The European GIGA Project

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Synopsis

The steadily increasing demand for natural gas necessitates the development of safe, well-controlled and reliable gas networks, at minimal cost. A similar situation exists in the telecommunications industry where there is a voracious demand for increased capacity and new installations. For utilities wishing to install new infrastructure, this presents problems associated with the detection and location of buried objects, particularly small non-metallic pipelines and cables, in difficult soil conditions.

On this subject the radar technique has proved very attractive, mainly because it is the only one, amongst the various state-of-the-art methods available, capable of accurately locating both metallic and non-metallic buried objects, without prior knowledge of their position.

However, state-of-the-art Ground Penetrating Radar (GPR) can provide location accuracy to a few tens of centimetres to depths of about 1 metre, but this is extremely dependent on the pipe material and the soil type; a very difficult case to detect would be, for example, a small diameter plastic pipe buried in wet clay.

Given that safety of the European Citizens is of primary importance, the European Commission has funded the GIGA collaborative research project to establish methods of improving the detection capability of GPR to a level where it can confidently be relied upon to locate all types of pipes and cables buried in a diverse range of soil types, whatever the moisture content.

Introduction

For the installation of all new underground infrastructure, trenchless techniques such as Horizontal Directional Drilling or Pipe Bursting can play a key role, particularly where it is important to reduce disturbance to traffic and people living nearby. However, using such techniques, without reliable information on existing utilities and the local geology, can be problematic, even dangerous. For example, it’s worth noting that, in Europe, during new installations, about 90,000 incidences of third party damage to gas pipelines are reported every year and 100,000 in USA. There is little doubt that these instances of damage would be reduced by the use of reliable location techniques.

On this subject, the general opinion is that one of the main technical problems with many trenchless applications is the detection and mapping of buried utilities; running such equipment, without having reliable information on existing utilities, can be dangerous for both operators and citizens and hits may cause interruptions to daily life and commerce and produce serious economic losses.
Furthermore, not all damage to utilities can be immediately detected, and it may only become apparent when it generates subsequent service problems that are both difficult and expensive to trace and which could have unexpected, safety consequences.

It is also recognised that occasionally the locations of sub-surface networks are not known with 100% accuracy and this can be problematic when planning routes for new services. Moreover, it is also true that most of the incidents that have happened during the installation of new pipes with directional drilling procedures, resulted from a lack of knowledge of the subsoil situation.
However, the combined use of Ground Penetrating Radar (GPR) systems and directional drilling equipment can solve most of these issues; unfortunately, poor results due to the limited performance achieved by unsuitable equipment and/or unskilled radar operators have meant that drilling contractors have been unable, so far, to rely totally upon GPR.

Surprisingly, current developments in GPR are oriented towards visualisation improvement, such as 3-dimensional plots and GPS positioning, with no attention paid to addressing the basic radar signal detection problem, which can be extremely challenging. Clearly, such developments will not increase system sensitivity but will merely improve the aesthetics of the display. If the received signal is too weak, as would be the case in wet, muddy ground, enhanced graphic software will solve neither the basic signal problem nor the detection performance.

As a consequence, the GIGA project was established with the main objective of enabling the design of a novel Ground Penetrating Radar capable of guaranteeing superior performance, especially in terms of location accuracy and detection robustness, for any type of pipe material buried in any type of soil.

GPR fundamentals

Radar is well-known for its ability to detect aircraft, ships, vehicles, birds, rainstorms and other above-ground objects. It relies for its operation on the transmission of electro-magnetic energy, usually in the form of a pulse, and the detection of the small amount of energy that is reflected from the target. The round-trip transit time of the pulse and its reflection provide range information on the target.

Buried objects can also be detected by radar and there are details of such work dating back to 1910, with the first pulsed experiments reported in 1926 when the depths of rock strata were determined by time-of-flight methods. The technique has since been used extensively in geophysical and geological investigation of, for example, salt and mineral deposits, rock strata, ice, fresh-water lake beds, coal seams and desert sand, with the emphasis usually on deep penetration, sometimes up to a few kilometres. Deep penetration requires operation at frequencies of a few MHz or tens of MHz, with the consequent need for large antennas and the accompanying consequence of low resolution of the objects detected.

