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PRINCIPLES OF USING GROUND PENETRATING RADAR AND GPS TECHNOLOGY FOR DETECTION OF UNDERGROUND UTILITIES

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ABSTRACT

This paper describes modern, non-invasive data acquisition methods in underground utility detection. The work presents the possibilities of connecting data acquired with a Ground Penetrating Radar with GPS data. Also, the basic parameters, methods and their influence on the acquisition speed and data quality are defined.

1. INTRODUCTION

No dig utility mapping technology is important in data acquisition for computation, modelling and control of underground infrastructure systems. Today, the development and realisation of new pipelines and cables in urban environment are significantly faster than conventional methods of utility mapping. Classic technology based on excavation, 30 year old maps with more or less precise pipeline routes and incorrect measurements causes incorrect information and major problems with underground utility mapping. A direct consequence of this approach is an expensive, uncoordinated process of establishing new pipelines accompanied with damage to existing utilities. Low quality information about condition and operation of, for example, city water supply system implicitly affects the flexibility of that system. This can be seen on the differnece between the amount of processed and distributed water.

2. PHYSICAL AND THEORETICAL CONCEPTS OF GPR WORK

The Ground Penetrating Radar (GPR) is a device used for non-invasive scanning and precise detection of underground utilities. GPR is composed of a receiver and transmitter antenna, a control unit with Win CE OS, battery supply and a survey cart. Survey cart is a tricycle equipped with incremental encoder. The incremental encoder is used for precise positioning of the center of the antenna above a pipeline route. The GPR also has a marker which is useful for marking interesting details on a radar scan. The GPR can be equipped with a GPS (*Global Positioning System*) rover which is used for measuring spatial coordinates of the projection of the pipeline route on the site surface. The GPS rover can measure coordinates either independently or synchronized with the GPR scan. In the second case, the GPS rover measures all points on the scanned trajectory, or just the start and end coordinates. Synchronized work imply direct communication between GPS rover and the GPR device. Measurement of pipeline parameters with GPR and GPS measurement coordinates on the site surface are with centimeter accurancy. This measurement accurancy satisfies geodethic mapping laws [1]. Figure 1 shows the schematic picture of the GPR equipment, its functional parts and the connections between them.

When the survey cart moves on the site surface the transmitting antenna sends polarised, high frequency electromagnetic (EM) waves in the ground. Because of different existing inhomogeneties in the ground, e.g. soil layers, underground utilities, stones, gravel, cavities and other anomalies, part of the EM waves is reflected from the dielectric boundary between different materials and the other part is refracted and goes to the deeper layers. The decribed process is repeated until the EM waves become too weak. Reflection of EM waves from the dielectric boundary is the consequence of differences in the electric and magnetic properties of materials of infrastructural objects and soil layers.

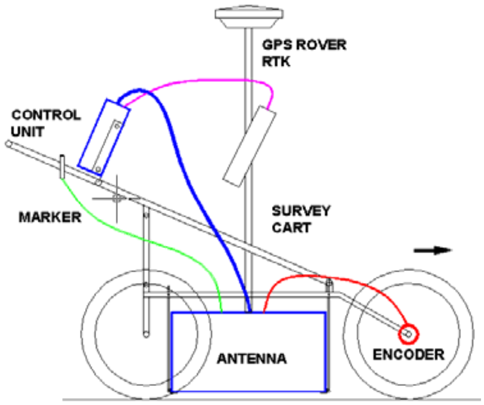

Figure 1. *Functional parts of GPR*

The principle of functioning GPR is the analyses of the propagation of EM waves, in matter of measurement of the electric and magnetic field strength vectors with respect to time and spatial coordinates. EM field vectors in linear, homogeneous environments satisfy Maxwell's equations and they can be written as wave equations, e.g. Helmholtz equations [2]:

$$\begin{aligned} \Delta\cdot\vec{E}-\varepsilon\cdot\mu\cdot\frac{\partial^2\vec{E}}{\partial t^2}-\mu\cdot\sigma\cdot\frac{\partial\vec{E}}{\partial t}=0 \\ \Delta\cdot\vec{H}-\varepsilon\cdot\mu\cdot\frac{\partial^2\vec{H}}{\partial t^2}-\mu\cdot\sigma\cdot\frac{\partial\vec{H}}{\partial t}=0 \end{aligned} \quad (1)$$

where:

