# Buried Cylinders Geometric Parameters Measurement by Means of GPR

**B. A. Yufryakov and O. N. Linnikov**
Scientific and Technical Centre of System Modeling, Russia

**Abstract**—Interactive technique that measures geometric parameters of buried cylinders in a homogeneous medium with unknown velocity of signal propagation is developed. After 3D GPR data processing, the velocity of signal propagation is estimated; radius, length and position of the cylinder are measured. Experimental data obtained by GPR "Defectoscope" are given.

## 1. Introduction

In paper [1] the hyperbola-fitting technique of radius estimation for subsurface cylindrical objects is presented. For that a direct least-square method for fitting hyperbola is used. Authors of paper [1] supposed that the propagation velocity is known or it can be estimated beforehand via finding a hyperbola resulting from a point reflector within the radarogram. In paper [2] they solved the questions of improving the accuracy of the interpretation of the radar returns reflected from buried cylinders by taking into account the influence of cylinder's orientation and electromagnetic radiation pattern of the antennas.

In [3] two-dimensional data obtained from orthogonal sounding of cylinders are analyzed. It is shown that the generalized Hough method can be used to measure buried pipe diameters from radar measurements and the velocity determination is best made independently from a point-like source at similar depth.

In this paper the interactive technique of 3D-data processing which allows us to estimate simultaneously signal propagation velocity in the medium and cylindrical objects parameters (orientation, radius, length and depth of occurrence) is proposed. Operator participation in data processing allows one to smooth reflected signals registration errors.

The technique is based on the frontal method of GPR 3D-data interpretation [4]. This method selects from the whole bulk of GPR data the first arrival of wave fronts from the recorded signals reflected from objects. These selected surfaces will be referred to as frontal hodographs.

This paper is development of the work in [5].

## 2. Measurement Technique

The technique proposed was developed during the creation of GPR data processing software of GPR "Defectoscope", designed for inspection of buildings [6]. The scan zone of this GPR is a rectangular area in the $XY$ plane, and $Z$ axis is directed to the probed medium. We will call the geometrical space with coordinate system $XYZ$ as object space. During the results registration at any scanning point the value of reflected signal is fixed at discrete time moments at time axis $T$. This data array we will call the signal space or data cube. In the signal space by means of software tools, it is possible to select the surfaces of frontal hodographs as a function of time delay $\tau$ from antenna system coordinates $(X, Y)$.

In Fig. 1, a cylinder with arbitrary orientation with respect to scanning plane is shown. Denote cylinder radius as $r$. Angle of inclination with respect to scanning plane $XY$ of cylinder axis is denoted as $\varphi$; its projection to the plane $XY$ intercepts $X$ axis at angle $\theta$. Let us carry out a parallel shift of axes $X$ and $Y$ into an arbitrary point O belonging to the cylinder axis projection into scanning plane. In Fig. 1 such shift has been made. Cylinder axis intersects the scanning plane at a point with coordinates $(CX, CY)$. The distance between point O and cylinder axis are denoted as $h_0$. This distance equals the length of the perpendicular drawn from this point to the cylinder axis.

Let us consider this perpendicular as vector $\vec{h}=\{X_0, Y_0, Z_0\}$, where $(X_0, Y_0, Z_0)$ are Cartesian coordinates of the perpendicular base, they are:

$$X_0 = -h_0 \sin\varphi \cos\theta, \quad Y_0 = -h_0 \sin\varphi \sin\theta, \quad Z_0 = h_0 \cos\varphi\,.$$

Let us introduce the unit vector $\vec{e}_C=\{l_0, m_0, n_0\}$ directed from the considered perpendicular base along the cylinder axis in increasing depth. Coordinates of this vector are:

$$l_0 = \cos\varphi \cos\theta, \quad m_0 = \cos\varphi \sin\theta, \quad n_0 = \sin\varphi\,.$$

