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Base Data Report

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Report title

Parabolic equation technique in vegetation and urban environments

Abstract (not more than 200 words)

The radio channel gives limitations for wireless communication systems regardless of the propagation environment. Therefore, it is important to model the propagation properly. FOI has developed a promising model using a two dimensional parabolic equation (PE) technique. This model is intended for irregular forest-covered terrain and shows good results.

By this report we study if this technique is useful also for urban environments, since operations in urbanized environment are gaining importance in the scenarios of the armed forces.

Urbanized environment differs very much from forest environment. The lack of line-of-sight propagation forces the radio waves to diffract over rooftops and around corners. This might result in significant multi-path propagation and back scattering, which usually makes the PE technique unsuitable to use in urban areas. Still some attempts have been made to use 2D PE models in such environments and a few papers on this topic are reviewed.

Propagation in urban environments usually requires modelling in 3D and approaches using 3D PE technique for built-up areas are described. 3D PE is a promising technique for the future, but still not fully mature for practical use in built-up areas. At present, we do not find it worthwhile for FOI to engage in 3D PE development.

Keywords

Wave propagation, urban environment, vegetation, modelling, parabolic equation

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Parabolisk ekvationsteknik i vegetation och urban miljö

Sammanfattning (högst 200 ord)

Radiokanalen sätter begränsningar för trådlösa kommunikationssystem oavsett utbredningsmiljön. Det är därför viktigt att modellera vågutbredningen på ett så korrekt sätt som möjligt. FOI har utvecklat en lovande modell, som använder en tvådimensionell parabolisk ekvationsteknik (PE). Denna modell, som är avsedd för kuperad skogsbeklädd terräng, visar på bra resultat.

Med denna rapport har vi studerat om den här tekniken också är användbar för urban miljö eftersom operationer i urbana miljöer förväntas bli allt viktigare i försvarets scenarier.

En urban miljö skiljer sig avsevärt från en skogsmiljö. Avsaknaden av frisiktsutbredning tvingar radiovågorna att diffraktera över hustaken och runt hörn. Detta kan ge upphov till icke försumbar flervägsutbredning och bakåtspridning, vilket vanligtvis gör PE-tekniken olämplig att använda i urbana miljöer. Trots detta har försök gjorts att använda 2D PE-modeller i sådana miljöer.

Vågutbredning i urbana miljöer kräver oftast 3D-modeller och försök att använda 3D PE-teknik i bebyggelse beskrivs. 3D PE är en lovande teknik för framtiden, men är ännu inte helt mogen att användas i urbana miljöer. För närvarande anser vi inte att det är lönt för FOI att engagera sig i utvecklingen av 3D PE.

Nyckelord

vågutbredning, urban miljö, vegetation, modellering, paraboliska ekvationer

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Contents

1 Introduction

In the future, the armed forces must be able to quickly respond to different types of threats and risks. The Swedish parliament has therefore decided that the armed forces are to be developed to the concept of network-based defence [Swedish Armed Forces, http://www.mil.se].

The network will, among other things, provide enhanced battle space awareness to the military forces. The requirement of a common picture of the battle space will lead to an increasing data flow in the communication network. Interoperability with the vital functions of the civilian society and with partners in international peace support operations is essential. Therefore there is an increasing need of flexible and high capacity wireless links as components in the network.

Operations in urbanized environment will be a more common task for the armed forces, both within Sweden when supporting the society in times of severe peacetime difficulties and abroad in international peace support operations. In many ways the communication scenarios may differ from those of peacetime civilian telecom, e.g. with respect to frequencies and waveforms used, locations of terminal antennas, possible base station infrastructure and interference and jamming environment. As a consequence, there is an increasing need for understanding and modelling the radio wave propagation in urban terrain with particular focus on the military scenarios.

It is well known that the radio channel sets limits for present and future wireless communication systems [Waern *et al.*, 2003]. This is true regardless of the nature of the propagation environment, be it a rural area or urban or indoor scenarios. One can use several different techniques to model the wave propagation and in this report we discuss wave propagation modelling by parabolic equation (PE) technique. FOI has developed a wave propagation model using the parabolic equation (PE) technique [Holm and Eriksson, 2002]. This model is intended for forest environment and the results so far are promising. The topic of the present work has been to study if this technique is useful also for urban environments. To start with, we review the propagation aspects in forest. Then we give a brief summary of the FOI model and show some results from calculations of the wave propagation in a forest environment. In chapter 3, we discuss the PE technique for urban areas. Finally, we conclude our report by a discussion leading to a suggestion for the next step in our studies on wave propagation modelling in urban environment.

2 PE technique for vegetation

Military activities in forest environments will most probably always be of importance; therefore it is important to understand how such environments affect the conditions for radio systems. Obstacles between the radio terminals will seriously degrade the propagation conditions. Diffraction effects from non-penetrable objects can usually be accounted for by knife-edge models or by models based on the Geometric Theory of Diffraction (GTD). On the other hand, semi-transparent obstacles in the form of trees or forest are somewhat more difficult to deal with because they allow for (partial) transmission through the obstacles, as well as diffraction over, or around, them. However, multipath propagation can sometimes be neglected in forest environment and a propagation model in two dimensions (2D) is often able to predict the signal or field strength well enough. One important class of such models is based on the parabolic equation (PE) technique in two dimensions. At FOI, a 2D PE model has been developed, which considers effects of vegetation [Holm and Eriksson, 2002]. This model is quite promising, as it is able to consider both the effects of the terrain height profile and the vegetation.

One of the first models especially designed for wave propagation in environments with vegetation is the model by Tamir [Tamir, 1967; Dence and Tamir, 1969]. Here, a forest is approximated by a homogeneous dielectric slab. For both the antennas within the forest, this model is able to give good results. However, outside the forest, that is, for one antenna or both the antennas outside the dielectric slab, it does not seem to work properly. An attempt to deal with these shortcomings can be found in [Tamir, 1977].

