Model-Based Inversion Algorithms for Improved Tunnel Detection via Borehole Ground Penetrating Radar

ALERT
AWARENESS AND LOCALIZATION OF EXPLOSIVES-RELATED THREATS
Northeastern University

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Abstract

The primary objective of this research is to develop new inversion algorithms for the BH-GPR system to detect tunnels utilizing a waveguide-based model to represent the layered profile of soil. These algorithms will more accurately represent the wave propagation properties that are not taken into account in current techniques. They are also likely to enhance the accuracy of the detection and localization of tunnels existing in the complex soil media.

Introduction

In recent decades, there has been an increasing emphasis on the border protection between America and its neighboring nations. The U.S. Customs and Border Protection, and Department of Homeland Security make ceaseless efforts to prevent illegal activities and threats from traversing the borders. As a result of the tightened security above ground, the utilization of underground tunnels has become more prevalent for illegal activities such as weapons smuggling and drug trafficking.[1] To help further the security of the United States' borders, there is a strong interest in developing technologies to detect and localize these tunnels.

Figure 1
Sophisticated tunnel with electric rails [2]

Detection and imaging of tunnels in any given region of ground are made possible because the air that fills them is materially different from anything else underground, but challenging because of the large noise to signal ratio introduced by unknown variation of the ground surface and volumetric inhomogeneities.

A Borehole Ground Penetrating Radar (BH-GPR) system has recently been explored for such purposes. The data collected by this system reflect the soil properties underground that in turn could suggest the presence of potential tunnels.

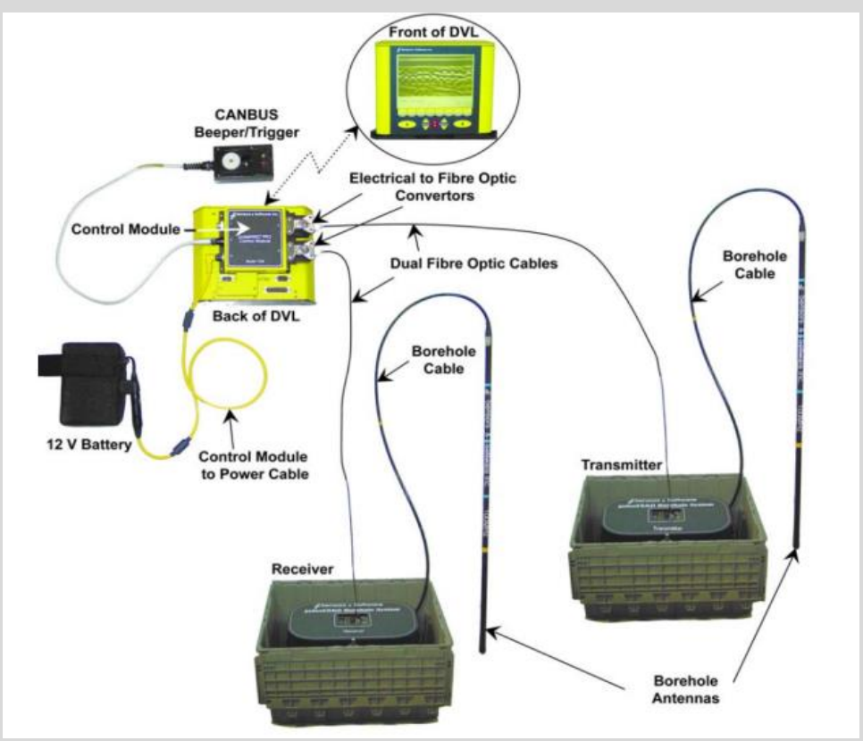


Figure 2
A pulseEKKO PRO
BH-GPR system [3]

