Template-matching based detection of hyperbolas in ground-penetrating radargrams for buried utilities

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Abstract

Ground-Penetrating Radar (GPR) is a mature geophysical technique that is used to map utility pipelines buried within 1.5 m of the ground surface in the urban landscape. In this work, the template-matching algorithm has been originally applied to the detection and localization of pipe signatures in two perpendicular antenna polarizations. The processing of a GPR radargram is based on four main steps. The first step consists in defining a template usually from finite-difference time-domain simulations made of the nearby area of the hyperbola apex associated with a mean size object to be detected in the soil whose mean permittivity has been previously experimentally estimated. The second step consists in a pre-processing on the raw radargram to correct variations due to antennas coupling, then the template matching algorithm is used to detect and localize individual hyperbola signatures in an environment containing unwanted reflections, noise and overlapping signatures. The distance between the shifted template and a local zone in the radargram based on the L1 norm allows to obtain a map of distances. A user-defined threshold allows to select a reduced number of zones having a high similarity measure. In a third step, in each zone minimum or maximum discrete amplitudes belonging to a selected hyperbola curve are semi-automatically extracted. In the fourth step, the discrete hyperbola data (i,j) are fitted by a parametric hyperbola modeling using a non linear least square criterion. The algorithm has been implemented and evaluated on numerical radargrams, and afterwards on experimental radargrams.

Keywords: Ground-penetrating radar, pipe detection, hyperfrequency, template matching, soil characterization, ultra-wide band

1. Introduction

Ground-penetrating radar (GPR) is a well-known non destructive technique for imaging shallow subsurfaces by a propagating electromagnetic energy downward into the ground from a transmitting antenna that is reflected at subsurface boundaries between media possessing different electromagnetic (EM) properties and is collected by a receiving antenna. GPR is a proposed technology to map utility pipelines in urban environments (fiber optics, telecommunication lines, electrical cables, water and gas pipes, district heating network), most of them have been buried within 1.5 m of the ground surface [1-2]. The buried targets produce characteristic hyperbolic signatures in the radargram (Bscan) issued from the moving of the GPR system along a linear path. Hyperbolic signatures represented in the distance-time domain are specific to the target size, shape and dielectric characteristics and the orientation of the electric field [3-4]. Challenges lie in detecting and classifying targets in an environment with variations in the surface cover (asphalt, paving, sand, gravel, grass), in the subsoil with spatial vertical or horizontal variability of the soil texture (water content, backfill soil, multilayers…), and the presence of buried targets that can be close to each other (overlapping hyperbolas) and have wide variations in dimensions, and in dielectric properties (metallic or non-metallic).

An ultra-wide band (UWB) ground-coupled radar operating in the frequency band [0.46 ; 4] GHz and made of bowtie slot antennas has been preferred to an air-launched radar because it increases energy transfer of electromagnetic radiation in the sub-surface and penetration depth [1,5]. Moreover, UWB GPR and SFCW (step frequency continuous wave) have been used to probe the soil structure using the benefit from both low and high frequencies bringing a compromise in terms of depth resolution and penetration in a single measurement. This paper is focused on the processing and analysis of radargrams using the semi-automatic template-matching algorithm applied to GPR application in order to recognize hyperbolas produced by buried targets and extract information from them: detection, localization, and characterization. Special attention has been paid to study the effects of the dielectric contrasts between the targets and the surrounding soil and also of the polarization configuration of the GPR system relative to the main axe of canonical targets (pipes or strips).

In the literature, several works deal with the semi-automatic buried target detection and characterization. There are two main classes of methods: in the first class the model of the pattern is given a priori or designed by hand, in the second class the model is learned from the collected data. The methods based on Hough transform and its derivatives [6-8], genetic algorithm (GA) [10], and image segmentation and hyperbola fitting [16] are in the first class. The methods based on artificial neural networks (ANNs) [8-11], support vector machine (SVM) [12], and wavelet analysis [13-15] are in the second class. The template matching [17-20] is widely used in pattern recognition, since it is a simple method, based on a prior model extraction from one or several images, which leads to a good accuracy for detecting targets with reduced variability in observed images. Surprisingly, this approach has not been previously used in GPR, when observed patterns due to objects of interest are of quite similar aspects in the radargrams.

