Beyond-Line-of-Sight Communications with Ducting Layer

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ABSTRACT

Near-surface wave propagation at microwave frequencies, especially 2 GHz and above, shows significant dependence on atmospheric ducts that are the layer in which rapid decrease in the refractive index occurs. The propagating signals in the atmospheric ducts are trapped between the ducting layer and the sea surface, so that the power of the propagating signals do not spread isotropically through the atmosphere. As a result, these signals have low path loss and can travel over the horizon. Since atmospheric ducts are nearly permanent in maritime and coastal environments, ducting layer communication is a promising method for b-LoS communications especially in naval communications. To this end, we overview the characteristics and the channel modeling approaches for ducting layer communications by outlining possible open research areas. In addition, we review the possible utilization of the ducting layer in network-centric operations to empower decision making for the b-LoS operations.

INTRODUCTION

Atmospheric ducts that are caused by rapid decrease in the refractive index of the lower atmosphere have tremendous effects on the near-surface wave propagation. In the presence of atmospheric ducts, the signals below the atmospheric duct are trapped between the sea surface and the duct. Therefore, the signals do not spread isotropically through the atmosphere. Instead, the signals spread mostly in the ducting layer, which is the area between the sea surface and the duct (Fig. 1). As a result, the spreading loss decreases considerably compared to the standard atmosphere, and there is a significant amount of increase in the received signal power. In this way, the trapped signals can travel over the horizon, making the ducting layer convenient for beyond-line-of-sight (b-LoS) communications.

The formation of atmospheric ducts entirely depends on the refractivity of the lower atmosphere, which is determined by atmospheric parameters such as wind, pressure, temperature, and, most important, humidity, the key and essential factor in duct formation, as further discussed later [1]. Experimental studies also show that atmospheric ducts are nearly permanent in the coastal and maritime environments due to high evaporation rates. As a result, the ducting layer communication becomes the dominant propagation mechanism at the lower troposphere, especially between 2 and 20 GHz. Since the transmitter and receiver antennas should be located within the ducting layer and this mechanism is effective at the lower troposphere, naval communications can especially utilize b-LoS communications with the ducting layer.

Ducting layer studies mainly focus on refractivity estimation techniques and radar path loss calculations [1, 2]. However, there are a few studies that focus on the utilization of the atmospheric ducts as a communication medium. To this end, [3] provides a high-data-rate employment of the evaporation ducts for b-LoS sensor networks, where continuous satellite communication is expensive and high data rate cellular communication is unavailable. In [3], the ducting layer is utilized to monitor a reef site in the Great Barrier Reef of Australia. According to their results, the atmospheric ducts can connect a 78 km link at 10.5 GHz with 10 Mb/s 80 percent of the time. Based on the available experimental results and our reviews, in particular, state-of-the-art military systems can connect distances up to 500–1000 km with the ducting layer.

Modern naval b-LoS communications can utilize either high frequency (HF) radio systems, which are band-limited, to support high data rates; satellites, which are prone to hostile jamming and have high transmission delays; or relay nodes, which can be exposed to hostile attacks. There is a significant need for a direct transmission channel between b-LoS units to empower strategical and tactical decisions in network-centric operations (NCO). To this end, the ducting layer is a promising communication medium for b-LoS applications because atmospheric ducts can provide a direct communication channel Navy–Navy and Navy–low flying units (especially unmanned aerial vehicles, UAVs) thanks to their low spreading loss. In this way, a naval ship can relay information coming from LoS sources to a b-LoS unit within the ducting layer. Thus, the ducting layer can provide a b-LoS link between sites with low transmission delays and low probability of detection and interception [4].