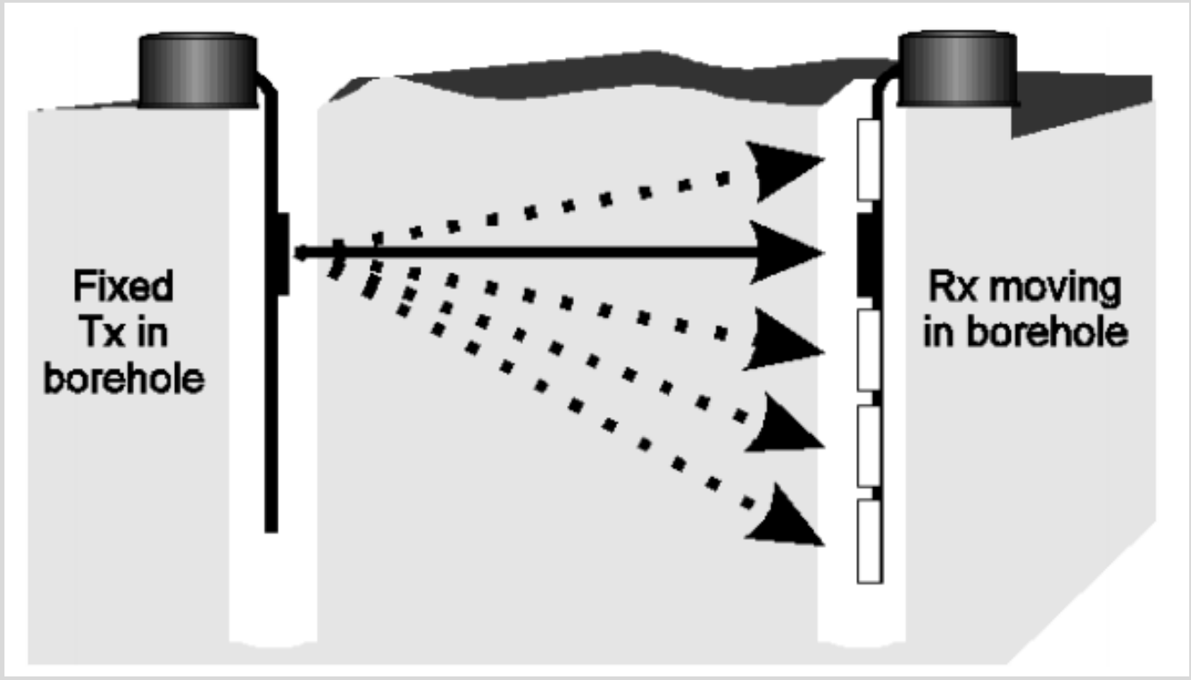


Figure 3
Cross-section of soil
with BH-GPR [4]

Identifying the Soil Layers

The current method used in BH-GPR systems to estimate the soil properties uses the assumption that electromagnetic waves propagate in a direct path between the transmitting and receiving antennas. This assumption is fallible since the wave propagation is more complex which makes detecting and localizing tunnels in inhomogeneous soil difficult (Figure 4).

To get a more accurate estimation of the wave propagation and soil properties, we are developing a waveguide -based algorithm to take into account the different layers of the soil, which will improve tunnel detection and localization.

