of the entire population, thus gradually bringing the whole population closer to the global optimal value.

At time t, the position of the i-th particle in the search space can be expressed as [3]:

$$X_i(t) = \left(x_{i1}\left(t\right), x_{i2}\left(t\right), \cdots, x_{iD}\left(t\right)\right) \tag{10}$$

where D is the dimension of the particle, $i = 1, 2, \ldots, K$, K is the number of particles in the population.

The individual optimal position experienced by each particle can be expressed as:

$$P_{best_i}(t) = (P_{best_{i1}}(t), P_{best_{i2}}(t), \ldots, P_{best_{iD}}(t)) \tag{11}$$

The globally optimal position experienced by all particles in a population can be expressed as:

$$g_{best_i}(t) = (g_{best_{i1}}(t), g_{best_{i2}}(t), \ldots, g_{best_{iD}}(t)) \tag{12}$$

In order to ensure the convergence of the PSO algorithm, each particle must converge to the local attractor $q_{ij}\left(t\right)$ according to the analysis of the particle trajectory in the population:

$$q_{ij}(t) = \varphi_j p_{best_{ij}}\left(t\right) + \left(1 - \varphi_j\right) g_{best_{ij}}\left(t\right), j = 1, 2, \cdots, D \tag{13}$$

where $\varphi_j = k_1 r_{1j}/(k_1 r_{1j} + k_2 r_{2j})$, r_{1j} and r_{2j} are random numbers uniformly distributed over the interval $(0, 1)$, and k_1 and k_2 represent learning factors.

3.4 A New Inversion Method Based on the AIS Signal Level

In order to perform over-the-horizon propagation, it is necessary to obtain information of the atmospheric duct characteristic parameters. At present, sea clutter power received by radar is mainly used to invert the refractivity distribution of atmospheric ducts (RFC). RFC fit the sea clutter power calculated by the parabolic equation method with the actual received sea clutter power, and finally obtain the optimum modified refractivity profile under the corresponding conditions. Although RFC has certain advantages, it has the following limitations: The currently used sea surface reflectivity models are not precise enough, which will seriously limit the accuracy of the inversion. When sea surface and weather (volume) clutter is hard to separate such as in precipitation, the shortcoming of the current RFC approaches is evident.

However, if the AIS signal level is used for atmospheric duct inversion, these problems do not exist. Unlike RFC approaches, the inversion method based on the AIS signal level uses one-way propagation loss. No additional equipment is needed, the cost is lower, and it is convenient to operate. Referring to the idea of RFC, this paper proposes a new inversion method based on the AIS signal level to improve the accuracy of inverting the modified refractivity profile. The inversion step is as follows:

(1) Obtain the observed propagation loss PL^{obs} when receiving AIS signals from a ship.

(2) Choose the appropriate atmospheric modified refractivity profile model. Evaporation duct has little influence on AIS signal propagation characteristics, so it is impossible to invert evaporation duct using AIS. Therefore, only surface ducts are considered, which can be modeled use Eq. (3).

(3) According to the modified refractivity profile model, use the parabolic equation method to calculate the simulated propagation loss $PL(x, \mathbf{m})$.

(4) The objective function is $f = \min \left| PL(x, \mathbf{m}) - PL^{obs} \right|$.

Using the global optimization algorithm, the atmospheric modified refractivity profile at the time of the best fitting is obtained from the objective function (f) determined in step (4), that is, it is regarded as the true atmospheric modified refractivity profile.

4 Results and Discussion

4.1 Calculation of the Propagation Loss

Because the transmitter and receiver of AIS system will always be located close to the earth, thus the elevated duct is not important. In this section, simulation results of the propagation loss of AIS signals under surface-based duct condition is presented. For comparison, Figure 2 depicts the propagation loss in standard atmosphere. AIS parameters are: the transmitting frequency is 162 MHz, the antenna type is omnidirectional antenna and the antenna height is 39.8 m, and the vertical polarization is adopted. As in the Figure 2, standard atmosphere does not meet the trapping condition, so AIS signals can only perform line-of-sight communication.

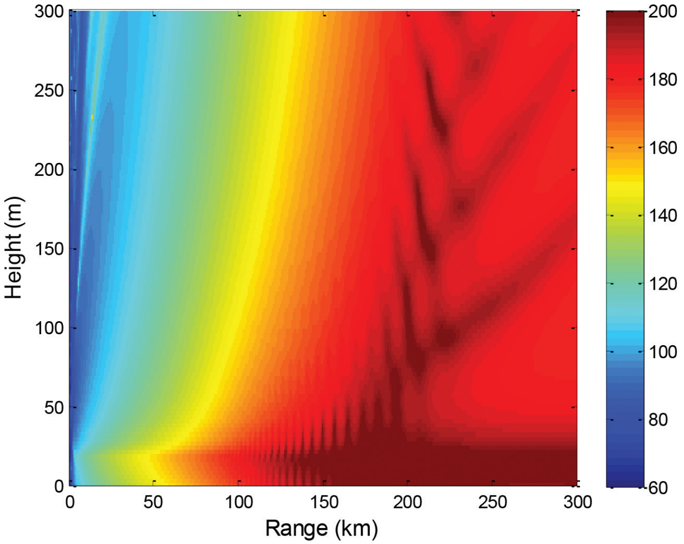


Figure 2: Propagation loss in standard atmosphere.

Figure 3 depicts the propagation loss of AIS signals for a surface-based duct with $c_1 = 0.118$, $z_b = 100\,\mathrm{m}$, $z_{thick} = 50\,\mathrm{m}$, $\Delta M = 30\,$M-units. Compared to standard atmosphere, the propagation loss of AIS signals under surface-based duct condition is significantly smaller, which can greatly extend the transmission distance of AIS signals, sometimes at distances of hundreds of kilometres.

