



HAL
open science

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

Florence Sagnard, Jean Philippe Tarel

► **To cite this version:**

Florence Sagnard, Jean Philippe Tarel. Template-matching based detection of hyperbolas in ground-penetrating radargrams for buried utilities. *Journal of Geophysics and Engineering*, 2016, 13 (4), pp.491-504. 10.1088/1742-2132/13/4/491 . hal-01524475

HAL Id: hal-01524475

<https://hal.science/hal-01524475>

Submitted on 18 May 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Template-matching based detection of hyperbolas in ground-** 2 **penetrating radargrams for buried utilities**

3 Florence Sagnard, and Jean-Philippe Tarel
4 University Paris-Est, IFSTTAR, Department COSYS,
5 14-20, bd Newton, 77420 Champs-sur-Marne, France
6 phone: +33 1 81 66 84 91
7 florence.sagnard@ifsttar.fr

8

9**Abstract**

10Ground-Penetrating Radar (GPR) is a mature geophysical technique that is used to map utility
11pipelines buried within 1.5 m of the ground surface in the urban landscape. In this work, the
12template-matching algorithm has been originally applied to the detection and localization of
13pipe signatures in two perpendicular antenna polarizations. The processing of a GPR
14radargram is based on four main steps. The first step consists in defining a template usually
15from finite-difference time-domain simulations made of the nearby area of the hyperbola apex
16associated with a mean size object to be detected in the soil whose mean permittivity has been
17previously experimentally estimated. The second step consists in a pre-processing on the raw
18radargram to correct variations due to antennas coupling, then the template matching
19algorithm is used to detect and localize individual hyperbola signatures in an environment
20containing unwanted reflections, noise and overlapping signatures. The distance between the
21shifted template and a local zone in the radargram based on the L1 norm allows to obtain a
22map of distances. A user-defined threshold allows to select a reduced number of zones having
23a high similarity measure. In a third step, in each zone minimum or maximum discrete
24amplitudes belonging to a selected hyperbola curve are semi-automatically extracted. In the
25fourth step, the discrete hyperbola data (i,j) are fitted by a parametric hyperbola modeling

26using a non linear least square criterion. The algorithm has been implemented and evaluated
27on numerical radargrams, and afterwards on experimental radargrams.

28

29**Keywords:** Ground-penetrating radar, pipe detection, hyperfrequency, template matching, soil
30characterization, ultra-wide band

31

321. Introduction

33Ground-penetrating radar (GPR) is a well-known non destructive technique for imaging
34shallow subsurfaces by a propagating electromagnetic energy downward into the ground from
35a transmitting antenna that is reflected at subsurface boundaries between media possessing
36different electromagnetic (EM) properties and is collected by a receiving antenna. GPR is a
37proposed technology to map utility pipelines in urban environments (fiber optics,
38telecommunication lines, electrical cables, water and gas pipes, district heating network),
39most of them have been buried within 1.5 m of the ground surface [1-2]. The buried targets
40produce characteristic hyperbolic signatures in the radargram (Bscan) issued from the moving
41of the GPR system along a linear path. Hyperbolic signatures represented in the distance-time
42domain are specific to the target size, shape and dielectric characteristics and the orientation
43of the electric field [3-4]. Challenges lie in detecting and classifying targets in an environment
44with variations in the surface cover (asphalt, paving, sand, gravel, grass), in the subsoil with
45spatial vertical or horizontal variability of the soil texture (water content, backfill soil,
46multilayers...), and the presence of buried targets that can be close to each other (overlapping
47hyperbolas) and have wide variations in dimensions, and in dielectric properties (metallic or
48non-metallic).

49An ultra-wide band (UWB) ground-coupled radar operating in the frequency band [0.46 ; 4]
50GHz and made of bowtie slot antennas has been preferred to an air-launched radar because it
51increases energy transfer of electromagnetic radiation in the sub-surface and penetration depth
52[1,5]. Moreover, UWB GPR and SFCW (step frequency continuous wave) have been used to
53probe the soil structure using the benefit from both low and high frequencies bringing a
54compromise in terms of depth resolution and penetration in a single measurement. This paper
55is focused on the processing and analysis of radargrams using the semi-automatic template-
56matching algorithm applied to GPR application in order to recognize hyperbolas produced by

57buried targets and extract information from them: detection, localization, and characterization.
58Special attention has been paid to study the effects of the dielectric contrasts between the
59targets and the surrounding soil and also of the polarization configuration of the GPR system
60relative to the main axe of canonical targets (pipes or strips).