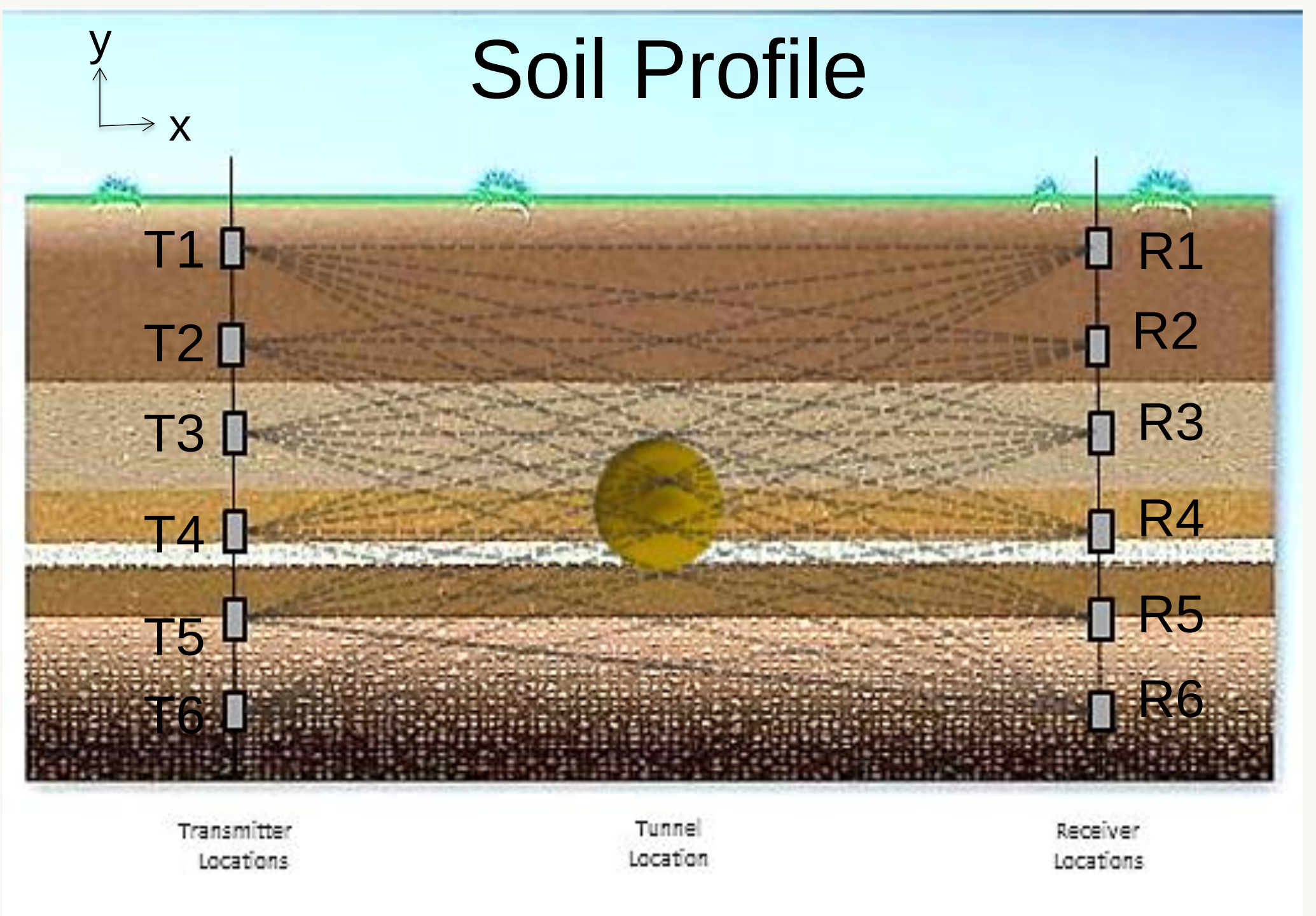


Figure 4
Cross-section profile of soil with inhomogenities including the BH-GPR and a tunnel [5]

The waveguide-based algorithm will attempt to excite a single mode of a soil layer structure which will propagate with a constant phase shift over all over all layers. To do this we need to first determine the mode of the layered structure.

Method to Determine Modes of Soil Layers

If we normalize the individual received fields by its respective transmitted fields, the total received fields can be related to the individual transmitted fields by the normalized individual received fields through the matrix equation:

$$\begin{bmatrix} E_{R_1T_1} & \cdots & E_{R_1T_n} \\ E_{R_2T_1} & & E_{R_2T_n} \\ \vdots & \ddots & \vdots \end{bmatrix} \cdot \begin{bmatrix} E_{T_1} \\ E_{T_2} \\ \vdots \end{bmatrix} = \begin{bmatrix} E_{R_1} \\ E_{R_2} \\ \vdots \end{bmatrix} \longrightarrow \bar{\bar{A}}\bar{x}=\bar{b}.$$

If the transmitted fields are a mode of the layered structure, they must be related to the total received fields by a constant phase shift.