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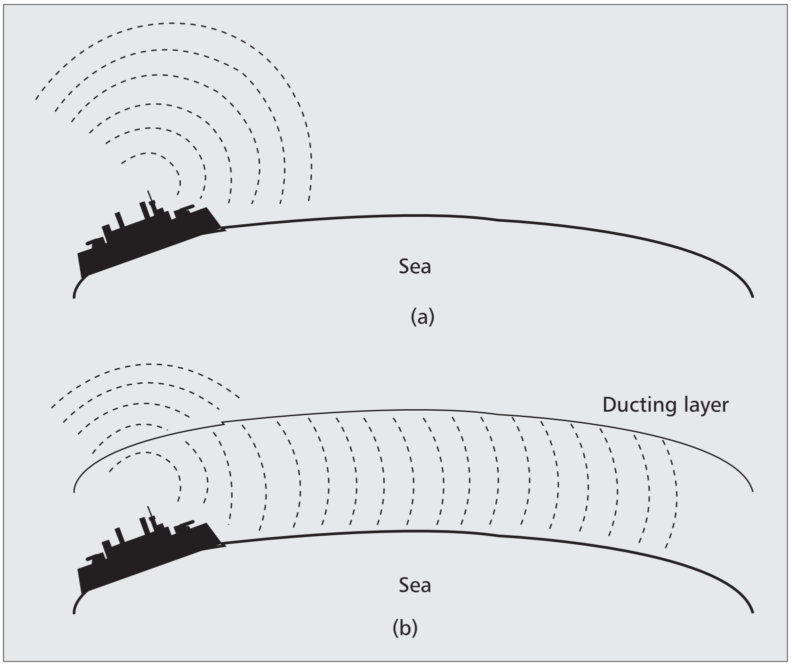

Figure 1. Signal spreading in a) the standard atmosphere; b) the atmospheric duct.

The main contribution of this work is an overview of the characteristics of ducting layer b-LoS communications and the possible utilization of the ducting layer in b-LoS naval communication networks. To this end, we review the channel modeling techniques and software tools that can be used for the ducting layer. We present a preliminary analysis to show that ducting layer can achieve lower path-loss up to 20 dB at 500 km compared to the free space. In addition, we make a linear regression fitting for the path loss curve to find the path loss exponent of the channel. To the best of our knowledge, there is no study that considers the path loss exponent for the ducting layer. Therefore, this study provides both the characteristics of the ducting layer and the possible application areas by outlining the open research issues in the field.

The remaining information in this article is organized as follows. First, we provide background information about refractivity and different types of atmospheric ducts. In addition, the effects of ducts on wireless communication are discussed. After that, the channel modeling approaches and software tools are reviewed, and a preliminary analysis investigating the path loss exponent of the ducting layer is presented. Next, open research issues on ducting layer channel modeling are also pointed out. Lastly, the possible application areas of ducting layer b-LoS communications are pointed out.

PROPERTIES OF ATMOSPHERIC DUCTS

The formation and the effects of atmospheric ducts entirely depend on the refractivity of the lower atmosphere. This section provides background on refractivity, the formation of ducts, and effects of ducts on wireless communications.

REFRACTIVE INDEX, REFRACTIVITY, AND MODIFIED REFRACTIVITY

Tropospheric radio refractive index (n) relies on weather conditions: wind, temperature, pressure, and humidity at the lower atmosphere. Refractive index changes slightly with height. It varies between 1.000250 and 1.000400. Therefore, instead of the tropospheric radio refractive index, refractivity, which is the scaled version of the tropospheric radio refractive index, is used, and the refractivity (N) is defined as [5]

$$N = (n - 1) \times 10^6 \text{ N-units}, \quad (1)$$

where n is the atmospheric refractive index.

Equation 1 is an idealized refractivity expression in which the Earth surface is assumed to be flat, but to be more realistic the Earth's curvature and the variation of height are considered in the modified refractivity (M) [5],

$$\begin{aligned} M &= N + \left(\frac{h}{a}\right) \times 10^6, \\ &= N + 157 \times h \text{ M-units}, \end{aligned} \quad (2)$$

where h is the height above sea level in kilometers, and a is the radius of the Earth in kilometers.

Tropospheric wave propagation depends on the rate of change in the modified refractivity that is associated with the refractivity gradient ($\partial M/\partial h$). There are four different refractive conditions according to the refractivity gradient, as shown in Fig. 2. In the sub-refraction condition, the signal is bent away from the surface. The standard refractivity condition is associated with the wave propagation in the standard atmosphere. The super-refraction condition causes the signal to propagate downward at a rate that is larger than the standard condition and smaller than the curvature of the Earth.

The last and most important one is the trapping condition in which the signal is refracted back to the Earth's surface. In this way, the refracted rays are trapped between surface or sea and ducting layer. The trapping condition is associated with a negative modified refractivity gradient and duct height is given by the height where the gradient of the modified refractivity changes from negative to positive, see Fig. 3.

