Towards cost-effective 3D imaging with GPR

Luigi Zanzi * and Maurizio Lualdi, Politecnico di Milano, Italy

Abstract

There are two situations that can motivate a GPR user to perform the investigation in a 3D mode rather than in the conventional 2D mode. The first case is when the 2D approach is not enough to achieve a reliable answer to a specific problem while 3D imaging has the potential for solving the problem correctly. The second situation occurs when it is important to facilitate the transmission of the results to the end-user. On the other side, the cost for 3D surveys is often beyond the budget planned by the end-user for the investigations. As a result, it often happens that GPR is applied with the conventional 2D mode or with very poor 3D acquisition schemes producing results that are below the potential of the method. We discuss the problems that affect the execution of 3D surveys and we present some contributions in the direction of making 3D surveys more cost-effective and successful. The major problem is how to drive and monitor the antenna position in order to survey the area with the required in-line and cross-line space interval. Commercial systems (GPS, laser-theodolite, etc.) are not cost-effective or present severe limitations in urban environment. Thus, we present two unconventional solutions that can be more effectively used to perform 3D surveys in a wide range of situations. Acquisition times are strictly related with the space interval. Thus, we discuss the spatial sampling requirements by comparing theory and experimental results. The conclusion is basically that a good positioning system is also essential to work at the limits posed by the Nyquist theory without affecting the quality of the focused images. Finally, we discuss some experiments related with the polarization issue. Of course, the importance of polarization is strongly related with the target of the investigation. As expected, there are situations where the area must be investigated twice, i.e., with the in-line and cross-line orientation of the antenna, so that an important step towards cost-effective 3D surveys would be the production of two-channel equipment with orthogonal antennas embedded in a single compact system.

Introduction

The diffusion of 3D radar investigations is still limited by the slow development of dedicated equipment and acquisition tools. The technology available on the market is not advanced enough to make 3D experiments fast, accurate and cost effective. 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; Tillson and Liang, 2005). As a result, the equipment is expensive and most suitable for extended investigations on large areas.

For small areas or for limited budget investigations 3D surveys must be performed with manually operated compact systems. The major problem is how to drive and monitor the antenna position in order to survey the area with the required in-line and cross-line space interval and with the required accuracy. If the accuracy of the data position is not ensured or the spatial density of the data is not enough 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; Grasmueck and Weger, 2003). A few solutions (GPS, laser theodolite systems) have been explored up to now for the problem of controlling the antenna position during 3D GPR surveying. Unfortunately, they are very expensive and/or their application is limited to favorable conditions. In addition they monitor the antenna position but they do not help the operator to move the antenna along the planned trajectory so that an irregular distribution of data points may result from the use of these systems. A few examples of feasibility studies for the design of new positioning systems are documented in the scientific literature. One of the most advanced is discussed by Doerksen (2002) and consists of an optical mouse mounted on one side of the antenna. It is an interesting and applicable technique, at least for high frequency antennas, but it still suffers from the problem that it cannot ensure a regular spatial distribution of the collected data.

As a result of all these problems, it often happens that GPR is applied with the conventional 2D mode or with very poor 3D acquisition schemes producing results that are below the potential of the method. Thus, to promote the use of 3D GPR investigations, new cost-effective and flexible solutions are needed.

Benefits of 3D investigations

There are two situations that can motivate a GPR user to perform the investigation in a 3D mode rather than in the conventional 2D mode.

The first case is when the 2D approach is not enough to achieve a reliable answer to a specific problem while 3D imaging has the potential for solving the problem correctly. This is often the case of archeological investigations where manmade features are discriminated by natural targets for the geometrical regularity observed on GPR time or depth sections. Another example is the application of GPR to the problem of landmine detection where 3D imaging is needed to discriminate between mines and false alarms (fig.1). Of course, the problem of mapping the distribution of subsurface utilities is another case where 3D surveys are needed (fig.2).

The second situation occurs when it is important to facilitate the transmission of the results to the end-user. As an example, fig.3 shows the improvement in interpretability of radar images resulting from a 3D reconstruction compared to a 2D approach when the target is the analysis of the metal reinforcements in a concrete floor. The benefit of 3D reconstructions is particularly important when the problem is complex and the interpretation of the results needs the cooperation of radar experts with experts of other disciplines (e.g., building constructions, archeology, …).

