# Evaluation of a geological radar at the LCPC geophysical test site in Nantes (France)

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## Introduction

The Laboratoire régional des Ponts et Chaussées (LRPC) based in Autun has for several years carried out investigations and non destructive geophysical surveys (electrical, radio-magnetotelluric, seismic, etc.) on behalf of Département-level departments of public works (DDE), local authorities and private customers. The non-destructive geophysical exploration seems particularly well suited to the growing needs of urban on-site surveys. Among these, the radar has strong potential and the LRPC in Autun acquired a geological radar in 1998 designed for monitoring roads, geological and geotechnical investigations on undeveloped land, and also to provide a better response to the location problems of objects buried in urban sites.

In order to test the performance and limits of this geophysical exploration equipment as well as its ease of implementation, a series of measurements was taken on the geophysical test site of the Laboratoire Central des Ponts et Chaussées (LCPC), Nantes. Since the investigation methods presented numerous interpretation problems, the LCPC created a test site with different objectives: evaluation of a material's performances and validation on a real site, validation of the efficiency of a development under operational conditions, evaluation of certain influence parameters, or even validation of numerical modelling. To this end, the site was set up under controlled conditions to provide reproducible measurements with well identified surrounding soils and a perfect knowledge of the objects to be detected.

Such explorations have already been carried out (e.g. see Grandjean et *al*. 2000) and can be used for comparison. The aim of this work is to show the performance of a geological radar used in a classic manner as well as the lessons that can be learnt while demonstrating the training aspect of the site.

## Physical principle

The radar technique is used to obtain a high resolution image of the subsurface. An electromagnetic pulse is sent into the subsoil, via an antenna, at a determined central frequency. This pulse propagates and is reduced by the materials or soils and, at each interface of the two different materials, part of its energy is reflected towards the surface. The successive echoes are recorded according to the time by the reception antenna (Daniels, 1996). The juxtaposition of the temporal signals recorded when the radar antenna moves can be used to obtain a radar profile or radargram, often represented with a colour scale correlated to the signal amplitudes and showing geometrical information on the structure monitored (fig. 1).

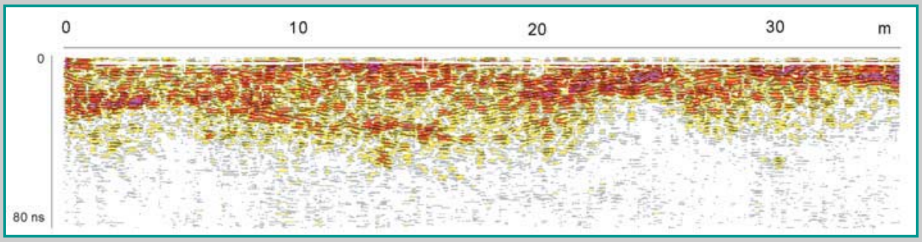



*Fig. 1 - Example of a radargram or radar profile. The horizontal axis represents a distance (in metres) and the vertical axis a double-time (both directions, in nanoseconds). The exploration shown here was carried out in the Parisian basin with a 400 MHz central frequency antenna. The top levels (bright colours) signify würmien carbonated conglomeratic paleochannels whilst below, in black and white, the levels without contrast correspond to Santonian age chalk.*

The wave propagation rate depends mainly on the dielectric constant (or relative permittivity) of the surrounding medium and can be represented at first in the following form (1):

$$v \approx c/(\varepsilon_r)^{1/2} \quad (1)$$

with

- $v$ = electromagnetic wave speed (m/s),
- $c$ = speed of light in the void (= $3 \times 10^8$ m/s),
- $\varepsilon_r$ = relative permittivity (without dimension).

The wetter a material, the slower the propagation rate (different values are shown in Cariou et *al*., 1997; this may influence the accuracy of the measurements when there is a moisture gradient with the medium (e.g. as for concrete).

The monitoring depth depends on several factors:

- the conductivity of the surrounding material, the main cause of wave attenuation;
- the choice of central frequency: the investigation depth decreases when the frequency increases;
- the radar system dynamic, which indicates the signal/minimum detectable noise ratio and can be linked to a monitoring depth limit;
- the adaptation of the antenna to the material (ability to transmit maximum energy in the material);
- the radiation lobe of the antenna which focuses the energy radiated in a given direction to a greater or lesser extent;
- the equivalent radar section (value describing the energy reflected in a given direction according to the shape and size of the object to be detected);
- the electromagnetic contrast of the object in relation to the surrounding material, taking into account that the higher it is the more significant the retrodiffused energy;
- the diffracting noise level due to the type of surrounding material (size and geometry of aggregates or units).

All these factors affect the radar waves recorded by the receiver antenna. However, it may be noted that, in a single environment, the maximum depth at which an object will cease to be detected can be markedly different depending on the type and shape of the buried object.

There is also a connection between the investigation depth and the resolution which is linked to the wave length emitted (Leparoux, 1997). A long wavelength causes low attenuation and the electromagnetic wave will penetrate deeply. Correlatively, the resolution is low and the wave is not affected by objects reduced in size.

## Test site description

The LCPC geophysical test site (fig. 2) is an excavation 20 m × 26 m × 4 m, separated into five compartments, each containing materials and components for testing (Chazelas et *al*, 1997). Their filling was carried out using a medium that can be considered homogeneous: basic layer compacting of 20 cm, prevention of water infiltration by lateral drainage and, at the bottom of the excavation, surface sealing.