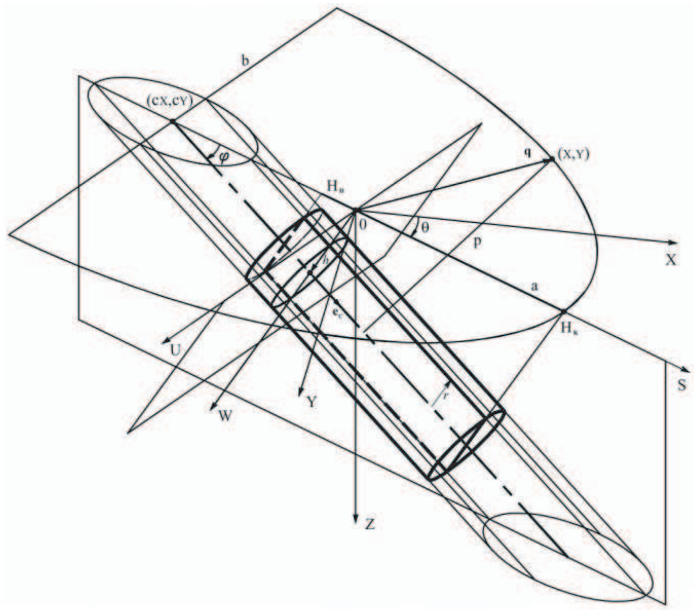


Figure 1: Geometry of data acquisition above an arbitrary located cylinder.

Then distance $p(X,Y)$ from arbitrary point $(X,Y)$ of scanning plane to cylinder axis equals:

$$p(X,Y) = \frac{\left|\left[\vec{q}-\vec{h},\vec{e}_C\right]\right|}{|\vec{e}_C|}$$

where $\vec{q}$=$\{X,\ Y,\ 0\}$, – radius-vector of the point $(X,Y)$, $\left[\vec{q}-\vec{h},\vec{e}_C\right]$ –vector product of vectors $\vec{q}-\vec{h}$= $\{X-X_0, Y-Y_0, -Z_0\}$ and $\vec{e}_C$, modulus means the length of the vector, i.e., $\left|\vec{h}\right| = h_0$.

Hence

$$p^2(X,Y) = [(Y-Y_0)n_0 + m_0 z_0]^2 + [(X-X_0)n_0 + l_0 z_0]^2 + [(X-X_0)m_0 - (Y-Y_0)l_0]^2.$$

Substituting appropriate coordinates and simplifying, we obtain:

$$p^2(X,Y) = (X\sin\varphi + h_0\cos\theta)^2 + (Y\sin\varphi + h_0\sin\theta)^2 + \cos^2\varphi(X\sin\theta - Y\cos\theta)^2$$

Point $(X,Y)$ belongs to the arc of ellipse with major semiaxis $a$ and minor semiaxis $b$ (see Fig. 1), where

$$a = p(X,Y)/\sin\varphi \quad \text{and} \quad \mathrm{b} = \mathrm{p(X,Y)}.$$

This ellipse is very interesting. Coordinates of ellipse center are $(CX, CY)$. The minor semiaxis $b$ equals the distance from any point of ellipse to cylinder axis. The major semiaxis $a$ is the cylinder axis projection into scanning plane. Therefore it defines angle $\theta$. Ratio $b/a = \sin\varphi$ shows the angle inclination of cylinder axis to scanning plane.

The shortest distance $R(X,Y)$ from arbitrary point with coordinates $(X,Y)$ at scanning plane to the cylinder surface can be derived as:

$$R(X,Y) = \sqrt{(X\sin\varphi + h_0\cos\theta)^2 + (Y\sin\varphi + h_0\sin\theta)^2 + \cos^2\varphi(X\sin\theta - Y\cos\theta)^2} - r. \tag{1}$$

Let us choose a measuring coordinate system SOU in the scanning plane which is formed by rotation of axes $OX$ and $OY$ by angle $\theta$. Then $OS$ axis will coincide with the projection of cylinder axis into the scanning plane and $OU$ axis will be orthogonal to it. The third axis of the measuring coordinate system $OW$ we will choose as a continuation of the perpendicular from the point O to the cylinder axis.

