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Research paper

How Can Environment Influence Ultra-Long Radio Propagation?

M.S. Mikhailov[1*], A.A. Volkova[1] And V.A. Permyakov[1]

[1]*department Of Radio Engineering Devices And Antenna Systems, National Research University "Moscow Power Engineering Institute", Krasnokazarmennaya 14, 111250 Moscow, Russia*
**Corresponding Author E-Mail:Mihailovms@Mail.Ru*

Abstract

Even a small deviation of the environmental parameter can lead to significant changes in the propagation over long distances. The article investigates the radio propagation above the sea, taking into account the distortion of the refractive index caused by evaporation. This feature of the troposphere is called the evaporation duct. The radio propagation over-the-horizon in the evaporation duct is possible. The conditions for optimal excitation of the evaporation duct by a highly directional antenna are studied. The main factors influencing the range of the radio link are studied, such as the height of the transmitting antenna and attenuation in air and in hydrometeors and diffraction at sea waves. Also, the effect of vertical variations the evaporation duct on radio propagation is considered. In addition, elevated-surface duct may appear over the sea surface separately or together with the evaporation duct. The effect of an elevated surface and mixed ducts on the radio propagation is considered. The radio propagation is calculated by the parabolic equation method.

Keywords: *Tropospheric duct; Radio propagation; Evaporation duct; Elevated-surface duct; Parabolic equation method,*

1. Introduction

Consideration of the influence of the environment on the propagation of radio waves is a very important and interesting task. One such task is the propagation of radio waves over-the-horizon in the tropospheric duct. In recent years, this problem has been intensively studied [1, 2]. This problem is studied in [1, 2], where the main attention is paid to taking into account evaporation-surface duct In this paper, in addition to the evaporation-surface duct, we consider the effect of the elevated-surface duct and their combination [3]. According to the Recommendations of International Telecommunication Union [4], ducts can be of three types: surface based, elevated-surface, or elevated ducts (Figure 1). The inversion of the refractive index affects the appearance of such ducts The refractive index of air differs little from unity. Therefore, a "modulus of refractive index" — N is introduced:

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

where h is the corresponding height above the sea surface.

Using the refractive index of reduced air m and the "modulus of refractive index of reduced air" M, one can take into account the curvature of the earth:

$$M(h) = (m(h) - 1) \cdot 10^6 = (n(h) + h/a - 1) \cdot 10^6 = \\ = N(h) + h \cdot 10^6 / a, \tag{2}$$

Also, the refractive index depends on the meteorological parameters. The formula is derived from the Debye equation and is as follows:

$$N = 77.6\, P/T + 3.73 \times 10^5\, e/T^2, \tag{3}$$

where P is pressure of dry air [hPa], T is current temperature [K], and e is partial pressure of water vapor [hPa]. An inversion in the refractive index arises due to an appearance of an inversion of the meteorological parameters, such as temperature or humidity.

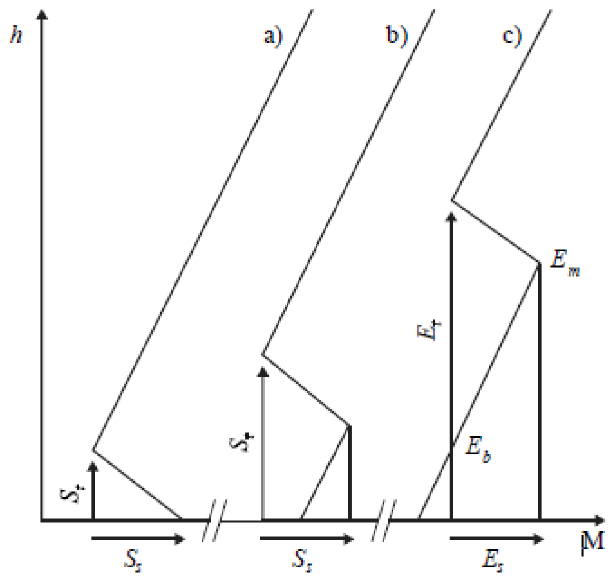

Fig. 1: Definition of parameters describing a) surface, b) elevated surface and c) elevated ducts