61In the literature, several works deal with the semi-automatic buried target detection and
62characterization. There are two main classes of methods: in the first class the model of the
63pattern is given a priori or designed by hand, in the second class the model is learned from the
64collected data. The methods based on Hough transform and its derivatives [6-8], genetic
65algorithm (GA) [10], and image segmentation and hyperbola fitting [16] are in the first class.
66The methods based on artificial neural networks (ANNs) [8-11], support vector machine
67(SVM) [12], and wavelet analysis [13-15] are in the second class. The template matching [17-
6820] is widely used in pattern recognition, since it is a simple method, based on a prior model
69extraction from one or several images, which leads to a good accuracy for detecting targets
70with reduced variability in observed images. Surprisingly, this approach has not been
71previously used in GPR, when observed patterns due to objects of interest are of quite similar
72aspects in the radargrams.

73The template-matching algorithm is readily implemented on a computer and has a reasonable
74calculation time providing that the image and the template sizes are not too large. The
75template does not need to contain a hyperbola response very similar to the one to be detected,
76it only needs to be able to discriminate between hyperbolas of interest and the background
77(noise and small heterogeneities in the soil compared to the targets). The analysis of the
78distance map based on the L1 norm using an optimal threshold has allowed to select a limited
79number of template positions. In this work, the use of two antenna orientations along a profile
80(named polarization diversity) has allowed to obtain two distance maps from which a mean
81distance map should improve hyperbola detection in one of the two radargrams where the

82polarized response appears too weak and thus not detectable. The fitting of each hyperbola
83applied on maximum or minimum amplitudes is performed by a parametric analytical model
84based on the straight ray path hypothesis and using the constraint least square (LS) criterion.
85Considering canonical objects (pipes and strips), the template-matching algorithm has been
86tested on simulated (commercial software Empire) and experimental radargrams.

87This paper is structured as follows: in section 2, the radar geometry is briefly described that
88was modeled using FDTD simulations. The parametric analytical ray path modeling was used
89to model hyperbolas. Section 3 deals with the steps of the pattern recognition algorithm that
90includes mainly the template-matching method and the parametric hyperbola fitting. The
91developments and validation were first performed on synthetic images. In section 4, a few
92experimental images acquired in a laboratory site are analyzed and the results associated with
93the parameter analysis are discussed. Finally, in section 5 conclusions and perspectives are
94drawn.

95

962. Modeling of the GPR system

97A. Numerical FDTD modeling

98The GPR SFCW system made of a pair of shielded bowtie slot antennas designed on a FR4
99substrate, with real relative permittivity $\epsilon' = 4.4$ and thickness $e = 1.6 \text{ mm}$ (see Fig. 1a), has
100been preliminary studied using FDTD simulations (commercial software Empire) [5]. The
101antenna radiation characteristics are adequate for operating in an UWB in the frequency range
102[0.46; 4] GHz very close to the soil surface (ground-coupled). Each antenna is enclosed in a
103shielded conductive rectangular box filled with a three-layered absorbing foam with
104dimensions $362 \times 231 \times 67.5 \text{ mm}^3$. Because the simulation time of the pair of antennas moving

105on the soil surface on a distance close to 1.6 m appears prohibitive for a parametric study
106(more than one week using a CPU i7-950 3.07 GHz), a pair of more simple planar antennas,
107named blade dipoles working in the same frequency band, but with a higher reflection
108coefficient, has been used. The blade dipoles designed on a FR4 substrate are non shielded
109and their dimensions are $290 \times 56 \text{ mm}^2$ (see Fig. 1c) [21, 22].

110The offset between antennas in simulations and experiments has been fixed to 60 mm, and the
111elevation h_s above the soil is equal to 10 mm. The soil electrical parameters (ϵ'_s, σ_s) are
112assumed constant across the frequency range. The GPR system is moved linearly on the soil
113surface with a step $\Delta y = 40 \text{ mm}$ (see Fig. 1a) to acquire a radargram. Because the
114experimental and modeled antennas appear as complementary UWB dipoles, the polarization
115of the electric field (E_θ, E_ϕ) appears perpendicular. In the simulations, the excitation current
116has the shape of the derivative of the Gaussian function with a time zero estimated to 0.3 ns
117and a duration (99% of the total energy) of 0.5 ns (peak frequency 1 GHz, bandwidth 3 GHz).

