Location of buried water pipes using evanescent electromagnetic waves

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Abstract: The ability to detect multiple interfaces at different depths below the surface, the interpretation of these numerous reflections, and the difficulty in correlating the abundance of reflections between many profiles within a grid can make Ground Penetrating Radar (GPR) data collection and processing a somewhat intimidating venture for the uninitiated. The equipment measures the time interval between the generation of the impulse and its reception after the scattering, the results being presented in B-scan representation. In order to obtain a superior accuracy in the evaluation, it is necessary the use of the signal post processing algorithm that allows the obtaining of a relatively easy interpretable radar image. In this paper are presented a series of methods and algorithms for signal processing (A-scan) and image processing (B-scan) which allows an easier and correct interpretation of the inspection results. The methods and the algorithms were tested for detection of buried pipes hot water, placed into a concrete duct bank, at depth over 150 cm under different layers.

Keywords: evanescent waves, ground penetrating radar, image processing, modeling, utility scan

1. Introduction

GPR is a non-destructive methodology. For the localization of buried structures, it uses short time duration electromagnetic (EM) pulses lasting. Therefore, GPR is characterized by a wide frequency band ranging from 10 MHz to some GHz, and is useful in the localization of EM discontinuities in the subsurface with high resolution.

Interesting applications fields of GPR are measurements for object location underground, such as buried artifacts, drain tiles, anti-personnel mines, and pipes and cables [1]. The coupling of energy into the ground is made by the near field of the transducers, or, more precisely, by evanescent waves as well as propagating waves in the spectrum for the radiation from the transducers [2]. In all these applications, it is very important to quickly obtain measurements with a high level of precision in terms of location and dimensions of buried objects.

The ability to detect multiple interfaces at different depths below the surface, the interpretation of these numerous reflections, and the difficulty in correlating the abundance of reflections between many profiles within a grid can make GPR data collection and processing a challenge for even professionals in the field. The equipment measures the time interval between the generation of the impulse and its reception after the scattering, the results being presented in B-scan representation [3]. In order to obtain a superior accuracy in the evaluation, it is necessary the use the models based on a plane-wave spectral analysis to perform a preliminary examination of the role that evanescent waves can play in the detection and identification of the buried object, as well as of the signal post processing algorithm that allows the obtaining of a relatively easy interpretable radar image. The degree to which features in the image of the object can be resolved is of particular interest, since the features can be used to distinguish the object from clutter.

The paper proposes to present the results from this theory applied to the GPR detection of utility pipes with unknown approximate position buried under a bike track on the bank of Bahlui River, Iasi, Romania, and a series of digital signal processing methods applied both to A-scan and B-scan that shall assure the easiest interpretation of the results.
The proposed methods and the algorithms are tested for the detection of a concrete duct bank containing 2 pipes for hot water transportation (turn return). The situation has been simulated using the FDTD software in order to emphasize the evanescent waves recorded by receiving GPR antenna, bowtie type, working at 400MHz.

2. GPR principles

2.1. Generic GPR system

GPR evaluations are widely used in nondestructive surveys of civil engineering structures. This nondestructive technique has one of the highest resolution capabilities achieved in field measurements of these kinds of structures, approaching to few centimeters. Two features resolution and penetration restricts the applications of this technique. Penetration increases as the frequency decreases [3] and the combination between these gives the favorable conditions. Resolution is usually identified as the capacity of the system to discriminate individual elements embedded in medium [4]. A block diagram of a generic GPR system is shown in Figure 1a. The transmitter can provide an amplitude frequency, phase modulated waveform signal and the selection of the bandwidth, repetition rate, or mean power will depend upon the path loss and target dimensions. The transmitting (Tx) and receiving (Rx) antennas are usually identical and are elected to meet the characteristics of the generated waveform. The majority of GPR systems uses an impulse time domain waveform and receives the reflected signal in a sampling receiver. The key of success of this method lies in proper pre-processing of the GPR data, which is a very important step before formal data analysis can begin. Models of the GPR situation range from a simple single frequency evaluation of path losses to complete 3D time domain descriptions of the GPR and its environment. Modeling techniques include single frequency models, time domain models, ray tracing, integral techniques and discrete element methods. The Finite Difference Time Domain (FDTD) technique has become one of the popular techniques [3], [5], [6].

