A NEW SYSTEM TO PERFORM 3D GPR SURVEYS FOR UTILITY MAPPING

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Abstract

The aqueduct, sewer, gas, electrical and telecommunication networks are usually managed by different public or private companies. In many countries, these companies are not organized to maintain an accurate and up-to-date map of their installations because the local regulations do not force them to move in this direction. As a result, the maintenance of the utility net and the utilization of the no dig technology are more and more difficult. 3D GPR investigations are the most effective method to map the utilities but the GPR systems developed till now to perform this type of survey are based on multichannel solutions with an array of antenna so that the equipment is expensive and difficult to use on small areas (e.g., sidewalks, narrow streets, …) or where it is not possible to stop the human activities (e.g., traffic).

To overcome these difficulties, we designed a low-cost and easy-to-use positioning system (PSG, Pad System for Georadar, patent of Politecnico of Milano) to collect a regular grid of GPR data with a single antenna and with the accuracy required to generate 3D migrated images. As a result of the position accuracy, there is no need to oversample the area; this reduces the amount of data to be saved and the time per square meter needed to survey the area. The prototype testing proves that the system is effective and quite convenient in many real situations.

Introduction

The aqueduct, sewer, gas, electrical and telecommunication networks are usually managed by different public or private companies. Many of these companies are not organized to maintain an accurate and up-to-date map of their installations. As a result, the first three meters of the urban subsoil are extremely congested with many types of active and also dismissed structures. This makes the maintenance of the different networks and the location of free space for new utilities (e.g., optical fibers) extremely difficult. Nevertheless, this maintenance cannot be deferred because some networks (gas, water…) are about thirty or forty years old and others (sewer) are even much older. Daily, in a city like Milan, we observe the opening of new digging sites with a lot of problems for traffic and with a high rate of accidents caused by utilities damaged by the excavators.

As a result, the exact map of the utility distribution in the urban subsoil is more and more essential to allow a safe and rapid management of the networks and to reduce the impact of the digging sites on urban life.

GPR is supposed to become the dominant technology to detect and map the buried utilities in the highly populated areas of the developed countries. However, despite an increasing effort of the GPR manufacturers for the development of new equipment specifically designed for this demanding task, the use of this technique before the opening of a new digging site is not forced yet by our regulations. Moreover, the popularity of the GPR among the technical staff of the subsoil maintenance companies is still limited. On one side, we must acknowledge the fact that the pipe detection rate still needs to be improved because several soil typologies severely decrease the GPR penetration. New broadband antennas are required to address the problem ensuring a satisfactory mapping down to a couple of meters. On the other side, we must complain about the rough use of the technique that is sometimes resulting from the restricted budget for investigations and some other times is caused by the insufficient technical education of the GPR operators. Because of that, GPR profiles are executed with a profile density that is not sufficient to ensure the success of the detection and to produce data that can be processed in a 3D mode. Instead, the complexity and the mess of the utility distribution below the surface really requires that 3D GPR data are collected and processed. Thus, a regular dense grid of profiles must be executed and the profile parallelism must be ensured with an accuracy of a few centimeters. If the accuracy of the data position is not ensured, the 3D survey is not going to be rewarding and the benefit of the 3D migration of the data will be lost (Groenenboom *et al.*, 2001). The most advanced solutions proposed by the GPR manufacturers to perform accurate 3D surveys are based on multi-channel systems

equipped with an array of antennas (Ciochetto *et al.*, 1998; Birken *et al.*, 2002; Eide and Hjelmstad, 2002). As a result, the equipment is expensive and most suitable for investigations on large roads but difficult to use on small areas such as on sidewalks or in narrow streets as those of many historical European cities (**Figure 1**).

Instead, the target for 3D surveys executed with the new positioning system described here is the excavation area needed for a maintenance work or the drilling area needed to install new subsurface utilities with the no-dig technology. The excavation areas are often on the sidewalks where most utilities are buried and run parallel to the road (**Figure 2**). In many European countries, sidewalks are often quite narrow (about 1m) and generally not larger than 4m. Thus, the size of an excavation for repair intervention or the critical areas where a no-dig drilling machine must submerge and emerge dribbling through the other utilities typically vary from 3 to 40 m^2. The new positioning system is a low cost and easy-to-use solution designed to work on these areas with a minimum impact on the urban activities (pedestrians, bicycles, cars, etc.).

