Anomalous tropospheric propagation: Usage possibilities and limitations in radar and wireless communications systems

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Abstract. The anomalous tropospheric propagation due to extreme superrefraction of radio waves (known also as ducting) has significant influence on radar and communication systems working in microwave range. Up to the last decade tropospheric ducting has been considered rather an unwanted phenomenon as it causes multipath propagation (with all related impairments on communications systems), missed target detection for radars, unexpected interference between different microwave systems working in the same range, etc. The tropospheric ducting mechanism is more typical for coastal and maritime areas than over land. On the other hand, the coastal and maritime areas are known to cause difficulties in planning and designing of the communications links due to the high environmental variability there. During the last years, the development of accurate operational propagation prediction/assessment models and the increasing improvement in meteorological data collection and environmental models gave rise to the idea of making use of the most common effect of ducting, namely, the long-range radio waves propagation leading to signal enhancement near and beyond the radio horizon. This paper aims at outlining the state, achievements and limitations in the usage of tropospheric ducting mechanism to maintain efficient coastal communications links. Reliability of such links from physical layer point of view, advantages and disadvantages of operational propagation and environmental models will be discussed.

INTRODUCTION

The anomalous tropospheric propagation due to variations in meteorological parameters leading to extreme vertical refractivity gradients $dN/dh < -157$ N-Units/km is known as ducting [1]. The tropospheric duct acts as a wave guide for electromagnetic energy of microwave range thus making the propagation conditions to differ significantly from the standard ones. This specific clear-air propagation mechanism of rather short duration may have determinant influence on radar and communication systems' performance and quality of service. Usually the tropospheric ducting is considered to be an unwanted phenomenon as it causes multipath propagation (with all related impairments on communications systems such as short-term fading, inter-symbol interference and increase in signal data bit-error-rate [2]), missed target detection for radars, dramatically increased radar surface clutter, unexpected interference between different microwave systems working in the same frequency range, etc. [3], [4]. Due to the strong moisture and temperature gradients at the immediate ocean surface, coastal and maritime areas are especially prone to ducts' formation [5]. As a result of intensive evaporation from large bodies of water and fast decrease of humidity with height is formed the most widespread duct - the evaporation duct. Advection over the sea or temperature inversions over the earth surface cause formation of surface-based ducts. The high environmental variability makes difficult the planning and designing of communications links in those zones. To overcome the above problems, numerical methods for efficient electromagnetic wave propagation prediction with accounting for the refractivity conditions, sea surface roughness and different propagation mechanisms have been developed and validated, see [6], [7], [8]. At the same time, propagation prediction and visualization tools, aimed at providing...
operationally applicable codes, have been created [9], [10], [11], [12]. All those tools make essential use of the parabolic equation (PE) method [13], [14], see Section 2, for operational performance assessment (i.e. radar/telecommunication coverage calculation) and apply graphical interfaces to visualize refractivity profiles and electromagnetic calculations output. Among them most widely used are: 1) Advanced Refractive Effects Prediction System (AREPS), developed by Space and Naval Warfare System Command (SPAWAR), San Diego, which is an approved electromagnetic systems assessment application for frequencies of 2 MHz to 57 GHz [9]; 2) Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER), developed by the Johns Hopkins University Applied Physics Laboratory [9]; 3) PREDiction de performances des systèmes ElectroMagnétiques (Performance prediction of EM systems -PRED-EM), a decision-aid tool dedicated to the French Navy [10]; 4) PETOOL - a MATLAB-based tool developed for the analysis and visualization of radio wave propagation over variable terrain which has been applied also for over-sea propagation [11].

Above mentioned models and tools are accompanied with increasing improvement in lower troposphere refractivity and sea state estimation/analysis in different area of the world and sophisticated refractive environmental modeling including inversion techniques [15-19]. In [18] are summarized the last 20 years field campaigns for data collection whereas [19] reviews previous work in estimating the atmospheric conditions from electromagnetic measurements which assures real-time tracking of atmospheric parameters. The most common effect of ducting is the long-range radio waves propagation leading to signal enhancement near and beyond the radio horizon [1]. Evaporation ducts exist most of the time in the first few meters above the water particularly in tropical areas. Some areas in the temperate zone (Black sea, Baltic sea, the British Channel, East Anglia) are also prone to anomalous propagation. This with the above achievements in characterizing the radio propagation in the marine atmosphere has led to the idea of taking advantage of the tropospheric ducting mechanism to maintain efficient coastal communications links [20-23]. To the best of the author’s knowledge, the first ever reported use of the evaporation duct for communications purposes is the 78-km experimental link operating at a frequency of 10.6 GHz and providing a data rate of 10 Mb/s which has been established from the Australian mainland to the Great Barrier Reef (GBR), North Queensland, Australia [20]. In [21] a critical overview of the link described in [20] is made. Papers [22], [23] describe an experimental 64 km setup made on the East coast of Malaysia. To design the link and assess link budget in [20-23] the PE method is proposed and used. Those experimental and theoretical investigations have shown that the evaporation duct, especially in the specifically studied areas, is capable of sustaining a high data rate microwave link over non-line-of-site ranges.