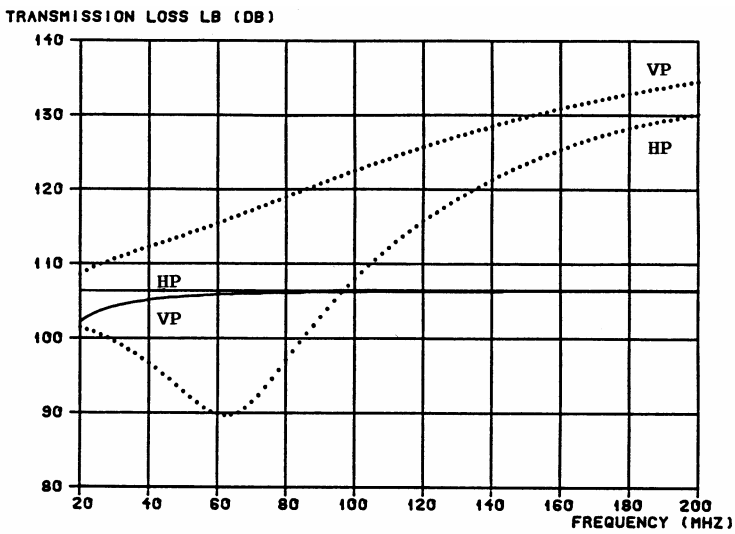

Fig. 1. The forest model by Tamir (dotted lines) for a propagation path of 5 km covered by forest. The solid lines are for smooth spherical earth. The figure is from [Asp, 1986].

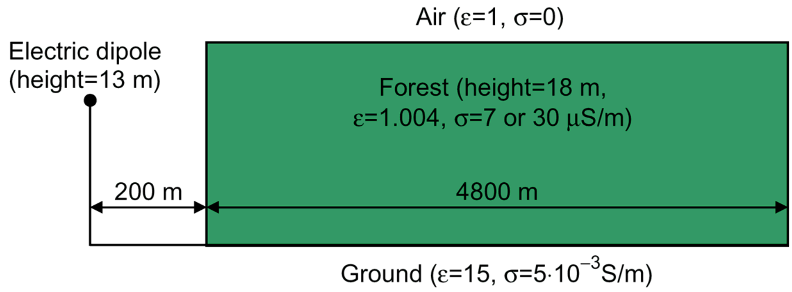

Fig. 2. Forest modelled as a homogeneous dielectric slab. The relative permittivity is 1.004, the conductivity is 7 μS/m for horizontal and 30 μS/m for vertical polarization.

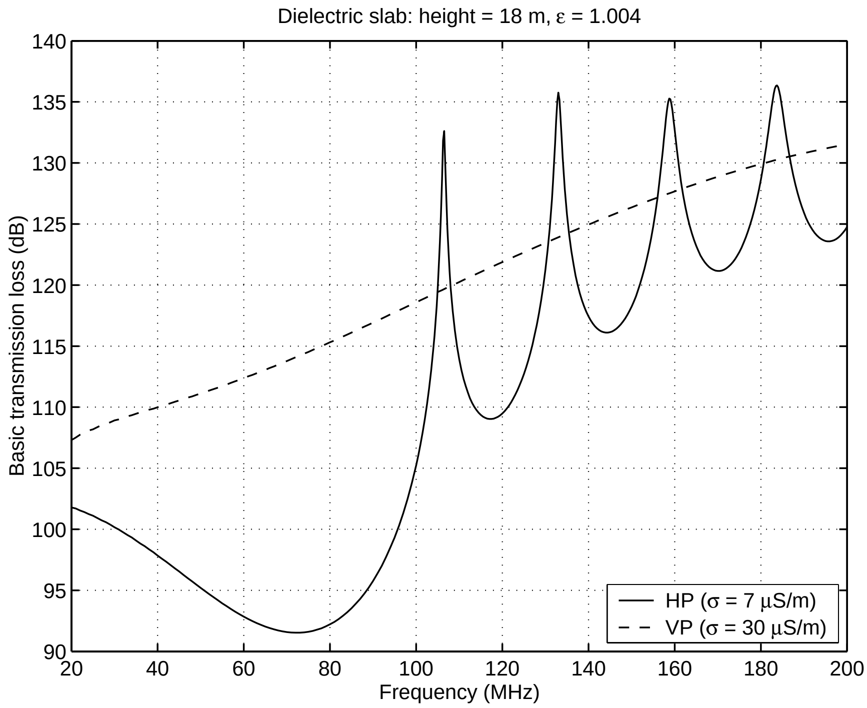

Fig. 3. The PE-model for the homogeneous dielectric slab in Fig. 2. The receiver height is 13 m.

In Fig. 1, a calculation example is shown using the model by Tamir for a propagation path of 5 km covered by forest [Asp, 1986]. The antenna heights are 13 m and the height of the slab is 18 m. The relative permittivity of the slab is 1.004, the conductivity is 7 μS/m for horizontal and 30 μS/m for vertical polarization. The interesting point with Fig. 1, which also is confirmed by experiments, is that the basic transmission loss is lower for horizontal than for vertical polarization.

An important circumstance with the model by Tamir is that, in some examples, the used complex index of refraction for the vegetation is close to unity [Asp, 1986]. If one can assume this, it would be possible to model wave propagation in the forest using the parabolic wave equation technique (PE). The forest region is then modelled by varying the refractive index in the PE-model. This is done in [Holm and Eriksson, 2002] and [Holm *et al.*, 2002].

In [Holm and Eriksson, 2002], an example corresponding to the one in Fig. 1 is calculated using a PE-model. The example, however, differs slightly from the one in Fig. 1. In order to be able to calculate an accurate initial field to the PE-model in a simple way, the first 200 m of the propagation path in Fig. 1 is assumed to be an open area. The remaining part of the path, i.e. 4800 m, is covered by forest, see Fig. 2. The initial field is calculated at 200 m using the ground wave propagation model by Norton [Norton, 1936; 1937]. The result is shown in Fig. 3. The most important findings here is that, below 100 MHz, the basic transmission loss is lower for horizontal than for vertical polarization; in line with the model by Tamir and experiments.

The PE model has also been tested against propagation measurements in a fir-forest environment near Östersund, in the northern part of Sweden, in November 2000, with good results [Holm and Eriksson, 2002; Holm *et al.*, 2002]. The measurement set-up was designed to investigate the obstruction effect of a forest edge close to the end terminal of a frequency hopping military tactical radio link. The measurement system consisted of a transmitter and a receiver synchronously swept in frequency. Although measurements exist for several frequencies, we will only show the result for the frequency 1355.5 MHz from [Holm and Eriksson, 2002].

From the terrain profile along the measurement path in Fig. 4, it can be seen that the first Fresnel zone is almost clear along the path except for the forest covered part at the end. The last part of the measurement path was a 170 m wide homogenous fir-forest area, followed by an open field where the receiver was placed; see Fig. 5. The trees were evenly aged and had a maximum height of approximately 22 m. The edge between the forest and the open area was sharply defined.

The antenna installation at each site consisted of two equal antennas, one mounted for vertical polarization, and one for horizontal polarization, making it possible to electronically switch the polarization. At the transmitter site, the heights above ground for the vertically and horizontally polarized antenna were 26.0 and 26.9 m, respectively. The two receiver antennas were mounted on a mast adjustable in height and separated vertically by 1.1 m, with the horizontally polarized antenna in the highest position. The antenna height above ground could be altered between 6 and 25 m (lower antenna).