It is also possible to detect shallow objects within the first one or two metres of the earth's surface, which include those of most interest to utilities, by using radar emissions at higher frequencies, up to 1000 MHz, for example. This enables a larger signal bandwidth which allows the higher resolution probing necessary for resolving small adjacent items. Applications include civil engineering site investigations, determination of the integrity of foundations and retaining walls, detection of voids and mineshafts, investigation of road and rail beds, as well as the location of cables, ducts and pipes (metallic or non-metallic). Optimum sub-surface radar system performance, particularly for high resolution detection of shallow objects, is obtained when the whole of the system is designed around a specific target type or geometry.

The detection of utilities' plant imposes a particular set of constraints on the design of an effective sub-surface radar system. The majority of buried plant is within 1.5 to 2 metres of the ground surface, but it may have a wide variation in its size, may be metallic or non-metallic, may be in close proximity to other plant and may be buried in a wide range of soil types, with implications for large differences in both the absorption and the velocity of propagation of electro-magnetic waves. The ground conditions may also vary rapidly within the area of a radar survey where, for example, variations in water content can be crucial and, particularly in urban areas, where there could be imported backfill of inconsistent quality. Consequently, it can be extremely problematic to achieve both adequate penetration of the radar pulse into the soil and good resolution of neighbouring plant; consequently, some design compromises may have to be made.

However, radar is the only non-invasive technique presently available that locates non-metallic buried objects.

Figure 1 shows the basic working principle of an impulse GPR system. The transmitter generates a very short pulse (few nanoseconds) and this is emitted by a ground-coupled antenna; energy backscattered by any target such as a pipe, is then captured by the receiving antenna, which is fixed to the transmitting antenna so that they move along the surface together. The receiver processes the data collected by the equipment and displays the results on a colour monitor (Figure 2).

Position and depth of the target are obtained simply by reading coordinates of the hyperbolic shape within the radar map displayed in Figure 2.