Then coordinates $X$ and $Y$ are related with measuring coordinates $S$ and $U$ as:

$$X = S\cos\theta - U\sin\theta \quad \text{and} \quad Y = S\sin\theta + U\cos\theta. \tag{2}$$

Section of cylinder by the $UW$ plane is a circle with radius $r$ and center, whose distance from point O equals $h_0$. For monostatic system frontal hodograph or reflections from this circle for movement along $OU$ axis one can obtain substituting (2) into (1) with conditions $S = 0$ and $R = \frac{V\tau}{2}$:

$$\frac{V\tau}{2} = \sqrt{h_0^2 + U^2} - r.$$

Let us analyze this hyperbolic hodograph. We fix the time delay $T_0$ of observed hyperbola vertex at point O and delays $T_1$ and $T_2$ for arbitrary coordinates $U_1$ and $U_2$ at axis $U$. According to the measurement results one can obtain equations set:

$$\frac{VT_0}{2} = h_0 - r; \quad \frac{VT_1}{2} = \sqrt{h_0^2 + U_1^2} - r; \quad \frac{VT_2}{2} = \sqrt{h_0^2 + U_2^2} - r.$$

The solution is:

$$V = \frac{2}{\sqrt{T_2 - T_1}} \sqrt{\frac{U_2^2}{T_2 - T_0} - \frac{U_1^2}{T_1 - T_0}}; \tag{3}$$

$$h_0 = \frac{1}{2\sqrt{T_2 - T_1}} \frac{U_1^2(T_2 - T_0)^2 - U_2^2(T_1 - T_0)}{\sqrt{U_2^2(T_1 - T_0)^2(T_2 - T_0) - U_1^2(T_2 - T_0)^2(T_1 - T_0)}}; \tag{4}$$

$$r = h_0 - \frac{VT_0}{2}. \tag{5}$$

It should be noted that $V$ and $h_0$ do not depend on $T_0$ but depend on differences $(T_1 - T_0)$ and $(T_2 - T_0)$. It means that signal propagation velocity and the depth of the cylinder axis could be defined unambiguously on hyperbola form independently the hyperbola position at time axis.

However, it is impossible to use (3)–(5) due to the coordinates registration errors and errors of the operator carrying out this measurements. Even little errors could lead to significant deviations of calculated $V$ and $h_0$ from true values. This is a typical incorrect problem, it is advisable to solve this problem by frontal hodograph $\tau(U)$ adjustment by means of graphical tools with the best approximation of the observed data. Similar procedures are widely used in GPR for the measurement of the signal propagation velocity on reflections from point-like objects.

Approximating hyperbola form selection can be organized by software tools via adjustment of measurable parameters $V, h$ and $r$ according to the equations:

for monostatic system

$$\tau(U, h_0, r, V) = 2\frac{\sqrt{U^2 + h_0^2} - r}{V}; \tag{6}$$

for bistatic system with base 2d (which is parallel to $X$ axis):

$$\tau(U, h_0, r, V) = \frac{1}{V}(\sqrt{R^2 + d^2 + 2Rd\cos\psi} + \sqrt{R^2 + d^2 - 2Rd\cos\psi}), \tag{7}$$

where $h_0 = \frac{VT_0}{2} + r$; $R = \sqrt{U^2 + h_0^2} - r$ ; $\cos\psi = \frac{U\sin\theta}{\sqrt{U^2 + h_0^2}}$.

Similar analysis of signal space SOT section shows that in this section frontal hodograph represents segment of the cylinder high generatrix. The slope of this segment equals the value of $\varphi$ angle. Denote time delays at beginning and the end of the approximating segment as $T_H$ and $T_K$ respectively, and the distance between points of measurements at $OS$ axis as D, then $\varphi$ can be calculated as follows:

$$\varphi = atctg\left(\frac{V(T_K - T_H)}{2D}\right).$$

The cylinder length is $L = D\cos\varphi$.

The technique developed was realized as a software module of GPR "Defectoscope" [6]. This software was approved experimentally by sounding three parallel cylindrical objects placed into a box filled with sand. Cylinders radii were 2 cm, 0.5 cm and 4 cm. Fig. 2 shows the geometrical position of these cylinders for two soundings.