The filling materials are used in vertical slices of varying widths:

- a slice of silts 5m wide;
- a "multilayer" trench 2.50 m wide, made up of a stack of layers from 0.60 to 1.30m of other site materials;

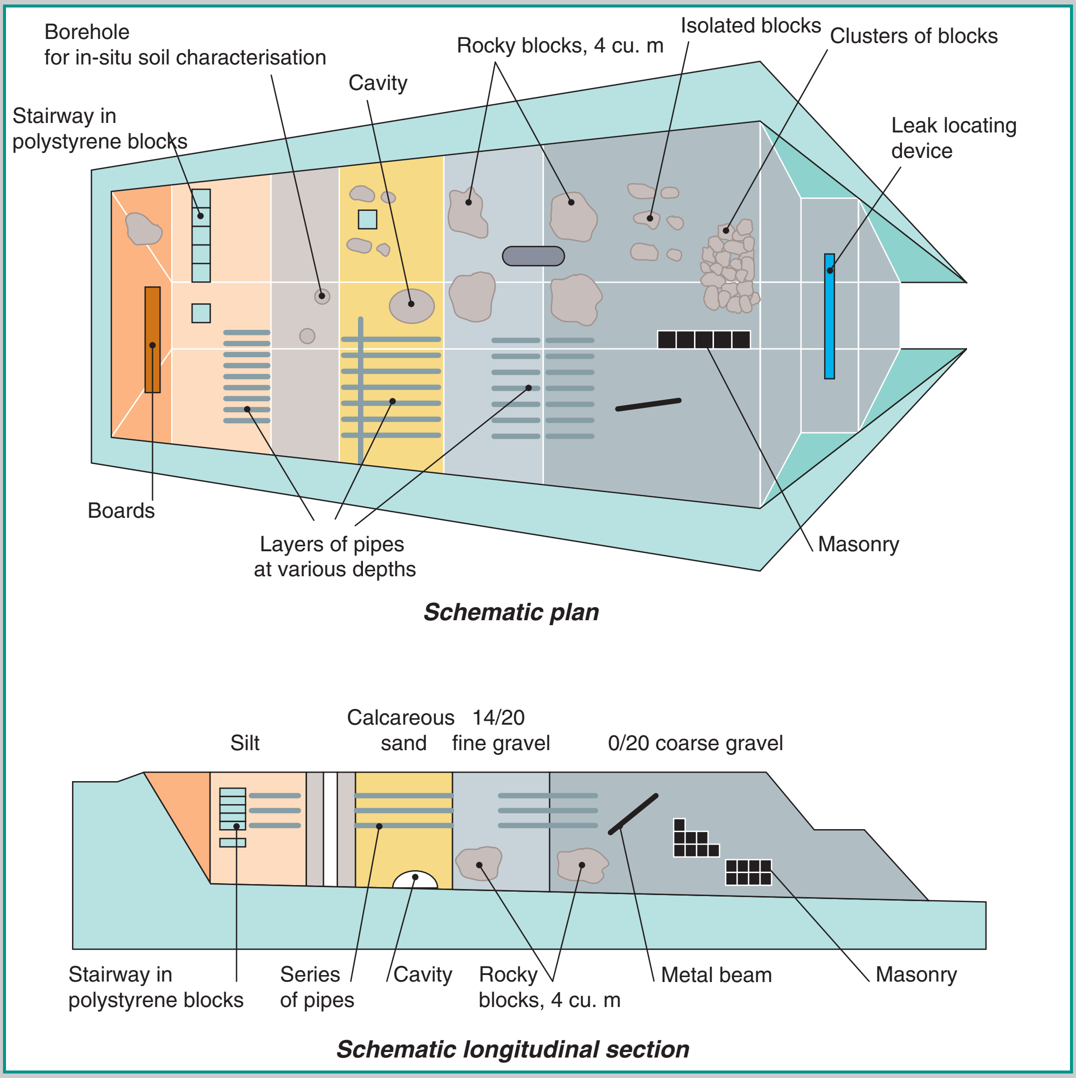



*Fig. 2 - Schematic drawing and crosscut diagram of the LCPC geophysical test site excavation in Nantes (Chazelas et al., 1997).*

- a trench of limy sand 5 m wide;
- a gneiss gravel trench 5 m wide, particle size distribution 14/20, to obtain a low density (approx. 1.8);
- two gneiss gravel trenches, each 5 m wide, particle size distribution 0/20, to obtain a high density (approx. 2.2);
- a 2.50 m berm at the end of the site for leak finding tests in the pipes.

In each of these slices, different objects are buried (fig. 2) to approximate the obstacles that can be encountered in a real urban site. These objects are perfectly located in the space using a local geodetic mark that is always available on site.

## Acquiring experimental data

### Description of the material/ Operating mode

The LRPC in Autun uses an SIR system 10H radar, developed by GSSI. It is associated with shielded antennae operating in monostatic mode: a single antenna is used to transmit and receive the electromagnetic wave. Three antennae were used, with central frequencies of 400, 500 and 900 MHz, respectively. Only the results obtained with the 400 and 900 MHz antennae are included in this work.

The data was acquired according to the bidimensional profiling method from the surface: an operators pulls the contact antenna along the profile implemented. Fourteen transveral and longitudinal profiles were made. The parallel transversal profiles were implemented with a gap of 2.50m to search for all the buried objects.

The measurement profiles (fig. 3) were carried out without the coding wheel, the distances were recorded manually by the operator every metre. For each profile, several runs were carried out with different antennae and different listening period and gain curve adjustments. The listening period corresponds to the time for recording echo returns and, therefore, the depth; the gain curve, variable with the listening period, can be used to correct the effects of attenuation by amplifying the most delayed echoes.

The data was processed using WinRad software, developed by GSSI. Several types of operation are possible to place the best emphasis on the heterogeneities recorded: choice of colour scale, vertical filtering, horizontal filtering, migration (all techniques for correctly replacing reflectors on a bidimensional profile) and gain amplification.

## Measurements and interpretations

The layout of the profiles used in this work are shown in the ground plan for the excavation (fig. 3).