The refractivity gradient and the duct height are the most important parameters for modeling atmospheric ducts. The characteristics of atmospheric ducts can be determined via the atmospheric parameters by using radiosonde or bulk atmospheric measurements. In addition, indirect methods are also available such as refractivity from clutter techniques which estimates the refractivity of the lower atmosphere from the clutter signal returns [2].

FORMATION AND CHARACTERISTICS OF DUCTS

The duct formation is an atmospheric phenomenon. Humidity, air-sea temperature, pressure and wind play significant roles in the duct formation. Among all the atmospheric conditions, humidity is the key and essential factor in the process. As a result, duct formation is more probable in regions with high evaporation rates such as equatorial and tropical regions.

The rapid humidity decrease in the few meters of the lower troposphere causes the duct formation. In addition, air-sea temperature is the most important contributing factor to the process. When the air is warmer than the Earth or sea surface, the temperature inversion occurs, and it enhances the duct formation. Temperature inversion is caused by advection of dry and warm air mass or cooling of land when the air is still warm at nights. In addition, negative air-sea temperature difference can prevent the duct formation. This weather condition is referred to as unstable. Factors such as rough terrain, high winds, and cold, stormy, rainy, and cloudy conditions also have destructive effects on duct formation [1].

According to their physical formation process, there are three main types of atmospheric ducts.

Evaporation Duct — Humidity difference in the air-sea boundary causes the formation of evaporation ducts. High evaporation rates are essential for evaporation ducts. Evaporation duct is the most common type of duct formation, and it presents up to 90 percent of the time in equatorial and tropical regions. The M profile of the evaporation duct is modeled with the logarithmic curve in Fig. 3a [6]. Evaporation duct height is mostly between 10–20 m, and it rarely reaches up to 40 m.

Evaporation ducts are the most promising duct formation with the potential to be utilized in the wireless communication applications thanks to their high availability rates. Since evaporation ducts are nearly permanent in coastal and maritime environments, b-LoS communications with evaporation ducts can be employed specifically for naval communications.

Surface-Based Duct — Surface-based ducts are mostly caused by advection of warm and dry air over the ocean or land, which creates humidity and temperature inversion. Surface-based ducts can be modeled with a trilinear curve in which the negative sloped part represents the trapping layer illustrated in Fig. 3b [2], and the duct height can reach hundreds of meters. Surface-based ducts occur up to 40 percent of the time depending on the season and location; these statistics can be found in [7].

Elevated Duct — The presence of marine layers results in the formation of elevated ducts. The physical mechanism that creates elevated ducts is similar to that for surface-based ducts. However, in the elevated ducts the lower boundary of the trapping layer is above the surface. Elevated ducts occur at relatively greater heights of 600 up to 3000 m, and can also be modeled with the trilinear curve in Fig. 3c [2]. In particular, air-to-ground links are prone to the trapping effect of elevated ducts because trapped signals follow longer paths than expected, and can reach the receiver with higher delay spreads and different angles than expected. Therefore, elevated ducts have the potential to create unexpected interference in the air-to-ground links. The occurrence rate of the elevated ducts can be up to 50 percent according to season and location; these statistics can also be found in [7].

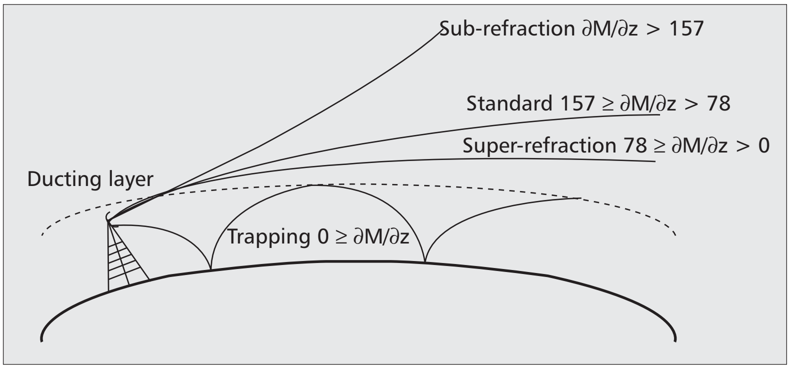

Figure 2. Rays under various refractive conditions.

Effects of Ducts on Wave Propagation

Besides the path loss enhancements, atmospheric ducts also introduce some challenges in b-LoS wireless communications. The main challenges introduced by atmospheric ducts and the techniques to overcome these challenges are outlined below.