Figure 1. *Examples of narrow streets in European historical cities.*

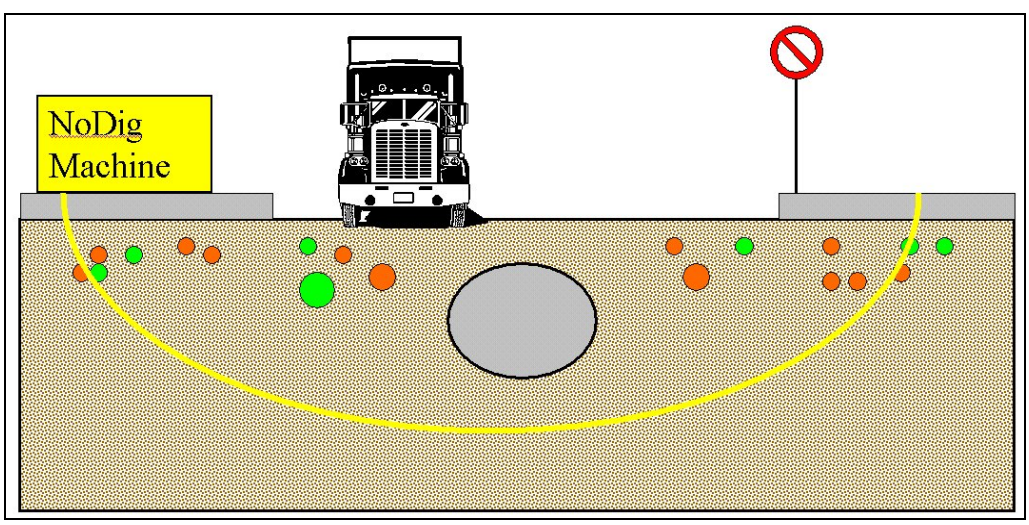

Figure 2. *No dig operations are mostly applied from sidewalk to sidewalk.*

The positioning system

PSG (Pad System for Georadar, patent of Politecnico of Milano) consists of a soft pad whose surface is modeled with parallel tracks that are a few millimeters high. A mate pad must be applied on the bottom of the antenna (**Figure 3**). The total thickness of the mating pads is about half a centimeter to keep the antenna in close contact with the soil.

Figure 3. *PSG (Pad System for Georadar).*

The GPR antenna is dragged along the tracks (**Figure 4**) so that parallel and regularly spaced profiles are rapidly executed. Moreover, the system presents the important benefit of ensuring that the antenna orientation does not vary during the survey. This is another advantage that helps in preserving the position accuracy and also the continuity of the pipe migrated images because the signal amplitude is sensitive to the relative orientation of the antenna with respect to linear targets (Reppert *et al.*, 2002).

We used PVC or similar materials to produce the prototypes. These materials meet all the mechanical requirements of the system. They are soft enough to adapt to the irregularity of the soil surface. The pad can be rolled up to facilitate the transport and also to adapt to the survey length (**Figure 4**). The antenna slides on the pad with a smooth movement. Instead, the friction between the bottom of the pad and the soil surface prevents the PSG from moving. As a result, vehicles, bicycles and pedestrians can cross the survey area without moving or damaging the pad (**Figure 5**).

Figure 4. *A 3D GPR survey using a 500MHz antenna and the PSG*.

Figure 5. *The PSG does not interfere with the daily activity around the investigation site.*

Test on controlled sites

To validate the detection rate and the failure rate of our GPR when applied in 3D mode with the PSG, we have been monitoring the digging sites around the campus of our university for more than a year. Thus, we had the chance to test the system on real sites perfectly known and documented with pictures. As an example, **Figure 6** shows a trench open on a sidewalk where some utilities run parallel to the road. The trench is about 1.2 m deep and from left to right the depth of the visible pipes increases from about 50cm to 110cm. Target A and B are metal pipes, target C is a plastic pipe. We collected a set of profiles orthogonal to the pipes with a PSG where the track separation is 0.8cm. This is the highest sampling rate achievable with this PSG but a cross-line sampling of 0.8 cm is actually not required for this application so that a larger profile interspace (3.2cm) was used. The data were processed with a 3D software developed by the authors. The software includes an efficient focusing algorithm where the velocity is defined as a time function and where the operator aperture can be controlled in the in-line and in the cross-line directions separately (Valle *et al*., 2000). **Figure 7** shows the pipe reconstruction represented as an iso-amplitude image extracted from the focused data volume. The figure indicates that all the pipes were detected although the image resolution is not enough to separate target A from target B because of the high energy scattered by the metal pipes. The diffraction observed on the upper right side is produced by the long stone posed at the sidewalk boundary. Some other pipes, not observed in **Figure 6** because beyond the area of the excavation, are also shown on the left.