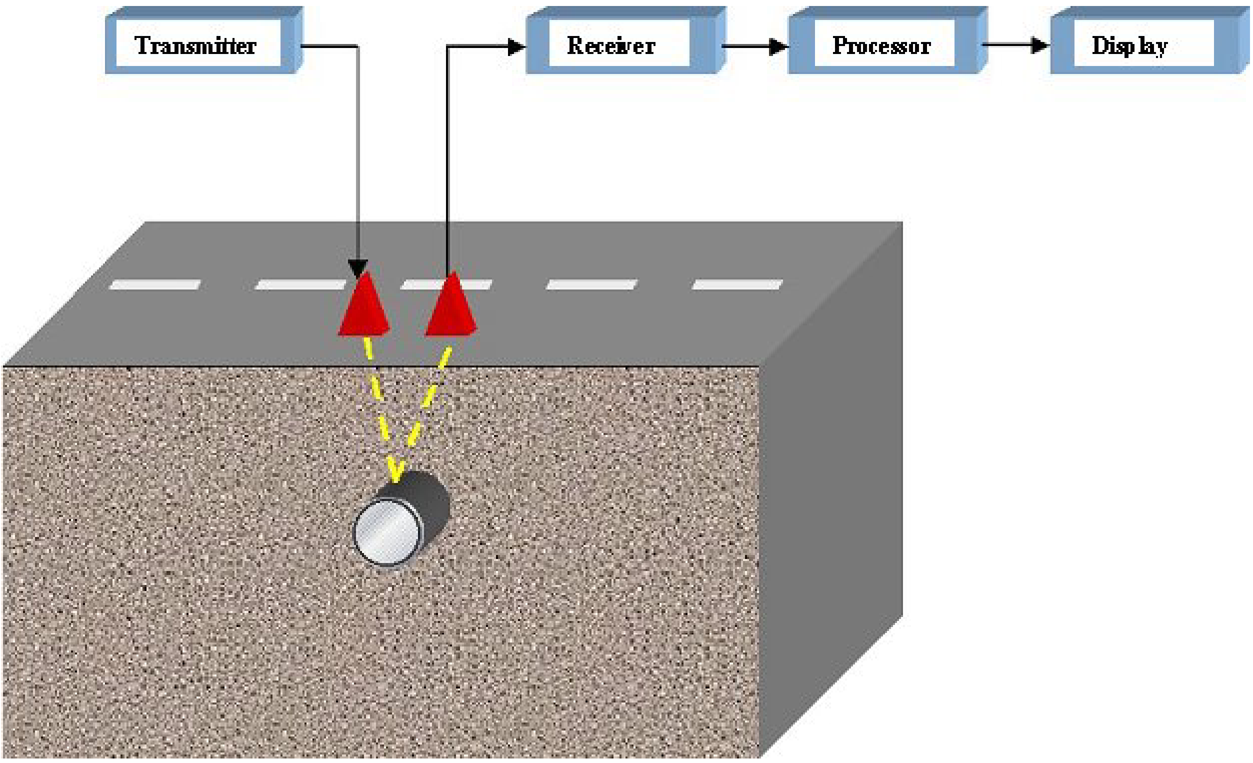

Figure 1: Basic GPR working principle

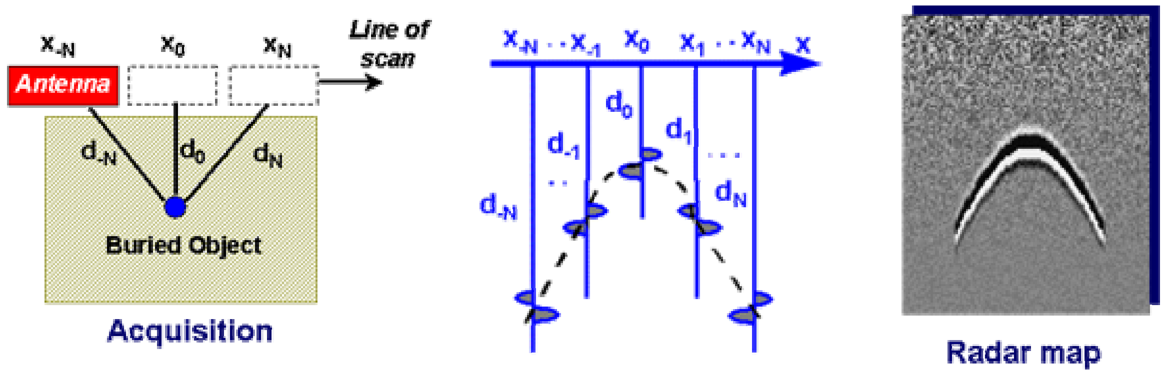

Figure 2: How a target is seen by a GPR.

The GIGA project

The GIGA (Ground Penetrating Radar Innovative research for highly reliable robustness/accuracy Gas pipe detection/location) project is a European Commission funded collaborative research study to inform and enable the design and build of a new and reliable Ground Penetrating Radar (GPR). Its overall objective is the design of a GPR with a detection performance that is significantly improved compared to the present generation of equipment, and robust enough to be used with confidence on diverse types of pipes buried in diverse types of soils.

GIGA has assembled a multidisciplinary team of GPR designers, developers, service providers and end-users to take a fresh look at GPR development. Their combined knowledge and experience has enabled a user-led evaluation of the project and a consequent high level of confidence in the results.

This innovative approach has comprised four main activities:

- a meticulous assessment of the performance of a state-of-the-art GPR in surveys conducted under controlled conditions at dedicated test sites;
- radar technology improvements, including multi-parameter/variable configuration of the radar;
- development of new simulation tools to enable a fresh, theoretical view of the problem to form the basis of an improved equipment design;
- development of software processing tools to reduce the need for highly trained operators.