$\vec{E}$ - electric field strength vector [V/m],

$\vec{H}$ - magnetic field strength vector [A/m],

ε - dielectric permittivity [F/m], $\varepsilon=\varepsilon_0\varepsilon_R$, σ – conductivity [S/m]

$\varepsilon_0= 8.854\cdot10^{-12}$ [F/m], dielectric permittivity of free space

μ - magnetic permeability [H/m], $\mu=\mu_0\mu_R$,

$\mu_0=4\pi\cdot10^{-7}$ [H/m], magnetic permeability of free space

If we consider the case when the EM wave passes through a perfect dielectric ($\sigma=0$) and with respect to the nature of plane uniform wave equations (1), it can be shown with a one dimensional wave equation of polarised EM wave propagation along Z axis [3]:

$$\frac{\partial^2 \vec{E}_x}{\partial z^2} = \mu \cdot \varepsilon \cdot \frac{\partial^2 \vec{E}_x}{\partial t^2}$$
$$\vec{H}_y(z,t) = \sqrt{\frac{\varepsilon}{\mu}} \cdot \vec{E}_x(z,t) = \frac{1}{Z} \cdot \vec{E}_x(z,t) \qquad (2)$$

where:

$Z = \sqrt{\mu / \varepsilon}$ [Ω] – medium impedance,

i.e.measure of influence electric and magnetic properties of medium

$\vec{E}_x, \vec{H}_y$ - EM wave vector components, perpendicular for each other and perpendicular on EM propagation route.

The general solution of equation (2) is the following:

$$\vec{E}_x(z,t) = C_1 \cdot f_1(t - z/c) = E_m \cdot \cos[\omega(t - \beta \cdot z)]$$
$$\vec{H}_y(z,t) = \frac{E_m}{Z} \cdot \cos[\omega(t - \beta \cdot z)] \qquad (3)$$

where:

E_m – electric field component E_x amplitude

ω - electric field component E_x frequency

$c = (\mu_0 \cdot \varepsilon_0)^{-1/2}$ - speed of light: c=2.998 x 10^8 [m/s] (4)

$\beta = \omega / c$ - phase ratio, $v_{WAVE} = (\mu \cdot \varepsilon)^{-1/2}$

The general solution (3) describes the propagation of EM waves moving with speed *c* along the Z axis. Function f_1 is a plain periodic function. The general solution shows the changes of speed of the EM wave and magnitude of electric and magnetic field strength vectors when the wave passes trough a medium. That is caused by the influence of electric and magnetic properties of a medium.

In real problems, the medium through which EM waves pass, is not a perfect dielectric medium. The general solution of equation (2) is the following [3]:

$$\vec{E}_x(z,t) = E \cdot \sqrt{2} \cdot e^{-\alpha \cdot z} \cos(\omega \cdot t - \beta \cdot z + \theta_E)$$
$$\vec{H}_y(z,t) = \frac{1}{|\underline{Z}|} \cdot E \cdot \sqrt{2} \cdot e^{-\alpha \cdot z} \cos(\omega \cdot t - \beta \cdot z + \theta_E - \theta_Z) \qquad (5)$$

E – effective value of electric field component E_x

θ_E – electric field start phase

θ_Z – medium impedance argument

α - attenuation constant of medium [Np/m]

ω - field component frequency

$\beta = \omega / c$ - phase ratio, c=2.998 x 10^8 [m/s] - speed of light

$\underline{Z} = \sqrt{\frac{\mu}{\varepsilon}\sqrt{\left(1 - j \cdot \frac{\sigma}{\omega \cdot \varepsilon}\right)}}$ [Ω] – complex medium impedance, in case of imperfect medium.