### In the gneiss gravel layers

#### *Gneiss gravel 14/20*

Figure 4 shows the profile used for the 14/20 gneiss gravel trench, with a 400 MHz central frequency antenna. The base of the excavation, made up of a 10 cm drainage layer, is attained in about 60ns on the radargram and all the buried elements are visible. The concrete pipe, diameter 500mm, is shown by two hyperbolae which indicate the top and bottom. The "butterfly" type antennae used emit with a certain area known as the radiation lobe or emission lobe with an angle of approximately 90°. Because of this, heterogeneities are detected before and after the antenna reaches their vertical point. The result on the profile is a hyperbola, the top of which denotes the passage of the antenna to the right of this interface (the top denotes the shortest journey, and thus the shortest distance between the antenna and reflection interface).

There are three layers of pipes to the right of the slice (from left to right: steel pipe, water filled PVC pipe and empty PVC pipe) at varying depths (each layer, depending on the slice, is located around 1m, 1.50m and 2m. In addition, the gap between the pipes in each layer increases with depth: 0.5m,

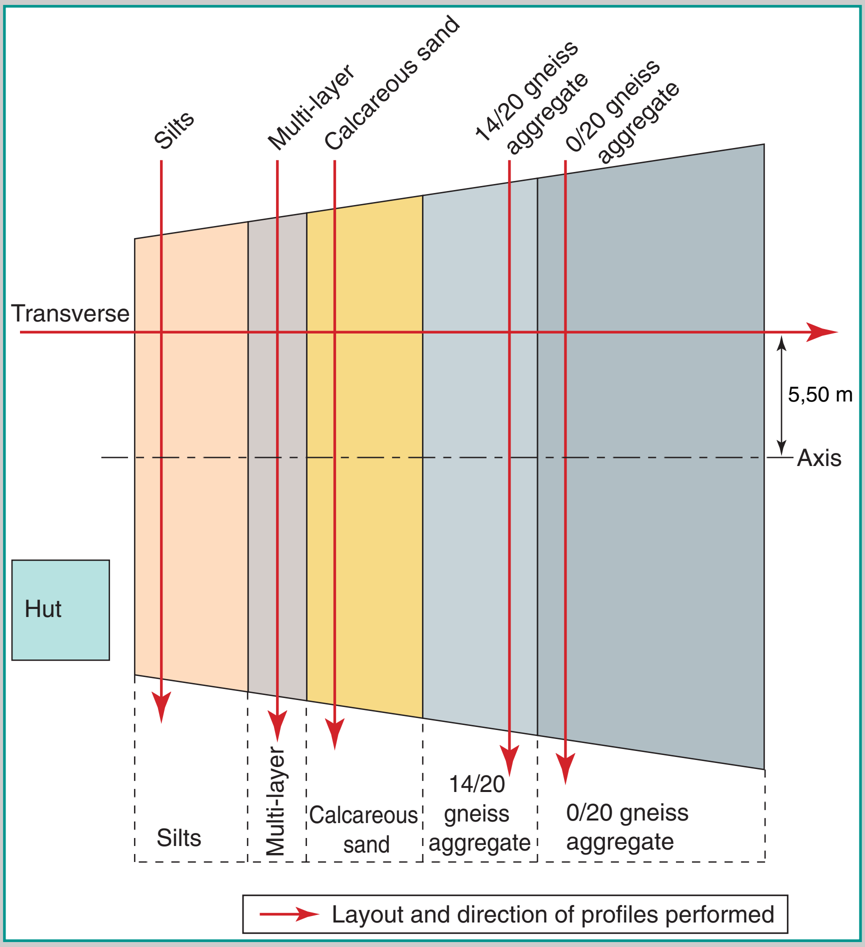



***Fig. 3 - Position of profiles in a ground plan. The section implantation is shown by the red line. The sections have the names of the filling trenches that they cut through.***

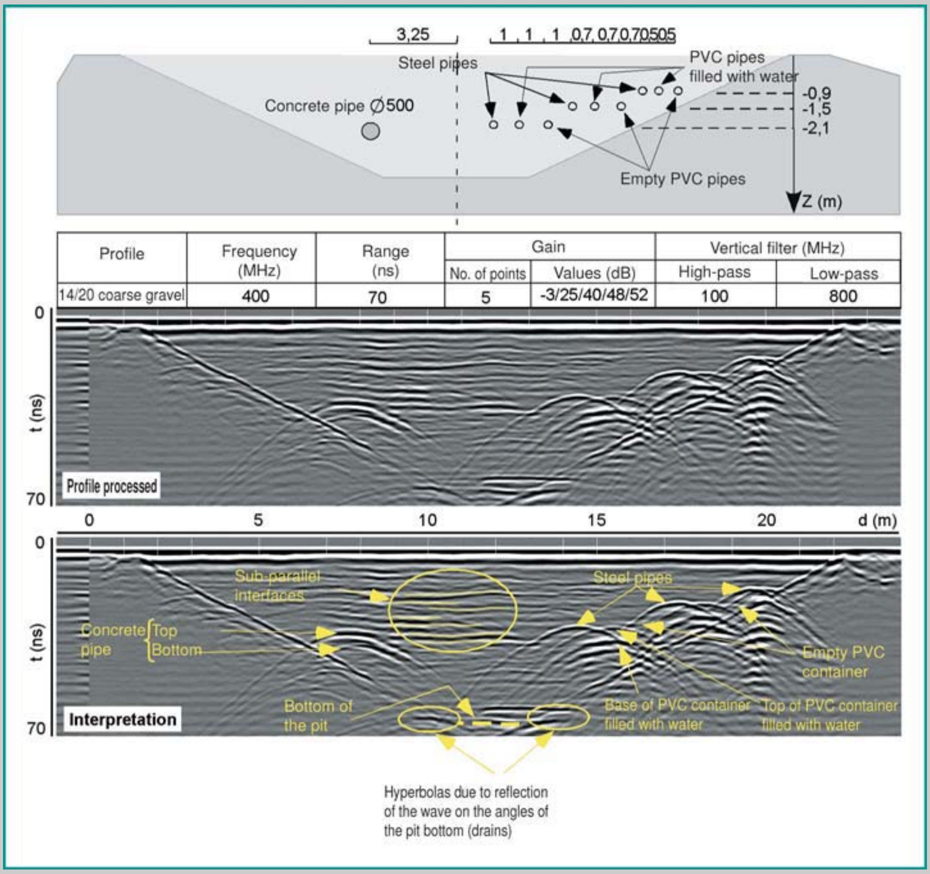



***Fig. 4 - Profile in the 14/20 gneiss gravel: theoretical crosscut diagram, adjustments, processed profile, interpretation (for Range, read listening period).***