The project's work plan is shown in Figure 3; it can be noted that a key responsibility has been given to the End-users that were in charge of both establishing the requirements and analysing the results achieved within the project.

It's crucially important to note that the following research activities were informed by the collection and evaluation of the requirements specification of the European utilities (gas, water, telecom, electricity, etc.) and European directional drilling companies; this activity was led by Gaz de France, Tracto-Technik (TT Group) and OSYS Technology.

This was followed by an assessment of the performance of a state-of-the art GPR; several GPR configurations amongst those currently manufactured by IDS were used in the trial area established by

Gaz de France in Saint Denis (Paris, France). At the same time, an experimental and flexible multi-parameter/multi-configuration GPR measurement tool developed by Thales Air Defence -TAD, allowed acquisition of data to provide a good knowledge of the underground "environment".

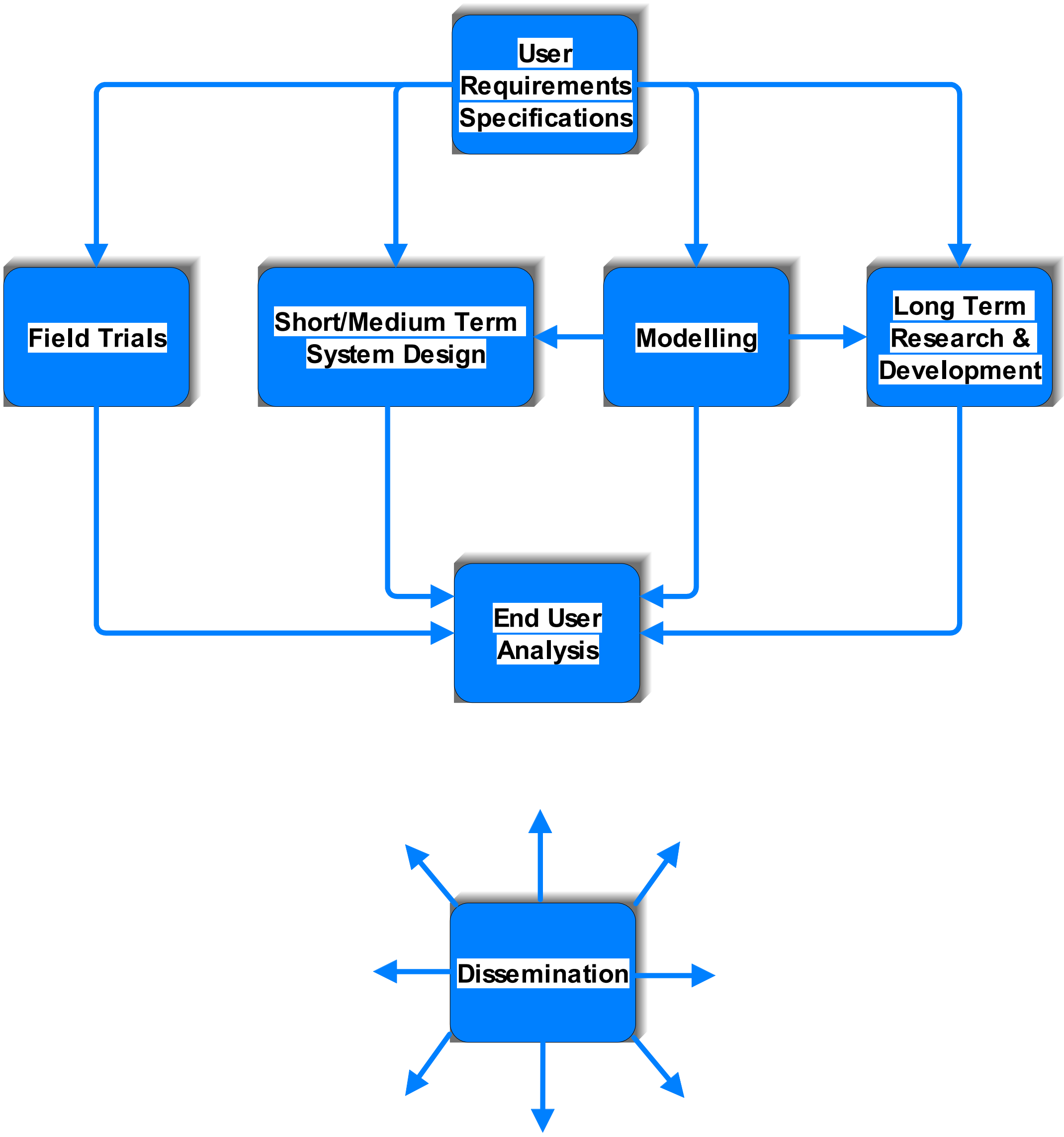

Figure 3: the Project Plan of GIGA

During the project, simulation tools were developed in order to enable a rigorous analysis of ground penetrating radar technology and to acquire useful information on the fundamental limits of detection so as to provide an invaluable guide to future equipment design

On this basis, and starting from the measurement of performance achievable with its current technology, IDS has addressed the "bottom-up" research and the design of a novel GPR system capable of matching, in the short-term, most of the end-user requirements. Simultaneously, the "top-down" research led by TAD allowed the definition of the issues that have to be addressed in further research phases, so that the final limitations of the technique can be addressed and, maybe, overcome.

Finally, the end-user analysis of the new technical solution has been executed, by comparing it against the requirement specification as drawn up early in the project - again, the responsibility of Gaz de France, Tracto-Technik and OSYS Technology.

Within this framework, GERG - the European Gas Research Group (which represents 15 natural gas R&D organisations from 10 European countries) has been responsible for the two-way dissemination of data and results of this research within the European gas companies and other utilities, thus ensuring both a solid and comprehensive database of information for the project and a conduit to potential End-users in the utilities.