118

119B. Analytical ray path modeling

120The analytical modeling based on the ray path hypothesis supposes that the target is localized
121in the far-field zone of the GPR system. Such a modeling helps the interpretation of the
122earliest reflection component of a hyperbola pattern. Considering a buried canonical object,
123such as a cylindrical pipe, the linear displacement of the GPR system on the soil surface ($h=0$)
124such as depicted in Fig. 1a gives a time-distance curve with the shape of a hyperbola. The
125two-way (round-trip) travel time can be expressed as a function of the horizontal position
126 y of the radar, the radius R , its horizontal location at y_0 and its depth d under the
127soil surface [16]. The lateral center-to-center antenna distance SR is considered in this

128study because of the marked dimension size of the antennas in the two main polarization
129configurations.

130The equations associated with the travel-time write as follows:

$$131 \quad \begin{aligned} y_T &= y_i - SR/2 \\ y_R &= y_i + SR/2 \end{aligned} \quad (1)$$

$$132 \quad \begin{aligned} T_{Tx2t\ arg\ et} &= [(y_0 - y_T)^2 + (d + R)^2]^{0.5} - R \\ T_{t\ arg\ et\ 2\ Rx} &= [(y_0 - y_R)^2 + (d + R)^2]^{0.5} - R \end{aligned}$$

133The velocity v of the medium depends on the real relative permittivity ϵ'_s such as:

$$134 \quad v = c / \sqrt{\epsilon'_s} \quad (2)$$

135The generalized hyperbola equation (y_i, t_i) including the antenna offset is expressed by:

$$136 \quad t_i = (T_{Tx2t\ arg\ et} + T_{t\ arg\ et\ 2\ Rx}) / v \quad (3)$$

137Thus, the hyperbola depends on five parameters (SR, y_0, d, R, v) .

138A preliminary parameter study presented in Fig. 2 was conducted considering two
139configurations of the SFCW GPR system: parallel (SR=291 mm), and end-fire (SR=422 mm)

140[5]. Assuming a soil with $\epsilon'_s = 3.5$ ($\sigma_s = 0$) and a buried pipe at depth $d = 180$ mm with several
141radius values [0,40,80,120,160] mm, we first remark from Fig. 2a that when SR=0 the radius
142reduces the arrival time as if the velocity was increased; when R=0, a time difference of 0.64
143ns at the apex is observed between the configurations SR=0 and SR=291 mm. We observe that
144the antenna distance SR flattens the apex and produces a delay in the arrival time, particularly
145significant when SR=422 mm (see Fig. 2b). The time difference at the apex increases with the
146soil permittivity as visualized in Fig. 2c. In the configuration SR=291 mm, we remark that the
147arrival time difference at the apex with a pipe radius less than 40 mm appears less than 0.1 ns

148(at the apex when $R=0$, if $SR=291$ mm $t_0=2.89$ ns, and if $SR=422$ mm $t_0=3.45$ ns); thus, in
149this range the radius value cannot be distinguished in a radargram and particularly when
150considering a time step of $\Delta t=5.56E-11$ s used in experiments. With a larger antenna
151distance $SR=422$ mm, the radius variations appear more easily separable at the apex, however
152the hyperbola apex appears more flat and its amplitude will appear lower when the arrival
153time is higher. The variation of the soil real relative permittivity in the range [4 ; 10]
154($R=40$ mm) and illustrated in Fig 3c highlights that the hyperbola slope increases with the
155permittivity value, and the apex appears sharper.

156

1573. Template matching technique and hyperbola fitting

158The proposed algorithm based on template-matching aims to detect semi-automatically
159hyperbola signatures without a preliminary training period, and to estimate target
160characteristics as reliably as possible.

161The radargram processing is made of a series of steps:

162- A pre-processing performed on the raw radargram to remove the antenna direct coupling and
163the clutter removal to enhance radargram quality;

164- The construction of an amplitude distance map based on the translation on the radargram of
165a predefined template at every possible positions where a mean amplitude distance is
166evaluated according to the L_1 norm [8-9]. A threshold value allows to select local discrete
167minima on the distance map that corresponds to a high level of similarity with the template.

168- At the selected positions, the hyperbola points close to the apex that can correspond to a
169maximum or a minimum amplitude are extracted. For each curve, a fitting of the points is
170performed using a parametric model;

171- The estimation of the parameters describing the hyperbola curve such as d, R, v is obtained
172using a hyperbola fitting of the points to the analytical relation (3) according to the LS

173criterion. The Hessian matrix in 2D and particularly its eigenvalues can be used to
174characterize the uncertainties on the estimated parameters (d,v) .

175

176A. Pre-processing

177In a radargram, the strongest and first signal detected associated with antenna ground-
178coupling may mask the hyperbolas of shallow buried objects. Depending on the depth of the
179objects and more precisely the degree of interaction of their responses with the signal of the
180clutter, an adequate clutter reduction technique has to be chosen [1, 22]. In this study, we have
181considered objects buried at a depth higher than 10 cm, thus the median subtraction at each
182time sample is assumed sufficient to reduce the horizontal component of the clutter.