0.7m and 1m). The steel pipes are highly reflective, with a single hyperbola denoting the summit. The empty PVC pipes are more difficult to distinguish. The water-filled PVC pipes show two reflections. The second reflection (the "deeper" one) showing the base of the pipe is the same as for the concrete pipe, detected just after its summit. This is due to the PVC being filled with water, which causes a slower wave speed in this medium and hence a reflection delay. The two reflections are not marked for the empty pipes as the propagation rate of the wave in air is too high.

It is also possible to observe two hyperbolae generated by the wave reflection on the angles at the base of the excavation. These are likely to have been generated by two drains (100mm diameter) located in these areas.

Several sub-parallel and sub-horizontal interfaces are also visible in the centre of the profile. Since the material is homogeneous with a constant water percentage and compacting every 20cm, the dielectric constant contrasts should be zero. They are likely to have appeared from the compacting surfaces. Their detection may be due to a compaction gradient or a different direction of particles on either side of each interface.

### *0/20 Gneiss gravel*

Monitoring was carried out with the same configuration as for 14/20 gneiss gravel, but this slice has different particle sizes (0/20), meaning that it contains fine clay-type particles.

The profile in figure 5 shows that the signal is absorbed beyond 35ns, at this central frequency of 400 MHz, with a 70ns listening period. It is possible to make a unique distinction between the steel pipes and the base of the PVC water filled pipes from the two layers of pipes closest to the surface. The blocks and concrete pipe are not visible. It is also possible to see the sub-parallel and sub-horizontal interfaces of the compacting layers.

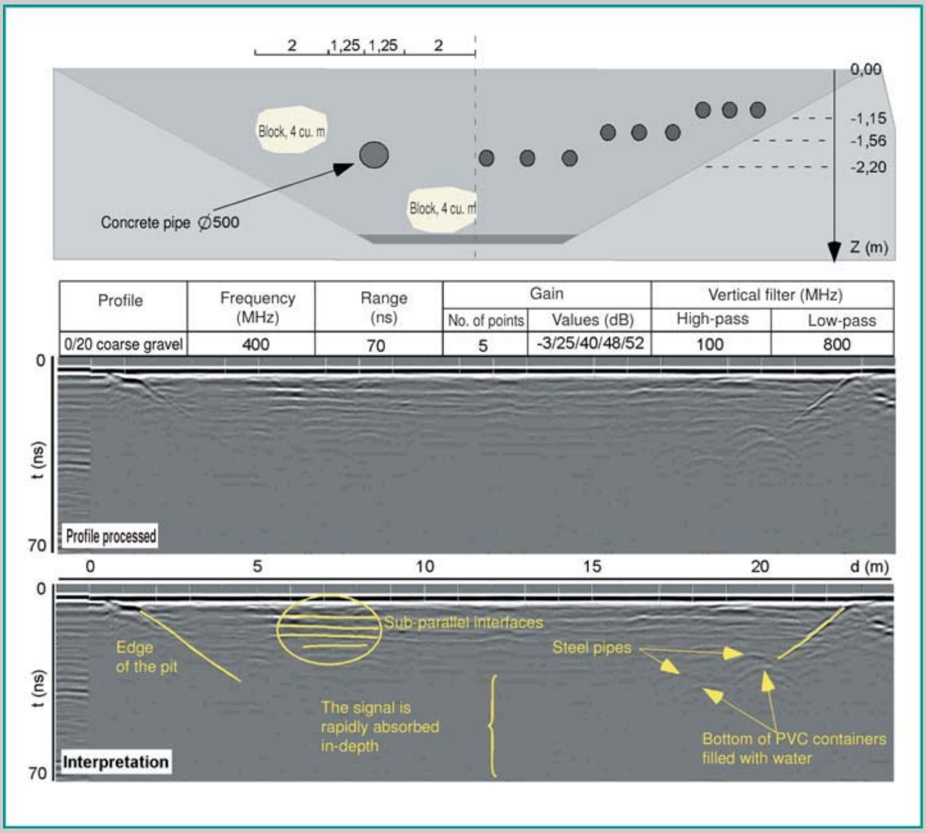
The depth of the investigation is lower according to the attenuation, which is more significant than in the 14/20 gravel, and the higher value of the dielectric constant of the medium (the values can be found in Grandjean et *al*. 2000).

The type of soils used to fill the excavation has an effect on the depth of wave penetration. In figure 4, the depth of the excavation is detected at a central frequency of 400 MHz in the 14/20 gneiss gravel, while it is not, in the 0/20 gneiss gravel (fig. 5), at the same frequency and for the same adjustments. The very strong influence of fine fractions is highlighted here, which, by their presence in the 0/20 gravel, prevent deep wave penetration in the soil.

The buried materials have an effect on the speed of the electromagnetic wave. The geometries of the objects shown in the profiles in figures 4 and 5 can cause possible errors in location if the type of these materials is not known. The profiles carried out in the 14/20 slice enabled all the pipes to be located, although the water pipe was denoted by its base. Location errors are therefore possible when the site configuration is not known, e.g. during prospection of an urban site.

Conversely, not everything was detected in the 0/20 slice, where only the top of the steel pipe and base of the water filled pipe were: à at this depth, the empty pipe was not detected, nor was the edge of the excavation. Therefore, when the burial depths are the same, the type of materials have an influence on the retrodiffused energy. This is the surface equivalent radar principle (see the main physics section), which is directly proportional to the reflected energy. Location errors are, therefore, possible is the type of objects buried is not known.