Equations (5) show exponential attenuation of the vector field amplitude along the Z axis. The rate of speed change is proportional to the attenuation constant of the medium - α. In general, ε, μ i σ are complex values, so exact calculation of parameters α i β is not simple. Equation (6) shows the speed of the EM wave propagation with a clearly visible influence of conductivity. Soil conductivity causes wave dispersion. Based on these facts, we conclude that media with high conductivity are impenetrable for EM waves [4].

$$v_{WAVE} = \frac{\omega}{\beta} \approx c \cdot \left(1 - \frac{\sigma^2}{8 \cdot \omega^2 \cdot \varepsilon^2}\right) \text{[m/s]} \qquad (6)$$

Practical use of Maxwell's equations for the determination of field properties during GPR scanning is difficult. Because of this, certain assumptions should be accepted. For the majority of media $\mu_R=1$, meaning that the influence of the magnetic properties of the medium can be ignored. This assumption introduces a small error in the majority of the cases. Also, the influence of the specific conductivity can be ignored. Medium types are characterized by looking up their parameter values from tables. Research is conducted in order to find a more precise method of determining the value of these parameters. Based on these assumptions, the speed of EM wave propagation is defined as:

$$v_{wave} = \frac{1}{\sqrt{\mu \cdot \varepsilon}} = \frac{c}{\sqrt{\varepsilon_R}} \text{[m/s]} \qquad (7)$$

Time necessary for the propagation of EM waves from transmit antenna to the boundary surface and its reflection back to the receiver antenna is defined as a two way travel t_R [ns] time. The GPR measures t_R, and finally calculates the relative depth of the underground object:

$$z = v \cdot \frac{t_R}{2} = \frac{c \cdot t_R}{2\sqrt{\varepsilon_R}} \text{ [m]} \qquad (8)$$

Because each location has its specific soil structure, ε_R has to be recalculated for each site. Usually, the GPR recalibration method is used on site. This method is based on a GPR scan of an underground object with known depth [3].

Methodology of radar scan generation is shown in Figure 2. A radar scan is a spatial section of the working area. The antenna's linear trajectory is shown on X axis, and Y axis shows the two way travel time t_R i.e. the relative depth z from the surface to the underground object.

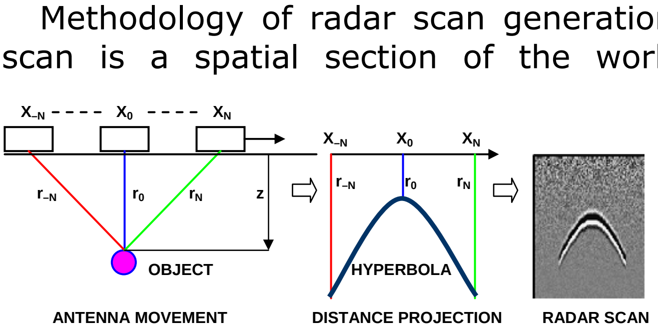

Figure 2. *Radar scan generation*

The distance between transmit and receive antenna is very small. Because of this, the distance from transmit antenna to boundary surface is approximately equal to the distance from boundary surface to the receiver antenna. The distance from antenna to the underground object continuously changes. Distances $r_0, r_1, ... r_N$ are projected ortogonally on the movement axis, see points x_{-N} ... x_0 ... x_N (see middle section of Figure 2.). By sequentially connecting the ends of these segments, a geometrical hyperbola is formed.

All points on the scan include reflected wave amplitude data. Points on top of the segments have peak amplitude value. The peak on the shortest segment r_0 (antenna center is on the pipe axis) is highest (positive or negative). This value is criteria for scan searching and determination of location and depth of underground utility. Negative peaks indicate empty pipes, while positive peaks indicate full pipes or cable. Pipe and cable reflection have different positive peaks. Cables reflect more, and have higher positive peaks.

Transmit antenna radiates a conical EM wave beam with a bandwidth $\beta=35^{\circ}\div45^{\circ}$. Based on these facts, it is not necessary for the center of the antenna to be above the underground object to detect it. Figure 2 shows an ideal one pipe radar scan in a homogenous soil layer. Antenna moved ortogonally to the pipeline axis. In real conditions scan is with different noises and hyperbolical reflections, caused by other infrastructural objects. This can be eliminated by postprocessing. Figure 3. shows a real scan from the GPR, with marked trajectories on the X axis and depth on the Y axis. The oscilloscope shows positive peaks, indicating a full pipe. If it was a cable, the hyperbola wouldn't have been as open, but would have had a larger amplitude.