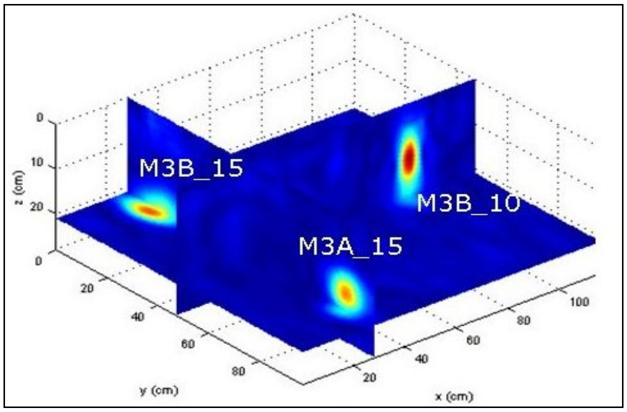

Fig.1. 3D reconstruction of three landmines. Experiment executed on the minefield test site of the Joint Research Center (Ispra, Italy).

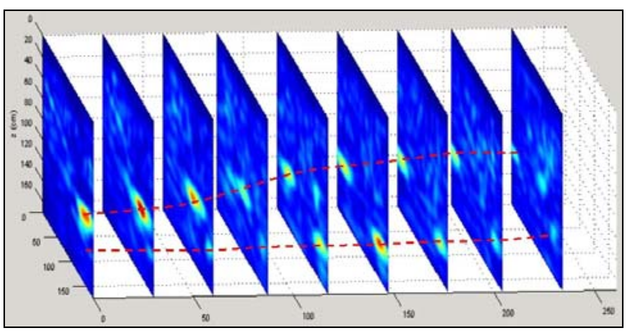

Fig.2. 3D mapping of two pipes in a gas station area.

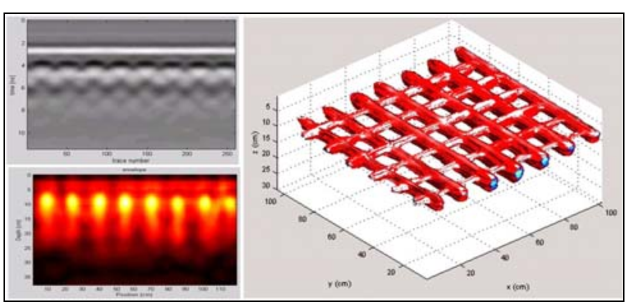

Fig.3. Analysis of metal reinforcements in a concrete floor. 2D data on the left, before and after migration; 3D focused data on the right.

Survey techniques

We present two unconventional methods that we have been testing during the last couple of years to solve the problem of antenna positioning during 3D surveys. The first method is very much indicated for accurate investigations (accuracy of a few mm) in small areas (a few square meters) as when medium frequency antennas are used to select a safe position for drilling a new borehole or for digging a test pit or when high frequency antennas are used for diagnostic investigations on building elements (e.g., walls, floors, pillars). The second method is very convenient when a large area (e.g., hundred of square meters) must be explored with an accuracy of a few cm to map the utilities and other buried infrastructures or to map the lateral distribution of a contaminant or to reconstruct the geometry of archeological remains. Both the methods have been developed with low cost and easy-to-use technologies. Nevertheless, they ensure the required accuracy and a good level of flexibility.