Finally, this profile underlines the great sensitivity of the technique, as the compacting layers were detected. This raises the issue of the large quantity of material that it is possible to recover and the difficulty in interpreting data, as urban site measures can have a lot of background noise.




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| 0/20 coarse gravel | 400 | 70 | 5 | -3/25/40/48/52 | 100 | 800 |

*Fig. 5 - Profil dans la grave-gneiss 0/20 : coupe théorique, réglages, profil traité, interprétation (pour Range, lire temps d'écoute).*

## In the multilayer

In this slice, two profiles, carried out at the same 400 MHz frequency but with different adjustments, are shown (fig. 6).

The objective was to test whether variation in the adjustment of the antenna could influence the quality of the recordings. To do this, two parameters were altered: the listening period (70 and 85ns) and the gain (see adjustments in figure 6) at each of the five points on the curve.

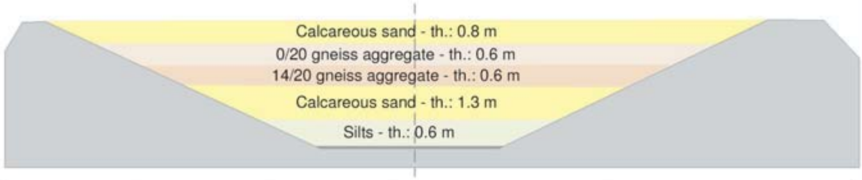
On the profile with a listening curve of 70ns, the signal is correct up to 30ns and can distinguish the different layers. Below this, it is rapidly absorbed and an interface, hardly visible at the depth, around 55ns, could correspond to the silt-lime sand limit.

The listening period increase from 70 to 85ns, with gain values adjustment, enables all the interfaces to be seen. The silt-lime sand interface is clearly visible here around 55ns. Below this, the noise increases very significantly. The bottom of the excavation could be reached around 80ns, but the signal is drowned by the noise. These two profiles show the importance of adjustments prior to monitoring.

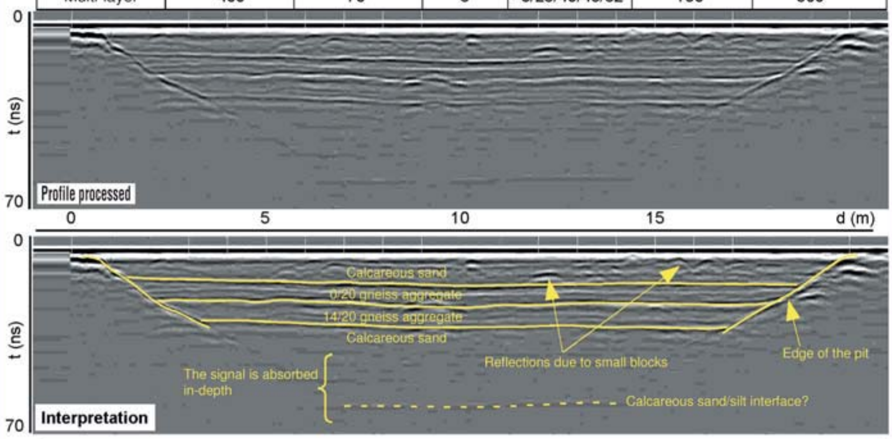
## In the silts

Two profiles carried out in the silts with two different antennae are shown (fig. 7): 400 MHz with 70ns listening period and 900 MHz with 60ns.

In the profile at 400 MHz, the first four polystyrene blocks are evident, but less and less clearly, the deeper they were buried. Below 30-35ns, nothing more is visible.




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Multi-layer | 400 | 70 | 5 | -3/25/40/48/52 | 100 | 800 |




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Multi-layer | 400 | 85 | 5 | -3/29/50/65/70 | 100 | 800 |