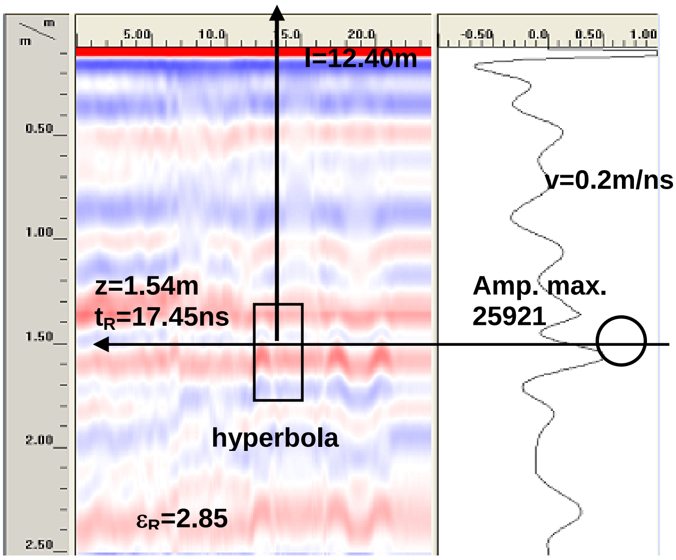

Figure 3. *Real GPR scan*

3. GPR TRANSFER FUNCTION

Basic GPR parameters are maximum penetration depth r_M and spatial (vertical δ_Z i horizontal δ_X, δ_Y) resolution δ_R.

GPR's transfer function is the ratio of signal powers at transmit and receive antenna, respectively. GPR transfer function is used to calculate r_M (Figure 4):

$$P_R = P_T \cdot \frac{G_T \cdot \sigma_{obj} \cdot S_R}{(4\pi)^2 \cdot r_1^2 \cdot r_2^2} \cdot e^{-2\alpha(r_1+r_2)} \qquad (9)$$

G_T – transmit antenna gain

S_R – radar cross section [m^2],

$s_R = \frac{\lambda^2}{4 \cdot \pi} = \frac{c^2}{4 \cdot \pi \cdot f^2}$ - for spherical objects whose circumference is approximately $O=2\pi r \approx \lambda$;

f – EM wave frequency [MHz],

r_1 – distance between the transmit antenna and the underground object [m],

r_2 – distance between the underground object and the receive antenna [m], $r_1 \approx r_2 \approx r_M$

$\alpha(f) \approx f^A$ – attenuation as a function of frequency [dB/m]

$A \approx 0.5$ for frequencies between 100 and 300 MHz, $A \geq 1$ for frequencies above 1000 MHz [5]

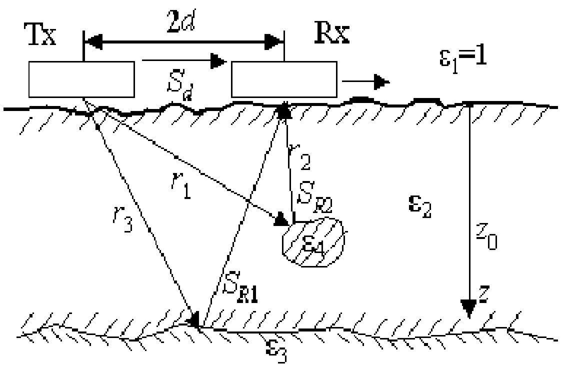

Figure 4 shows important variables for time space transfer function definition. Maximum penetration depth in pipeline detection is usually 3.5 to 7m (400MHz and 200MHz antenna, respectively).

Figure 4. *The principle of functioning GPR*

Spatial resolution δ_R is a function of the frequency band and of the complex dielectric permittivity [5]. The GPR's vertical resolution (along Z axis) δ_Z is:

$$\delta_Z \approx \frac{c}{2 \cdot \Delta f \cdot \sqrt{\varepsilon(f)'}} \qquad (10)$$

Vertical resolution in pipeline detection is usually 3 to 7cm (400MHz and 200MHz antenna, respectively).