Inter-Symbol Interference — Atmospheric ducts trap the propagating signals at the lower atmosphere, causing signals to follow different paths. The trapped signals reach the receiver with different delay spreads and phase components. Therefore, these trapped signals can create destructive/constructive interference at the receiver. The receiver should optimally combine these components by using adaptive antenna techniques to prevent interference. To this end, optimal transmit and receive beam patterns should be designed according to the characteristics of the atmospheric ducts; these techniques provide both diversity and array gain along with interference suppression as recommended in [4].

Unexpected Interference — Up to now, we have considered both the transmitter and receiver being located within the duct. On the other hand, the effects of ducts are prominent even if one of the antennas stays within the duct, such as in satellite communications and air-to-ground links in maritime and coastal environments. When satellite signals have low elevation angles, these signals can be trapped by atmospheric ducts, and the trapped signals may be received by the receiver with different delay spreads and angles of arrival (AOAs). As a result, the receiver may misinterpret the AOA of an incoming signal that is refracted by the ducting layer, and the surveillance system can be adversely affected by this effect.

The trapped signals in ducts follow longer paths and reach the receiver with higher delays, as experimentally measured in [8]. Therefore, even in LoS ranges, this effect can create multipath fading and change the pattern of the interference in naval systems. As a result, orthogonal frequency-division multiplexing (OFDM) can be promising for the ducting layer if the channel creates high delay spreads that make the coherence bandwidth much lower than the bandwidth of the signal.

Sea Surface Roughness — The trapped signals in the ducting layer are in contact with the sea surface. Especially under strong winds, open

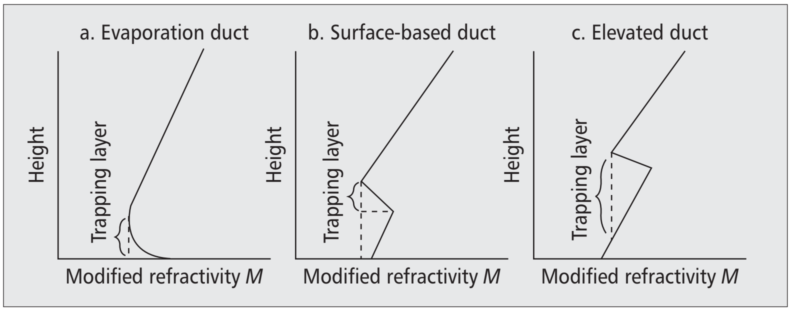

Figure 3. Modified refractivity models for duct types.

sea surfaces form rough surface boundaries. As a result, the reflection from a rough sea surface makes signals follow different paths; even some of the transmitted signals are backscattered. Therefore, sea surface roughness causes a decrease in the received power strength, and modeling the rough surface boundary is an important challenge in ducting layer propagation modeling. There are some experimental studies that investigate the effects of rough sea surfaces on the wave propagation within ducts [9], but these experimental works do not provide enough data to model extreme surface conditions, and there are no more than a few theoretical models for sea surface roughness in the presence of atmospheric ducts. To this end, this topic requires both experimental and theoretical research attention.

Aerosols and Weather Conditions — The presence of aerosols such as bacteria, pollen, and dust are highly probable in the lower atmosphere. The presence of such aerosols in the communication layer may create scattering and reflection, which cause radar echoes and path loss increase at the receiver side. In addition, hydro-meteors in the lower atmosphere, especially rain, can create significant path loss due to its reflective effects between 10 and 20 GHz. To this end, rain and aerosol attenuation in the ducting layer is a promising open research field as well.

Channel Modeling Techniques for Atmospheric Ducts

Ducting layer wave propagation is complex due to the trapping effect because the trapped signals are in contact with both the rough sea surface and the duct layer. In addition to these factors, the ducting layer wave propagation depends on multiple channel parameters such as antenna heights, duct height and type, carrier frequency, and polarization. In this section, we review the channel model approaches to modeling ducting layer communication by outlining open research fields. More important, we present preliminary simulation results for analyzing the path loss exponent to indicate the received signal level improvements:

Parabolic Equation Methods

A parabolic equation (PE) method utilizes parabolic approximation to Helmholtz wave equation. This technique is the dominant technique to model the ducting layer wave propagation with the capabilities of including both complex boundary conditions and refractivity variations of the lower atmosphere [10]. The existing numerical methods can provide fast and accurate results for PE. For these reasons, PE methods can be used especially for estimating the large-scale path loss in the ducting layer under different refractivity conditions, polarization, and surface types.

