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Ship-to-ship beyond line-of-sight communications: a comparison between ray tracing simulations and the PETOOL

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Abstract

A Matlab-based ray tracing (RT) simulator is implemented for the analysis of ship-to-ship communications. The anomalous propagation effect due to the evaporation duct which results in bending and/or trapping the rays is modelled. Based on extensive RT simulations, the received rays are identified and their parameters are estimated. We briefly describe the implementation of the RT simulator and compare the obtained ray tracing results with those obtained from a widely used simulation tool, the PETOOL. We highlight the excellent agreement between the two tools for line-of-sight (LOS) ranges and also highlight that there is significant disagreements between them for beyond-line-of-sight (beyond-LOS) ranges. Then, based on our RT simulator, we provide detailed results describing the effect of the evaporation duct phenomena on the communication link quality in the beyond-LOS zone.

1 Introduction

The evaporation duct is a weather phenomenon that occurs over sea surfaces due to the rapid change in water vapor; consequently, the gradient, versus height, of the refractivity index of the atmosphere layers above the sea surface changes in a unique pattern which is characterized by the modified refractivity profile [1]. This phenomenon causes anomalous propagation of electromagnetic waves where the electromagnetic waves might be bent or trapped, thus travel over distances beyond-line-of-sight (beyond-LOS) [2]. For waves that are trapped, the duct layer acts like a waveguide with an upper boundary equals to the height at which the modified refractivity profile has a zero gradient. The receiver (Rx) can benefit from the trapped waves only if its height is within the duct layer. On the other hand, waves that are bent by the duct are able to serve the Rx at heights above the duct layer and maintain communications beyond-LOS ranges, though relatively shorter than the ranges served by the trapped waves.

In this paper, we consider ship-to-ship communications, where the height of both the transmitter (Tx) and the Rx are above the duct layer. We are interested in developing a ray tracing (RT) simulation tool that allow us to evaluate the effect of evaporation duct on improving the communication link at distances beyond-LOS, where, strictly speaking, only the waves (rays) that are bent - and not those that are trapped - by the duct are the main contributor to this improvement. We identify the received rays and their parameters (e.g., their length, phase, and reflection angle - if applicable) and based on these parameters, the quality of the communication link and its temporal/spatial dynamics - due to the temporal changes in the weather conditions as well as the dynamics of the sea surface - is planned to be studied. However, for the work presented in this paper, only the effect of the height of the evaporation duct on the behavior of the range-dependent path loss is evaluated. The results from our RT simulator are compared with the Matlab-based parabolic equation software tool (PETOOL) [3], where the similarities/differences between the results obtained from the two approaches are highlighted. The reminder of this paper is organized as follows. In Section 2, the developed RT simulator is introduced and the procedures used to identify and characterize the received (direct and reflected) rays are detailed. Section 3 gives a very brief introduction to the the PETOOL. The results of this paper are discussed in section 4, and finally, a summary is given in section 5.

2 The Matlab-based Ray Tracing Simulator

The RT simulator is implemented by solving the Snell's equation for stratified atmosphere [4]. The modified refractivity index, M, of each layer as a function of its height, h, is given by the evaporation duct range-independent modified refractivity profile [1]

$$M(h) = M_0 + 0.125h - 0.125d \ln(h/z_0), \qquad (1)$$

where, M_0 is the modified refractivity at the surface taken as 340 M-units, d is the duct layer height, and z_0 is the roughness length taken as 1.5×10^{-4} m. For a layer with height, h, in the stratified medium, the relationship between the refractivity index, n, and, M is given by

$$M = (n-1)\times10^6 + 0.157h. \qquad (2)$$

The term $(0.157h)$ is used in order to introduce a curvature to the rays which is equal to the earth's curvature. Hence, a convenient coordinate system can be obtained such that: ranges are measured along the spherical earth, and heights are measured along radials passing through the earth's center. Based on Snell's equations, angles of incidence, refraction, and reflection (if applicable) of each ray passing through the stratified troposphere are calculated until either