The template-matching algorithm is readily implemented on a computer and has a reasonable calculation time providing that the image and the template sizes are not too large. The template does not need to contain a hyperbola response very similar to the one to be detected, it only needs to be able to discriminate between hyperbolas of interest and the background (noise and small heterogeneities in the soil compared to the targets). The analysis of the distance map based on the L1 norm using an optimal threshold has allowed to select a limited number of template positions. In this work, the use of two antenna orientations along a profile (named polarization diversity) has allowed to obtain two distance maps from which a mean distance map should improve hyperbola detection in one of the two radargrams where the polarized response appears too weak and thus not detectable. The fitting of each hyperbola applied on maximum or minimum amplitudes is performed by a parametric analytical model based on the straight ray path hypothesis and using the constraint least square (LS) criterion. Considering canonical objects (pipes and strips), the template-matching algorithm has been tested on simulated (commercial software Empire) and experimental radargrams.

This paper is structured as follows: in section 2, the radar geometry is briefly described that was modeled using FDTD simulations. The parametric analytical ray path modeling was used to model hyperbolas. Section 3 deals with the steps of the pattern recognition algorithm that includes mainly the template-matching method and the parametric hyperbola fitting. The developments and validation were first performed on synthetic images. In section 4, a few experimental images acquired in a laboratory site are analyzed and the results associated with the parameter analysis are discussed. Finally, in section 5 conclusions and perspectives are drawn.

2. Modeling of the GPR system

A. Numerical FDTD modeling

The GPR SFCW system made of a pair of shielded bowtie slot antennas designed on a FR4 substrate, with real relative permittivity $\varepsilon'=4.4$ and thickness $e=1.6\ mm$ (see Fig. 1a), has been preliminary studied using FDTD simulations (commercial software Empire) [5]. The antenna radiation characteristics are adequate for operating in an UWB in the frequency range [0.46; 4] GHz very close to the soil surface (ground-coupled). Each antenna is enclosed in a shielded conductive rectangular box filled with a three-layered absorbing foam with dimensions $362\times231\times67.5\ mm^3$. Because the simulation time of the pair of antennas moving on the soil surface on a distance close to 1.6 m appears prohibitive for a parametric study (more than one week using a CPU i7-950 3.07 GHz), a pair of more simple planar antennas, named blade dipoles working in the same frequency band, but with a higher reflection coefficient, has been used. The blade dipoles designed on a FR4 substrate are non shielded and their dimensions are $290 \times 56\ mm^2$ (see Fig. 1c) [21, 22].

The offset between antennas in simulations and experiments has been fixed to 60 mm, and the elevation h_s above the soil is equal to 10 mm. The soil electrical parameters ($\varepsilon_s^{'}, \sigma_s$) are assumed constant across the frequency range. The GPR system is moved linearly on the soil surface with a step $\Delta y = 40\ mm$ (see Fig. 1a) to acquire a radargram. Because the experimental and modeled antennas appear as complementary UWB dipoles, the polarization of the electric field $\left(E_\theta, E_\phi\right)$ appears perpendicular. In the simulations, the excitation current has the shape of the derivative of the Gaussian function with a time zero estimated to 0.3 ns and a duration (99% of the total energy) of 0.5 ns (peak frequency 1 GHz, bandwidth 3 GHz).

B. Analytical ray path modeling

The analytical modeling based on the ray path hypothesis supposes that the target is localized in the far-field zone of the GPR system. Such a modeling helps the interpretation of the earliest reflection component of a hyperbola pattern. Considering a buried canonical object, such as a cylindrical pipe, the linear displacement of the GPR system on the soil surface (h=0) such as depicted in Fig. 1a gives a time-distance curve with the shape of a hyperbola. The two-way (round-trip) travel time can be expressed as a function of the horizontal position y of the radar, the radius R , its horizontal location at y_0 and its depth d under the soil surface [16]. The lateral center-to-center antenna distance SR is considered in this study because of the marked dimension size of the antennas in the two main polarization configurations.