In the following, the main results of the project are described.

Field Trials

A pipe location system should have the capability to detect and map all classes of buried pipes and cables. For the system to be accepted by users as reliable, its ability to detect real buried objects must be accompanied by a low rate of false target generation, and a low rate of failure to detect real buried objects.

To assess the performances achievable by a GPR when used for detecting utilities, an intensive survey was carried out in the trial area established by Gaz de France in Saint Denis (Paris, France). On this site, back-fill materials were chosen to be as representative as possible of real world conditions. In addition, the pipes and cables and their configuration and burial depths, have been designed both to be representative and to test the major aspects of Ground Probing Radar performance. In particular, the following characteristics of the GPR under test can be measured:

- probability of detection and false alarm rate;
- accuracy of location in the Horizontal plane;
- accuracy of location in the Vertical plane;
- range depth;
- resolution of multiple objects in the Horizontal plane.

Figure 4: Data collection with the RIS 2K – MF configuration at the GDF test site

Following the analysis of the huge amount of data collected during the trial, and taking account of results obtained from other trials to test the validity of the results of GdF trials, it was possible to verify that IDS' state-of-the-art equipment showed:

- a detection rate greater than 80% to 2 metres depth;
- a false alarm rate smaller than 10%;
- a 40 mm accuracy of location both in the horizontal and vertical plane, and;
- a resolution better than 300 mm.

These results are remarkable and confirm that the GPR has no equivalent as a tool for pipe location; the analysis has also emphasised that two important issues need to be addressed, in both the short and long term; these are penetration depth and the detection of small diameter plastic pipes (and, perhaps, other small, non-metallic targets) particularly where the ground consists of highly conductive material.