The remainder of this section includes the numerical methods to solve PE, available software tools, and preliminary simulation results to show the signal level enhancement due to the atmospheric duct formation.

Numerical Methods for PE — PE can be solved by numerical operations. There are three popular numerical methods for solving PE: split step Fourier (SSF), finite difference (FD), and finite element (FE) [11]. The choice between these methods strongly depends on the scenario and conditions. The SSF method takes advantage of fast Fourier transform (FFT) algorithms. Therefore, the implementation of PE with SSF is computationally efficient compared to other methods, and the technique can yield accurate and stable solutions. Second, FD provides the highest resolution in modeling the boundary conditions by utilizing the Crank-Nicholson finite difference scheme. Lastly, FE provides better modeling of the fast variations in the atmospheric conditions and flexibility to model the complex boundary conditions. A good review of these techniques can be found in [11].

Wave Propagation Tools — Wave propagation tools are available that can be used to model the ducting layer. The most important and widely used one is AREPS, developed by the Atmospheric Propagation Branch at the Space and Naval Warfare Systems Center, San Diego, California [12]. AREPS is a hybrid wave propagation tool that combines ray optics and PE with SSF methods. It is capable of taking the refractivity index as input from various sources like satellite, meteorological, and bulk measurements. In addition, PETOOL, a free tool available online, can model both forward and backward scattered waves under different terrain and refractivity conditions [13]. Since PETOOL also considers backward scattered waves, unlike AREPS, it can be used to analyze regions with terrain blocks between the transmitter and the receiver such as islands. PETOOL is calibrated using ray-based methods and AREPS as described in [13]. Since PETOOL can give reliable results like AREPS and is a free tool, researchers may prefer PETOOL to model the wave propagation in the ducting layer. Furthermore, TEMPER, developed by the John Hopkins University Applied Physics Laboratory, is especially preferred for R&D applications such as high fidelity radar design and 3D wave modeling applications. TEMPER is solely based on the PE method [14]. Lastly, Wireless InSite, developed by REMCOM, is a hybrid model and utilizes the frequency distributed (FD) time domain method in

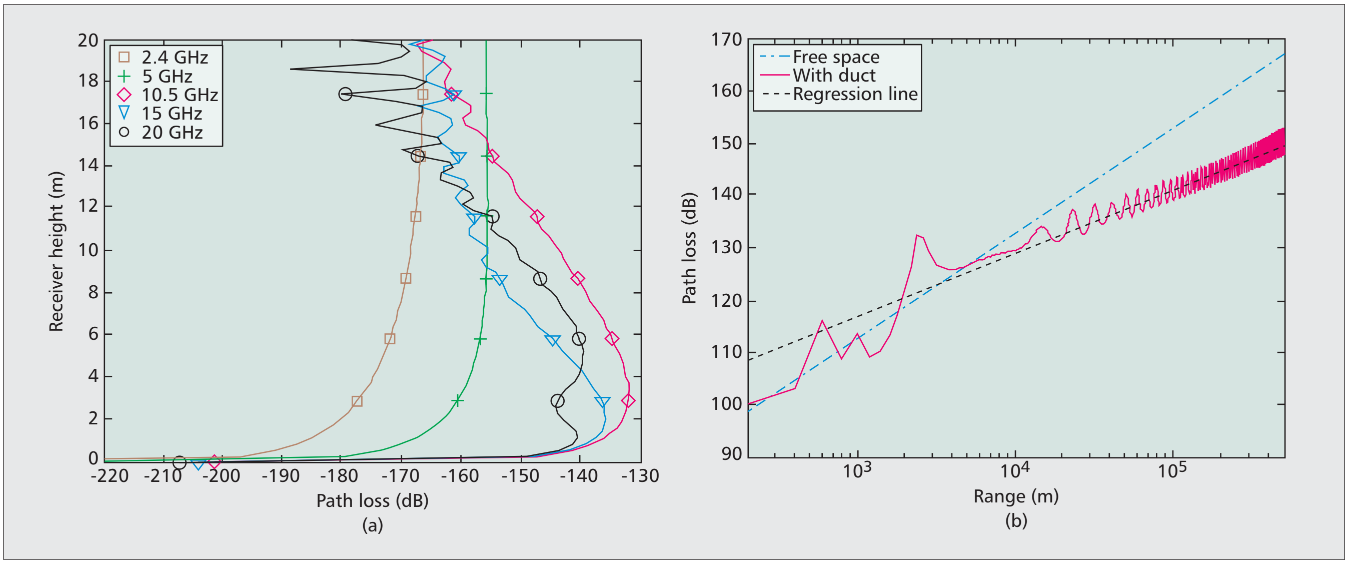

Figure 4. Path loss variations with respect to receiver height and range in 13 m ideal evaporation duct: a) receiver height vs. path loss; b) path loss vs. range.