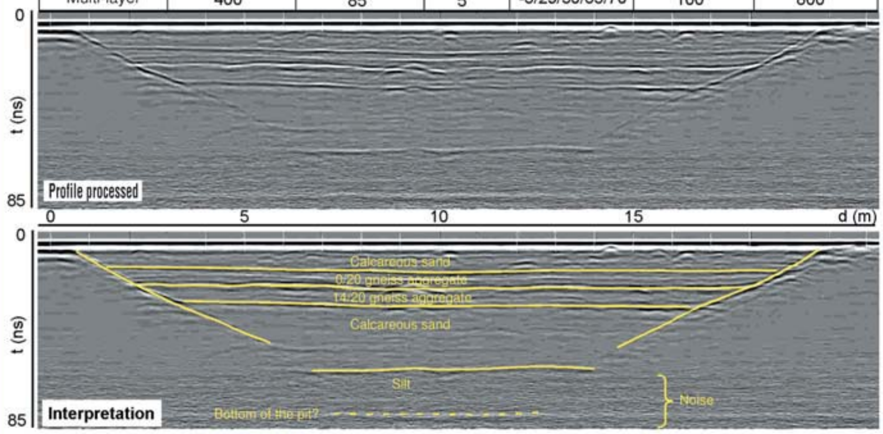
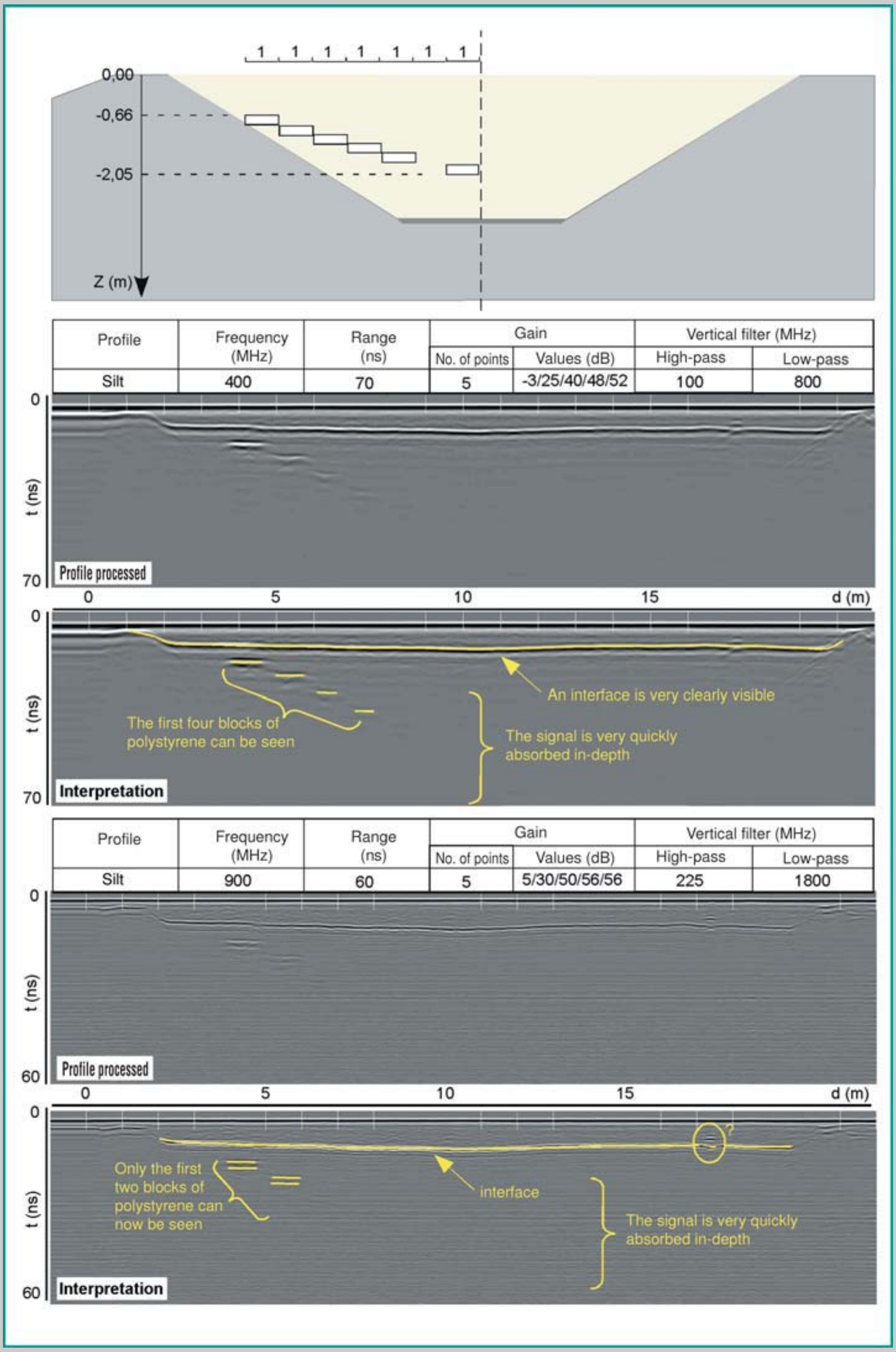



***Fig. 6 - Profiles in the multilayer with 400 and 900 MHz antennae: theoretical crosscut diagram, adjustments, profiles processed, interpretations (for Range, read listening period).***

With the 900 MHz antenna, only the first two blocks are discernible, each giving two reflections denoting their tops and bottoms. The signal is integrally absorbed below 20ns. Therefore a maximum investigation depth is attained at a double path of 20ns, at this central frequency and for these adjustments.

However, on both profiles, a reflector is very clearly visible close to the surface. This does not correspond to any structure in the theoretical crosscut diagram. In fact, this interface shows a change in lithology, as the top of the excavation was filled in with another material (layer of sand about 40cm deep).

The frequency of the antenna has a strong influence on the monitoring depth. This is more significant with the 400 MHz antenna. The higher the frequency the faster the wave emitted is absorbed. A high frequency antenna gives better resolution than the low frequency antenna since the top and bottom of the first two polystyrene blocks were distinguished with the 900 MHz antenna.




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Silt | 400 | 70 | 5 | -3/25/40/48/52 | 100 | 800 |

| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Silt | 900 | 60 | 5 | 5/30/50/56/56 | 225 | 1800 |

*Fig. 7 - Profiles in the silts with 400 and 900 MHz antennae: theoretical cross-cut diagram, adjustments, profiles processed, interpretations (for Range, read listening period).*

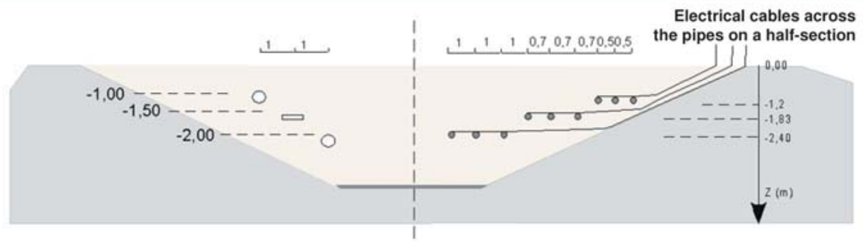
Therefore, the choice of monitoring frequency depends on the recognition objective: investigation depth or resolution, in view of the necessary compromise between these two parameters

## In the limy sand

Figure 8 shows the profile used for the limy sand, with a 400 MHz antenna and a listening period of 85ns.

The bottom of the excavation is clearly visible at around 75ns. In the left section of the profile, two strong reflections clearly denote the top and bottom of the polystyrene block. The rocky blocks are not detected as clearly: the block buried at 1m is visible, but it is not possible to observe the one at a 2m depth. The three layers of pipes are visible in the right section of the profile. The signal from the water-filled PVC pipes (in the centre of each layer) includes two hyperbolae, the one at the bottom being the most notable (i.e. which returns the most energy), as well as multiple reflections "deeper down". The steel pipes are clearly marked; however, it is more difficult to denote the PVC empty pipes as the dielectric contrasts are weaker.