Measurements were made with the antennas located in the open area at three different distances from the forest. The first antenna location was 9 m, the second 51 m, and the third 109 m behind the fir-forest edge, see Fig. 5. For each of these antenna positions, the antenna heights were varied between 6 and 25 m in steps of about 2 m.

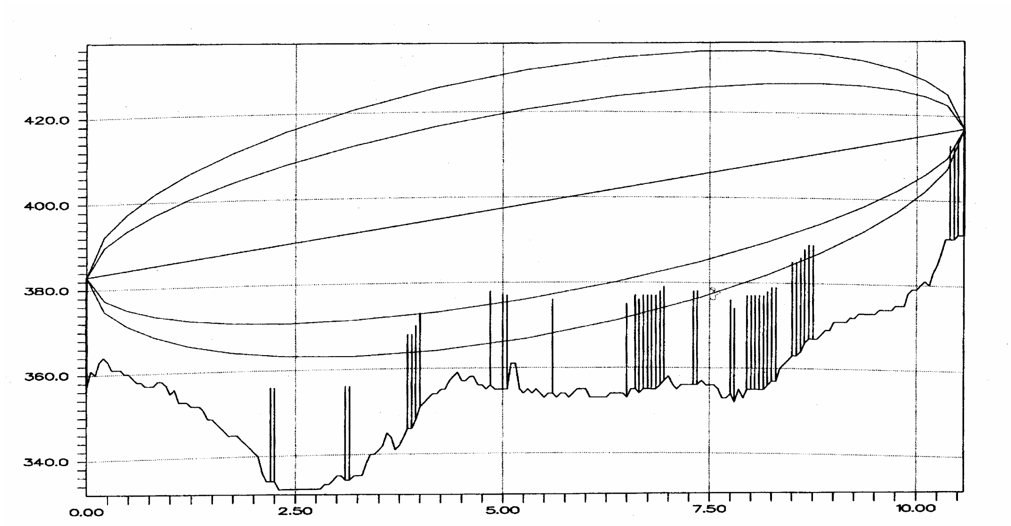

Fig. 4. Terrain profile along the measurement path. The profile has a resolution of 50 m and the vertical bars indicate segments covered with forest. The first and second Fresnel zones shown in the figure are for the frequency 1600 MHz and a receiver height of 25 m above ground.

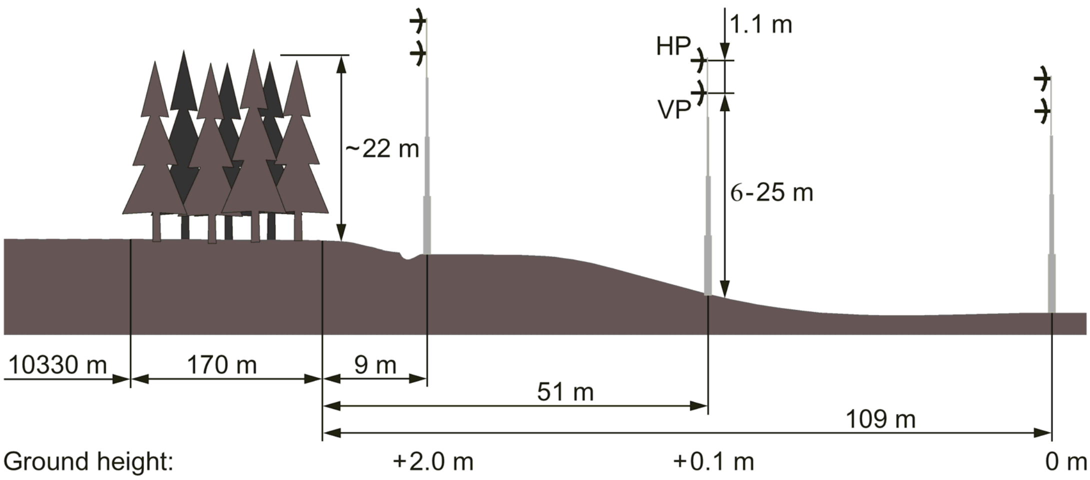

Fig. 5. The receiver antenna locations.

For the comparisons, the somewhat simplified terrain profile in Fig. 6 is used. The initial field is computed using geometrical optics at a distance of 750 m from the transmitter. Furthermore, each segment covered with forest is approximated by a dielectric slab following the terrain. The slab is characterized by its height and complex dielectric constant, i.e. its relative permittivity ε_r and conductivity σ. The values of these parameters have been chosen in such a way that a good agreement between theory and experiment is obtained. The height is set to 18 m, the relative permittivity to 1.004, and the conductivity to 180 μS/m. In addition, the relative permittivity and the conductivity for the ground, which do not significantly affect the result, are set to 15 and 10^{-3} S/m, respectively.

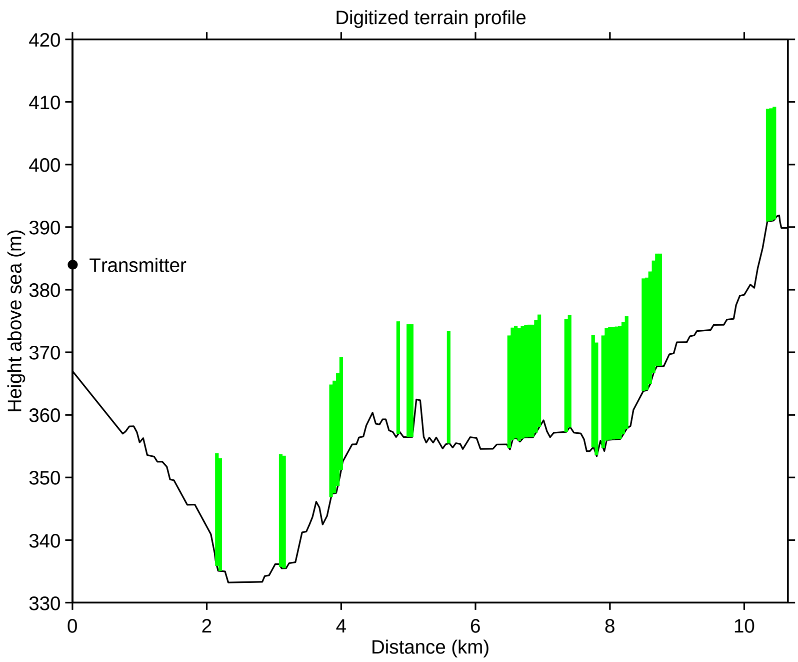

Fig. 6. Approximated terrain height profile used for the PE calculations. The green vertical lines, 50 m wide, are segments in the terrain database covered by forest.