order to solve PE. Although this tool is not widely used in ducting layer wave propagation modeling, it is a promising modeling tool for projects that require modeling of complex boundary conditions.

Path Loss Analysis for Evaporation Duct — In this section, we present our preliminary analysis to show the received power enhancement with atmospheric ducts. Since evaporation ducts are more probable compared to other types of ducts, we analyze an ideal 13 m evaporation duct modeled with a logarithmic curve as in [6]. We utilize PETOOL to solve PE for our preliminary large-scale path loss analysis.

Large-scale path loss in wireless communications can be represented with the generic formula of

$$PL = A + 10\gamma \log d/d_0 + X_s, \quad (3)$$

where γ is the path-loss exponent, d_0 is the b-LoS range, A is the path loss at d_0, and X_s is the shadow fading.

Ducting conditions show significant dependence on the carrier frequency because the trapping condition becomes dominant above a certain frequency [5]. To this end, we simulate the wave propagation within a 13 m evaporation duct for different carrier frequencies (the transmitter is 4 m above sea level). Figure 4a represents the receiver height vs. path loss at 80 km distance. As noticed from this figure, 10.5 GHz can reach the lowest path loss values; similar experimentally validated results can be found in [3]. Therefore, the signal level enhancements become highest in this high frequency range.

To show the signal level enhancement with respect to the free space, we present path loss vs. range at 10.5 GHz for the transmitter and receiver that are located 4 m above sea level. As in Fig. 4b, path loss in the ducting layer is significantly lower than in free space. Therefore, we can expect the path loss exponent to be smaller than 2 (free space) because the signal energy is not spread through the atmosphere. Instead, it is concentrated within the ducting layer. The simple linear regression analysis with Eq. 3 yields a path loss exponent of 1.2087 for an ideal duct and a flat sea surface (black line in Fig. 4b). We expect that the path loss exponent will be higher for real-world conditions with range-dependent refractivity conditions and rough sea surfaces.

Although several works are available to model the amount of path loss within the atmospheric ducts, there are no studies that provide the statistical modeling of the path loss exponent and shadow fading with respect to the atmospheric conditions, sea surface roughness, duct height, antenna heights, and carrier frequency in ducting layer communication. In addition, the effects of the polarization and correlation between antennas are open research fields that can be solved by PE simulations.

Ray Optics Methods

Ducting layer wave propagation modeling is dominated by PE because ray analyses introduce significant errors at high ranges and are much slower. However, ray optics methods are still used in hybrid models in order to provide fast and reliable estimates of the behavior of the wave-front and propagation angles [10].

Ray analyses utilize the solution for the Eikonel equation under nonstandard refractivity conditions, and they can give the approximate behavior of the delay spreads and AOA of the multipath components. Since PE is inefficient in modeling these parameters, which are essential to channel modeling, ray optics methods should be used in ducting layer studies. There are some experimental studies that focus on AOA in the presence of the atmospheric ducts [15]. In [15], they also estimate AOA for the ducting layer by using both ray optics and PE methods. However, the distribution of delay spreads and AOAs in the ducting layer is not well studied, and requires significant experimental and theoretical research efforts. In addition, angles of departure (AODs)