183Preliminary to image processing, the duration of the radargrams considered has to be limited
184(10 ns for numerical data, and 5 ns for experimental data) in order to eliminate the soil
185background without potential targets. Moreover, the distance-time units ($\Delta y=40\text{ mm}$ in
186numerical and experimental data) of the template image defined have been scaled according
187to the image to be analyzed that supposes to perform a time interpolation; as in synthetic
188radargrams the time step was fixed to $\Delta t=2.396\ 10^{-11}\text{ s}$ and $1.791\ 10^{-11}\text{ s}$ in the parallel and
189end-fire configurations, respectively (see Fig. 3a and 3b), in experiments it was fixed to
190 5.5610^{-11} s . A time zero correction has been applied in each radargram according to the
191shape of the excitation signal (the first positive amplitude component arrives here at 0.5 ns) to
192obtain a time zero at the wave ground bounce.

193It must be underlined that in a radargram the data representing discrete amplitudes can be
194either binary or signed, depending on the quality and the dynamic range before the
195conversion; as in simulated data there is no background noise or unwanted reflections, the

196conversion of signed amplitudes into binary amplitudes doesn't change the image quality. In
197experimental data, the signed amplitudes will be preferred.

198

199B. *Template-matching technique*

200The template-matching algorithm supposes to preliminary define a template including the
201average aspect of the different hyperbolas of interest in the radargrams to be analyzed. A
202preliminary study involving buried pipes under study was made to visualize and interpret a
203few synthetic hyperbola signatures. This study is an extension of the work in [3,23]. Synthetic
204radargrams have been obtained from FDTD simulations (software Empire) considering a
205system with blade dipoles (offset=60 mm, $h_s=10$ mm) in both configurations, parallel and end-
206fire (see Fig. 3a and 3b) moving linearly on a homogeneous soil ($\epsilon'_s=3.5$, $\sigma_s=0.01$ S.m⁻¹ ,
207 $h=1$ cm). A pipe (radius R=32 mm) with fundamental dielectric characteristics such as air-
208filled, conductive, and dielectric ($\epsilon'=15$) was buried at depth d=168 mm [3-4]; the depth
209 d is measured between the soil surface and the top surface of a pipe. The hyperbola
210signatures visualized in Fig. 4a, 4b, 4c, 4d, 5a 5b and 5c are plotted in the time range 8 ns, and
211the time vectors were interpolated to match the experimental time step $\Delta t=5.56 \cdot 10^{-11}$ s .
212In general, we remark that the parallel configuration such as presented in 4a and 4b
213(SR=116 mm) generates multiple reflections with higher amplitudes in the hyperbola legs
214whatever the dielectric characteristics of the pipe as compared to the end-fire case. These
215reflections correspond to wave bounces between the soil surface and the pipe top. In the case
216of a non conductive pipe, waves propagate in the pipe, and we observe a marked reflection at
217the bottom of the pipe when it is filled with a medium having a high contrast with the soil, in
218particular in water, that induces a wave velocity difference. Moreover, the amplitude of the
219backscattering waves appears reduced when the soil is attenuating.

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

231

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

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

$$240 \quad E(m, n) = \sum_i \sum_j |t(i, j) - g(i - m, j - n)| \quad (4)$$

241 The summation is evaluated at all pixels (i, j) of the template t that is translated to all possible
 242 positions (m, n) along the observed image g . This leads to an image of L1 distances, also
 243 named absolute distance map. The position (m, n) at which the smallest value $E(m, n)$ is

244obtained corresponds to the best match between the template t and the corresponding sub-
245image in g . A threshold value allows to select a limited number of local minima
246corresponding to distances E less than the threshold where the template is well matched
247with enough amplitude (visualized by “+” signs on the radargram, see Fig. 7c and 8c).

248The template-matching algorithm has been first applied on synthetic data. The GPR system
249made of blade dipoles in the parallel (see Fig. 6) and end-fire configurations has been
250considered on a homogeneous soil structure including three close buried pipes at several
251depths. The pipes, from the left to the right, made of conductor ($n^\circ 1$), dielectric ($n^\circ 2$, $\epsilon'_s=9$
252) and air ($n^\circ 3$, $\epsilon'_s=1$) are separated by a distance equal to 300 and 250 mm respectively. The
253pipe radii are respectively 32, 22 and 11 mm. The radargrams after clutter removal are
254presented in Fig. 7c and 8c in the parallel and end-fire configurations (time range 10 ns). The
255comparison of both radargrams highlights a difference in shape and amplitude in the
256hyperbola signatures of the three objects that is explained by excitation direction of the
257electric field towards the pipes which are either conductive or dielectric. In both polarizations,
258we observe that the air-filled pipe has a significant lower response than the two other pipes,
259and thus appears masked; this phenomenon is caused by the weak permittivity contrast
260between the pipe and the soil that will be higher in a real soil.