This paper aims at outlining the state, achievements and limitations in the usage of tropospheric ducting mechanism to maintain efficient coastal communications links. Reliability of such links from physical layer point of view, advantages and disadvantages of operational propagation PE-based model, some deficiencies of the environmental modeling, are discussed. The paper is organized as follows: the next Section describes briefly the PE method and essential functionalities of the above mentioned operational tools; in the third Sections are discussed the still unresolved issues and possible sources of errors when trying to take advantages of the evaporation duct as propagation environment.

**PE BACKGROUND**

As far as the PE method is well documented in the literature, as well as its application in maritime environments [13], [14], [24], [25], here is reported a very brief description of the most widely used (called standard) PE form. For electromagnetic field calculations the 2D narrow-angle forward-scatter scalar PE, which accounts simultaneously for microwave diffraction, refraction and forward scattering, is given by:

\[
\frac{\partial u(x,z)}{\partial x} = \frac{i}{2k} \frac{\partial^2 u(x,z)}{\partial z^2} + \frac{ik}{2} \left( m^2(x,z) - 1 \right) u(x,z).
\]  

(1)

In Eq. (1) \( k \) is the free-space wave number, \( m=M10^{6}+1 \) is the modified refractive index (the modified refractivity \( M \) is defined as \( M = N + (z/a_e)10^6 \) where \( a_e \) is the Earth’s radius), \( u(x,z) \) is the reduced (slow-varying along the propagation direction \( x \)) function obtained by factoring out the rapid fluctuations of the electromagnetic field component, \( x \) and \( z \) stay for range and altitude. Equation (1) refers to both horizontal and vertical polarization the difference between them being contained in the boundary conditions at the Earth surface. This parabolic approximation of the wave equation is easily solved numerically by means of marching algorithms provided the
field is known on an initial plane and respective boundary conditions are available. The PE accounts for the antenna pattern through the initial field needed to start the calculations. The above characteristics have turned the PE-based method in one of the most widely used methods to solve wave propagation problems. The major drawback of Eq. (1) is that it neglects the backscattering. Under tropospheric ducting conditions the forward-propagated field plays dominant role and this assures the applicability of the Eq. (1) to this type of tropospheric propagation problems. For this reason the PE (1), with its split-step (SS) solution [13], has been adopted in the above mentioned operational propagation tools. The SS solution to the PE is preferred to other numerical solutions for its stability which allows larger step sizes and shorter computational time. The tools described in [9-11] have common characteristics such as: use of 2D SSPE based on the APM model [12] which is a hybrid ray-optic/PE code; this combined model runs faster than the PE with overall accuracy as good as the PE model alone. The hybrid code applies PE only in the regions of strong refractivity gradients or/and at low altitude using other methods, such as geometrical optics/ extended geometrical optics at short ranges and above the PE region. The TEMPER code is solely based on the PE method but applies pseudo-3D version of the 2D PE. AREPS and TEMPER use predefined environmental conditions as input to the PE. Both AREPS and TEMPER allow for specification of atmospheric gaseous absorption as well. The propagation code PREDEM is also based on the APM. This tool is compatible with the outputs of the Numerical Weather Prediction (NWP) codes of the local meteo service and is able to describe the short-term meteorological environment. The sea surface roughness is accounted for in all three tools with modeling of sea clutter included in PREDEM. Another tool, named PETOOL, has been developed by the authors of [11] for modeling terrain effects on radiowave propagation through homogeneous and inhomogeneous atmosphere. Even though not designed for maritime propagation, this free/open-source code which also uses SSPE is mentioned here because of its unique feature over the previously enumerated tools: it applies the two-way SSPE approach by utilizing an iterative forward–backward scheme with wide-angle propagator (Eq. (1) presents the narrow-angle form of the PE).

The output of the PE model is the path loss (PL) or the propagation factor (PF) calculated following Eq. (2):

\[ PL = 20 \log \left( \frac{4\pi r}{\lambda} \right) - PF, \quad PF = 20 \log |\mu(x, z)| + 10 \log(r) + 10 \log(\lambda), \]

where \( \lambda \) is the free-space wavelength, \( r \) is the distance between the corresponding points and the first term in the right-hand side of the expression for the PL is the free-space loss. The PL is an essential parameter for radars and communications links; it determines the link budget and radar coverage.

In spite of all the progress in experimental and theoretical investigations on microwave propagation over the sea and reported possibility of exploiting the evaporation duct to maintain a high data rate microwave communication link, it has been shown as well that unexplained discrepancies (especially, additional losses, [20], but not only) between measurements and theoretical predictions exist. Those discrepancies lead to lower than expected availability of the link and make it unreliable. In the next Section some still unresolved issues (related both to the environmental modeling and the PE model) which could be the reasons for above mentioned inconsistencies are considered.