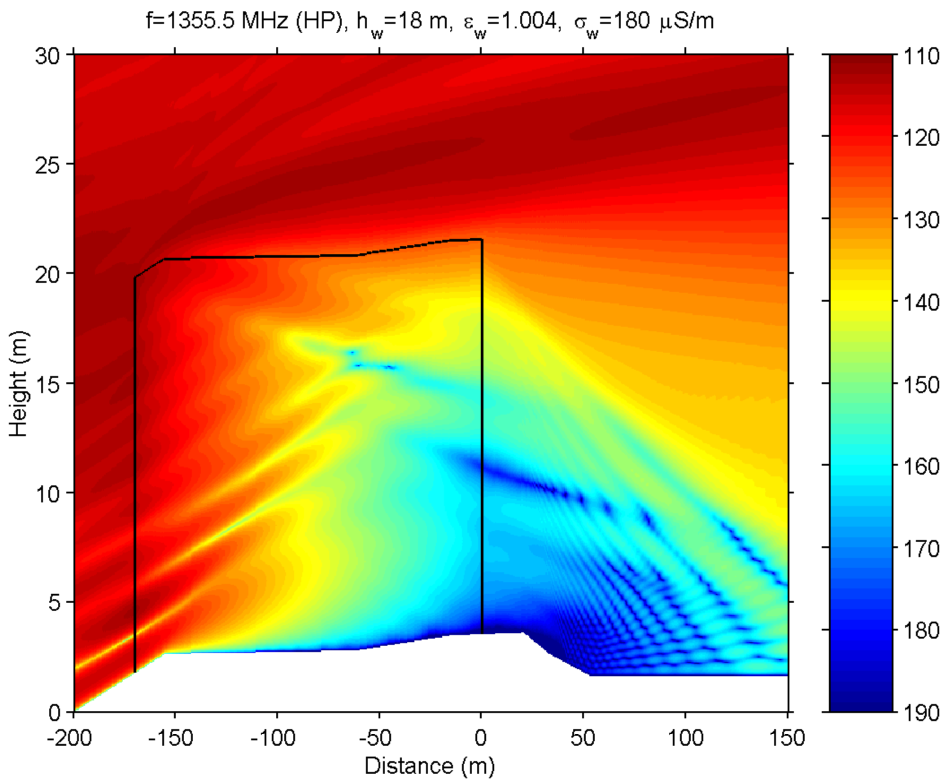

Fig. 7. Basic transmission loss for the frequency 1355.5 MHz. The forest slab at the end of the propagation path is located between −170 m and 0 m, see the solid line in the figure. Its height, relative permittivity, and conductivity are 18 m, 1.004, and 180 μS/m, respectively. The height zero in the figure is located about 388 m above sea level. In the bottom of the figure the terrain profile is visible.

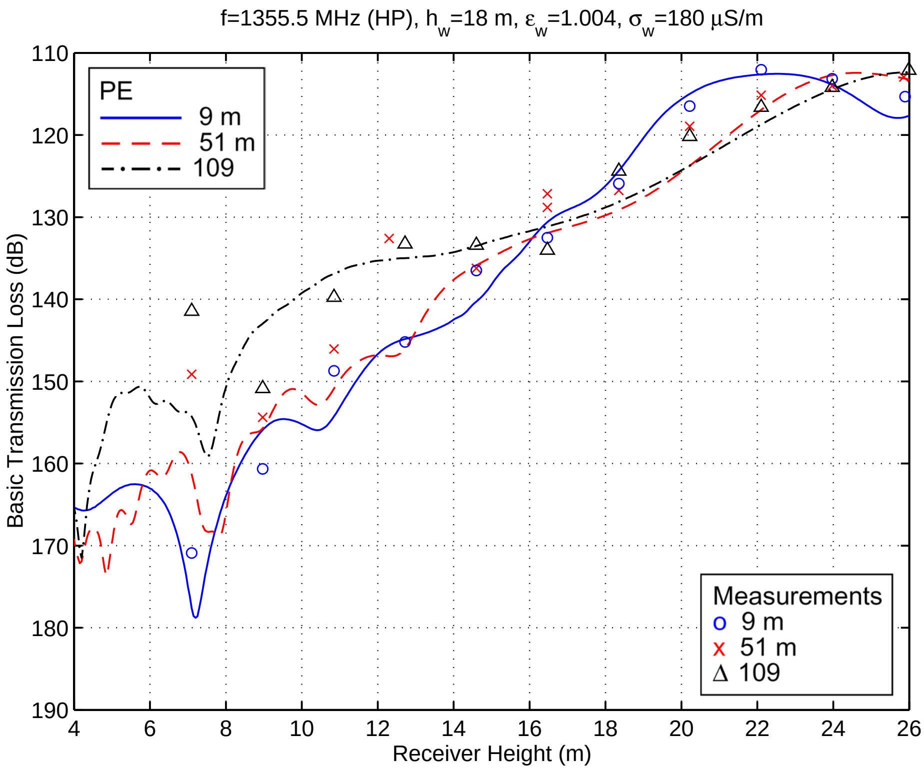

Fig. 8. Basic transmission loss versus receiver height above ground for the frequency 1355.5 MHz. The solid, the dashed, and the dashed-dotted line are the transmission losses at the distances 9, 51, and 109 m, respectively, from the forest edge. Corresponding measurements have the markers o, ×, and Δ, respectively.

The calculated PE-field for the last part of the propagation path is shown in Fig. 7 for the frequency 1355.5 MHz. The figure shows that the field propagating within the forest slab is attenuated quite rapidly. On the other hand, the figure also suggests that the main contribution to the field near the forest edge is transmitted through it rather than diffracted over it. However, for larger distances from the edge, the diffracted field gives the main contribution.

Fig. 8 shows the basic transmission loss versus the receiver height for the frequency 1355.5 MHz. The figure presents results for the distances 9, 51, and 109 m from the forest edge. Largely, an agreement in the general behaviour of the curves between the PE-model and measurements can be seen in the figure. Oscillations for lower receiver heights are present in both the PE-calculations and the experiments. However, the height resolution in the measurements is too low to determine the interference pattern more in detail.

The somewhat low resolution in the experiments affects, of course, the possibility to assign accurate electrical parameters for the forest. However, the results obtained here suggest that vegetation can be modelled through the refractive index in a PE-model, at least if one can assume refractive index values close to unity for vegetation.