The buried items influence the quality of the reflection by their type. Theory states that the quality and intensity of the wave reflection are proportional to the dielectric contrasts between the interfaces. This is clearly shown in figure 8, in the limy sands. The dielectric contrast between the rocky blocks and the surrounding material is not significant enough to cause a sufficient reflection of energy. Also if the closest block to the surface is only faintly detected, the one lower down is invisible on the radargram. In the same figure, the polystyrene block, however, appears very clearly with its top and bottom.




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Calcareous sand | 400 | 85 | 5 | -3/29/50/65/70 | 100 | 800 |

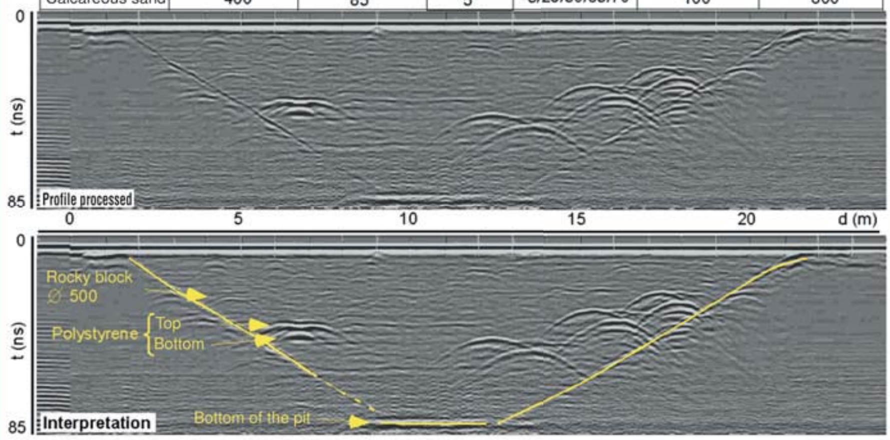


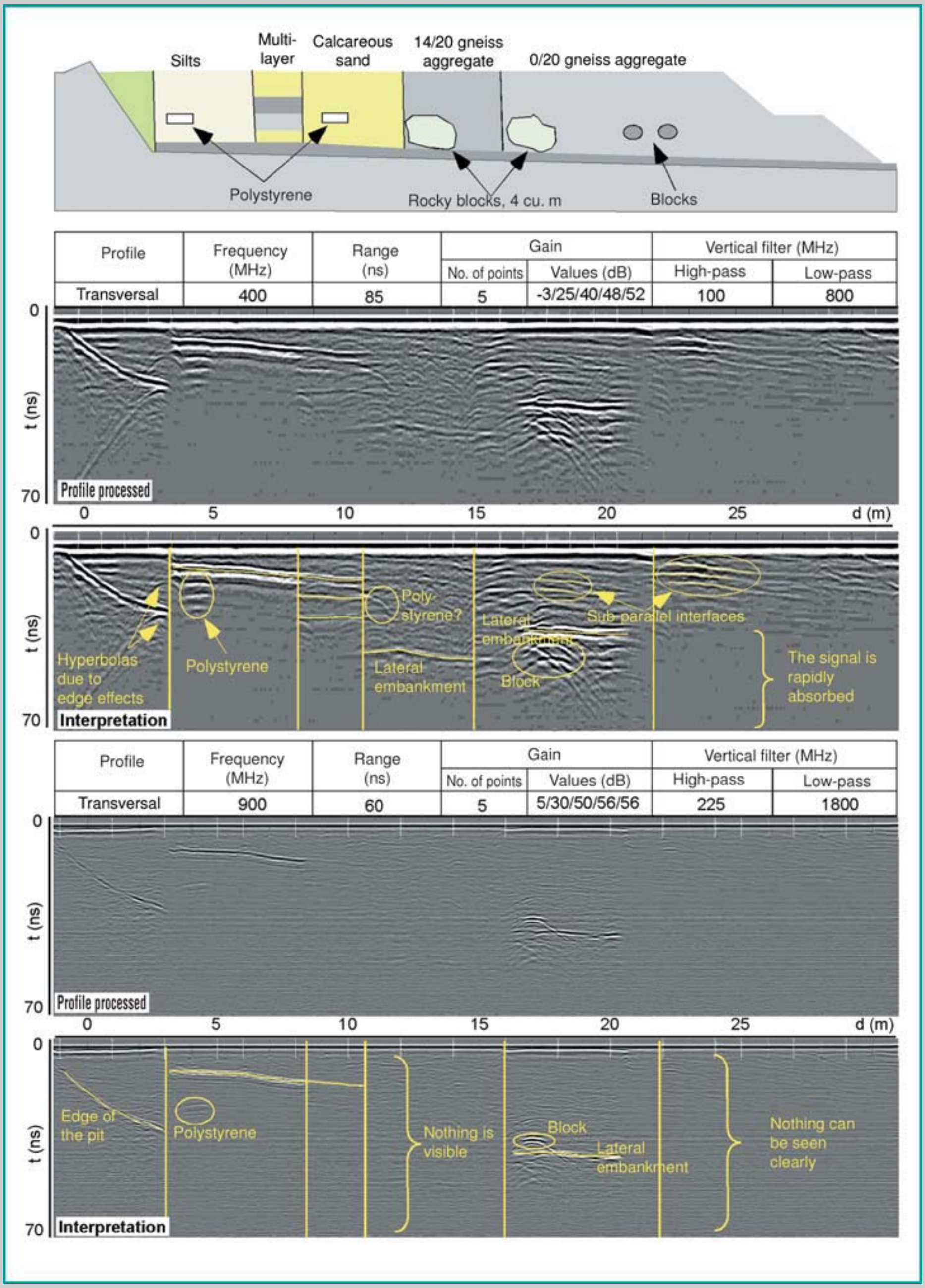

*Fig. 8 - Profile in the limy sand: theoretical crosscut diagram, adjustments, processed profile, interpretation (for Range, read listening period).*

## Transversal profile

This profile cuts out all types of surrounding material to be found in the test excavation.