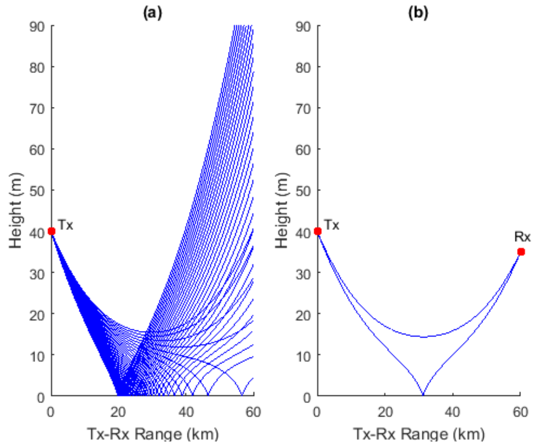

Figure 1. Examples of rays trajectories for 10 m evaporation duct. (a) A small number of the initial rays, Tx = 40 m. (b) Direct and reflected rays identified using the ray shooting bisection search procedure for Rx = 35 m and Tx-Rx distance = 60 km.

the ray travels the intended Tx-Rx distance or it reaches the maximum allowed height which is set to 100 m.
In order to accommodate for the rapid change of the refractivity profile at very low heights close to the surface, stratifying the medium is performed using exponential step size such that layers at low heights are much thinner. The thickness of the ith layer is $e^{si} - 1$ m, where $i = 1, 2, 3, ...$. Selecting the value s was done based on trying different values and choosing the largest possible one that makes the trajectory of the traced rays as well as their parameters - such as their lengths and propagation factors - converge. In this work the value of s was selected to be 10^{-5}, which, when applied to the first 100 m of the troposphere that we are interested in, it results in layers' thickness in the sub-millimeter range.

2.1 Finding the Direct and Reflected Rays

The signal at the Rx is estimated as the superposition of the direct and the reflected rays. The Tx and the Rx in the concerned scenario (i.e., ship-to-ship) are high enough such that the rays that are trapped by the duct do not contribute to the received signal. At the beginning of the simulation, initial rays are launched and traced. The angles of departure of the individual initial rays are chosen such that they have equal inter-ray angular spacing of 1 millidegree and they span a predefined angular range. This angular range is selected to be very small (few degrees) yet it includes the direct and reflected rays that are successfully received for the concerned Tx-Rx ranges of 5 to 60 km. Each one of these initial rays is traced throughout the stratified medium until it either reaches the maximum considered range, i.e., 60 km, or it reaches the maximum allowed height which is set to 100 m. Based on the trajectory of the initial rays, search for the direct and reflected received rays is performed considering Tx-Rx distances that vary between 5 km to 60 km in steps of 100 m. For each increment in the Tx-Rx distance, the direct and reflected rays are found as follows:

1. The intervals of the angle of departures that include the direct and the reflected rays are identified (two intervals are identified each of which has a width of 1 millidegree).

2. Within each one of these identified angle of departure intervals, ray shooting with bisection search procedure is applied in order to identify the ray that successfully reaches the Rx. Where, the angular interval is repeatedly bisected, then the trajectory of the bisecting ray is used to select the angular sub-interval in which the sought ray (i.e., eigenray) is expected to lie. A ray is identified as being received successfully by the Rx if it reaches the Rx with vertical spatial error not exceeding 1 cm. The searching procedure continues until either the ray of interest is found or the maximum number of ray shooting attempts is reached.

Figure 1 illustrates examples of the initial rays and the identified direct and reflected rays based on the bisection search procedure. Please notice that the plots in figure 1 are plane earth illustrations in which the curvature of the earth is eliminated and substituted by upward curvature for the rays.

2.2 Estimating the Optical Path Length and Phase of the Direct and Reflected Rays

In order to add direct and reflected rays in phase, their optical length is required. The optical path length of a ray is defined as the integral of the product of the geometric length of the ray path throughout its trajectory, and the index of refraction of the layers through which it propagates [1]. The phase of each ray is related to its optical length by $2\pi L/\lambda$, where L is the optical length of the considered ray, and λ is the wavelength. In addition to the effect of the ray length, the phase change due to the reflection by the surface is added to the phase of the reflected ray. In this work, we assume this phase change to be π.