Figure 3 shows data processing results obtained from these soundings. Frame 3a shows GPR data when cylinders ware located at angle $\theta = 60°$ to $X$ axis and angle of $\varphi = 0°$ to the scanning plane. Frame 3b

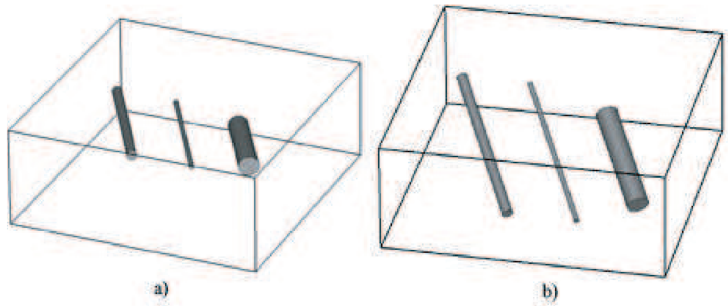


Figure 2: Cylindrical objects position in testing soundings.
(a—horizontal cylinders $\theta = 60°$ and $\varphi = 0°$, b—inclined cylinders $\theta = 60°$ and $\varphi = 30°$).

shows GPR data when $\theta = 60°$ and $\varphi = 30°$. Every frame shows control panel of the dialog window and four fragments. Two uppers fragments (1 and 2) show two vertical mutually perpendicular to each other time sections of GPR data cube. Down left fragment (3) shows a horizontal projection of data cube section which is cut in accordance with angles $\theta$ and $\varphi$. Fragment 4 is horizontal projection of data cube with signals exceeded the threshold specified by the operator.

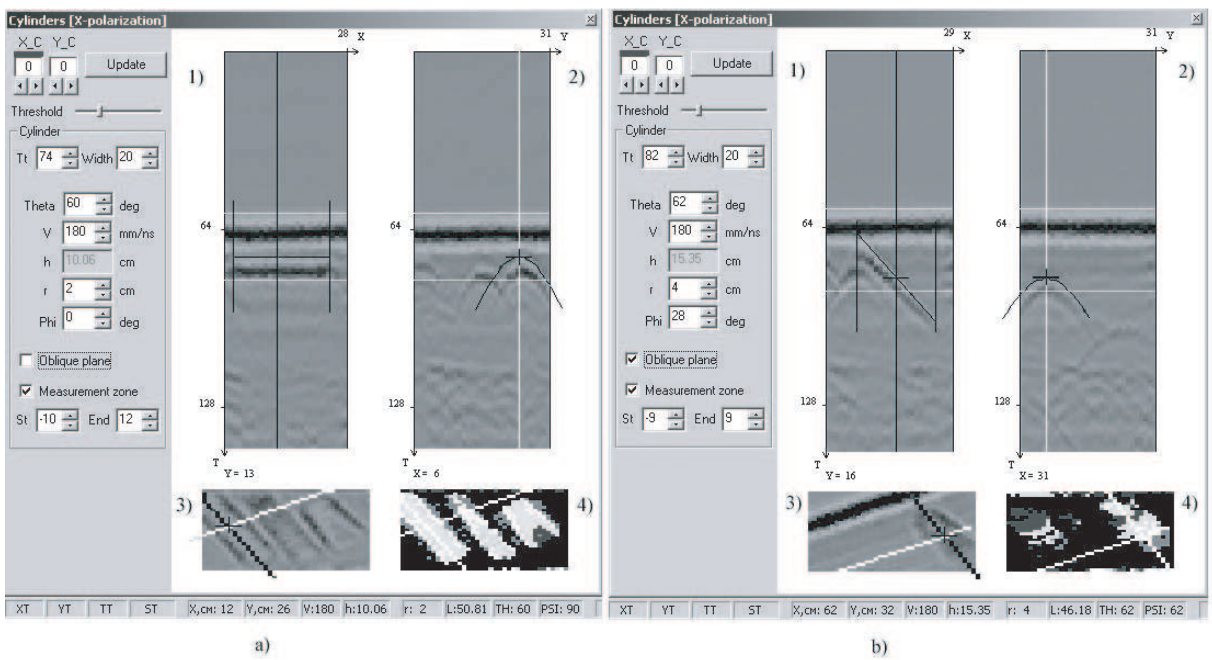


Figure 3: Measurement results of unknown parameters of medium and cylinders using GPR data. (a—horizontal cylinders $\theta = 60°$ and $\varphi = 0°$, b—inclined cylinders $\theta = 60°$ and $\varphi = 30°$, 1—vertical data cube section along $S$ axes shown in section 3 black line, 2—vertical data cube section along $U$ axes shown in section 3 white line, 3—section which is parallel axis of cylinder, 4—horizontal projection of data cube which show signals exceeded the threshold specified by the operator).