![Image](image1.png)

Figure 1: a) Block diagram of a generic GPR system; b) concrete duct bank containing two pipe for hot water transportation

2.2. Propagation and evanescent waves

The transducer (antenna GPR) is used in this case for detecting buried pipes (Figure 1b) located at small depth under the surface. The coupling of energy into the ground is made by near field of the transducer, or more precisely, by evanescent waves [7] (inhomogeneous waves) as well as propagating waves (homogeneous waves) in the spectrum for the radiation
from the transducer. Evanescent waves also contribute to the coupling of the scattered field from the shallowly buried object to the transducer. We will use simple analytical model to perform a preliminary examination of the role that evanescent waves can play in the detection and identification of the pipes. We will assume that the field is transverse electric (TE), which, in this notation means that the field has only the components $E_y$, $H_x$, $H_z$. The electrical properties of the nonmagnetic soil ($\mu_s = \mu_0$) containing the pipe are relative permeability $\varepsilon_{rs}$, the conductivity $\sigma_s$ and the field created by antenna having the characteristics of the rectangular coil [8]. In a region without sources, the Helmholtz wave equation is [8]

$$\left( \nabla^2 + k^2 \right) E(x, y, z) = 0$$  \hspace{1cm} (1)

with k-vector waves number, $k = \omega/v$, $\omega$-angular speed, $v$- propagation speed electromagnetic waves in considered media. When a stratified plane soil model is used, to simplify, we present only a model with two layers. The expression of the field produced by a rectangular emission coil, using the dyadic Green’s function [9] and the integral method, supplied with a current with f frequency and $I_0$ amplitude is given by [10]

$$E_0(\vec{r}) = j\omega \mu_0 \int_{V_{source}} G_{12}(\vec{r}, \vec{r}') J(\vec{r}') d\vec{r}'$$  \hspace{1cm} (2)

According to [11] for the buried object having the electric conductivity $\sigma_1$ and $\sigma_2$ the conductivity of stratified soil the total electric field is

$$E_z(\vec{r}) + j\omega \mu_0 \sigma_2 \int_{V_{body}} \tilde{G}_{2z}(\vec{r}, \vec{r}') E_z(\vec{r}') \left[ \frac{\sigma_1(\vec{r}')}{\sigma_2} - 1 \right] d\vec{r}' = E_0(\vec{r})$$  \hspace{1cm} (3)

and perturbation field in air due the presence of conductive object is

$$E_z(\vec{r}) = j\omega \mu_0 \sigma_2 \int_{V_{body}} \tilde{G}_{2z}(\vec{r}, \vec{r}') E_z(\vec{r}') \left[ \frac{\sigma_1(\vec{r}')}{\sigma_2} - 1 \right] d\vec{r}'$$  \hspace{1cm} (4)

In soil

$$k^{soil}_z = \left( k_z^* + k_z^{soil} z \right); \quad k_z^{soil} = \beta_z^{soil} - j\alpha_z^{soil} = \left( k_z^2 - k^{soil}_z \right)^{1/2}$$  \hspace{1cm} (5)

and in free space

$$k^{space}_z = \left( k_z^* + k_z^{space} z \right) = \left( k_0^2 - k_z^2 \right)^{1/2}$$  \hspace{1cm} (6)

with

$$k_z^{space} = \begin{cases} \beta_z^{space} = \omega \mu \varepsilon_i & i = 1, 2 \text{ propagating wave} \\ -j\alpha_z^{space} = -j\mu \sigma_i & i = 1, 2 \text{ evanescent wave} \end{cases}$$  \hspace{1cm} (7)

In free space, waves with $k_z^2 \leq k_0^2$ propagate in the (-z) direction as $\exp(-jB_z^{space} z)$, while waves with $k_z^2 \geq k_0^2$ evanescence or decay in the (-z) direction as $\exp(-\alpha_z^{space} z)$. When there is loss in the soil $\sigma_{soil} \neq 0$, all waves decay, so it is not possible to estimate clearly $k_z$ value for propagating waves and respectively evanescent waves.

3. The experimental set-up and the tested region

The GPR equipment is Utility Scan Standard System GSSI USA (Figure 2a), having a 400 MHz antenna. In function of the soil humidity, this system allows the investigation in depth until $4\div 4.5$ m. The antenna and the electronic block are placed on a displacing system. The front wheel of the displacing system has an encoder which allows the determination of position with ±1 mm precision. The sampling rate is 0.04 ns, the quantization of the signal being made on 16 bits. The equipment has been set-up to record A-scan at each 10 cm, the
interval for which the signals are obtained being 32 ns. In the basis of previous measurements of dielectric constant of the soil from the scanned region, this has been set-up at $\varepsilon_r = 12$.

A region of [2000x320] cm from the Bahlui river bank, river that passes through the downtown of Iasi city, Romania, has been scanned (Figure 2b), very closely to the riverbed. The existence of a decommissioned two pipes for hot water has been suspected (Figure 3).

The pipes have approximate 70 cm diameter and it is supposed to be from tubes for hot water transportation and have 15 cm wall thickness of insulation (nonwoven glass fiber). The exact
position of the pipes is unknown, maybe is buried parallel with the riverbed. Due its orientation and to the practical scanning possibilities, the scanning has been effectuated in 3 parallel traces with 2000 cm length, separated between them with 100 cm, Figure 3a. After that, the scanning of directions orthogonal on the direction of riverbank (Figure 3a) has been facilitated. In order to simplify the data presentation, a zone of [320x500] cm has been selected and the scanning has been effectuated in 6 transversal traces on pipes with 320 cm length, separated between them with 100 cm (the traces has been effectuated in both direction, see Figure 4).