2. Radio Propagation in Evaporation-Surface Duct

2.1. Evaporation-Surface Duct

The change in humidity leads to the appearance of an evaporation duct. 100% humidity is achieved directly on the sea surface At a distance, the humidity decreases, although under normal conditions the humidity is practically altitude independent. The evaporation duct arises in the tropics with a 100% probability and can reach up to 50 meters in height. In temperate latitudes, the probability of occurrence falls to 50%, and the altitude drops to 8–15 meters.
The vertical profile of the reduced refractive index module is described by the Paulus-Jeshke model [5, 6]. In a theoretical analysis of radio waves propagation in an evaporation duct, this model is usually used:

$$M(h) = M(0) + 0{,}125\left\{h - h_d \cdot \ln\left[\left(h + h_0\right)/h_0\right]\right\} \quad (4)$$

where h_d is the evaporation duct height [m], and h_0 is a length characterizing boundary roughness and is equal to $1.5\cdot10^{-4}$ m for calm sea. Using the parabolic equation method, radio waves propagation was calculated taking into account the heterogeneity of the troposphere [7, 8]:

$$\frac{\partial^2 V}{\partial z^2} - 2ik_0\frac{\partial V}{\partial \rho} + k_0^2\left(n^2\left(\rho, z\right) - 1\right)V = 0. \quad (5)$$

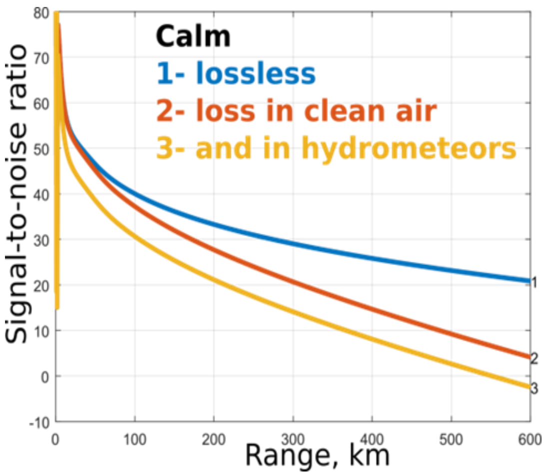

Fig. 2: Signal-to-noise ratio in evaporation duct in the calm.

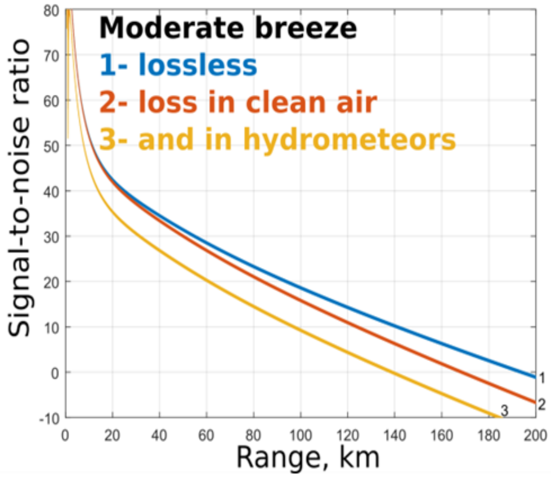

Fig. 3: Signal-to-noise ratio in evaporation duct in the moderate breeze.

It is estimated that in ideal conditions, the range of a radar operating in the centimeter range in the case of describing the evaporation duct along the profile (4) and the optimal excitation of the evaporation ducts [9] reaches several hundred kilometers. The range of radar under normal conditions is limited to losses in clean air and hydrometeors (Figure 2) and dispersion of radio waves by the turbulent troposphere and sea waves (Figure 3). An analysis of the effects of sea waves and tropospheric turbulence was carried out in [10, 11]. For more details, you can see in [12–15].

2.2. Limitations on the Range of the Radar in the Evaporation-Surface Duct

There is an approximate formula for calculating the critical length of an electromagnetic wave in an evaporation-surface duct height of h_d:

$$\lambda_{critical} = 0{,}085 h_d^{3/2} \quad (6)$$

Here are the calculations for 10 GHz. The critical electromagnetic wavelength is 2.7 cm for evaporation duct height of 10 meters. If the length of the radiated wave is greater than the critical one, then the evaporation-surface duct is not excited (Figure 4, line 1). The range of the radar is the distance to the radio horizon.

The critical electromagnetic wavelength is 5 cm for evaporation duct height of 15 meters. The length of the radiated wave is less than the critical one according the evaporation-surface duct is effectively excited (Figure 4, line 2). In the case of placement of an antenna and a target at an altitude of 5 meters, the range of radar stations is 500 km

The critical electromagnetic wavelength is 7.6 cm for evaporation duct height of 20 meters. If the length of the emitted wave is less than twice as critical, then multimode excitation of the evaporation-surface duct is manifested (Figure 4, line 3). The figure 3 shows an in-phase addition of modes at a height of 4 meters, as well as an anti-phase addition at an altitude of 15 meters. The range of the radar is almost 650 km for the location of the antenna and target at altitudes of 4 meters. And the range of the radar is 0 km for the location of the antenna and target at altitudes of 15 meters.