The first method is based on the use of a PSG (Pad System for Georadar) (Lualdi and Zanzi, 2003a and 2003b). It consists of a soft pad whose surface is grooved with parallel tracks that are a few millimeters high. A mate pad must be applied on the bottom of the antenna (fig.4). The total thickness of the mating pads is about half a centimeter to keep the antenna in close contact with the soil. The GPR antenna is dragged along the tracks (fig.5) 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 quality of the final 3D images especially when the shape of the target generates a radar response that is sensitive to the orientation of the antenna (Reppert et al., 2002). PVC or similar materials can be used to produce the pad. 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. 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 and operators can cross the survey area without moving or damaging the pad. In order to exploit all the advantages of this system also for GPR applications to humanitarian demining or to security problems, a modified version of the PSG have been developed. The modification consists in producing an Armored-PSG (A-PSG), i.e., a PSG that is reinforced by a dielectric ballistic material to ensure a protection for the operator and the equipment. The Armored-PSG prototype that we have been testing consists of a standard PSG protected by a 1.5cm layer of a dielectric ballistic material (fig.6). The permittivity of the protection material was specifically tested with a laboratory experiment finding a relative value around 6 that corresponds to a medium velocity of about 12.5cm/ns. Such a value is expected to be appropriate for the application since it is very far from the free-space velocity while it is close to the EM velocity in a lot of soils or natural or building materials. Thus, no artifacts are expected from the introduction of the protection pad between the antenna and the medium. The density of the material is low enough (0.07 g/cm3) to prevent any risk that the weight of the protection pad can activate a device like a landmine. A light pad is also desirable for investigations on non-horizontal surfaces as on building walls or similar situations. Light antennas (below 2kg) with frequencies higher than 600MHz are commercially available. The weight decreases at higher frequencies. Specifically dedicated antennas could be even lighter. In addition, the armored pad contributes to distribute the antenna weight over a larger area reducing the risk of high pressure. On the whole, the pressure transmitted by the antenna to the soil through the A-PSG is expected to be far below the triggering threshold of an antipersonnel landmine. Tests performed on the JRC minefield in Ispra (Italy) demonstrate that the ballistic material does not introduce any quality degradation and show the benefit that is given by a system that ensures regular dense acquisitions and physical contact between the antenna and the medium (Lualdi and Zanzi, 2005).

Fig.4. Pad System for Georadar (PSG).

Fig.5. A 3D acquisition using the PSG with a 500MHz antenna.

Fig.6. Preliminary prototype of Armored-PSG for application to hazardous situations.

The second survey method is based on the use of a low-cost rotary laser (fig.7). It is a laser equipment where the laser ray is deviated by a rotating prism so that the resulting laser beam projection defines a plane. To ensure that the beam is vertical, the tool is equipped with an electronic leveling system that self-levels automatically as soon as the system is turned on.

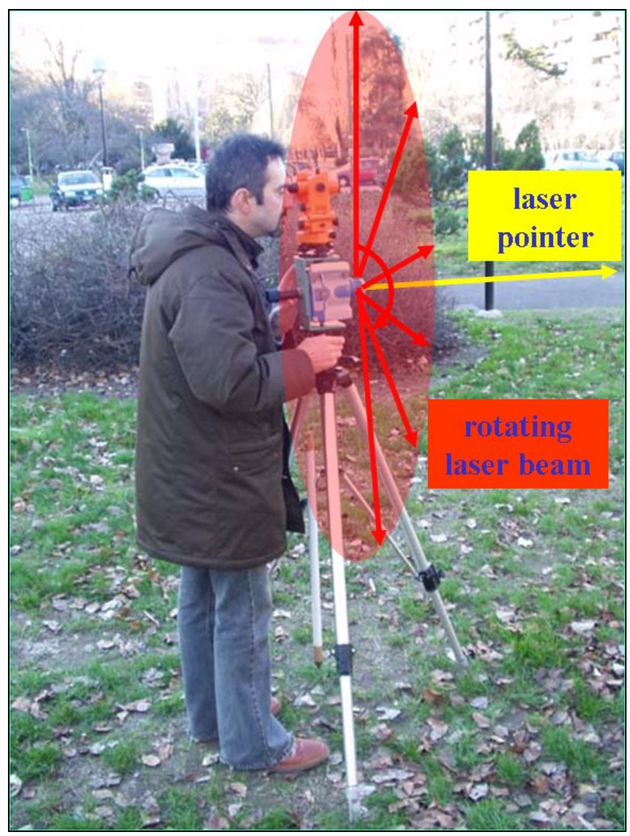

Fig.7. The rotary laser used to assemble the positioning prototype for large investigation areas.

The power of the laser is calibrated to produce a beam that is visible in normal outdoor conditions in a distance range of about 300m. The beam is used to keep the antenna in the direction of the profile. Thus, the antenna is equipped with a photodiode sensor that must be illuminated by the laser beam. The sensor produces sound and/or visual indications that are proportional to the deviation from the correct trajectory. Fig.8 shows the scheme of the survey procedure. First a virtual baseline, i.e., the starting line orthogonal to the planned profile, must be defined by fixing two alignment targets at the baseline ends. Flags or reference signs on the ground will be prepared along the baseline with the spacing (e.g., 1m) planned for the parallel profiles. These are the points where the rotary laser will be moved every time the antenna is ready for starting a new profile. The profiles can be executed with alternate directions to speed up the survey. Each time the rotary laser is moved to the next position, it is necessary to check that the plane defined by the laser beam is orthogonal to the baseline. This is obtained by checking that the laser pointer orthogonal to the beam plane is illuminating one of the targets at the end of the baseline (fig.7). Once the rotary laser is aligned, the GPR profile can be executed by moving manually the antenna equipped with the laser beam detector as shown in fig.9. The laser detector indicates through a led display and/or an audio signal how to move the antenna to preserve the alignment with the beam plane.