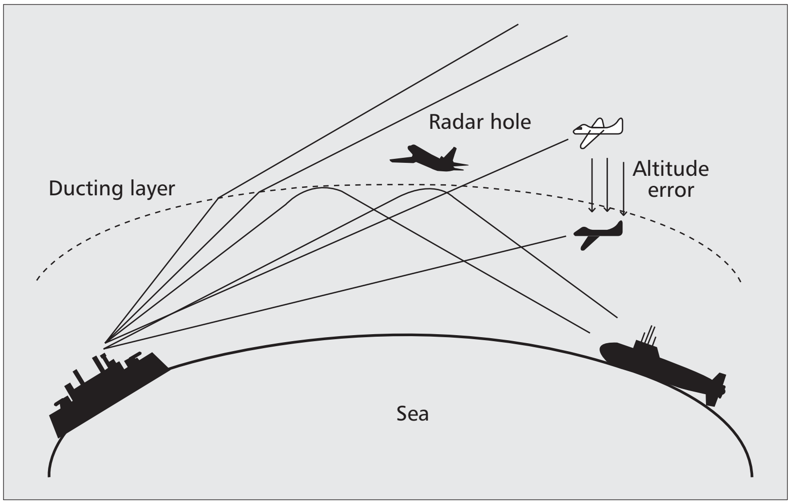

Figure 6. Wave propagation with a ducting layer.

should also be studied for the ducting layer. Since only signals with low grazing angles can be trapped by the ducting layer, most of the transmitted power can spread through the atmosphere instead of the ducting layer if the beamwidth of the antenna exceeds a certain value, which depends on the antenna placement and atmospheric conditions. To prevent signal spreading through the atmosphere instead of the ducting layer, the maximum beamwidth that can be trapped by the atmospheric ducts should be derived with respect to transmitter antenna height, duct height, and carrier frequency by utilizing the ray optics methods.

Application Areas of Ducting Layer b-LoS Communication

This section provides answers on how the usage of atmospheric ducts as a propagation medium can improve current state-of-the-art naval communication links. To this end, we review the possible application areas of ducting layer b-LoS communications by focusing on military naval applications.

Military Applications

In current naval b-LoS communications, the transmitter and receiver can use high frequency (HF) radio systems, or satellites or air units as a relay node to deliver data packages. However, HF radio systems are band-limited by nature and inadequate to provide the high data rates modern military communications require. The other often used option is satellite communications, which is expensive and introduces high communication delays. In addition, satellite communication has security problems in modern warfare because it can be strongly affected by hostile jamming. Furthermore, using an air unit as a relay node is dangerous because the unit can be exposed to hostile attacks, and the replacement of a relay node can waste a considerable amount of mission time [4]. To this end, ducting layer b-LoS communications is a promising alternative because the communication at the lower troposphere is less prone to be affected by hostile jamming; also, utilization of the ducting layer eliminates the need for an air unit as a relay node. The ducting layer is expected to employ nearly 10 GHz as in the previous section, and with the signal level enhancements, will be able to provide the high data rates that modern military applications require.

In NCO, the connectivity between units is critical to empower strategical and tactical decisions. With the employment of atmospheric ducts, there will be a direct communication channel between navy-navy and navy-low flying units (especially UAVs). Therefore, the employment of ad hoc networking with the b-LoS ducting layer can provide end-to-end connectivity in naval warfare. For example, a naval ship can relay information coming from a LoS source to a b-LoS naval ship. To this end, ad hoc b-LoS networks with atmospheric ducts should be designed, and the distribution of data rates and relay delays should be derived for the ducting layer b-LoS systems. Since there are only a few works using atmospheric ducts as a communication medium, ad hoc networking with the ducting layer is a promising open research field to improve naval NCOs.

Radar Applications

Radar coverage is strongly affected by ducts in coastal and maritime environments [2]. Without considering the effects of ducts, the coverage can be miscalculated, and miscalculations impose unwanted problems like radar holes and altitude errors, as shown in Fig. 5. Since the military radar applications require precise and accurate estimations, the effects of ducts should be taken into account in coverage estimations. Therefore, ducting layer studies also contribute to the radar coverage analysis as well.

Wireless Sensor Networks

Ducting layer b-LoS communications can be used to monitor civil or military sensor networks in maritime and coastal areas as in [3] because the implementation of satellite or cellular communication are expensive in large maritime areas. As a result, the ducting layer can provide low-cost high data rate monitoring for maritime wireless sensor networks.

Conclusion

Ducting layer b-LoS communication is a promising communication method, especially for the military naval applications to empower tactical decisions in NCOs. Since the ducting layer b-LoS communications show strong dependence on the refractive index, which is highly affected by the atmospheric conditions, well developed channel models are required to determine the characteristics of the channel. To this end, this article reviews the channel modeling approaches by outlining the open research areas and possible application areas of ducting layer b-LoS systems. More important, this work also provides the path loss exponent for an ideal evaporation duct.

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