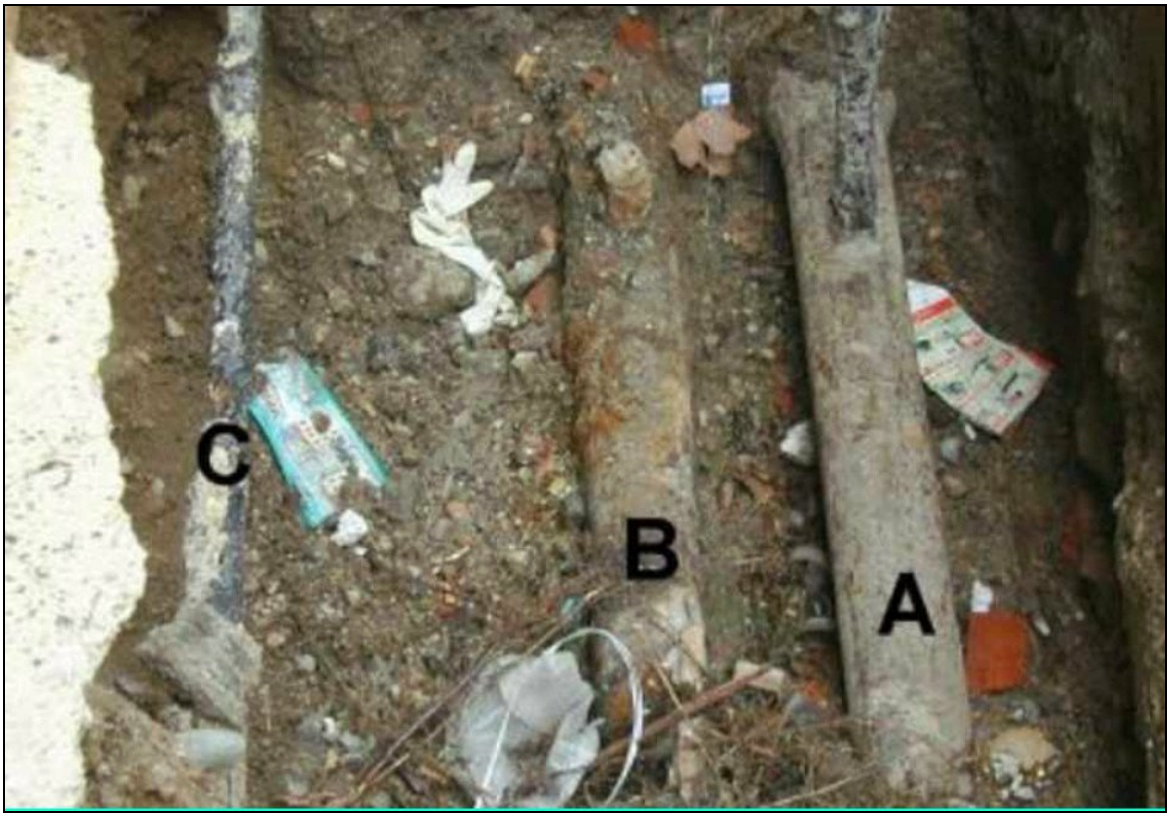

Figure 6. *Metal (A, B) and plastic (C) pipes in one of the excavated sites used to validate the performances of the GPR combined with the PSG system.*