3 PE technique for urban areas

As operations in urbanized environment are gaining importance in the scenarios of the armed forces, it is important to understand how such an environment affects the conditions for radio systems. Urbanized environments differ very much from forest environments. The lack of line-of-sight propagation forces the radio waves to diffract over rooftops and around corners. Furthermore, the waves will reflect against and scatter at, not only big obstacles, like walls and asphalt, but also cars parked in the street, lamp posts and traffic signs. The amount of reflections and scattering depends on the frequency, angle of arrival and the surface material. The result is called multi-path propagation and cannot usually be neglected in urban environments. Instead, it can here be the main process contributing to the field strength. Also, multi-path propagation means that energy will arrive to the receiver from several different directions, which requires a treatment in three dimensions (3D). One way of solving this problem is to use a ray based model such as Geometrical Theory of Diffraction (GTD) [McNamara *et al.*, 1990]. GTD is commonly used in built-up areas and is able to account for multi-path propagation in 3D, also back scattered rays, that is, propagation paths going backward. An example of a backscattered ray is the multiple reflected one in Fig. 9.

Back scattering is a process that can often be disregarded in rural terrain but not in built-up areas. This makes the PE technique a doubtful method to use in urban areas, simply because PE techniques do not include back scattering. The starting point of the PE technique is the choice of a paraxial direction (often chosen as the line-of-sight direction between the terminals), which makes it possible to use certain approximations resulting in a parabolic equation. However, the approximations are only valid if the energy propagates at angles close to the paraxial direction. Usually, that is a condition that is hard to satisfy for built-up areas due to multi-path propagation. On the other hand, one problem within ray based models is to find the important propagation paths, that is, the important rays connecting the transmitter with the receiver. Usually, a built-up area gives a huge number of possible rays and one has to find the rays that contribute most to the field strength. For scenarios involving a large number of buildings, the implementation of an efficient routine, tracing important rays in three dimensions, is far from straightforward. Thus, we shall here take a closer look at a few papers using the PE technique in built-up areas. The purpose is to assess the usefulness of the PE technique in urban environments and its expected accuracy in such environments.

Although a 2D model usually is not sufficient in urban environments, attempts have been made to use 2D PE models in such environments. In [Eibert, 2003], a 2D PE model is used, but only to find a solution on a macroscopic level for a transmitter above vegetation and buildings. Close to the receiver, which is assumed to be in a built-up area, a 2D ray optical method is used for the last part of the propagation path in order to take care of propagation effects due to the buildings. Even though the ray method is in two dimensions, it is believed to be more accurate than a pure 2D PE model in urban environments. The two models together form a so called hybrid PE model and will be described more in detail in Sec. 3.1.

Propagation calculation in urban environments usually requires modelling in 3D. In [Janaswamy, 2003], such an approach using the PE technique for built-up areas is described. This is a so called 3D vector PE model able to consider polarization effects, which are important in urban areas. The model differs from the 2D PE model, where the field is calculated in a vertical plane between the transmitter and the receiver location, in that it also includes the horizontal plane between the transmitter and receiver in the calculation. A situation in a built-up area that can be handled by this model is shown in Fig. 10. However, the model is still a PE model, and because of that, it is not able to consider cases with back scattering, like the situation shown in Fig. 9, as back scattered waves are not included at all in PE techniques. The 3D vector PE model will be described in Sec. 3.2.

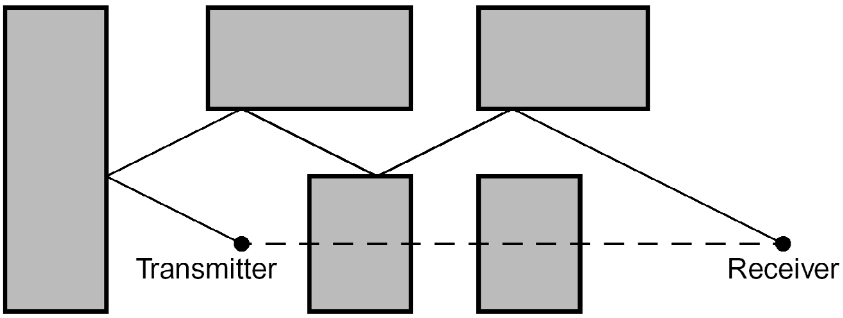

Fig. 9. Example of a multiply reflected ray (solid line) and a (multiply) diffracted ray (dashed line) in an urban area. The reflected ray is scattered by the building walls in both forward and backward directions towards the receiver. The diffracted ray is bent as it passes over the roof tops.

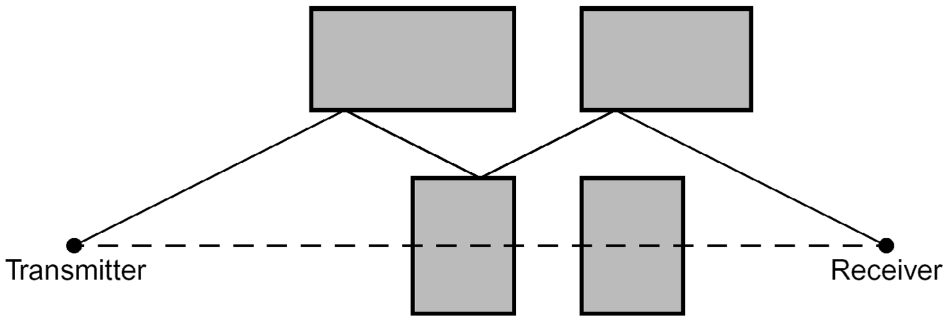

Fig. 10. Example of a multiply reflected ray (solid line) and a (multiply) diffracted ray (dashed line) in an urban area. The reflected ray is scattered by the building walls in forward direction towards the receiver. The diffracted ray is bent as it passes over the roof tops.

3.1 2D hybrid PE

From the above it is clear that the PE technique has some limitations; for instance, it is not able to take care of backscattering or propagation situations where there are rays with large angles measured from the paraxial direction. This does not make the PE technique the first choice of model to use in built-up areas, as it is often impossible to choose paraxial directions that do not give propagation paths with large angles in such environments. One way of dealing with the limitations is to switch to another method in regions where the PE technique is not accurate enough. In doing so, one obtains a so called hybrid PE model. Here, we will describe a 2D hybrid PE model for built-up areas, in which, at some point, a ray optic technique is used instead of the PE technique.

In [Eibert, 2003], a ray optical model is used in combination with a 2D PE. The PE technique is here used to find a solution on a macroscopic level, when the transmitter is above vegetation and buildings. The irregular terrain profile is approximated by linear sections. Vegetation and buildings are represented by homogeneous layers; see Fig. 11, which is from [Eibert, 2003]. The goal for this part of the calculation is to find the field distribution in the air above the terrain.