The equations associated with the travel-time write as follows:

$$y_T = y_i - SR/2 \qquad y_R = y_i + SR/2 \qquad (1)$$

$$T_{Tx2target} = \left[(y_0 - y_T)^2 + (d+R)^2\right]^{0.5} - R \qquad T_{target2Rx} = \left[(y_0 - y_R)^2 + (d+R)^2\right]^{0.5} - R$$

The velocity v of the medium depends on the real relative permittivity $\varepsilon_s^{'}$ such as:

$$v = c/\sqrt{\varepsilon_s^{'}} \qquad (2)$$

The generalized hyperbola equation (y_i, t_i) including the antenna offset is expressed by:

$$t_i = \left(T_{Tx2target} + T_{target2Rx}\right)/v \qquad (3)$$

Thus, the hyperbola depends on five parameters (SR, y_0, d, R, v).

A preliminary parameter study presented in Fig. 2 was conducted considering two configurations of the SFCW GPR system: parallel (SR=291 mm), and end-fire (SR=422 mm) [5]. Assuming a soil with $\varepsilon_s^{'} = 3.5$ (σ_s=0) and a buried pipe at depth d=180 mm with several radius values [0,40,80,120,160] mm, we first remark from Fig. 2a that when SR=0 the radius reduces the arrival time as if the velocity was increased; when R=0, a time difference of 0.64 ns at the apex is observed between the configurations SR=0 and SR=291 mm. We observe that the antenna distance SR flattens the apex and produces a delay in the arrival time, particularly significant when SR=422 mm (see Fig. 2b). The time difference at the apex increases with the soil permittivity as visualized in Fig. 2c. In the configuration SR=291 mm, we remark that the arrival time difference at the apex with a pipe radius less than 40 mm appears less than 0.1 ns (at the apex when R=0, if SR=291 mm t0=2.89 ns, and if SR=422 mm t0=3.45 ns); thus, in this range the radius value cannot be distinguished in a radargram and particularly when considering a time step of $\Delta t = 5.56E-11\, s$ used in experiments. With a larger antenna distance SR=422 mm, the radius variations appear more easily separable at the apex, however the hyperbola apex appears more flat and its amplitude will appear lower when the arrival time is higher. The variation of the soil real relative permittivity in the range [4 ; 10] (R=40 mm) and illustrated in Fig 3c highlights that the hyperbola slope increases with the permittivity value, and the apex appears sharper.

3. Template matching technique and hyperbola fitting

The proposed algorithm based on template-matching aims to detect semi-automatically hyperbola signatures without a preliminary training period, and to estimate target characteristics as reliably as possible.

The radargram processing is made of a series of steps:

- A pre-processing performed on the raw radargram to remove the antenna direct coupling and the clutter removal to enhance radargram quality;
- The construction of an amplitude distance map based on the translation on the radargram of a predefined template at every possible positions where a mean amplitude distance is evaluated according to the L_1 norm [8-9]. A threshold value allows to select local discrete minima on the distance map that corresponds to a high level of similarly with the template.
- At the selected positions, the hyperbola points close to the apex that can correspond to a maximum or a minimum amplitude are extracted. For each curve, a fitting of the points is performed using a parametric model;
- The estimation of the parameters describing the hyperbola curve such as d, R, v is obtained using a hyperbola fitting of the points to the analytical relation (3) according to the LS

criterion. The Hessian matrix in 2D and particularly its eigenvalues can be used to characterize the uncertainties on the estimated parameters (d,v) .

A. Pre-processing

In a radargram, the strongest and first signal detected associated with antenna ground-coupling may mask the hyperbolas of shallow buried objects. Depending on the depth of the objects and more precisely the degree of interaction of their responses with the signal of the clutter, an adequate clutter reduction technique has to be chosen [1, 22]. In this study, we have considered objects buried at a depth higher than 10 cm, thus the median subtraction at each time sample is assumed sufficient to reduce the horizontal component of the clutter.

Preliminary to image processing, the duration of the radargrams considered has to be limited (10 ns for numerical data, and 5 ns for experimental data) in order to eliminate the soil background without potential targets. Moreover, the distance-time units ($\Delta y=40\ mm$ in numerical and experimental data) of the template image defined have been scaled according to the image to be analyzed that supposes to perform a time interpolation; as in synthetic radargrams the time step was fixed to $\Delta t=2.396\ 10^{-11}\ s$ and $1.791\ 10^{-11}\ s$ in the parallel and end-fire configurations, respectively (see Fig. 3a and 3b), in experiments it was fixed to $5.5610^{-11}\ s$. A time zero correction has been applied in each radargram according to the shape of the excitation signal (the first positive amplitude component arrives here at 0.5 ns) to obtain a time zero at the wave ground bounce.