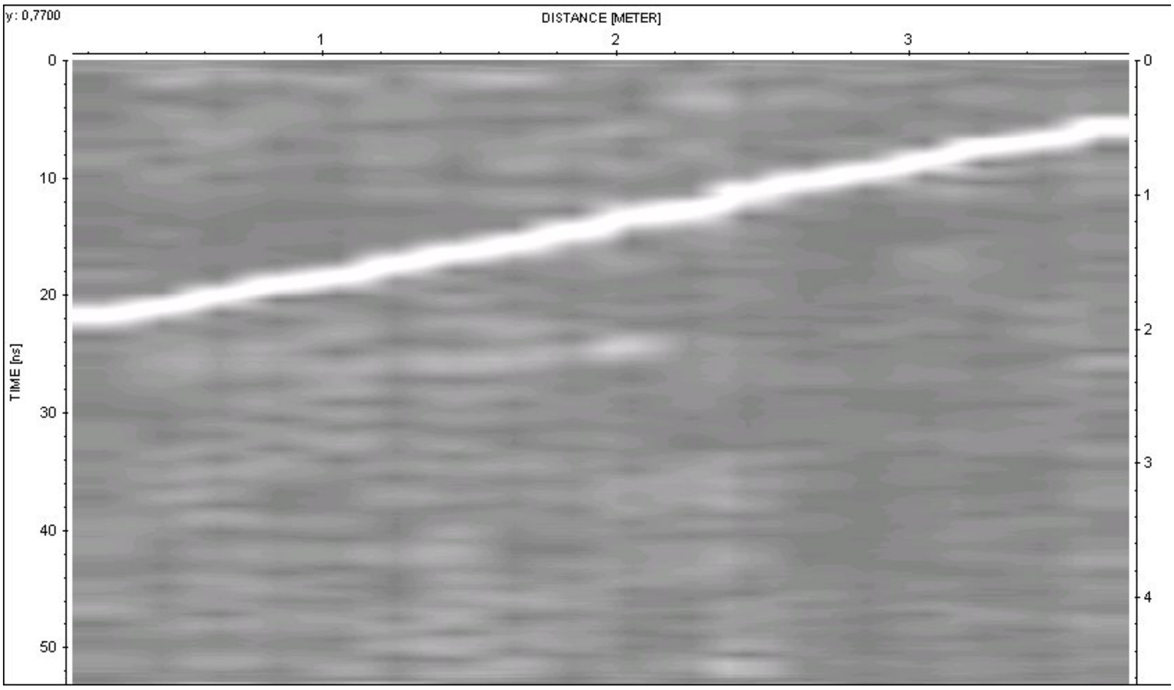

Figure 5: Imaging of a sloping pipe buried in the GDF test site

Modelling
During GIGA efforts were made to develop simulation tools capable of modelling the electrical behaviour of buried targets and their environment.

In particular, two different tools were utilised during the project. The first, developed by IDS, uses the Transmission Line Matrix Modelling (TLM) for reproducing typical GPR scenarios by working in time-domain.

TLM is an innovative 3D simulation technique based on the analogy between the propagation of an electro-magnetic wave in a medium and a signal propagating along a transmission line. Equivalences are drawn between the electric and magnetic fields of Maxwell's equations with the voltages and currents at the nodes of the transmission line. Hence, it provides a simple and explicit method for the modelling of wave propagation through a medium.

The structure to be modelled is represented as a Cartesian mesh of electrical transmission lines joined where they cross. The junction of transmission lines is termed a 'node' and represents a TLM cell. The entire problem space is therefore a collection of interconnected nodes, with junctions at the centre of each cell used in the geometric representation of the structure in question. This mesh therefore defines the space discretisation of the model.

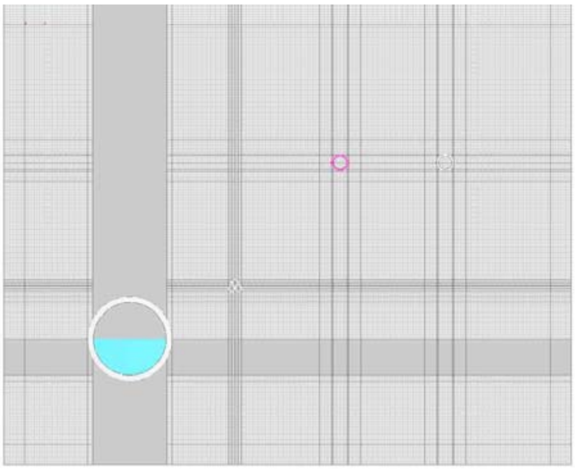

Figure 6: TLM mesh of a typical scenario

With this approach, different materials, including the ground, can be modelled according to their electro-magnetic properties via judicious choices in the values of the inductance, capacitance, and admittance of the transmission lines in the modelling process. TLM can therefore model features such as lossy dielectrics and finite conductivity.