2.3 Estimating the Power of the Direct and Reflected Rays

Due to the difference in their trajectories, the power of the direct and reflected rays might significantly differ. The power of the two rays are affected by the following three factors:

1. Both rays are subjected to the same attenuation due to the free space path loss (FSPL).

2. The reflected ray is affected by the surface reflection coefficient. However, in this work, the surface reflection does not affect the strength of the reflected ray where we assume a smooth surface and a reflection coefficient equals to -1.

3. Each ray is subjected to a propagation factor determined by its trajectory. The propagation factor of a ray is defined as the reduction in the intensity of the field due to the increase of the cross-section of the tube of the ray. The propagation factor of the direct (reflected) ray is estimated by launching two rays spaced by 10^{-5} degree,

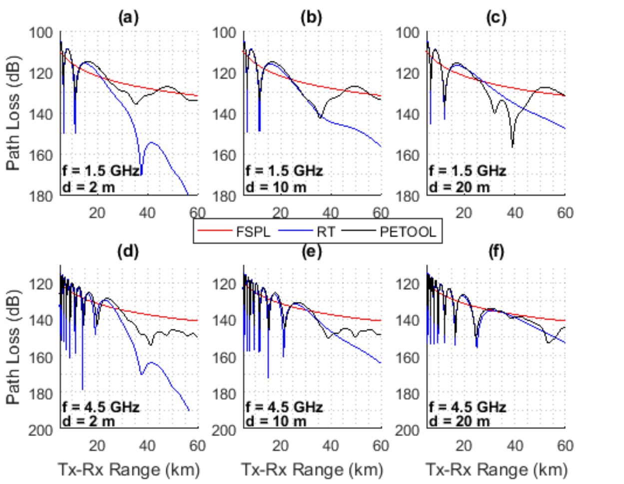

Figure 2. Range dependency of path loss estimated using the RT versus the PETOOL for different frequencies, f, and duct heights, d, throughout a Tx-Rx range of 5 to 60 km. Tx and Rx heights are 40 m and 35 m, respectively.

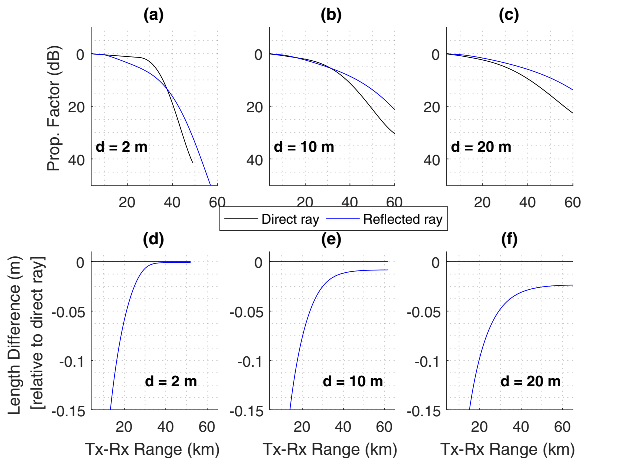

Figure 3. Parameters characterizing the direct and reflected received rays (which correspond to the plots in figure 2) based on the RT for different duct heights, d.

one of which has the same angle of departure as the direct (reflected) ray. These two launched rays construct a tube representing the direct (reflected) ray and based on the size of the cross-section of this tube at the Rx, the propagation factor, PF, is estimated as [5]:

$$PF(dB) = -10log_{10}\left(L\cos\theta_0\left|\frac{d\theta_0}{dz}\right|\right), \qquad (3)$$

where, L and θ_0 are the length and the angle of departure of the concerned ray, respectively. $d\theta_0$ is the angle separation of the two launched rays that construct the ray tube. And, dz is the perpendicular cross-section of the ray tube at the Rx.