It must be underlined that in a radargram the data representing discrete amplitudes can be either binary or signed, depending on the quality and the dynamic range before the conversion; as in simulated data there is no background noise or unwanted reflections, the conversion of signed amplitudes into binary amplitudes doesn’t change the image quality. In experimental data, the signed amplitudes will be preferred.

B. Template-matching technique

The template-matching algorithm supposes to preliminary define a template including the average aspect of the different hyperbolas of interest in the radargrams to be analyzed. A preliminary study involving buried pipes under study was made to visualize and interpret a few synthetic hyperbola signatures. This study is an extension of the work in [3,23]. Synthetic radargrams have been obtained from FDTD simulations (software Empire) considering a system with blade dipoles (offset=60 mm, h_s=10 mm) in both configurations, parallel and end-fire (see Fig. 3a and 3b) moving linearly on a homogeneous soil ($\varepsilon_s'=3.5$, $\sigma_s=0.01\,S.m^{-1}$, $h=1\,cm$). A pipe (radius R=32 mm) with fundamental dielectric characteristics such as air-filled, conductive, and dielectric ($\varepsilon'=15$) was buried at depth d=168 mm [3-4]; the depth d is measured between the soil surface and the top surface of a pipe. The hyperbola signatures visualized in Fig. 4a, 4b, 4c, 4d, 5a 5b and 5c are plotted in the time range 8 ns, and the time vectors were interpolated to match the experimental time step $\Delta t=5.56\,10^{-11}\,s$.

In general, we remark that the parallel configuration such as presented in 4a and 4b (SR=116 mm) generates multiple reflections with higher amplitudes in the hyperbola legs whatever the dielectric characteristics of the pipe as compared to the end-fire case. These reflections correspond to wave bounces between the soil surface and the pipe top. In the case of a non conductive pipe, waves propagate in the pipe, and we observe a marked reflection at the bottom of the pipe when it is filled with a medium having a high contrast with the soil, in particular in water, that induces a wave velocity difference. Moreover, the amplitude of the backscattering waves appears reduced when the soil is attenuating.

In the end-fire configuration, such as visualized in Fig. 4c and 4d (SR=340 mm), hyperbola patterns have few components, and appear more compact. The conductive pipe induces a specific inverse polarity (negative amplitude) in the reflection pattern that allows to distinguish it. In both polarizations, we remark that the conductive pipe has the strongest reflection amplitude. In the case of a high dielectric pipe ($\varepsilon' = 15$), Fig. 5a and 5b highlight that in both polarizations multiple reflections induced between the top and bottom of the pipe can be distinguished because the velocity is relatively low inside the pipe; the parallel polarization gives a higher amplitude response. In Fig. 5b, artifacts that are induced by the clutter removal treatment appear visible because in the present case the clutter component and the target signature overlap (see Fig. 5c). Samples of these synthetic pipe signatures can serve as template images in the experiments.

The template does not need to be perfect, it only needs to allow us to discriminate between hyperbolas of interest and the background (small heterogeneities). When the set of hyperbolas of interest is too large to be represented by a single pattern, several patterns can be used in sequence. Each defined template includes a small portion of a hyperbola pattern in the vicinity of the apex and is scaled in time, distance and amplitude to the radargram under analysis.

Assuming an observed image $g(i,j)$ with a size $M \times N$, and a template image $t(i,j)$, both with scaled amplitudes, we define the L_1 norm distance map E between *g* and *t* by the following relation [18]:

$$E(m,n) = \sum_i \sum_j |t(i,j) - g(i-m, j-n)| \qquad (4)$$

The summation is evaluated at all pixels (i,j) of the template t that is translated to all possible positions (m,n) along the observed image *g*. This leads to an image of L1 distances, also named absolute distance map. The position (m,n) at which the smallest value $E(m,n)$ is obtained corresponds to the best match between the template *t* and the corresponding sub-image in *g*. A threshold value allows to select a limited number of local minima corresponding to distances E less than the threshold where the template is well matched with enough amplitude (visualized by “+” signs on the radargram, see Fig. 7c and 8c).