Therefore, when there is an atmospheric duct phenomenon over the sea surface, the trapping effect can greatly enhance the transmission range of AIS signals, even at distances of several hundred kilometres. Therefore, over-the-horizon communication between ships and shore stations can be achieved under atmospheric ducting conditions. In addition, the long range AIS detection reliance on atmospheric duct propagation conditions also can be a useful supplement to normal shore-based AIS detection, thus meet the need to monitor shipping at longer distances which cannot be achieved via conventional propagation mechanisms.

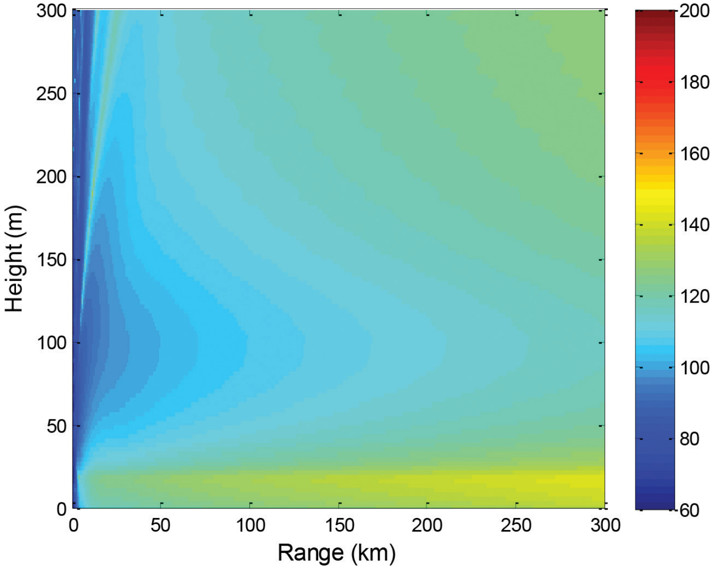


Figure 3: Propagation loss for a surface-based duct.

4.2 Inversion of Surface-based Ducts

In this section, inversion of surface-based ducts using the AIS signal level is investigated, and the PSO algorithm is selected to minimize the objective function for obtaining the best atmospheric modified refractivity profile. For the surface-based duct, there are four-parameters $\mathbf{m} = (c_1, z_b, z_{thick}, \Delta M)$ need to be estimated. AIS parameters are the same as those of the simulation for the propagation loss of AIS signals and the simulated surface-based duct parameters are chosen as $\mathbf{m} = (0.118, 100, 50, 30)$. Propagation losses between 10 and 50 km with 1 point every 250 m at a receiver height of 10 m calculated using Eq. (8) is used to invert the atmospheric duct. The control parameters of PSO algorithm for the surface-based duct inversion are given as follows: the number of iteration is 30, the population size is 50, and the learning factor is 1.49445. The linear decreasing weight strategy is adopted, and the value of inertia weight decreases from 0.9 to 0.4. Figure 4 gives the simulated modified refractivity profile and the inverted profile. For comparison, inversion result of the genetic algorithm (GA) is also given [24].

It can be seen from Figure 4 that compared with the genetic algorithm, the atmospheric refractivity profile obtained by the PSO algorithm is closer to the true profile, indicating that the PSO algorithm has better inversion performance. Inversion results show that the inversion method based on the

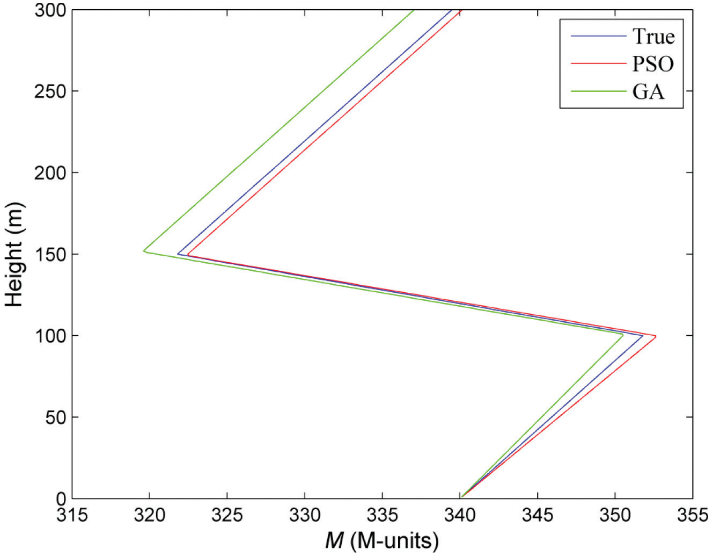


Figure 4: The simulated and inverted refractivity profile of the surface-based duct.

AIS signal level is feasible to invert atmospheric ducts accurately, and can provide effective data support for improving efficient application of AIS.

5 Conclusion

In this work, the propagation characteristics of AIS signals under atmospheric duct conditions are investigated, and the parabolic equation method is used to calculate the propagation loss of AIS signals in ducting channel. Simulation results show that the propagation loss of AIS signals under surface-based duct condition is greatly reduced and the transmission distance is greatly extended. This verifies the possibility of AIS for realizing over-the-horizon communication, thus meet the need to monitor shipping at a longer distance. In addition, a new inversion method based on the AIS signal level is proposed, and simulation results validated its accuracy, which allows the ship to obtain the distribution of atmospheric ducts over the entire sea without adding any additional equipment. And it also has real-time performance, which provides strong support for the over-the-horizon propagation of AIS and other radio systems. However, an important topic that needs to be addressed more extensively is the validation of results that obtained with this study for AIS. In the future investigation, the method proposed in this work will be further verified and improved through more experiments.

Acknowledgement

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