2.3. Evaporation-Surface Duct

An evaporation-surface duct is considered under the condition that a tropospheric region with a positive gradient of the refractive index is located directly above the sea surface. Figure 5 shows the result of calculating the range of the radar as a function of a segment of the normal troposphere.. At the top of the figure is a graph of the height change in the “refractive index module of reduced air” (M-profile). The constitutive M-profile consists of the section of the normal troposphere with height h_{NT} and the section of the Paulus–Jeshke model higher. In the above calculation, the height of the evaporation duct h_d=15 m. For the height of the section of the normal troposphere shorter than 2.5 m, the range of radar stay almost constant. As height h_{NT} increases further, the range of radar monotonically diminish. At $h_d \approx h_{NT}$ = 10 m, the target detection range becomes close to the radio horizon distance (≈ 18 km) and the superfefraction region disappears.

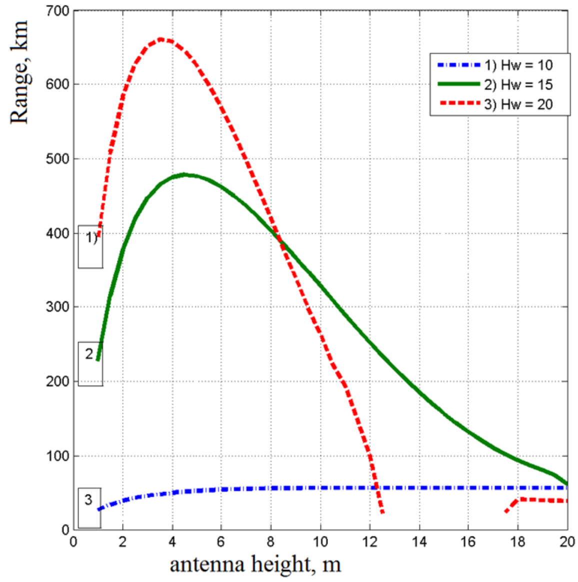

Fig. 4: Range of the radar from antenna height

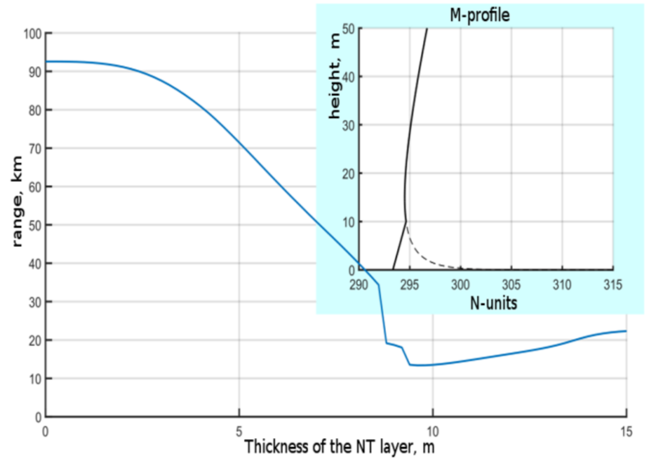

Fig. 5: Perturbing the profile of the evaporation-surface duct (see the inset at the top right of figure) and addiction of the target detection ranges of the radar on the height of the section of the normal troposphere h_n

3. Radio Propagation in Elevated-Surface and Mixed Ducts

3.1. Elevated-Surface Duct

Also, a change in temperature leads to a change in the refractive index. Positive refraction occurs if the above change is stronger than the influence of the sphericity of the Earth, and hence a surface tropospheric duct arises. The impact of the refractive index on radio propagation is shown in the Figure 6.

The modification in temperature of 1.2K or a modification in humidity of about 0.7% corresponds to the modification 1 N-unit of the refractive index.

3.2. Mixed Duct

There is also the case when these duct occur simultaneously. The effect of the thickness of the surface duct on radio propagation in the evaporation duct is shown in Figure 7.