The template-matching algorithm has been first applied on synthetic data. The GPR system made of blade dipoles in the parallel (see Fig. 6) and end-fire configurations has been considered on a homogeneous soil structure including three close buried pipes at several depths. The pipes, from the left to the right, made of conductor (n°1), dielectric (n°2, $\varepsilon_s'=9$) and air (n°3, $\varepsilon_s'=1$) are separated by a distance equal to 300 and 250 mm respectively. The pipe radii are respectively 32, 22 and 11 mm. The radargrams after clutter removal are presented in Fig. 7c and 8c in the parallel and end-fire configurations (time range 10 ns). The comparison of both radargrams highlights a difference in shape and amplitude in the hyperbola signatures of the three objects that is explained by excitation direction of the electric field towards the pipes which are either conductive or dielectric. In both polarizations, we observe that the air-filled pipe has a significant lower response than the two other pipes, and thus appears masked; this phenomenon is caused by the weak permittivity contrast between the pipe and the soil that will be higher in a real soil.

In the end fire configuration, the synthetic template (189×7 pixels, $\Delta t=1.791\ 10^{-11}\ s$) visualized in Fig. 8a represents the upper part, near the apex, of the hyperbola signature of the conductive pipe in the end-fire configuration to further consider hyperbolas that overlap because of close objects; the apex appears in the middle of the time range. The complementary version of this template (141×7 pixels, $\Delta t=2.396\ 10^{-11}\ s$) has been used in the parallel configuration as it appears more adapted. At present, the template includes a significant upper zone without signal to allow the detection of first hyperbolas containing information.

In the parallel configuration, the similarity measure, applied on Fig. 7c (considering a time range 8 ns to reduce late reflections) while translating the template of Fig. 7a, leads to the distance map of Fig. 7b. In this last figure, two marked minima can be visualized that correspond to the positions of both significant hyperbolas. Defining the maximum threshold value to 120, the first two local positions of hyperbolas are detected, as visualized in Fig. 7c (time range 10 ns). We remark that the air-filled pipe has not been detected. In the end-fire configuration, the analysis of the radargram presented in Fig. 8c using the template of Fig. 8a according to the template matching algorithm, gives the distance map of Fig. 8b. The maximum threshold value of 162 allows to detect the two first hyperbola zones associated with the conductive and dielectric pipes such as visualized in Fig. 8c (time range 10 ns). As previously, the pipe air-filled pipe cannot be detected.

The polarization diversity (joint information from both perpendicular polarizations) can be used to enhance the detection in each polarization [23]. Thus, a mean distance map can be calculated from the individual distance maps in the parallel and end-fire configurations. A validation with experimental data of this point is described in Section 4.

C. Hyperbola fitting

For each detected template location, the next processing step consists in three sub-steps: location of the maximum or minimum amplitude arch associated with first arrival times, extraction of the discrete amplitudes, and fitting of the arch by an analytical hyperbola equation.

The curve points associated with the first arrival times of a hyperbola may correspond to a maximum or a minimum amplitude. Because higher order reflections in a hyperbola pattern may produce a stronger amplitude as compared to the amplitude of the first reflection, an user interaction is necessary (semi-automatic) to select a hyperbola curve either on the upper or on the lower half zone of the template position. Starting from the middle point of the template, close points belonging to the hyperbola curve on the left and on the right legs (usually 3 or 4 points) are extracted step-by-step. It is possible to extract points outside the template location mainly when no signature overlaps. Because the number of curve points extracted is limited, a polynomial fitting of the second order was made to refine the estimate of the abscissa y_0 at the apex. Then, knowing a priori parameters SR and y_0 , a fitting with the analytical modeling described by equation (3) and based on a constraint LS criterion has allowed to estimate the three parameters (d,R,v) . The constraint consists in defining for each parameter a minimum value, such as in the present case 40 mm (or 30 mm), 50 mm and 70 mm.ns^{-1} for R, d and v, respectively and a maximum value 60 mm, 200 mm and 190 mm.ns^{-1}, respectively. In the analysis of the numerical radargrams, initial values are respectively 40 mm, 100 mm and 134.16 mm.ns^{-1} (for $\varepsilon'=5$). In order to confirm the stability of the algorithm, a second fitting in a similar manner based on the analytical formula is performed using the last estimated parameters of R, d and v as initial values. Each hyperbola fitting in the radargram is made independently of each other.