2.4 Estimating the Received Signal Power and the Path Loss

Based on the previous steps, five parameters characterizing the two rays (i.e., the lengths and the propagation factors of both rays as well as the reflection angle of the reflected ray) are found for each 100 m increment in the Tx-Rx range. However, these parameters are further interpolated because at some Tx-Rx distances the ray shooting and bisection search procedure fails to find both rays; hence, the missing rays parameters are interpolated. Also, interpolation allows us to improve the spatial resolution of the estimated parameters. Therefore, linear interpolation is performed in order to estimate the rays parameters and consequently estimate the received signal and the path loss with a step size of 10 m throughout the considered Tx-Rx range.

3 The Parabolic Equation Software Tool (PETOOL)

The parabolic equation software tool (PETOOL) is a free and online-available Matlab-based one-way/two-way split-step parabolic equation software that was developed for the analysis and visualization of radiowave propagation over variable terrain and through homogeneous and inhomogeneous atmosphere [3]. PETOOL supports different ducting profiles as well as range-dependent ducting profiles; however, all results reported in this work are for over-water range-independent evaporation duct M-profiles. A comparison between the results obtained from the PETOOL and those obtained from the RT is detailed in the next section.

4 Results

4.1 Comparison: the Ray Tracing Simulator versus the PETOOL

In this section the similarities/differences in estimating the path loss for different evaporation duct heights using the RT versus the PETOOL are highlighted. All the reported PETOOL results are simulated using a Tx horizontally polarized antenna with a 3dB beamwidth of 2 degrees and an elevation angle of 0 degree. The maximum range, maximum altitude, range step, and altitude step are set to 60 km, 100 m, 10 m, and 10 cm, respectively. Besides a vector specifying the increments in the Tx-Rx range, the PETOOL provides the propagation factor - at each Rx height - defined as the difference between the estimated path loss and the FSPL. In order to eliminate any effect due to assumed system or antenna gains when the comparison between the RT and the PETOOL is carried out, the propagation factor associated with the selected Rx height is extracted from the PETOOL and superimposed on the FSPL to realize the PETOOL path loss estimate.

Figure 2 depicts the path loss estimate, for up to 60 km Tx-Rx range, based on the RT and the PETOOL. The simulations are carried out for two carrier frequencies: 1.5 GHz and 4.5 GHz as well as three duct heights: 2 m, 10 m, and 20 m. The heights of the Tx and the Rx are assumed to be 40 m and 35 m, respectively. Figure 2 shows excellent agreement between the RT and the PETOOL at ranges up to 30 km. This agreement is clearly demonstrated in the excellent match for the path loss and the fading dips. However, at beyond-LOS the path loss estimated by the two approaches differ significantly, where the PETOOL has a tendency to underestimate the path loss compared to the RT. Also, at beyond-LOS ranges, the RT path loss results demonstrate a smooth and mild gradual growth behavior which has been reported in different publications (for example, pp. 81 in [1], and pp. 4 in [6]).

The curves in figure 3 illustrate the RT estimates of the parameters characterizing the direct and reflected received rays and examining these curves allows us to understand the behavior of the RT path loss estimate as follows.

- At ranges beyond-LOS the reflected ray is affected by smaller propagation factor compared to the direct ray. This behavior is due to the effect of ducting on making the cross-section of the ray tube associated with the reflected ray be always smaller than that of the direct ray.
- The reflected ray has longer range compared to the direct ray. This effect is especially clear when the duct height is low. On the other hand, high duct maintains the existence of both rays throughout the entire 60 km range.
- At low duct height (d = 2 m), see figures 2.(a) and (d), the path loss experiences drastic increase at about 37.5 km range, where the direct and reflected rays (almost) cancel each other. Where, at this range both rays have (almost) the same length and the same propagation factor; see figures 3.(a), and (d).
- Figures 3.(d), (e), and (f) show that at beyond-LOS ranges, given that the Tx and the Rx heights are fixed, the length difference between the direct and the reflected rays saturates at a very small value (a maximum of few cm) that depends on the duct height: the higher the duct, the higher the difference is.