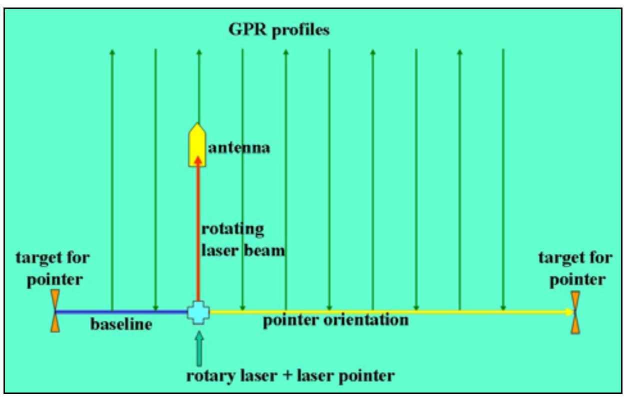

Fig.8. Scheme of the survey procedure.

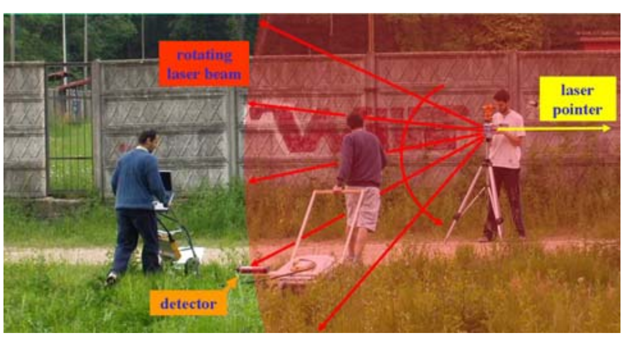

Fig.9. Application of the laser-beam system for archeological investigations with a 250MHz antenna.

As a result, the laser-beam system helps the operator to keep the correct trajectory with an accuracy of a few centimeters while a standard 1-D triggering tool such as the odometric wheel can be used to control the spatial sampling along the profile direction. The method is faster and more accurate than using tapes or ropes and the whole positioning equipment can be assembled with very low-cost commercial devices.

Spatial sampling

The definition of the space interval that is required to generate an alias-free dataset is a key issue because the high cost of 3D acquisitions is very much related with the time needed to collect the data. For 3D dataset produced by collecting parallel profiles with a single antenna, this time is directly proportional to the number of profiles, i.e., is inversely proportional to the cross-line space interval. For the following discussion we assume that in-line and cross-line spacing must fulfill the same requirement. This is the general case that ensures a correct reconstruction of any target, whatever shaped and oriented. The main requirement that must be fulfilled to collect a dataset that can be successfully transformed into a realistic 3D reconstruction is expressed by the Nyquist Theorem. According to Nyquist, the area must be surveyed with a density of the measuring points sufficient to prevent spatial aliasing problems. When this requirement is not satisfied we can expect a severe degradation of the migration results and a decrease of resolution. In principle, the Nyquist requirement is

$$\Delta x \le \frac{\lambda}{4}$$

where Δx is the maximum distance between two measuring points and λ is the wavelength of the highest frequency in the antenna band. Actually, the requirement expressed by the above equation is the most restrictive requirement corresponding to the most unfavorable situation that occurs when a very near-surface target is illuminated laterally with a surface wave. In such a case the diffraction curve that appears in the radar section, under the assumption of a constant velocity medium and a monostatic system, consists of two symmetric dip lines departing from the surface in the position of the target (fig.10). Instead, the diffraction curves for deeper targets are hyperbolas that asymptotically tend to the lines of the surface target. The Nyquist theory requires that the delay of the reflection time between two subsequent measuring points is lower than half a period of the wave. By applying this condition to a generic point belonging to a diffraction hyperbola we get the following equation (fig.10)