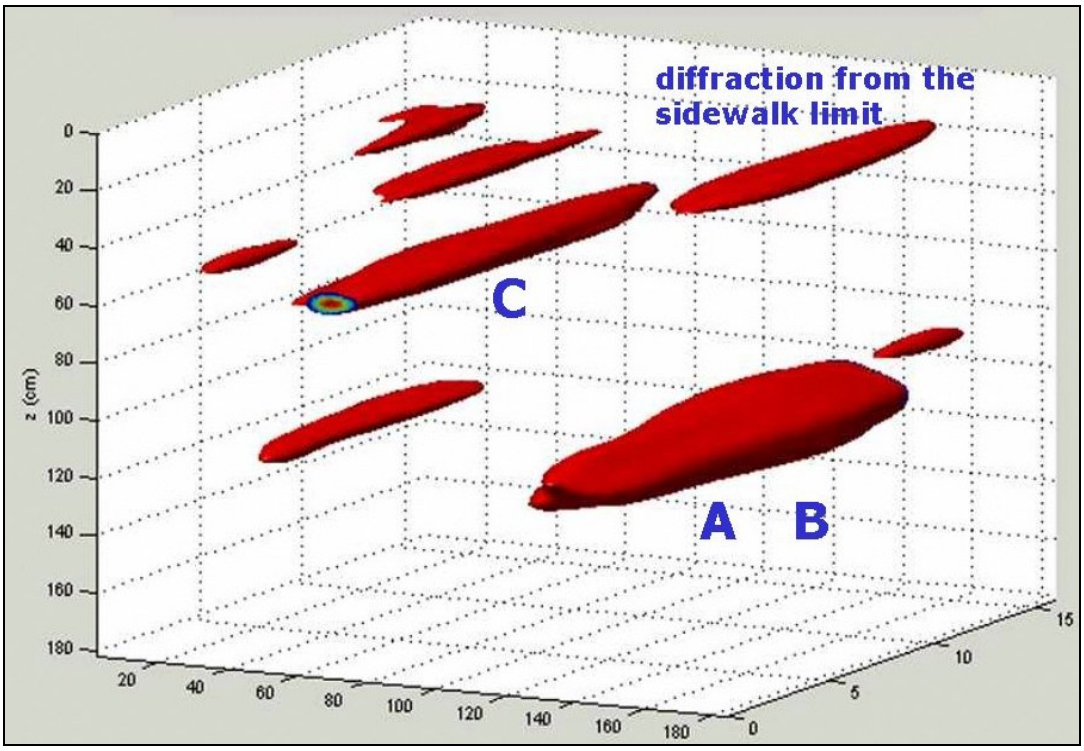

Figure 7. *3D reconstruction through iso-amplitude representation of the migrated volume of the 500MHz data obtained in the area of the trench shown in* ***Figure 6****. All the pipes observed in the trench can be detected although the image resolution is not enough to separate the two metal pipes. The diffraction on the upper right side is produced by the stone at the sidewalk boundary. Some other pipes are detected on the left beyond the area of the excavation.*

As a second example, we discuss the results obtained on another sidewalk site where many utilities run parallel to the road as documented by **Figure 8**. The trench is not very deep (about 1m) and from left to right the depth of the visible pipes decreases from about 80cm to 30cm. Target A is a pair of plastic pipes with an approximate diameter of 6 cm, target B and C are metal pipes with a diameter of about 8 and 20 cm respectively, target D is a triplets of plastic pipes with an approximate diameter of 15 cm. Again, we used the PSG to collect a set of profiles orthogonal to the pipes.

Figure 9 shows the iso-amplitude reconstruction of the processed data derived from a volume collected with a profile spacing of 3.2 cm. Thanks to the PSG, it was possible to collect these data in less than 20 minutes without creating any inconvenience to the daily activity on the sidewalk. Actually, a larger spacing could also be used without affecting the quality of the result but the acquisition time with the PSG is so short that there is no need to work with a larger spacing, at least when the investigation area is so small as in this example (2.5x1.2m). **Figure 9** indicates that all the pipes were detected although it is difficult to obtain a 3D iso-amplitude reconstruction where all the pipes appear as distinct objects with the same quality and continuity. This is due to the unbalanced scattering of the targets resulting from the fact that the pipes are distributed at different depths and consists of different materials (both metal and plastic pipes are present). **Figure 9** also shows the presence of another pipe that is beyond the area of the excavation and the presence of some scattering targets (stones ?) below the excavation level.

This site was also used to compare the performances of different antennas. **Figure 9** was obtained from the 250MHz data. A similar picture was also produced by the 500MHz data with the exception of target X that was missed by this antenna. This indicates that this frequency is not enough to ensure a sufficient penetration. On the other side, **Figure 9** demonstrates that the 250MHz data do penetrate enough but suffer from severe resolution problems. As a conclusion, we stress the need of new antennas with larger band and higher penetration performances.