Two profiles are shown (fig. 9), carried out in the same spot, but with two different test antennae, one 400 MHz and one 900 MHz. A comparison of the two profiles shows a very clear difference in wave penetration. The two antennae are quickly blinded in the silts and 0/20 gneiss gravel. Conversely, only the 400 MHz detected all the multilayer interfaces and the interface between the filling and surrounding material in the limy sand. This profile is not central but lateral (see layout in figure 3) ; also, the interface displayed is not the bottom of the excavation but the side edge.

The importance of the effects of the sides must also be underlines. These are denoted by semi-hyperbolae at the level of the basic dihedrals bordering the slice/basic layer.




| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Transversal | 400 | 85 | 5 | -3/25/40/48/52 | 100 | 800 |

| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Transversal | 900 | 60 | 5 | 5/30/50/56/56 | 225 | 1800 |

***Fig. 9 - Transversal profile with 400 and 900 MHz antennae cutting through all types of surrounding material: theoretical crosscut diagram, adjustments, profiles processed, interpretations (for Range, read listening***

## Data processing

A migration operation was performed on a profile carried out in limy sand. Migration is a mathematical process where the objective is to plot the heterogeneities in a depth crosscut diagram from a time crosscut diagram. To do this, it is necessary to know the radar wave speed in the medium. It is then possible to obtain a more real image of the geometry of the buried objects.

Figure 10 shows an example of a migration result where the nine pipes are perfectly repositioned; the inclination of the edge of the excavation is correct. The polystyrene block is well represented while the existence of two pipes side by side could have been supposed from studying the rough profile.

| Profile | Frequency (MHz) | Range (ns) | Gain | | Vertical filter (MHz) | |
|---|---|---|---|---|---|---|
| | | | No. of points | Values (dB) | High-pass | Low-pass |
| Calcareous sand | 400 | 85 | 5 | -3/29/50/65/70 | 100 | 800 |

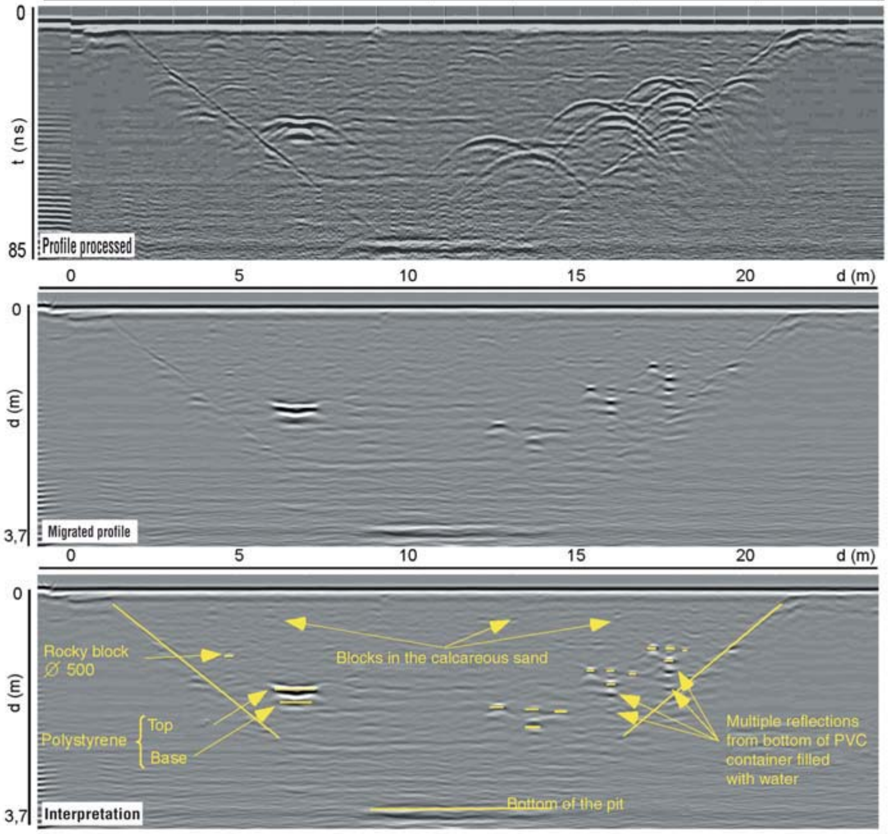



*Fig. 10 - Migration operation applied to a profile carried out in limy sand (for Range, read listening time).*

## Conclusions

The investigations carried out in a classic manner on the LCPC test site in Nantes have provided an introduction to the method of non destructive monitoring by geological-radar following measurements on a controlled site, reproducing what is currently used in urban sites. This technique has proved extremely easy to implement with a high return during prospection. However, several parameters have considerable influence on the quality of the measurements:

- the central frequency to be used depends on the monitoring depth and the desired resolution, taking into account that there is a necessary compromise between depth and precision;
- the type of structures being sought and the nature of the surrounding material (soil and subsoil) bear influence on the quality of the data recorded and the depth of the investigation. Fine clay particles create a mask, whereby the wave is absorbed. The quality of the reflections depends on the dielectric contrast between the materials being monitored;
- adjustments to the antennae, prior to the investigations, can noticeably improve the acquisition quality. Profiling carried out using different listening periods and gain curve adjustments have shown a significant improvement in the quality of the measurements;
- finally, data processing plays a not inconsiderable role in the quality of the returned images. This work can enable better depiction (contrast and geometry) of the structure being monitored, and can also be a source of artefacts, such as noise amplification in the lower section of the profiles.

The geological radar has a wide range of applications for geological recognition in earthworks tests. However, it can be frustrating to implement, e.g. when the subsoil contains clay particles that make the tool partly or completely blind.

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