$$\Delta x \le \frac{1}{2f\,\frac{dt}{dx}}$$

where f is the wave frequency. In real experiments the diffraction hyperbolas are observed with a limited aperture because of absorption and antenna directivity. Thus, we understand from fig.10 that when we observe buried targets, the Nyquist requirement can be relaxed into a less restrictive condition to be estimated where the diffraction dip is higher, i.e., at the limit of the diffraction aperture. As a result, the actual space requirement is hardly predictable being dependent on parameters (diffraction aperture, diffraction dip, highest frequency) that changes in relation with absorption, antenna directivity, target depth, soil velocity.

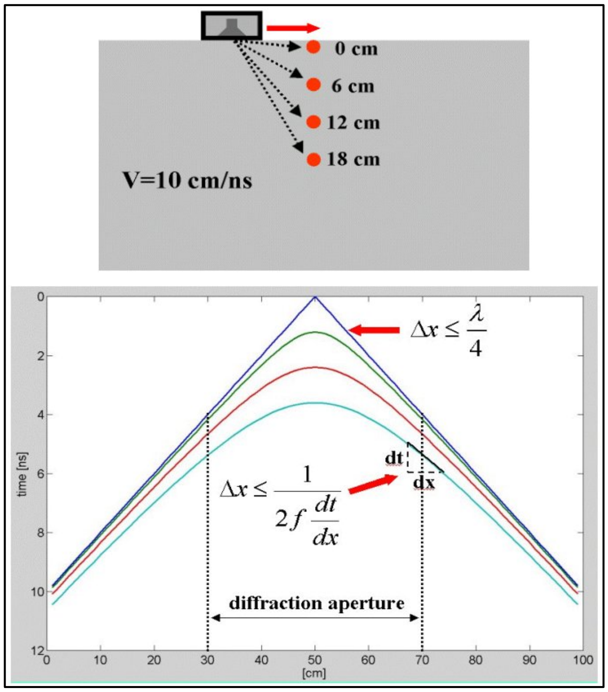

Fig.10. Diffraction curves expected on a radar profile executed with a monostatic system for scattering targets buried at different depths.

Thus, we have been performing several tests on data collected in different situations in order to explore experimentally the spatial sampling requirement. Fig.11 shows an example obtained from a 1GHz dataset collected over a reinforced concrete floor. The data were collected accurately with a very dense spatial sampling and then were progressively decimated to explore the spacing that should not be exceeded to preserve the quality of the final result. Fig.11 presents a vertical section of the collected data volume after progressive decimation. The corresponding sections obtained after the application of the processing sequence, including migration, are shown in fig.12. If we look at the subsampled raw data that produced these results, it is amazing to see how the quality of the final image is stable in comparison with the apparent severe degradations observed on the raw data. This is a very interesting conclusion: provided that the data are collected with a high position accuracy, there is no need to oversample the data, i.e., the focusing algorithm can be very effective even though the data interval is set up according to the largest value needed to prevent aliasing. In the specific case, this value seems to be 2.76 cm, which is an interval much longer than a quarter of the shortest wavelength emitted by the antenna. The rule of thumb that comes from a number of similar experiments repeated under different conditions (Lualdi and Zanzi, 2003c; Lualdi and Zanzi, 2005) is that a quarter of the wavelength calculated at the nominal antenna frequency rather than at the highest emitted frequency is generally a good estimate of the minimum space interval needed to preserve resolution and quality in the focused images.

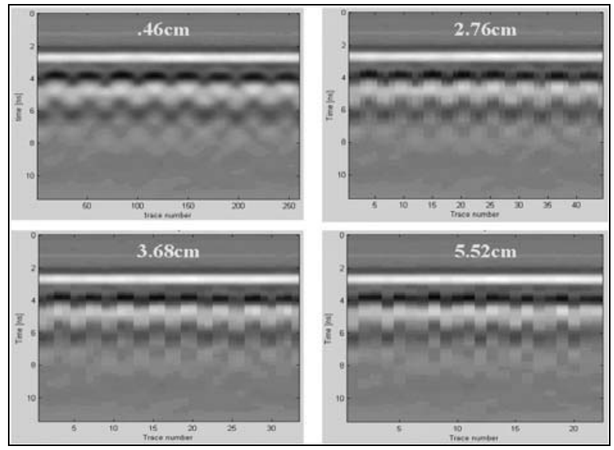

Fig.11. Raw data belonging to a radar profile orthogonal to the concrete rebars after progressive spatial decimation.