Considering the radargrams in Fig. 7c and 8c associated with the parallel and end fire configurations, the parameter values obtained from the hyperbola fitting are collected in Tables 1 and 2, respectively. In each template location, the hyperbolas fitted were plotted (see Fig. 7c and 8c). From the parameter values, we remark that the pipe radius cannot be properly estimated, as it appears smaller than the radiating aperture of an antenna (on the order of the first Fresnel zone in the soil [24]); thus, the radius estimate remains equal to the initial value defined in the optimization function. In general, the real permittivity value was estimated with an uncertainty less than 15%, and this uncertainty influences the estimation of the depth. We observe that the curve fitting of pipe n°2 gives a lower permittivity estimate in both configurations as compared to the curve fitting of pipe n°1. In the end-fire configuration, we remark from Fig. 8c that the pipe signature n°2 is made of a significant second reflection that appears quite higher that the first reflection, that makes it difficult to detect. Consequently, the second hyperbola signature which arrives 0.4 ns later has been analyzed and the depth will need an adjustment of -69.3 mm (see Table 2). The fitting of this signature gives a higher objective function *fval* for pipe n°2 because 4 points has been considered in the left leg of the hyperbola. Otherwise, the objective functions are of the order of 10^{-3}. In general, we observe that the uncertainty of the depth is less than 22%.

	d	R	ε’	t_0	x_0	fval
Pipe n°1 (1st maximum)	184.3 mm	40	3.25	2.3 ns	-189.1 mm	$1.68\ 10^{-3}$
Pipe n°1 (true values)	*168 mm*	*32*	*3.5*		*-185 mm*	
Pipe n°2 (1st maximum)	98.8 mm	40	2.92	1.26 ns	113.1 mm	$7.67\ 10^{-4}$
Pipe n°2 (true values)	*79 mm*	*20 mm*	*3.5*		*115 mm*	

Table 1: Parameter estimation in the parallel configuration for the synthetic Bscan of Fig. 7c

	d	R	ε’	t_0	x_0	fval
Pipe n°1 (1st minimum)	150 mm	30	3.93	2.94 ns	-188.3 mm	$8.23\ 10^{-3}$
Pipe n°2 (2nd minimum) (1st minimum by extrapolation)	149.9 mm 80.6 mm	30	2.99	2.55 ns 2.11 ns	113.9 mm	$1.67\ 10^{-2}$

Table 2: Parameter estimation in the end-fire configuration for the synthetic Bscan of Fig. 8c

4. Evaluation on experimental data

Targets with different dielectric characteristics have been buried in a large sandy box of the public square Perichaux, Paris 15th district. The sand was not compacted and its relative dielectric permittivity was estimated to 3.5 from CMP (Common Mid Point) measurements. The time zero was corrected according to CMP measurements that have allowed to locate the direct waves. The pair of bowtie slot antennas (see Fig. 1b) separated by a 60 mm offset was moved linearly on the soil surface with a step of 40 mm to acquire a radargram. Both polarizations, parallel and end-fire, have been considered separately.

The complex transmission coefficient $\tilde{S}_{21}$ at the receiving antenna port was measured and stored using a vector network analyzer (VNA) ANRITSU MS 2026B in the frequency range [0.05;4] GHz (1601 samples). To obtain the transmitted signal in the time domain, an apodization (zero padding) has been applied to $\tilde{S}_{21}$ in order to smoothly extend the frequency band from 4 to 9 GHz. The excitation signal used in FDTD simulations, the first derivative of the Gaussian function with a duration equal to 0.5 ns, has been introduced in each experimental signal in the frequency domain. The product of the spectrum of the excitation signal (convolution in the time domain) with the measured $\tilde{S}_{21}$ has been performed to further calculate the inverse Fourier transform (IFFT) and obtain time data.