Using the eigenvalue decomposition of the individual received fields from each transmitter we can determine the eigenvalues and eigenvectors of the system that satisfies equations:

$$\begin{bmatrix} E_{R_1} \\ E_{R_2} \\ \vdots \end{bmatrix} = e^{-jk_xd} \begin{bmatrix} E_{T_1} \\ E_{T_2} \\ \vdots \end{bmatrix} = \lambda \begin{bmatrix} E_{T_1} \\ E_{T_2} \\ \vdots \end{bmatrix} \longrightarrow \bar{b} = \lambda\bar{x}, \qquad \bar{\bar{A}}(1-\lambda\bar{\bar{I}})\bar{x} = 0.$$

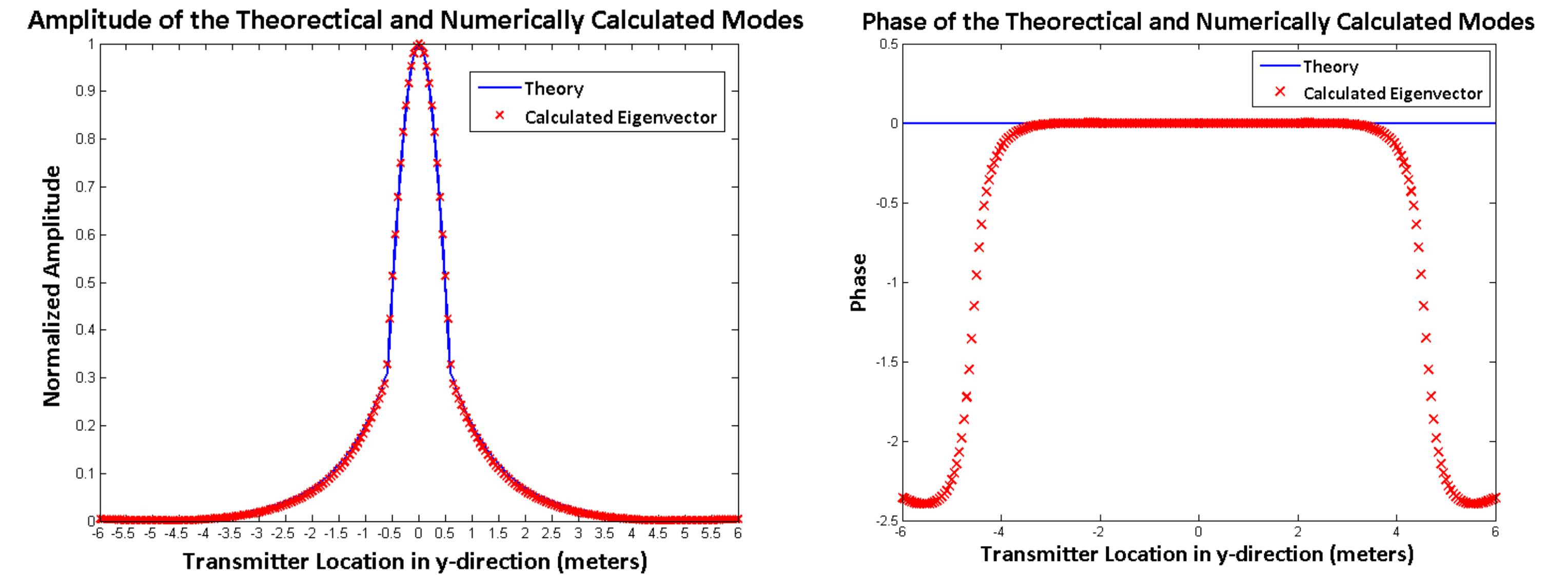
Since the eigenvectors are orthogonal vectors, they can represent the mode of the soil layers.