Figure 8. *Metal (B, C) and plastic (A, D) pipes observed in one of the excavated sites used to validate the performances of the GPR combined with the PSG system.*

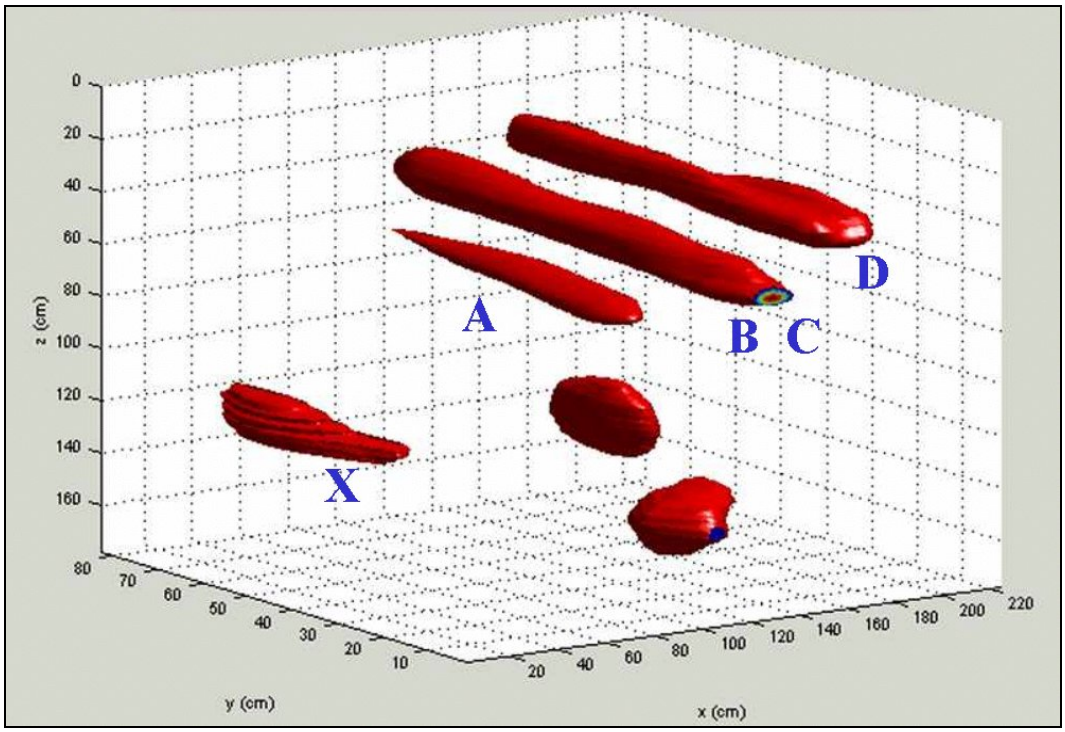

Figure 9. *3D reconstruction through iso-amplitude representation of the migrated volume of the 250MHz data obtained in the area of the trench shown in* ***Figure 8****. All the pipes observed in the trench can be detected although the signal resolution is not enough to separate the scattering from the pipes that are very close. An additional pipe X is detected on the left beyond the area of the excavation.*

Applications

We also tested the performances of the new positioning system in some real applications in the area of Milan. Here we discuss a case study where we surveyed a gas station area using the PSG to locate the exact position of the utilities in view of the fact that the Regional Agency for Environmental Protection (ARPA) was requesting to drill 13 boreholes for measuring the level of hydrocarbon pollution.

Since the station is located on a public area of a residential district, the subsoil was really crowded with every type of utility: water, gas, telecommunication, sewer, plus, of course, the pipes and the fuel tanks of the gas station. As a result, the request of drilling 13 new boreholes without hitting anyone of these targets was quite challenging. To look for 13 safe positions distributed on the whole area, we used the 3D GPR technique with the help of the PSG. The method was very effective: we performed all the 13 investigations in about 10 hours. The PSG was 3 meter long and 2 meter wide, with a track interspace of 9 cm (**Figure 10**). The activity of the gas station during the survey was not stopped as the cars were allowed to cross over the PSG.

Figure 10. *Acquisitions with the PSG at a gas station during normal service hours*.