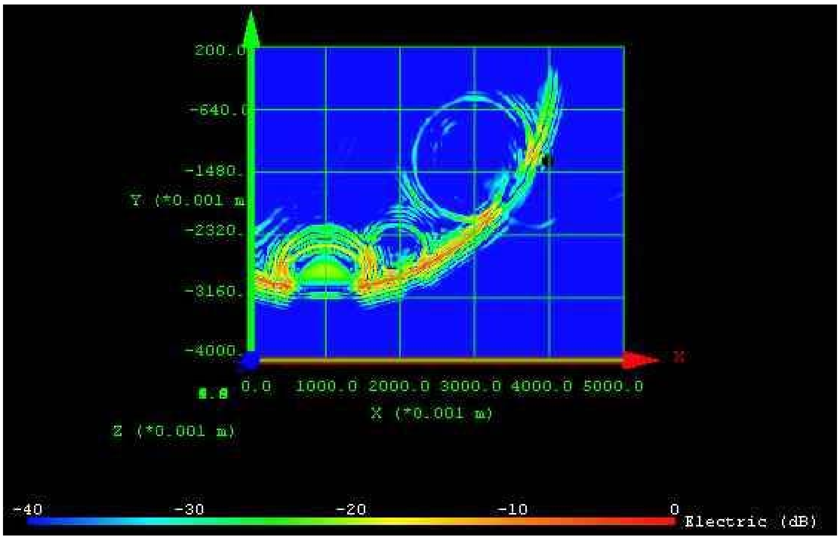

Figure 7: Electric field reflected by a dielectric pipe

The second model, which was developed by TAD, uses an approximation, based upon optical propagation laws and ray tracing, instead of solving Maxwell's equations, and is very economical in processing time.

By employing these tools, it was possible to produce radargrams very similar to the ones actually collected in the field; by varying the characteristics of the dielectric medium as well as the physical properties and geometric arrangement of targets, it is possible to provide useful information on the fundamental limits of GPR detection and to guide equipment design decisions.