The parabolic wave equation is solved using Fourier split-step (FSS) technique [Donohue and Kuttler, 2000; Levy, 2000; Eibert, 2002], which gives solutions that represent fields in terms of plane wave decompositions. In [Eibert, 2003], it is assumed that such a plane wave representation of the fields in the air region above the terrain is available close to all receiver positions of interest. Each plane wave is then assumed to be incident on the receiving environment. The received field is in the next step calculated based on a 2D ray optical model including direct, reflected and diffracted rays and, in a forest environment, also attenuated rays; see Figs. 12 and 13, which are from [Eibert, 2003]. We will not consider forest here, as we believe that the approach in Sec. 2 above is a better way of taking into account effects of vegetation.

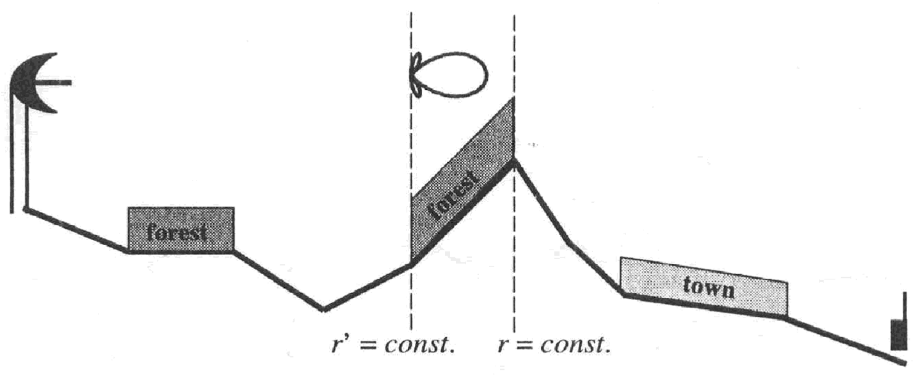

Fig. 11. Macroscopic terrain profile model including vegetation and urban areas as homogeneous layers. The figure is from [Eibert, 2003].

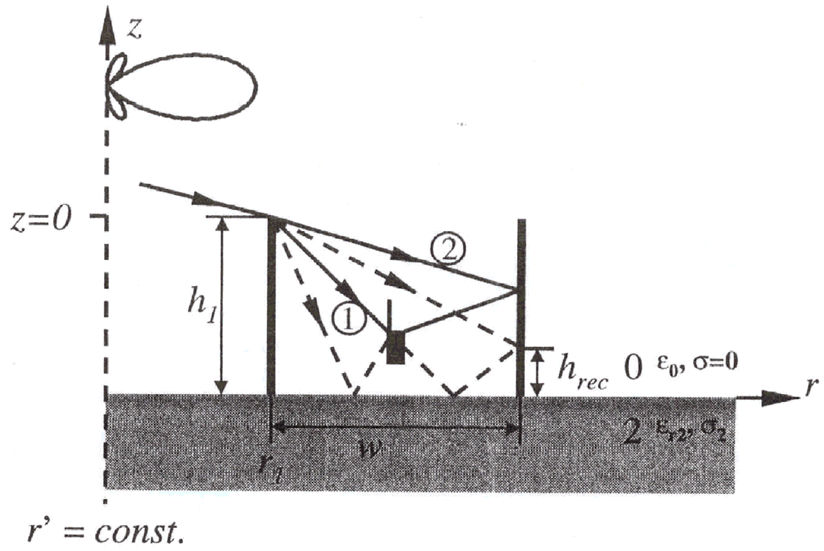

Fig. 12. Diffracted and reflected ray contributions in a built-up area. The figure is from [Eibert, 2003].

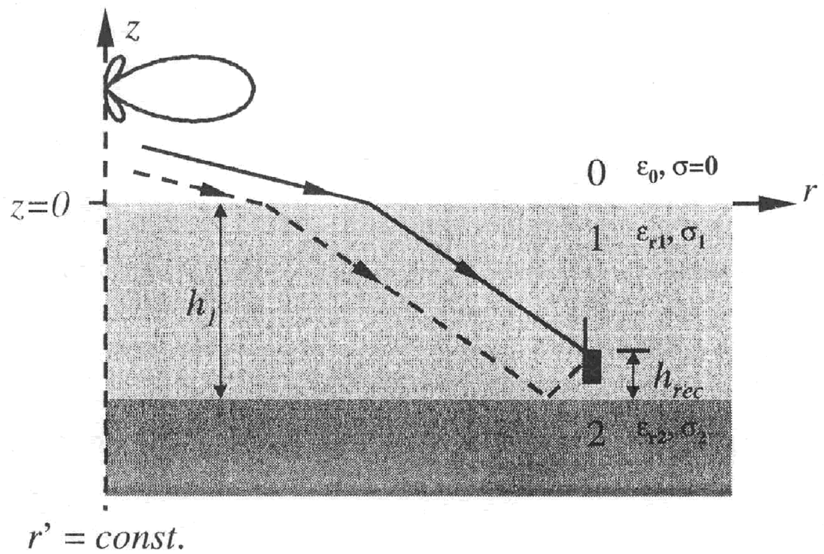

Fig. 13. Refracted and attenuated ray contributions in a forest area. The figure is from [Eibert, 2003].

Thus, the PE model is used to calculate the field above buildings and vegetation close to the receiver point. Then a ray optical model is used for the last part of the propagation path. As FSS gives a plane wave decomposition, all ray contributions have to be integrated to get the total field. In practice, just a few ray types are used for the last part of the propagation path, as too many rays might result in excessive computation times. Fortunately, a few important rays should be enough, as the ray optical model is only used in a small area near the receiver.

In [Eibert, 2003], the hybrid PE model is compared to measured data. It is said that the model produces better results than state-of-the-art semi empirical models. That might be true, but the differences between the models are quite small compared to the magnitude of the computational errors. Even if the new model is more advanced than the semi empirical ones, it is still a 2D model. An urban environment in reality is believed to yield propagation paths (or rays) requiring a treatment in three dimensions (3D). Concerning propagation paths with large angles to the receiver point, the model in [Eibert, 2003] is only able to take care of these if they originate from the last roof top. It cannot take care of situations in an urban environment where important rays require a 3D treatment. Examples of rays requiring a 3D treatment are shown in Figs. 9 and 10, i.e. the rays represented by solid lines that propagate in the horizontal plane.