The data were processed with the software developed by the authors. Each data volume obtained by assembling the parallel profiles executed with a 500MHz antenna on the 6 m^2 PSG consists of about 250x90x30 samples with a sampling interval of 2 cm in the in-line direction and 9 cm in the cross-line direction. **Figure 11** shows an example of one of these volumes after 3D data processing consisting of bandpass filtering, trace alignment, background subtraction, gain and 3D migration. A couple of pipes are clearly detected in the depth range from 1 to 1.5 m. The deeper one is basically horizontal and parallel to the long side of the PSG whereas the other one is gently dipping and curved. **Figure 12** shows the same data as a 3D reconstruction obtained by representing an iso-amplitude surface of the scattered energy contained into the volume. In principle, this representation is preferred by the end-users because it is easier to interpret. Unfortunately, it is not easy to produce high quality reconstructions in this format because the energy scattered by the targets in the volume can be very unbalanced being dependent on the pipe material, depth, orientation, diameter, etc.. As a result, artifacts, noise, pipe deformation, pipe discontinuity and other effects might disturb the iso-amplitude representation (**Figure 12**) more than the parallel section representation (**Figure 11**).

On the whole, the GPR survey was fully successful since we were able to propose 13 safe locations that were drilled without any accident or damage to the subsurface utilities.

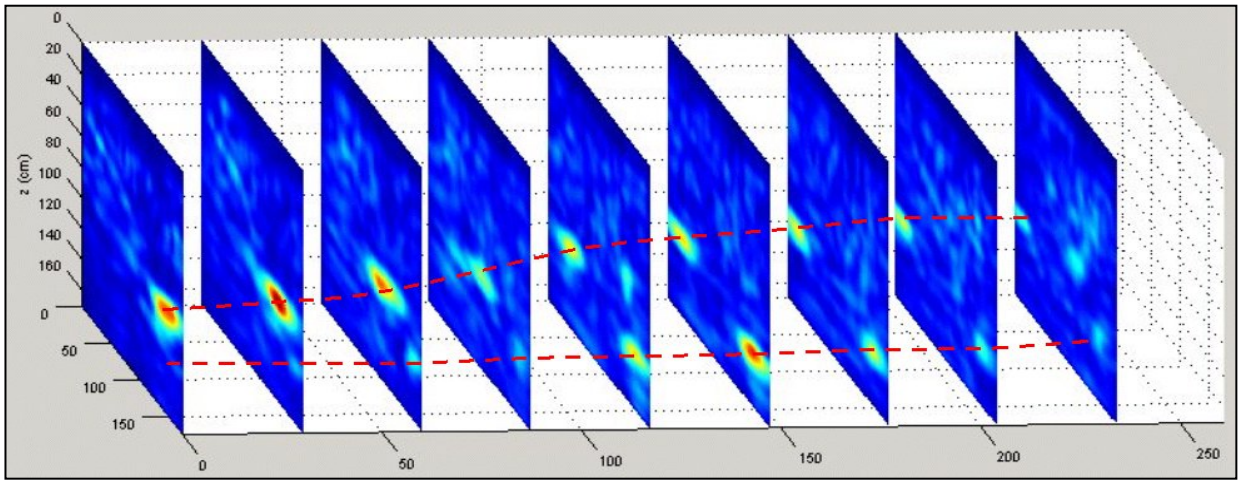

Figure 11. *Vertical sections of a migrated volume in the gas station area. Two pipes are detected.*