In the sandy box, a 25 mm diameter dielectric pipe and a thin vertical 10 mm width (2 mm thick) conductive strip were buried at depths estimated to 160 and 170 mm respectively such as presented in Fig. 9. Both objects are separated by a 750 mm distance. Firstly, a synthetic template was computed from 3D FDTD simulations (software Empire) considering the detailed bowtie slot antenna geometries (section 2.A) and 32 mm radius conductive pipe buried in a soil with a real relative permittivity $\varepsilon'=3.5$ ($\sigma=10^{-2}\,S.m^{-1}$). In this template visualized in Fig. 10, it was wise to define a compact hyperbola signature with reduced multiple reflections to further detect different hyperbolas in a radargram in both polarizations. Thus, a conductive pipe in the end-fire configuration has been considered. The template (see Fig. 10) was scaled in time and amplitude to match the experimental time step $\Delta t = 5.56E-11\ s$ (step distance 40 mm also used in experiments), and the amplitude range of the radargrams presented Fig. 11b and 11d (time range 5 ns). Signed amplitudes have been used here to not deteriorate the image quality.

The template-matching algorithm was performed on the experimental radargrams visualized in Fig. 11b and 11d and associated with both parallel and end-fire polarizations. The L1 norm distance maps are presented in Fig. 11a and 11c. The maximum threshold values leading to the detection of the first and most significant hyperbolas are 0.162 and 0.195 respectively; higher values give additional detections (false alarms) that don’t correspond to buried objects but to background heterogeneities. We remark that the end-fire polarization does not permit to detect the air-filled pipe. The results of the parameter evaluation from the LS fitting of each hyperbola detected are collected in Tables 3 and 4. In general, the positions y_0 of the objects appear correctly evaluated. Concerning the real permittivity value of the soil, the parallel configuration gives higher estimates as compared to the end-fire configuration, and consequently the target depths appear more important; from Table 3, we remark that the depths of the pipe and the strip have been both evaluated to 200 mm, and more important than those a priori evaluated (see Fig. 9). In the case of a soil having weak permittivity variations, an additional step would be to find an optimum permittivity value issued from the several estimates. We remark that the objective function *fval* associated with the LS fitting is presently higher for experimental data than for synthetic data, of the order of 10^{-2}, because the image quality appears lower.

To detect the air-filled pipe in Fig. 11d, joint information from radargrams issued from the parallel and end-fire configurations (polarization diversity) could be used. Thus, the mean distance map was calculated from the individual distance maps in the parallel and end-fire configurations (see Fig. 11a and 11c) leading to the result visualized in Fig. 12a. A weak threshold (0.18) situated between the previous ones (0.162 and 0.195) associated with both polarizations, has allowed here to detect both hyperbolas without false alarms in the end-fire configuration, that was not possible when this polarization was only considered.

Further insight into the solutions of the parameters estimated in the fitting has been gained by calculating the Hessian matrix H at the stationary point to evaluate its nature using its eigenvalues.

The rate of convergence and sensitivity to round-off errors is given by the condition number of matrix H, that is the ratio of its largest to its smallest eigenvalues. In the present examples, fixing the pipe radius that cannot be evaluated properly has led to a decrease of the condition number. The eigenvalues associated with the several fitting in both polarizations are collected in Table 5. In general, the condition number is high, that means that correlation may exist between the two parameters and thus the convergence of the estimation algorithm appears slow.

	d	R	ε’	t_0	y_0	fval
Pipe n°1 (maximum)	200 mm	60	3.6	3.08 ns	458.9 mm	$2.68\ 10^{-2}$
Pipe n°1 (true values)	*~160 mm*	*12.5 mm*	*3.5-4*		*~500 mm*	
Strip n°2 (maximum)	200 mm	60	3.47	2.99 ns	1232 mm	$2.23\ 10^{-2}$
Strip n°2 (true values)	*~170 mm*	*5 mm*	*3.5-4*		*~1200 mm*	

Table 3: Parameter estimation in the parallel configuration for the experimental Bscan of Fig. 11b

	d	R	ε’	t_0	y_0	fval
Strip n°2 (maximum)	165.6 mm	25.5	2.65	2.82 ns	1250 mm	1.85 10^{-2}

Table 4: Parameter estimation in the end-fire configuration for the experimental Bscan of Fig. 11d