![Figure 4. Scanning scheme on both directions](image)

4. **Experimental results**

4.1. **GPR signal processing and evanescent waves**

Figure 5 present the scan on pipes on longitudinal directions (Figure 4) which represent the scans of a zone where two pipes with 85 cm diameter each were buried in ground into concrete duct at 21.8 ns depth. It can be observed that in the case of real measurements, the image is very noisy, containing, in addition, clutters. Using the specific technology of ultrasound examinations, the images from Figure 5 and 6 present a B-scan made from 55 raw A-scan types.

![Figure 5a and 5b](image)
At the distance of 44 m from the starting point, a signal having the form of distorted parabola with the peak pointing upwards is observed at the depth of 21.8 ns; this is indicating the fact that the pipes with the axes parallel with the scanning direction change their orientation.

The presence of a two pipes for hot water transportation, having 85 cm diameter each buried in concrete duct ($\varepsilon_s = 12$), the top of pipes being at 21.8 ns depth has been simulated using GPRMax2D [6], free software that solves Maxwell’s equation using FDTD method. The processing of simulated data has been made using a code elaborated in Matlab 2011b. The simulated geometry is presented in Figure 7 and was visualized using GPRMax2D GnuPlot viewer - a plot script autoformatter.

Idealized near-surface, near field propagation paths along the interface of the free space and a dielectric half-space (ground) for a TE mode antenna orientation is presented in Figure 8: a). O - the location of the TE mode source; 1 - the wave front of the air wave; 2 - the wave front of the ground wave; 3 - representation of the inhomogeneous evanescent air wave match in the ground wave 2; and 4 - the wave front of the head or lateral wave in the ground matching the spherical air wave; $\theta$ - the critical angle. The modeling was carried out at the interface of the free space and a dielectric half-space with dielectric constant of 12 (for concrete) [7]. The
source is a Ricker wavelet with central frequency of 400 MHz. The evanescent wave has a fast decay with respect to height, Figure 8b.

Figure 7: a) Simulation using GPRMax 2D; b) the simulated geometry and visualization using GPRMax2D Gnuplot viewer

The positive x - direction is that of wave propagation from the transmitter to the receiver; along the GPR profile. The y - axis is vertical downward; and the z - direction is perpendicular to the x-y plane, in accordance with the right-hand-rule. The evanescent wave decays exponentially with increasing elevation above the surface, and is in phase with the ground wave below the surface; whereas the air wave and the ground wave have opposite phases.

Figure 8: a) Near field propagation paths (O - the location of the TE mode source; 1 - the wave front of the air wave; 2 - the wave front of the ground wave; 3 - representation of the inhomogeneous evanescent air wave match in the ground wave 2; and 4 - the wave front of the head or lateral wave in the ground matching the spherical air wave; θ - the critical angle.); b) The amplitude of the electric field

4.2. Signal processing: A scan and B scan

The data obtained during inspection were stored in the PC in .txt format, their post-processing being made according to [12], in Matlab 2011b. In Figure 9a is presented an original A-scan and in Figure 9b, is presented the same A scan after the method which made mean value to be close to zero and the noise was reduced according to [12] has been applied, for our specific case, K has been chosen as 1.02.

Figure 10 emphasize the results of B-scan processing one line GPR survey of the inspection zone. To the original B-scan image from the scanned zone the signal processing algorithm described in [12], is applied. The results after background removal with sliding window with length L≈20pixels is presented in Figure 10a and after application of migration technique, is
presented in Figure 10b, respectively. The reflections on the top and respective on the bottom of concrete duct bank where the two pipes are located – can be observed at the depth of approximate 21 ns, respectively 39.4 ns. The horizontal line at 39.4 ns represents the reflections on the remnant water on the bottom of the pipes. The rest of horizontal line are due to multiple reflections on the interfaces from the soil in the scanned zone and concrete duct bank of the pipes. In the same area, we can notice the signals whose shape may indicate the presence of buried electrical cables (for example at 98.1 m, 127.7 m, 152 m, 170 m, etc.).

Concatenating the B scan images and following the horizontal line placed at 21.8 ns, the profile of the pipes is obtained, its diameter could be estimated (Figure 11).
5. Conclusions

GPR has started to be used with good results, in different types of applications, as the detection of buried pipes, metallic or made from dielectric materials. In order to interpret correctly the images delivered by GPR, (B-scan), due to high level of noise and of clutters, it is necessary to develop a lot of specific procedures of signal and image processing. Even in extremely difficult conditions for scanning, when the terrain imposes only the scanning along the pipe, applying optimal algorithms for signal and image processing, the images become easier to interpret.

We developed post processing algorithms that take into consideration also the evanescent waves in order to improve the interpretation of the GPR radargrams. The method allows the determination of depth and location of buried pipes, the shape being estimated with good precision.

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References