261In the end fire configuration, the synthetic template (189×7 pixels, $\Delta t = 1.791 \cdot 10^{-11}$ s)
262visualized in Fig. 8a represents the upper part, near the apex, of the hyperbola signature of the
263conductive pipe in the end-fire configuration to further consider hyperbolas that overlap
264because of close objects; the apex appears in the middle of the time range. The
265complementary version of this template (141×7 pixels, $\Delta t = 2.396 \cdot 10^{-11}$ s) has been used in
266the parallel configuration as it appears more adapted. At present, the template includes a

267significant upper zone without signal to allow the detection of first hyperbolas containing
268information.

269In the parallel configuration, the similarity measure, applied on Fig. 7c (considering a time
270range 8 ns to reduce late reflections) while translating the template of Fig. 7a, leads to the
271distance map of Fig. 7b. In this last figure, two marked minima can be visualized that
272correspond to the positions of both significant hyperbolas. Defining the maximum threshold
273value to 120, the first two local positions of hyperbolas are detected, as visualized in Fig. 7c
274(time range 10 ns). We remark that the air-filled pipe has not been detected. In the end-fire
275configuration, the analysis of the radargram presented in Fig. 8c using the template of Fig. 8a
276according to the template matching algorithm, gives the distance map of Fig. 8b. The
277maximum threshold value of 162 allows to detect the two first hyperbola zones associated
278with the conductive and dielectric pipes such as visualized in Fig. 8c (time range 10 ns). As
279previously, the pipe air-filled pipe cannot be detected.

280The polarization diversity (joint information from both perpendicular polarizations) can be
281used to enhance the detection in each polarization [23]. Thus, a mean distance map can be
282calculated from the individual distance maps in the parallel and end-fire configurations. A
283validation with experimental data of this point is described in Section 4.

284

285C. *Hyperbola fitting*

286For each detected template location, the next processing step consists in three sub-steps:
287location of the maximum or minimum amplitude arch associated with first arrival times,
288extraction of the discrete amplitudes, and fitting of the arch by an analytical hyperbola
289equation.

290The curve points associated with the first arrival times of a hyperbola may correspond to a
291maximum or a minimum amplitude. Because higher order reflections in a hyperbola pattern

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

309 Considering the radargrams in Fig. 7c and 8c associated with the parallel and end fire
310 configurations, the parameter values obtained from the hyperbola fitting are collected in
311 Tables 1 and 2, respectively. In each template location, the hyperbolas fitted were plotted (see
312 Fig. 7c and 8c). From the parameter values, we remark that the pipe radius cannot be properly
313 estimated, as it appears smaller than the radiating aperture of an antenna (on the order of the
314 first Fresnel zone in the soil [24]); thus, the radius estimate remains equal to the initial value
315 defined in the optimization function. In general, the real permittivity value was estimated with

316an uncertainty less than 15%, and this uncertainty influences the estimation of the depth. We
317observe that the curve fitting of pipe n°2 gives a lower permittivity estimate in both
318configurations as compared to the curve fitting of pipe n°1. In the end-fire configuration, we
319remark from Fig. 8c that the pipe signature n°2 is made of a significant second reflection that
320appears quite higher than the first reflection, that makes it difficult to detect. Consequently, the
321second hyperbola signature which arrives 0.4 ns later has been analyzed and the depth will
322need an adjustment of -69.3 mm (see Table 2). The fitting of this signature gives a higher
323objective function f_{val} for pipe n°2 because 4 points have been considered in the left leg of the
324hyperbola. Otherwise, the objective functions are of the order of 10^{-3} . In general, we observe
325that the uncertainty of the depth is less than 22%.