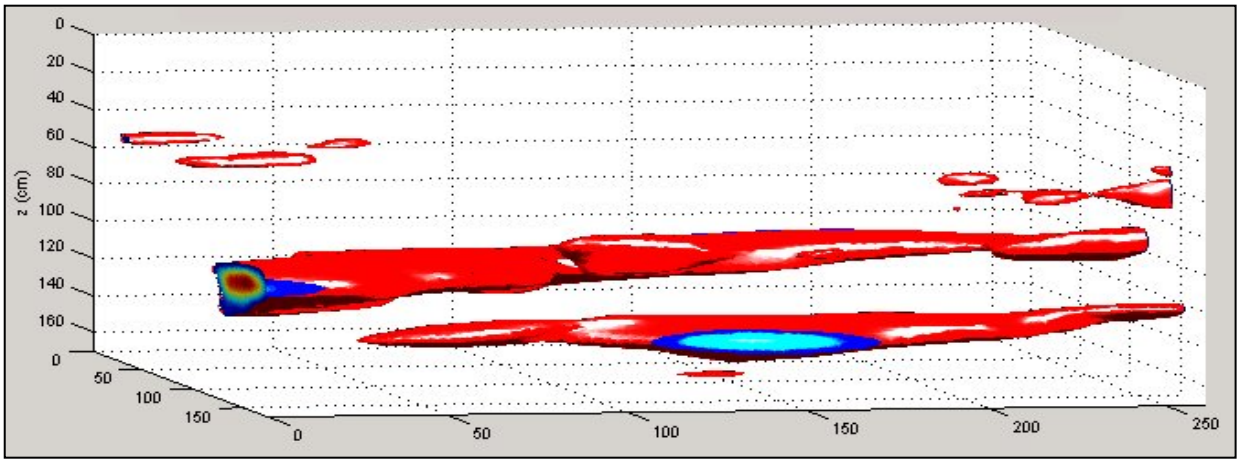

Figure 12. *3D reconstruction through iso-amplitude representation of the volume in* ***Figure 11.***

Conclusions

A new system named PSG was developed to solve the problem of antenna positioning on small areas that must be investigated with a 3D survey. The system was tested on controlled real sites where recent maintenance works required trench excavations and was also successfully applied to real applications. The advantages of the PSG can be summarized as follows: the system is extremely easy-to-use, cheap and flexible (i.e., it can meet many practical constraints that are normally faced when the GPR activity must interfere with the daily life on the roads or on the sidewalks). The PSG ensures an accuracy of 1 mm in the antenna position that is more than enough for the application. An additional benefit of the new system is that it forces the antenna to preserve the correct dipole orientation. As a result of these performances, there is no need to oversample the area of the investigation. The minimum amount of data as indicated by the Nyquist theory is enough to produce the optimal result (**Figure 13**) whereas more dense acquisitions are usually needed to preserve the quality when the positioning system is not accurate enough. For all these reasons, the PSG significantly contributes to reduce the time and the cost of the acquisitions and to improve the quality of the 3D final reconstructions.

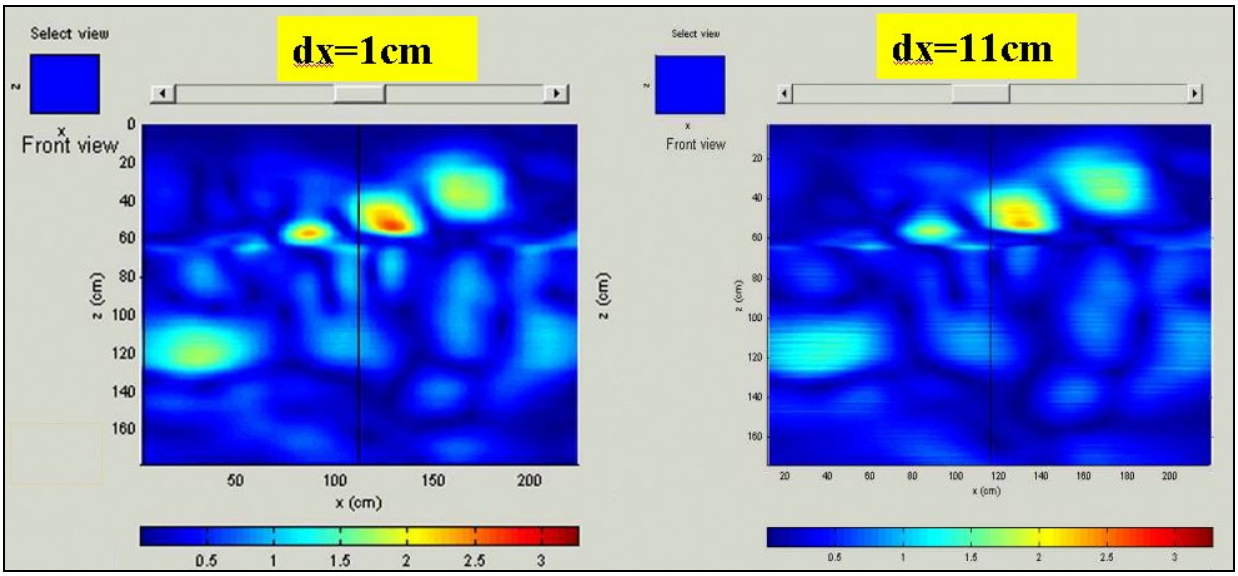

Figure13. *Comparison of a 250MHz vertical section intersecting several pipes as obtained from a dense acquisition (spatial sampling of 1 cm) and from a much lower dense acquisition (spatial sampling of 11 cm). The quality is nearly the same. Note that 11 cm was approximately the spatial sampling limit required by the Nyquist theory.*

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