4. PARAMETERS ACQUISITION METHODS

Parameters are detected by 2D and/or 3D scans of the site. Complexity, type of pipeline network and amount of data determine which method is used for scaning. 2D scanning is useful for quick underground utilities location. The first step is the recalculation of ε_R based on a scan of an underground object with known depth. Ortogonal scanning is used to determine pipeline depth and direction. To determine pipeline direction, at least two scans are needed.

A regular hyperbola shows up on the scan when ortogonally crossing above the pipeline axis. In that case, rules explained in figure 2 are satisfied, and the reflected wave amplitude is maximal because of maximum radar cross section. When antenna crosses at a sharp angle above the pipeline axis, the hyperbola has a totally different shape which is no longer hyperbolic. In an extreme case, when the antenna trajectory is along the pipeline axis, the hyperbola is distorted into a straight line [6,7].

Explained properties of EM waves show the possibility to detect pipes of different materials. Differences between reflected waves would be only in amplitude values (reflection strength) [6,7].

Huge water supply networks have about 20% of losses caused by pipe leakage. Beside several another modern methods, GPRs have a significant role in the process of quick and efficient detection of pipe leakage, especially in pipes with small diameter. Identification of pipe leakage is possible by detecting of cavities created by leaking fluids, or analysing changes in soil structure caused by moisture (change of dielectric permitivitty ε_R) [8].

Taking this into account, 2D scanning is useful in determining depth, directions in the horizontal and vertical planes, pipe inclination, pipe length, fluid/void ratio, changes of pipe diameter, pipe material, detection of pipe leakage, pipe radius estimation etc. Pipe radius estimation requires additional software processing because it depends on hyperbolic reflection geometry.

In 3D scanning the software connects a number of 2D scans in a predefined sequence, hence creating a 3D model of the site. It overcomes the obvious limitations of the common form of GPR data display, which is a 2D vertical cross-section. Voids between the 2D scans are filled with software interpolation methods. The 3D display has the advantage of looking at the entire survey site at once. Technology of 3D scanning is useful for complex processing. This is especially important in areas with multiple intersecting, dipping or layered targets (pipes, rebar, etc.) that may be hard to identify on single radar profiles.

Postprocessing software RADAN is used for filtering, normalization and transformation of raw signals. RADAN has special functions for applications that require linear feature recognition [7].

Spatial coordinates of all characteristic points on the surface were measured with various GPS equipment: high precision (~1cm) GPS equipment (rover *Trimble 5800* using RTK (*Real Time Kinematic*)), or with a GPS rover in decimeter precision (*GeoExplorer XT*). The measured coordinates have to be corrected to achieve even higher precision. Corrections come from a network of permanent base stations with fixed positions, and can be acquired in real time or offline [9]. Real time corrections (RTK- *Real Time Kinematic*) can be received through GPRS (*General Packet Radio Service*) or from a GSM modem. Offline PPK (*Post Processing Kinematic*) corrections can be downloaded from the Internet [10]. A network of base stations covers the region Vojvodina, enabling the measurement of GPS coordinates with a precision of 1cm [10]. The network is fully operational longer than a year now. It is in the phase of final extension, after which it will cover the territory of Serbia.

5. CONCLUSIONS

This paper presents the physical-theoretical principles of functioning of a ground penetrating radar (GPR). Special emphasis was put on analysing the capabilities of GPR in the acquisition of data required for the creation of complete model of water supply networks.

The GPR can determine the lengths of straight pipeline segments, pipeline direction, directions in the horizontal and vertical planes, pipe inclination, pipe length, fluid/void ratio, changes of pipe diameter, pipe material, detection of pipe leakage, pipe radius estimation etc.

The limitations of this method include poorer results in highly conductive media. Another limitations is that it is usually difficult to estimate the pipe diameter on site, or even using post-processing algorithms. These problems are still subjects of scientific research.

The presented of 2D/3D site scannings allow 3D representation and complex analyses. The presented principles and techniques allow the detection of pipes and cables of different materials, groundwater level detection, the anlysis of road state, soil contamination levels, etc. This paper presents the basic principles and techniques of efficient mapping using a network of permanent base stations and high precision equipment. Further research is aimed at develop procedures for even better parameter estimation, and finding new areas of use.

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