326

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

327 **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 (1 st minimum)	150 mm	30	3.93	2.94 ns	-188.3 mm	$8.23 \cdot 10^{-3}$
Pipe n°2 (2 nd minimum) (1 st minimum by extrapolation)	149.9 mm 80.6 mm	30	2.99	2.55 ns 2.11 ns	113.9 mm	$1.67 \cdot 10^{-2}$

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

3304. Evaluation on experimental data

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

338 The complex transmission coefficient \tilde{S}_{21} at the receiving antenna port was measured and
 339 stored using a vector network analyzer (VNA) ANRITSU MS 2026B in the frequency range
 340 [0.05;4] GHz (1601 samples). To obtain the transmitted signal in the time domain, an
 341 apodization (zero padding) has been applied to \tilde{S}_{21} in order to smoothly extend the
 342 frequency band from 4 to 9 GHz. The excitation signal used in FDTD simulations, the first
 343 derivative of the Gaussian function with a duration equal to 0.5 ns, has been introduced in
 344 each experimental signal in the frequency domain. The product of the spectrum of the
 345 excitation signal (convolution in the time domain) with the measured \tilde{S}_{21} has been
 346 performed to further calculate the inverse Fourier transform (IFFT) and obtain time data.

347 In the sandy box, a 25 mm diameter dielectric pipe and a thin vertical 10 mm width (2 mm
 348 thick) conductive strip were buried at depths estimated to 160 and 170 mm respectively such
 349 as presented in Fig. 9. Both objects are separated by a 750 mm distance. Firstly, a synthetic
 350 template was computed from 3D FDTD simulations (software Empire) considering the
 351 detailed bowtie slot antenna geometries (section 2.A) and 32 mm radius conductive pipe
 352 buried in a soil with a real relative permittivity $\epsilon'=3.5$ ($\sigma=10^{-2} S.m^{-1}$). In this template

353 visualized in Fig. 10, it was wise to define a compact hyperbola signature with reduced
354 multiple reflections to further detect different hyperbolas in a radargram in both polarizations.
355 Thus, a conductive pipe in the end-fire configuration has been considered. The template (see
356 Fig. 10) was scaled in time and amplitude to match the experimental time step
357 $\Delta t = 5.56 E - 11$ s (step distance 40 mm also used in experiments), and the amplitude range of
358 the radargrams presented Fig. 11b and 11d (time range 5 ns). Signed amplitudes have been
359 used here to not deteriorate the image quality.

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

377To detect the air-filled pipe in Fig. 11d, joint information from radargrams issued from the
 378parallel and end-fire configurations (polarization diversity) could be used. Thus, the mean
 379distance map was calculated from the individual distance maps in the parallel and end-fire
 380configurations (see Fig. 11a and 11c) leading to the result visualized in Fig. 12a. A weak
 381threshold (0.18) situated between the previous ones (0.162 and 0.195) associated with both
 382polarizations, has allowed here to detect both hyperbolas without false alarms in the end-fire
 383configuration, that was not possible when this polarization was only considered.

384Further insight into the solutions of the parameters estimated in the fitting has been gained by
 385calculating the Hessian matrix H at the stationary point to evaluate its nature using its
 386eigenvalues.

387The rate of convergence and sensitivity to round-off errors is given by the condition number
 388of matrix H , that is the ratio of its largest to its smallest eigenvalues. In the present examples,
 389fixing the pipe radius that cannot be evaluated properly has led to a decrease of the condition
 390number. The eigenvalues associated with the several fitting in both polarizations are collected
 391in Table 5. In general, the condition number is high, that means that correlation may exist
 392between the two parameters and thus the convergence of the estimation algorithm appears
 393slow.

394

	d	R	ϵ'	t_0	y_0	fval
Pipe n°1 (maximum)	200 mm	60	3.6	3.08 ns	458.9 mm	$2.68 \cdot 10^{-2}$
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	$2.23 \cdot 10^{-2}$
Strip n°2 (true values)	~ 170 mm	5 mm	3.5-4		~ 1200 mm	

395 **Table 3:** Parameter estimation in the parallel configuration for the experimental Bscan of Fig.

396

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	$1.85 \cdot 10^{-2}$

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

398

11d

399

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

400 **Table 5:** Eigenvalues of the Hessian matrix at the estimates of the depth d and velocity v from

401 hyperbola fitting in both polarizations

402

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

412 values collected in Table 6. The permittivity estimate appears close to the value issued from
 413 the previous experiments in the end-fire configuration.

414

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

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

416

13c

4175. Conclusion

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

432 The template-algorithm validated on numerical radargrams issued from FDTD simulations
 433 has shown that distinct templates have to be associated with both polarizations. Depending of
 434 the level of details required, several templates may be successively used to identify

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

461References

462[1] Benedetto A and Pajewski L Civil engineering applications of ground penetrating radar
463(Springer 2015)

464[2] Proceedings of the General Meeting of COST Action TU1208 Rome (Italy) 22-24 July
4652013 (http://www.cost.eu/domains_actions/tud/Actions/TU1208)

466[3] Radzevicius S J and Daniels J J 2000 Ground penetrating radar polarization and scattering
467from cylinders J. Applied Geophysics **45** 111-125