Consider the sequence of measurements the result of which is shown in Figs. 3(a) and 3(b). Using reflections from a cylinder it is necessary to fix a point of measurements above the axis of a cylinder (see intersection of black and white lines on fragments 3 and 4). Furthermore, an interpreter chooses the direction along the axis of cylinder using reflections in horizontal section (see black line on fragment 3) and measures an angle $\theta$. Next, an interpreter measures of signal propagation velocity $V$ and radius of a cylinder $r$ by means of fitting a hyperbolic curve by interactive varying of these parameters (see fragment 2). In the end the interpreter fixes inclined line by changing $\varphi$ value to obtain parallel bounds of reflections of the cylinder high generatrix (see fragment 1).

All data entered by the interpreter are displayed in group of operating elements "Cylinder". Meaning of these elements is given in the following list:

Tt—depth of top of an approximating hyperbole measured in time samples;

Width—number of the samples in the approximating hyperbole of a fragment 2;

Theta—value of a corner $\boldsymbol{\theta}$ measured in degrees;

V—propagation speed for of signals measured in millimeters/nanoseconds;

h—depth of cylinder measured on a normal in centimeters;

r—estimation of radius of the cylinder in centimeters;

Phi—value of a corner $\varphi$ measured in degrees;

Oblique plane—the tag, which passive condition is used at measurements of parameters of horizontal cylinders, and an active condition—at a choice of an inclined secant of a plane in parallel an axis of the cylinder;

Measurement zone—a tag at which installation on a fragment 1 there are vertical borders of the measured length of the cylinder;

St—position of the left border of the cylinder measured in samples of scanning zone;

End—position of the right border of the cylinder measured in samples of scanning zone.

Measured parameters such as coordinates of the measurement point, the propagation velocity and also parameters of a cylindrical object such as radius, length and location are shown in status bar (Fig. 3). Value PSI shows direction of vector $h$. It equals $PSI = \pi/2 - \varphi$.

Inaccuracy of measurements of unknown parameters depends on next factors: the time discretization, the discrete location of antenna, the size of a object, insufficiently stretched "tails" of hyperbolic reflections restricted by directional diagram, GPR resolution, the small amplitude of reflections and the level of suppression of useful signals by reflections from other objects.

## 3. Conclusion

An interactive measurement technique developed in this paper allows the use of 3D GPR data which are reflections from a buried cylinder to define the signal propagation velocity in a medium and parameters of a cylindrical object such as radius, length, depth, azimuth angle and angle of inclination can be found.

Parameters which are found can be use both for direct interpretation of observed objects and for automatic shaping of reflecting surfaces of all objects detected in the scan area using the method in [4].

### REFERENCES

1. Shihab, S., W. Al-Nuaimy, and A. Eriksen, "Radius estimation for subsurface cylindrical objects detected by ground penetrating radar," *Tenth Intern. Conference on Ground Penetrating Radar*, Delft, The Netherlands, June 21–24, 2004.
2. Al-Nuaimy, W., S. Shihab, and A. Eriksen, "Data fusion for accurate characterisation of buried cylindrical objects using GPR," *Tenth Intern. Conference on Ground Penetrating Radar*, Delft, The Netherlands, June 21–24, 2004.
3. Windsor, C. G., P. Falorni, and L. Capineri, "The estimation of buried pipe diameters by generalized hough transform of radar data," *PIERS 2005*, Haungzhou, China.
4. Yufryakov, B. A., B. S. Surikov, Y. G. Sosulin, and O. N. Linnikov, "A method for interpretation of ground-penetrating radar data," *Journal of Communications Technology and Electronics*, (English Translation of *Radiotekhnika i Elektronika*), Vol. 49, No. 12, 1342–1356, December 2004.
5. Sosulin, Y. G., O. N. Linnikov, B. A. Yufryakov, and V. Y. Bodrov, "Interpretation of ground-penetrating radar data when probing cylinder objects in medium with unknown parameters," *Intern. Radar Symposium IRS 2005*, Germany, Sept. 6–8, 2005.
6. Andryukhin, A. N., O. N. Linnikov, V. N. Trusov, B. A. Yufryakov, V. Y. Bodrov, and Y. G. Sosulin, "Pulse GPR with optoelectronic sensor," *Tenth Intern. Conference on Ground Penetrating Radar*, Delft, The Netherlands, June 21–24, 2004.