Even though the model by Eibert clearly has shortcomings, it should be able to handle some of the effects due to buildings at the receiver point. Furthermore, it should be able to offer a reasonably computer efficient model, at least if one tries to keep the ray optical model as simple as possible. This model together with our approach to include effects due to vegetation in Sec. 2, could be interesting to use for upgrading Detvag [Asp *et al.*, 1997] developed at FOI. Detvag is a program which uses 2D propagation models and it is today not able to handle vegetation properly. If computation times can be kept reasonable, the approach in Sec. 2 to include vegetation effects using a 2D PE model is a very promising method to implement in Detvag. Moreover, when the transmitter is above vegetation and buildings, the approach by Eibert [2003] to include propagation effects due to buildings at the receiver point is also promising.

3.2 3D vector PE

A 3D PE model is able to take care of situations like the one shown in Fig. 10, which are beyond the capability of a 2D PE model. This could make it possible, to some extent, to use a 3D PE model as a stand alone method in built-up areas. However, in a 3D PE model, one still has to choose a paraxial direction and, consequently, a 3D PE model is also only valid if the energy propagates at angles close to this direction. Here, a so called 3D vector PE model will be described.

One of the first attempts to find a 3D PE solution is reported in [Zaporozhets and Levy, 1996]. In that paper, a 3D approach is presented using the scalar PE for one isolated building. Application of this approach to realistic scenarios with multiple buildings is not straightforward, though. In [Zelley and Constantinou, 1999], a more useful 3D scalar PE for propagation over irregular terrain with gentle slopes is put forward. However, both these 3D formulations are based on the scalar Helmholtz equation, which means that depolarization of waves is ignored. A natural extension of the 3D scalar to vector formulation is to consider three scalar equations, one for each field component. In a source-free region, the three scalar functions must be coupled at all points in space through the divergence-free condition.

In [Zaporozhets, 1999], a 3D vector PE model is formulated and solved by finite difference technique. There, however, the divergence-free condition is only applied near an object, that is, the three scalar functions are not coupled outside the object. At least, this will couple the field components at the boundary of the object, which means that depolarization is included in the formulation. Outside the object, the field components are not coupled and the number of unknown scalar functions is regarded as three, which has no clear theoretical justification [Janaswamy, 2003]. The reason is due to difficulties in combining a wide-angle Padé scheme with the boundary conditions. Instead, a low-angle scheme, which is able to handle the field-to-object interaction, is used close to buildings. Further away from the object (3-5 wavelengths), the solution is propagated as in free-space with a wide-angle Padé scheme. This assures a better large angle behavior, but the coupling between the field components may be incorrect.

In [Janaswamy, 2003], a more rigorous approach is presented. There, one starts with the formulation of the exact boundary value problem, found by considering the scalar potentials from the electric and magnetic currents. Of course, excessive computational resources will be required to numerically solve this elliptic problem, and for long-range problems, it will be nearly impossible. Thus, approximations have to be made. In [Janaswamy, 2003], one assumes a paraxial direction along which only forwardly propagating waves are permitted. Then the parabolic approximation is used in order to give a parabolic equation in three dimensions. As the basic formulation is an exact boundary value problem in three dimensions, the resulting 3D vector PE model should describe the coupling between the fields better than the one in [Zaporozhets, 1999]. An advantage with the approach in [Zaporozhets, 1999] though, is its simplicity compared to the one in [Janaswamy, 2003], that is, an implementation of the model in [Zaporozhets, 1999] is more straightforward than an implementation of the one in [Janaswamy, 2003].

The 3D vector PE model differs from a 2D PE model, where the field is calculated in a vertical plane between the transmitter and the receiver location, in that it also includes the perpendicular direction between the transmitter and receiver in the calculation. This is inevitable if one wants to include polarization effects. Even though the 3D PE model is able to account for polarization effects, such as depolarization, the initial solution that has to be marched towards the receiver is confined to a perpendicular plane, which gives a considerably increased number of solution points to march along the range direction. As a result, a 3D vector PE model could easily require 100 times longer runtimes than a 2D one, which, of course, is a disadvantage. Furthermore, in line with 2D PE models, it is not able to consider cases with back scattering or propagation paths having large angles measured from the chosen paraxial direction.

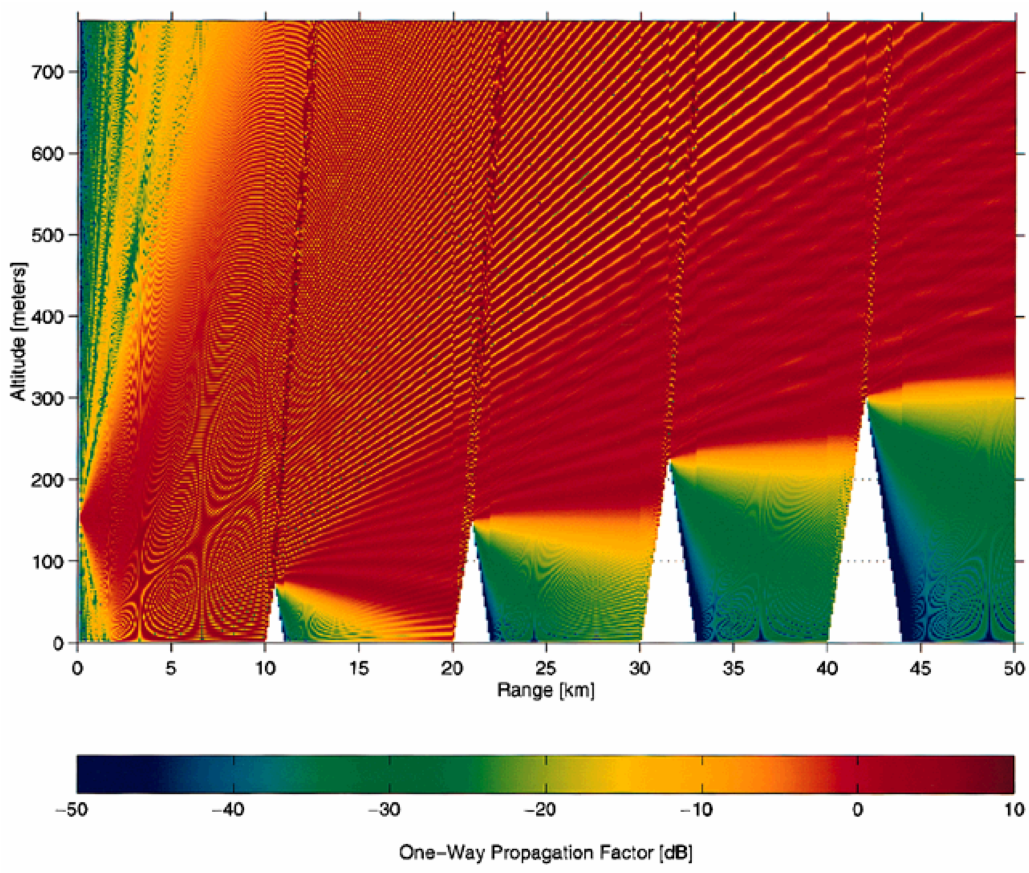

Fig. 14. Propagation over a model terrain profile calculated by the piecewise linear wide-angle shift map. The pyramid slopes are each 8.67°. A horizontal polarized 3-GHz source with 3° beam width is located 152 m above origin. The surface is perfectly conducting. The figure is from [Donohue and Kuttler, 2000].