468 [4] Gonzalez Huici M A 2012 Accurate ground penetrating radar numerical modeling for
469automatic detection and recognition of antipersonnel landmines PhD Dissertation
470(Rheinischen Friedrich-Wilhelms Universität Bonn)

471[5] Sagnard F 2014 Design of a compact ultra-wide band bow-tie slot antenna system for the
472evaluation of structural changes in civil engineering works, Progress in Electromagnetic
473Research PIER B **58** 181-191

474[6] Windsor C G Capineri L and Falorni P A data pair-labeled generalized Hough transform
475for radar location of buried objects IEEE Geoscience and Remote Sens. Letters **11**(1) 124-127

476[7] Wang J and Su Y 2013 Fast detection of GPR objects with cross correlation and Hough
477transform, PIER C **38** 229-239

478[8] Al-Nuaimy W Huang Y Nakhkash M Fang MTC Nguyen VT and Eriksen 2000 A
479Automatic detection of buried utilities and solid objects with GPR using neural networks and
480pattern recognition Journal of Applied Geophysics **43** 157-165

481[9] Gamba P Neural detection of pipe signatures in ground penetrating radar images IEEE
482Trans. Geoscience and Remote Sensing **38**(2) 790-797

483[10] Kobashigawa J S Youn H S Iskander M F and Yun Z 2011 Classification of buried targets
484using ground penetrating radar: Comparison between genetic programming and neural
485network IEEE Antennas Wireless Propag. Letters **10** 971-974

486[11] Nunez-Nieto X Solla M Gomez-Perz P and Lorenzo H 2014 GPR signal characterization
487for automated landmine and UXO detection based on machine learning techniques Remote
488Sens **6** 9729-9748

489[12] Muniappan N Hebsur A Rao E P and Venkatachalam G 2012 Utility detection and
490parameter estimation using ground penetrating radar. Proc. Intern. Conf. Engineering and
491Information Technol. ICEIT 2012 (Toronto, Canada) 29-34

492[13] Cieszczyk S Lawicki T and Miaskowski A 2013 The curvelet transform application to the
493analysis of data received from GPR technique *Electrika IR Elektrotechnika* **19**(6) 99-102

494[14] Zhan R and Xie H 2009 GPR measurement of the diameter of steel bars in concrete
495specimens based on the stationary wavelet transform. *Insight* **51**(3) 151-155

496[15] Ni S H Hunag Y H Lo K F and Lin D C 2010 Buried pipe detection by ground
497penetrating radar using the discrete wavelet transform *Computers and Geotechnics* **37** 440-
498448

499[16] Shihab S and Al-Nuamy W 2005 Radius estimation for cylindrical objects detected by
500ground penetrating radar, *Subsurface Sensing Technologies and Applications* **6**(2) 151-166

501[17] Jain A K, Duin R P W and Mao J 2000 Statistical pattern recognition: A review. *IEEE*
502*Trans. Pattern Analysis and Machine Intelligence* **22**(1) 4-37

503[18] Vernon D 1991 *Machine vision- Automated visual inspection and robot vision* (Prentice
504Hall)

505[19] Zyada Z and Fukuda T 2007 3D template based automatic landmine detection from GPR
506data. Annual Conf. SICE (Kagawa, Japan) 1552-1557

507[20] Jain A K, Duin R P W and Mao J 2000 Statistical pattern recognition: A review, *IEEE*
508*Trans. Pattern Analysis and Machine Intelligence* **22**(1) 4-37

509[21] Tebchrany E Sagnard F Baltazart V Tarel J P Derobert X 2014 Assesment of statistical-
510based clutter reduction techniques on ground-coupled GPR data for the detection of buried

511objects and cracks in soil. 15th International Conference on Ground Penetrating Radar (GPR)
51230 June-4 July 2014 (Brussels, Belgium)

513[22] Rejiba F Sagnard F Schamper C Froumentin M and Guerin R 2011 Zero-offset profiling
514using frequency cross-hole radars in a layered embankment test-site: antenna design,
515numerical and experimental results *Near Surface Geophysics* **9**(1) 67-76

516[23] Sagnard F and Tebchrany E 2015 Using polarization diversity in the detection of small
517discontinuities by an ultra-wide band ground penetrating radar *Measurement* **61** 129-141

518[24] Rial F I Pereira M Lorenzo H Arias P and Novo A 2009 Resolution of GPR bowtie antennas: An
519experimental approach *Journal Applied Geophysics* **67** 367-373

520[25] Chen H and Cohn A G 2010 Probabilistic robust mixture model for interpreting ground
521penetrating radar data. The 2010 International Joint Conference on Neural Networks (IJCNN)
52218-23 July 2010