Initial Results for Mode Identification

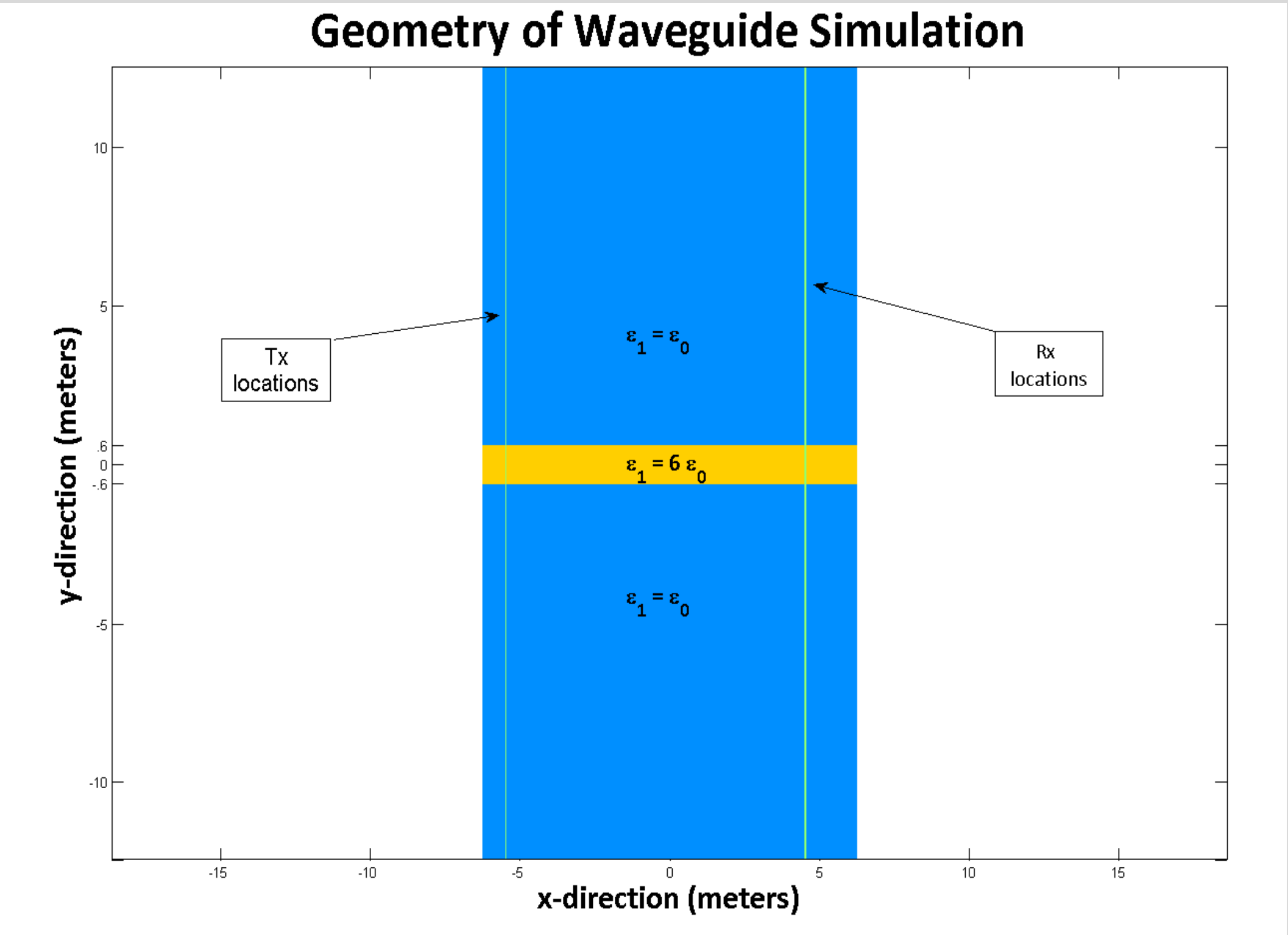
The method has been tested on simple test cases with a two-dimensional finite difference frequency domain simulation. The Theoretical solution to the mode is compared to the numerically calculated mode from the eigenvalue decomposition

The simulation parameters are tested with point sources at 50 MHz with dielectric slab of relative permittivity of 6 with thickness of 1.2 meters and is surrounded by free space. There is only one possible mode for this waveguide with the simulation parameters.

Modes



Geometry



Conclusion

- Eigenvalue decomposition of the received fields can give an estimate of the waveguide mode for a simple case.
- Future work will expand the analysis to multimodal/multilayer cases with lossy dielectrics.
- These modes will be used to identify the properties of the soil and to develop an inversion algorithm for tunnel localization.

References

[1] DHS OIG from HSI Baseline Assessment of Illegal Tunnel Activity, December 2010.
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