Turning now to the computational examples in [Janaswamy, 2003], they are all for quite simple object geometries. None of the examples is for a realistic and probable scenario in a built-up area. In particular, the terminals are located rather far away from the buildings. Our concern with this may be illustrated by results from a 2D PE calculation in another paper by Donohue and Kuttler [2000]. Looking at Fig. 14, which is from [Donohue and Kuttler, 2000, Fig. 6], a distortion of the field can be seen near the vertices of the wedges. This error might be due to limitations in the shift-map method and/or the split-step solution, which is directly related to the discontinuous change in surface slope [Donohue and Kuttler, 2000]. As a building standing on the ground means serious discontinuous changes in the surface slope, distortion of the field would be expected near buildings also for the method by Janaswamy [2003]. How severe this distortion might be in the 3D model is not indicated by the examples, as these do not at all show what happens when moving close to the objects. This circumstance makes it hard to tell how well the model by Janaswamy would perform in a realistic scenario in a built-up area, where it is highly possible to end up close to a building.

4 Conclusions and discussion

Two dimensional parabolic equation techniques can be applied to irregular terrain with good results. It is possible to include effects of vegetation, such as forest, by approximating each terrain segment covered with forest by a dielectric slab following the terrain. The slab is then modelled by varying the index of refraction in the PE-model. In order for the PE-model to give accurate results, the choice of the refractive index for a forest region has to be close to unity. A refractive index close to unity is also the choice that gives the best agreement between the PE-model and experiments. Overall, the results obtained suggest that vegetation can be modelled through the refractive index in a PE-model and that one can assume values of this index close to unity for the vegetation.

The finite difference (FD) implementation of 2D PE developed at FOI is well suited for calculating propagation in vegetation. We recommend that the software Detvag be upgraded with this PE model as an option.

A popular alternative to FD schemes when implementing the PE technique is the Fourier split step (FSS) approach. The former gives more straight forward computer codes than the latter but requires smaller marching steps and, hence, may lead to heavier computations. If we decide to proceed with further development of the PE technique, it is probably worthwhile to perform a deeper assessment of the trade-offs between the two approaches.

The hybrid model by Eibert may have potential as an extension to Detvag in urban areas. However, the technique must be further assessed before any such upgrading is undertaken. In particular, it is not clear whether it has any real benefits beyond purely ray optical technique.

3D PE is a promising technique for the future, but much work remains before a reliable software for practical calculations can be realized. A major problem is that the computations will be excessively time consuming even for computations over rather small volumes (measured in wavelengths). After some years of normal processor development this problem will probably be eliminated. Furthermore, the mathematics of the 3D PE is rather complicated and there are uncertainties in the theoretical foundations of the method that have to be sorted out.

One fundamental limitation with the PE method is its inability to handle very large propagation angles, and backscattered rays in particular. In urban propagation such rays give essential, and sometimes the only, contributions to the received signal. It may be conceivable to devise schemes where the paraxial direction is changed after reflections at building surfaces, but this will become extremely complicated in real urban scenarios with dozens of propagation paths to the receiver, also paths involving multiple reflections. At present, we therefore do not find it worthwhile for FOI to engage in 3D PE development. When time is ripe user friendly softwares based on this technique will probably emerge.

One exception where 3D PE may be a realistic approach already today is for propagation calculations in tunnels. The paraxial direction then is in the forward direction of the tunnel and the perpendicular area of calculation is limited in size and has a well-defined boundary. If the tunnel does not have any sharp bends and its walls are reasonably smooth, a straight forward 3D FD PE implementation may work very well. FOI has the necessary expertise and experience to take on this kind of task.

5 Further work

As mentioned in Sec. 4, a 3D vector PE model for calculating wave propagation in a tunnel environment is an interesting topic for further research. We have the expertise and experience to do this, and we believe that such a model is valuable for simulating the communication link for rescue operations etc. in tunnels. However, at present we have no financing for this work, at least not within the current project "The properties of the communication channel in urban environments" *(in Swedish: Kommunikations kanalens egenskaper i tätort – KOMET)*. We will therefore search separate funding for this task.

The PE models for urban environments presented in this report are more or less only useful for macroscopic profiles, typically for wave propagation over long distances where buildings appear along the path. The likely military scenarios are somewhat different. The soldiers will act in the streets, on the roofs, inside buildings and in basements. The distance between transmitter and receiver will mostly be rather short, but on the other hand both the transmitter and the receiver will often be below rooftops, and use peer-to-peer communication. The wave propagation in such scenarios will to a large extent occur via multi path, including reflections, diffractions and backscattering. Based on our knowledge in PE methods we believe that this technique is not yet ready to be used for calculating the wave propagation in military urban scenarios.

Within the current project we will, instead, focus on models based on ray-optics. Commercial softwares are available, but these are above all developed with focus on scenarios with a base station and a mobile, and are mainly built for GSM-frequencies. The further development is directed towards UMTS-frequencies, rather than the lower frequencies of the NATO-band or TETRA. Military urban communication will be between man-held or vehicle-mounted equipments, i.e. peer-to-peer communication, and the frequencies will mostly be in the VHF and lower UHF band. Those frequencies will probably show wave propagation effects, which are not so well reproduced by standard commercial softwares. To modify relevant program routines in a commercial software to account for those propagation effects is probably the most efficient way to achieve a program that meets the military requirements. However, such a task will definitely require some cooperation with the software manufacturer.

Deterministic wave propagation calculations in urban environments make use of detailed building data bases. One aspect of our evaluation of commercial programs is to look at the usefulness of Swedish building data bases in these softwares. Furthermore, we investigate the flexibility with respect to connecting the result outputs to subsequent external calculations and the possibility to modify software routines according to user needs.

Within our collaboration with Lund University we will have good opportunities to analyse propagation conditions for the interesting military frequency ranges. Together with Lund University we will perform measurements with a MIMO Channel Sounder in the frequency range around 300 MHz in urban environments. The experience from those measurements will be very useful for the research in urban wave propagation and for developing new models.

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