Configurations	Eigenvalues for (d;v)
Parallel	
Pipe n°1	(4.1 10^{-5}; 2.1 10^{-2})
Strip n°2	(4.2 10^{-5} ; 1.9 10^{-2})
End-fire	
Strip n°2	(4.0 10^{-5} ; 9.6 10^{-3})

Table 5: Eigenvalues of the Hessian matrix at the estimates of the depth d and velocity v from hyperbola fitting in both polarizations

A second soil structure built in the sandy box includes two buried objects, a 25 mm diameter water-filled pipe and a horizontal 2 mm width strip with a 10 mm height such as visualized in Fig. 13a. In the parallel configuration, the radargram not presented here shows two very similar weak hyperbola signatures quite difficult to detect. In the end-fire configuration, the radargram presented in Fig. 13c shows two different hyperbola signatures. Using the template of Fig. 10, the template-matching algorithm has permitted to localize only the strip signature (threshold value 0.202) because the water filled pipe shows a quite different and specific hyperbola pattern; a threshold value higher than 0.202 will lead to detect several signatures in the background. The parameter estimations issued from the hyperbola fitting lead to the values collected in Table 6. The permittivity estimate appears close to the value issued from the previous experiments in the end-fire configuration.

	d	R	ε’	t_0	y_0	fval
Strip n°2 (maximum)	187.8 mm	60	2.49	2.61 ns	1299 mm	$1.07\ 10^{-1}$

Table 6: Parameter estimation in the end fire configuration for the experimental Bscan of Fig. 13c

5. Conclusion

This study is focused on the feasibility of detecting the location, depth, lateral dimension of long but thin buried objects such as pipes or strips in a soil using a GPR system. The most difficult tasks in the analysis of GPR radargrams is the split of overlapping signatures, the detection of a hyperbola pattern in a noisy background and in a weak image quality, the detection of an object with a small lateral dimension and a weak contrast with a perturbed surrounding medium. The work presented was carried out in two main steps: firstly, a theoretical parameter study (based analytical and numerical results) has consisted in analyzing hyperbola signatures of different dielectric pipes as a function the dielectric contrast with the surrounding medium, the polarization of the electric field and their diameter, and secondly a semi-automatic algorithm based on the template-matching technique and LS hyperbola fitting was developed to detect, localize and characterize a given but not restrictive hyperbola pattern. The template-matching algorithm does not need a training period, but needs the help of the user because of the great diversity of hyperbola signatures and the objective of the algorithm is to operate with a non perfect template.

The template-algorithm validated on numerical radargrams issued from FDTD simulations has shown that distinct templates have to be associated with both polarizations. Depending of the level of details required, several templates may be successively used to identify progressively the dielectric nature of a buried target among several in a radargram. A template has to consider the lateral dimension of the GPR system when it is quite larger than the size of the object to be detected. A sensitivity analysis has to be perform to study in details the influence of the soil permittivity used in the template to detect hyperbolas in a radargram. The advantage of using a SFCW GPR is that the excitation signal used in the simulated template can be used in the IFFT transform. Even with a few extracted hyperbola points, the present work shows that main parameters associated with the target can be estimated, but may be slightly correlated. This correlation can be diagnosed by means of the Hessian matrix. Considering measurements in a controlled environment, this work has shown that synthetic templates can be used to analyze radargrams provided that the templates have the same time step and amplitude range adjusted if necessary by interpolation; thus, a set of patterns has to be collected. The analysis of an experimental radargram in the end-fire configuration has shown that in the case of a buried water-filled pipe and a vertical conductive strip, the selected synthetic template was not able to detect the signature of the water-filled pipe because of its specific signature. The template-matching algorithm applied to GPR was extended by using the benefit of polarization diversity. This implies to define a mean distance map using the distance maps of both polarizations to improve the detection of weak hyperbola signatures in a polarization and strengthen the algorithm robustness. Further studies will be focused on bringing improvements to the template-matching algorithm, particularly during its validation on experimental radargrams acquired in the laboratory site Sense-City [26] where different targets representing utilities and cracks were buried. Thus, we are planning to build a data base of templates with variable sizes and variable dielectric contrasts of pipes and strips and variable surrounding materials. This new site is a good opportunity to refine the clutter removal procedure and to evaluate the performances of the template matching algorithm in a situation close to a real environment.

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