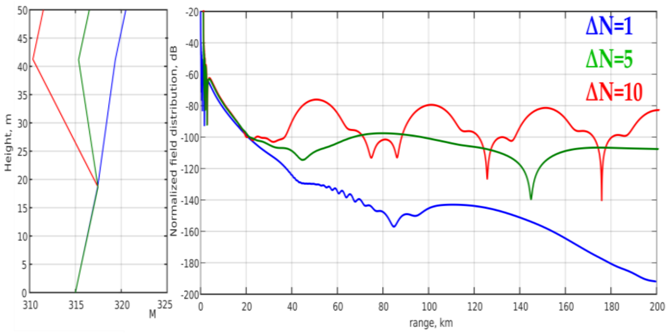

Fig. 6: The influence of the refractive index on radio propagation.

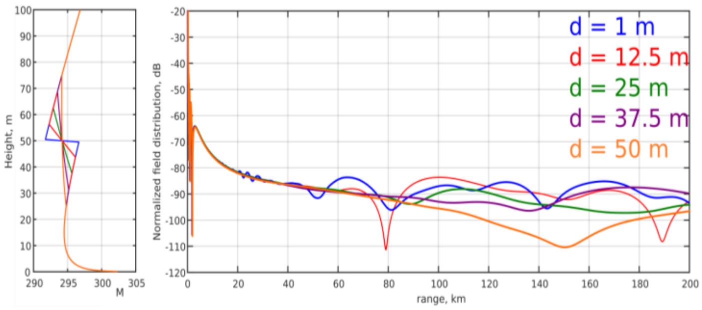

Fig. 7: The impact of the fatness of the elevation-surface with evaporation duct on radio propagation

3.3. Mixed Duct. Comparison with P. Frederickson

We also made a comparison with P. Frederickson [3]. The radio propagation loss in the evaporation-surface and the elevation-surface ducts and in a mixed was compared. Figures 8 and 9 show complete agreement of the results.

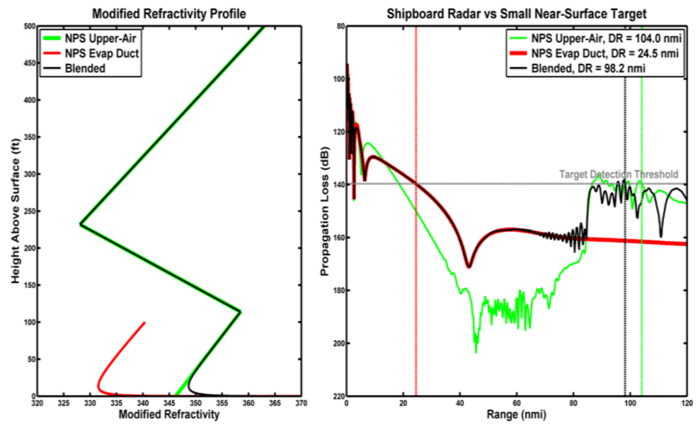

Fig. 8: Propagation loss calculated by P. Frederickson

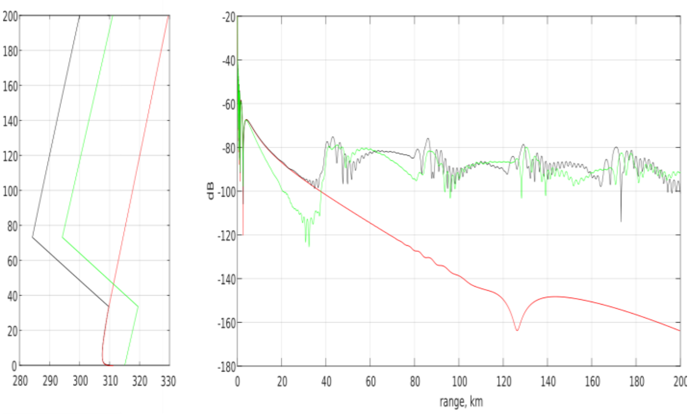

Fig. 9: Propagation loss calculated from our model

4. Conclusion

The impact of the atmosphere in the form of the not only the evaporation-surface duct but also the elevation-surface duct wave on over-the-horizon radio propagation is shown. The impact of the vertical perturbing the profile of the evaporation-surface duct and the impact of the transmitting antenna height on radio propagation is shown. The obtained results to be important for interpretation and setting of ex-periment on surveillance of processes of over-the-horizon of radio waves propagation above the sea. And for forecast of work of radar, it is advisable to supplement the radar complex with a facility for measuring the refractive index profile with the help of a computer program for calculation of the radio link by the parabolic equation method and sensors.

Acknowledgement

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