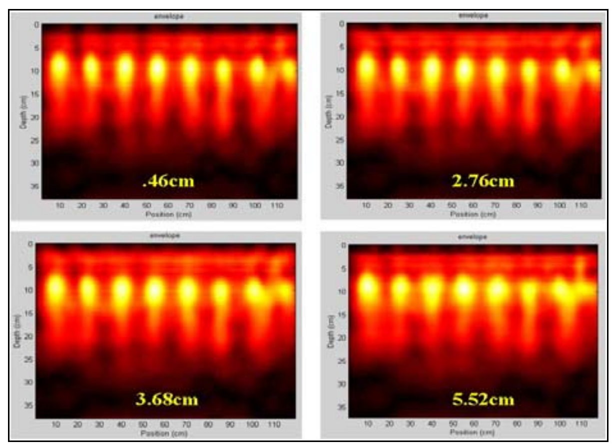

Fig.12. Migrated sections obtained from the decimated data of fig.11.

Antenna orientation

The importance of antenna polarization is strongly related with the target of the investigation. Typically, the response of linear targets such as pipes is sensitive to the antenna orientation. The standard approach for maximizing the detection probability is to orient the antenna so that the dipoles are parallel to the expected direction of the pipes. Unfortunately, the situation of the urban subsoil is becoming more and more similar to a crazy uncontrolled net of utilities with a lot of connections and branches so that although the road direction is the prevalent pipe direction a lot of exceptions exist. As a result, there are complex situations where the area must be investigated twice, i.e., with the in-line and cross-line orientation of the antenna. In addition, the response of pipes versus dipole orientation is also related with the pipe material, size and depth. As an example, fig.13 shows a graph of the different behavior produced by a metal and a PVC pipe during a polarization test. The pipes where surveyed several times, progressively changing the antenna orientation. As expected, the response from the metal pipe is maximum when the dipoles are parallel to the pipe. Instead, a different behavior is presented by the PVC pipe. This indicates that further information on the nature of pipe materials are potentially available when the area is investigated with more than one dipole orientation, e.g., with orthogonal orientations. On the other hand, we must consider the cost of the acquisitions that is going to duplicate if we need to survey the area twice. As a result, the cost-effective solution consists of a two-channel equipment with orthogonal antennas embedded in a single compact system.

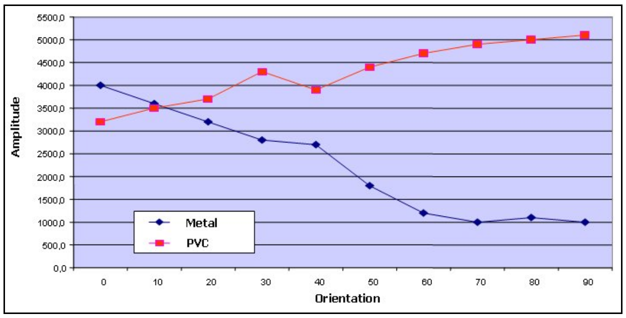

Fig.13. Experimental analysis of the amplitude response from a metal and a PVC pipe as a function of the orientation of the antenna dipoles. At 0° dipoles are parallel to the pipes. The size of the metal and PVC pipe is 3 and 9 cm respectively.

Conclusions

To cut the costs of 3D acquisitions and to ensure the quality of the results, new solutions are needed for the problem of antenna positioning. The positioning system should ensure simultaneously position accuracy and full coverage of a regular grid of measurement points. The PSG and the laser-beam methods discussed in this work represent two possible solutions for small and large 3D surveys respectively. Both the systems are easy-to-use, cheap and flexible. They ensure the proper accuracy needed to perform high quality 3D data with the larger space interval admitted by the Nyquist theory whereas more dense acquisitions are usually needed to preserve the quality when the positioning system is not accurate enough. As a result, these systems allow the user to perform a 3D survey with the minimum number of parallel profiles. Moreover, if the systems are used with a compact array of two orthogonal antennas driven by a dual-channel equipment, the 3D survey can be completed with a single set of parallel profiles without the need of running orthogonal profiles.

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