UNRESOLVED ISSUES AND POSSIBLE SOURCE OF ERRORS

Errors related to the refractivity profile reconstruction. The average refractivity profiles serve as input to the PE model which is very sensitive to their accuracy. Normally the profiles are extracted from the available reliable meteorological models. The problem is that usually those models do not provide data for the first meters immediately above the sea surface, as is the case of ECMWF current model TL799L91 which lowest level, 91, refers to a height of about 10 meters, i.e. evaporation ducts (as well as other heterogeneties) with thickness below 10 meters (the most common case) can not be identified [26]. Also, the meteorological grid in the first 100 meters (at least) should be refined in order to correctly reconstruct the refractivity profile which determine the essential evaporation duct parameters, namely duct height \( z_d \) and duct strength (or \( M \)-deficit). Measurements close to the shore have shown that evaporation duct modified refractivity profiles may differ significantly from the widely used log-linear evaporation duct profile, see Eq. (3), typical for tropical open ocean. A lot of attempts have been made to improve this model adjusting its parameters and slope in order to make it to fit better the measurements, see Ref. [27]. Recently, the US Naval Postgraduate School has developed a state-of-the-art bulk evaporation duct model known as NAVSLaM.
Navy Atmospheric Vertical Surface Layer Model) which is recognized to restore high-fidelity profiles and evaporation duct heights especially under unstable troposphere [28], [29]. This model is now implemented in AREPS. However, in highly stable conditions the model still needs improvement.

\[ M(z) = M_0 + c_0 \left[ z - z_d \ln \left( \frac{z + z_0}{z_0} \right) \right], \]

where \( M_0 = M(z = 0) \), \( z_0 \) is the aerodynamic roughness parameter usually taken to be \( 1.5 \times 10^{-4} \text{ m} \) [13], \( z_d \) is the duct height corresponding to the height at which \( dM/dz = 0 \), \( c_0 \) is the critical potential refractivity gradient usually taken to be 0.13 [27].

Errors related to the lack of reliable and refined local meteorological statistics. A long-term statistics (including seasonal and day/night variations) and analysis will show if the evaporation duct refractivity profiles in the area of interest coincide or differ from the above mentioned models. Also, a good knowledge of troposphere stability conditions in the specific area would help to choose the right profile functions for temperature, humidity, and wind speed, and thus to compute the right modified refractivity profiles [29].

Importance of horizontal resolution. The coastal zone is characterized by changes in duct height and \( M \)-deficit as one goes from the shore to the sea and vice versa. The correct assessment of propagation conditions in those zones requires knowledge of meteorological data along the entire propagation path [16, 18]. The horizontal resolution in the case of range-dependent profiles is still to be determined for the specific area. The PE method and available operational software allow for range-dependent refractivity profiles to be introduced but data about the refractivity profiles is usually available only at the one end of the link.

The refractivity variations (turbulence, aerosols absorption), especially in the first few meters above the sea, are not well studied neither included in the environmental and electromagnetic models.

Adequate consideration of the sea surface roughness. This is another open issue in maritime propagation prediction. Ducting is characterized by very low grazing angles which additionally complicates the problem of rough sea reflection modeling because the effects of wave shadowing should be accounted for [24]. Under low grazing angles, the application of an effective reflection coefficient representing multiplication of the smooth-surface Fresnel reflection coefficient by a roughness reduction factor may not be enough. As an illustration, in Fig. 1 is shown the influence of the roughness on the path loss pattern, see equation (2), for the simple (and still widely used) Miller-Brown roughness reduction factor [30] as implemented in the APM model. Figure 1 is obtained with the following parameters: \( z_d=50 \text{ m} \), \( M \)-deficit of 10 M-units, omni directional antenna at height \( z_a=5 \text{ m} \), vertical polarization, frequency \( F=10 \text{ GHz} \), two values for the wind speed \( u_{10} \), rough sea modeled following [30]. As it is seen from this figure, the increase of the wind speed and, hence, the sea surface roughness, changes the \( PL \) pattern.

FIGURE 1. Path loss under ducting conditions with rough sea modeled by Miller-Brown roughness reduction factor: (a) \( u_{10}=7 \text{ m/s} \); (b) \( u_{10}=10 \text{ m/s} \).
The sea surface roughness destroys the trapping property of the duct structure and thus affect the availability of a possible communication link. Also, as indicated in [10], the low grazing angles are a challenge for the available clutter models. Simulation results with accounting for clutter under evaporation duct conditions have shown significant decrease in the maximum radar detection range [10]; this indicates the need of including clutter modeling in the electromagnetic propagation model.

Open issues related to the PE method. The major difficulty here is the implementation of sea surface roughness and clutter models (existing and, eventually, new) within the PE boundary conditions in a manner to assure stable numerical solution. The same refers to the accounting for the sea waves' motion and high and low tide which are not included in the discussed propagation prediction tools. The two-way wide-angle PE is worth further development and increased application in maritime propagation prediction.

**CONCLUSION**

An attempt is made to summarize the open issues in environmental modeling and electromagnetic wave propagation prediction based on the PE model related to the assessment of a (possible) use of the evaporation duct propagation mechanism to maintain reliable microwave communication links. The above considerations indicate that a lot of efforts are still to be made in order to improve the environmental input to the PE model and strengthen the PE model itself. On the other hand, the good knowledge of the propagation under ducting could improve the maritime (naval and civil) communications even though they are not intended to use the ducting mechanism and will help radar operators to compensate for anomalous tropospheric effects.

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