523[26] <http://www.sense-city.univ-paris-est.fr/index.php>

524

525

526

527 LIST OF FIGURES

528

529 **Figure 1:** (a) Scheme of the GPR system imaging a subsurface with a buried pipe; (b)
530 Geometry of the bowtie slot antenna used in the measurements; (c) Geometry of the blade
531 dipole used in the simulations

532 **Figure 2:** Results of the parameter study performed using the ray-path modeling: variation of
533 the pipe radius ($\epsilon_s' = 3.5$; $d = 180$ mm; $y_0 = 500$ mm) for antenna distances (a) $SR = 0$ and 291
534 mm, and (b) $SR = 291$ and 422 mm ; (c) variation of the soil permittivity considering $SR = 291$
535 and 422 mm ($d = 180$ mm; $R = 40$ mm; $y_0 = 500$ mm)

536 **Figure 3:** Geometry of the GPR system used in FDTD simulations considering of a pair of
537 blade dipoles moving on a soil with a buried pipe ($d = 168$ mm, $R = 32$ mm) in the two
538 polarizations: (a) parallel, and (b) end-fire

539 **Figure 4:** Synthetic radargrams (after clutter removal) obtained from FDTD simulations using
540 a pair of blade dipoles (offset 60 mm) on a soil ($\epsilon_s' = 3.5$, $\sigma_s = 0.01 \text{ S.m}^{-1}$, $h_s = 10$ mm)
541 including : (a, b) a buried air-filled dielectric pipe in the parallel and end-fire configurations
542 respectively, and (b, c) a buried conductive pipe in the parallel and end-fire configurations
543 respectively

544 **Figure 5:** Synthetic radargrams (after clutter removal) obtained from FDTD simulations using
545 a pair of blade dipoles (offset 60 mm) on a soil ($\epsilon_s' = 3.5$, $\sigma_s = 0.01 \text{ S.m}^{-1}$, $h_s = 10$ mm)
546 including a buried dielectric pipe ($\epsilon' = 15$) in the (a) parallel and (b) end-fire configurations
547; (c) end-fire configuration without clutter removal

548**Figure 6:** Geometry of the GPR system, used in FDTD simulations, considering of a pair of
549blade dipoles moving on a soil including 3 different buried pipes (n°1 metal, n°2 dielectric
550with $\epsilon' = 9$, and n°3 air-filled) in the parallel polarization

551**Figure 7:** Analysis of the synthetic radargram (in pixels) associated with 3 pipes in the
552parallel configuration using the template-matching algorithm: (a) template defined, (b) L_1
553norm distance map calculated, and (c) positions of the image template detected in the original
554Bscan

555**Figure 8:** Analysis of the synthetic radargram (in pixels) associated with 3 pipes in the end-
556fire configuration using the template-matching algorithm: (a) template defined, (b) L_1 norm
557distance map calculated, and (c) positions of the image template in the original Bscan

558**Figure 9:** Geometry of the sandy box with two buried objects, an air-filled pipe and a
559horizontal conductive strip, probed experimentally using a pair of bowtie slot antennas

560**Figure 10:** Synthetic template issued from FDTD simulations involving a pair of bowtie slot
561antennas (end-fire configuration) moved on a soil ($\epsilon'_s = 3.5$, $\sigma_s = 0.01 S.m^{-1}$, $h_s = 10$ mm)
562with a buried conductive pipe (R=32 mm)

563**Figure 11:** Analysis of experimental radargrams (in pixels) associated with a air-filled pipe
564and a horizontal conductive strip using the template matching algorithm in the parallel (a, b)
565and end-fire (c, d) configurations ; (a, c) distance maps, (b, d) positions of the image template
566in the original Bscans and hyperbola fitting

567**Figure 12:** (a) Mean distance map in the parallel and end-fire configurations associated with
568an air-filled pipe and a horizontal conductive strip, and (b) positions of the image template in
569the experimental Bscan of the end-fire configuration

570**Figure 13:** Analysis of experimental radargrams (in pixels) associated with (a) a water-filled
571pipe and a vertical conductive strip using the template matching algorithm in the end fire
572configuration ; (b) distance map, (c) positions of the image template in the original Bscan and
573hyperbola fitting

574**LIST OF TABLES**

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

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

577**Table 3:** Parameter estimation in the parallel configuration for the experimental Bscan of Fig.

57811b

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

58011d

581**Table 5:** Eigenvalues of the Hessian matrix at the estimates of the depth d and velocity v from

582hyperbola fitting in both polarizations

583

584

585

586

587

588