4.2 Effect of the Duct Height on Ship-to-ship Communications

Figure 4 shows the path loss for different duct heights. In general, it is clear that for ranges beyond-LOS, duct provides consistent gain for the received signal. For the considered scenario, the communication LOS range in normal atmosphere is about 40 km, however, figure 4 shows that a moderate duct height, d = 10 m, (the worldwide duct height mean is about 13 m) is enough to carry out successful communications up to 60 km with moderate path loss difference compared to the FSPL. For example, with duct height of 10 m, the difference between the FSPL and the estimated path loss at 60 km range is around 28 dB (23 dB) for 1.5 GHz (4.5 GHz). With a higher duct of 20 m, the difference between the FSPL and the estimated path loss is around 11 dB (9 dB) for 1.5 GHz (4.5 GHz).

The effect of the duct height on the length of the individual rays (and consequently on the difference between their phases as demonstrated by figure 3) results in a complex pattern of fading dips before the smooth behavior at beyond-LOS starts (see figure 4 with Tx-Rx range up to 30 km). Hence, higher duct height does not always result in better communication conditions unless the Tx-Rx range is large enough such that the optical length difference between the direct and the reflected rays is (almost) not affected anymore by increasing the Tx-Rx range.

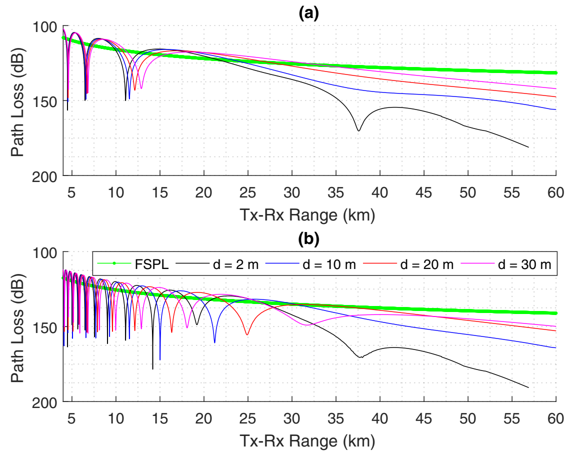

Figure 4. Range dependency of path loss for different duct heights. (a) f = 1.5 GHz, and (b) f = 4.5 GHz.

5 Summary

A ray tracing (RT) Matlab simulator is implemented for ship-to-ship long distance communications, where the anomalous propagation effect due to the evaporation duct is modelled. The goal of the RT is to estimate the received signal and consequently to study different aspects of the communication link. The RT implements a ray shooting with bisection search algorithm in order to identify the successfully received direct and reflected rays. The results from the RT has been compared with the PETOOL for ranges up to 60 km. We highlighted that the two tools have excellent match for ranges up to 30 km. We also highlighted that at beyond-LOS ranges, when compared with the RT, the PETOOL tends to underestimate the path loss. Based on the RT estimates of the parameters characterizing the received rays, e.g., the optical lengths and propagation factors of the direct and reflected rays, the path loss results obtained by the RT are explained.

References

[1] M. Levy, *Parabolic equation methods for electromagnetic wave propagation*. No. 45, IET, 2000.

[2] H. Hitney and R. Vieth, "Statistical assessment of evaporation duct propagation," *IEEE Transactions on Antennas and Propagation*, vol. 38, pp. 794–799, June 1990.

[3] O. Ozgun, G. Apaydin, M. Kuzuoglu, and L. Sevgi, "Petool: Matlab-based one-way and two-way split-step parabolic equation tool for radiowave propagation over variable terrain," *Computer Physics Communications*, vol. 182, no. 12, pp. 2638–2654, 2011.

[4] J. B. Anderson, *Digital transmission engineering*, vol. 12. John Wiley & Sons, 2006.

[5] J. M. Hovem, "Ray trace modeling of underwater sound propagation," *Modeling and Measurement Methods for Acoustic Waves and for Acoustic Microdevices*, vol. 10, pp. 573–598, 2013.

[6] K. Anderson, "Evaporation duct communication: Test plan," tech. rep., DTIC Document, 1991. Available at http://www.dtic.mil/dtic/tr/fulltext/u2/a233467.pdf, [Online; accessed 19-Jan.-2017].