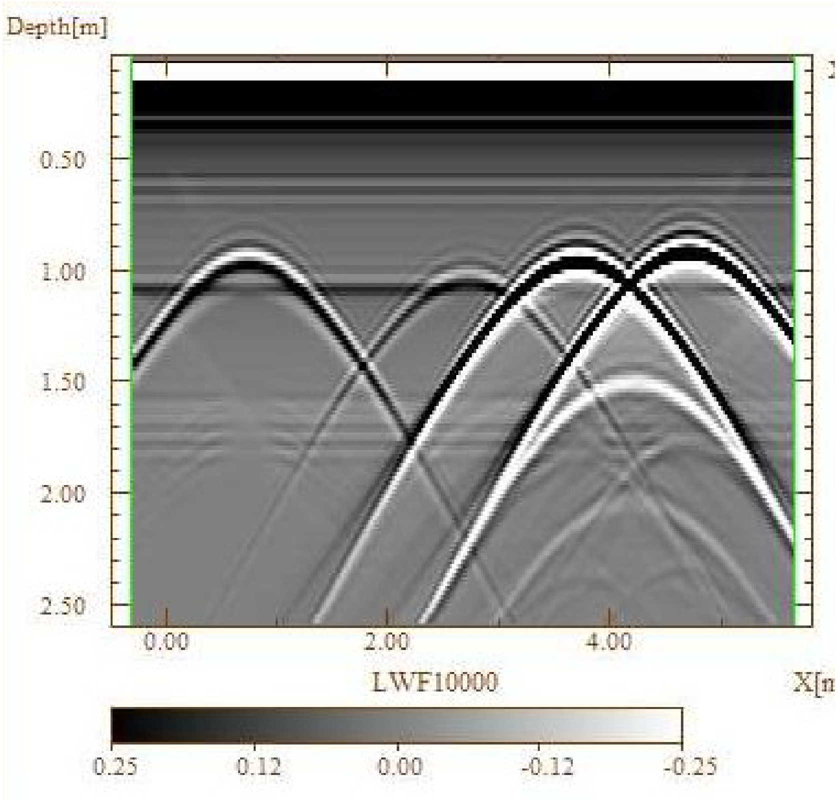

Figure 8: Example of a TLM simulated radargram

Short/Medium Term developments

This phase of GIGA was aimed at the design of a new GPR system to be implemented in the short term and capable of fulfilling most of the end-user requirements; due to the unavailability today of a low-cost technology suitable for implementing FMCW radar[1], the GIGA short term GPR will be an impulsive system with its own restrictions in terms of dynamic range and, consequently, in penetration depth.

Its architecture assumes the use of an array of multi-frequency antennas, lined up in the transverse direction, with respect to the direction of movement, and operating simultaneously; in fact, the use of an array of antennas is essential in GPR as it has been proved to aid the detection of utilities in the ground, simply because a pipe produces an echo (hyperbola) in the same position in most (ideally in all) of the radargrams collected by the different antennas; therefore, the operator can easily distinguish this kind of target from a concentrated one (e.g. a stone) and, hence, performance in terms of probability of detection, is increased.

A further benefit of the system's architecture, based on the use of an array, is the possibility to survey the site with a regular grid, so that advanced signal processing techniques can be used.

[1] FMCW systems are claimed to be capable of guaranteeing a wider dynamic range and greater penetration depth. (See below)

The choice of the antenna composing the array, comes from the requirements in terms of penetration depth, resolution (both vertical and horizontal) and detection of small, plastic pipes that form an important class of objects that End-users wish to locate.

Actually, some of these requirements are mutually in conflict as high frequencies are needed to enable greater resolution but, conversely, cannot guarantee the desired penetration depth. For that reason, the approach that seems to be imperative for an impulsive system like the short-term equipment, is the contemporaneous use of wide-band, multi-frequency antennas. This approach means that higher frequencies will enable the desired resolution, whilst the lower frequencies can achieve penetration to up to 2 m in many soils, although this is very dependent on moisture content.

Therefore the GIGA short term GPR will utilise different antenna modules, integrated into a single unit, to cover the frequency range 150MHz to 2GHz, in order to be able to satisfy those requirements.

Figure 9: Aspect of the GIGA short-term GPR

Further research activities should be focused on the improvement of the antenna/receiver design to extend the dynamic range and coupling of energy into the ground; moreover, polarisation techniques should also be analysed to investigate the possibility of performing a feature extraction from GPR data.

Another outcome of the project is related to the analysis of the data collected by the system; in fact, the quality of information obtained using the GPR technique has, until now, depended strongly upon the know-how of the operator.

The GIGA project has addressed this aspect of the technology and software techniques have been developed:

- to reduce the need for data analysis by highly trained operators,
- to apply strong “data reduction” in order to highlight the most useful information and, therefore, to make the analysis in the shortest possible time.

In other words, the automatic detection tool and the 3-D migration algorithms that have been developed and tested in GIGA, will improve consistency of performance by helping to remove the variable contribution - the “human factor” - from the reliability of results achievable by the new GPR.

Another key achievement of the efforts that have been paid in this direction is the possibility to get a precise evaluation of the GPR waveform propagation velocity which will help to increase the accuracy in determining the depth of utilities detected by the system.

The developments in computer technologies are so rapid that it is not difficult to imagine executing some of the advanced processing tools directly on site, in coming years.

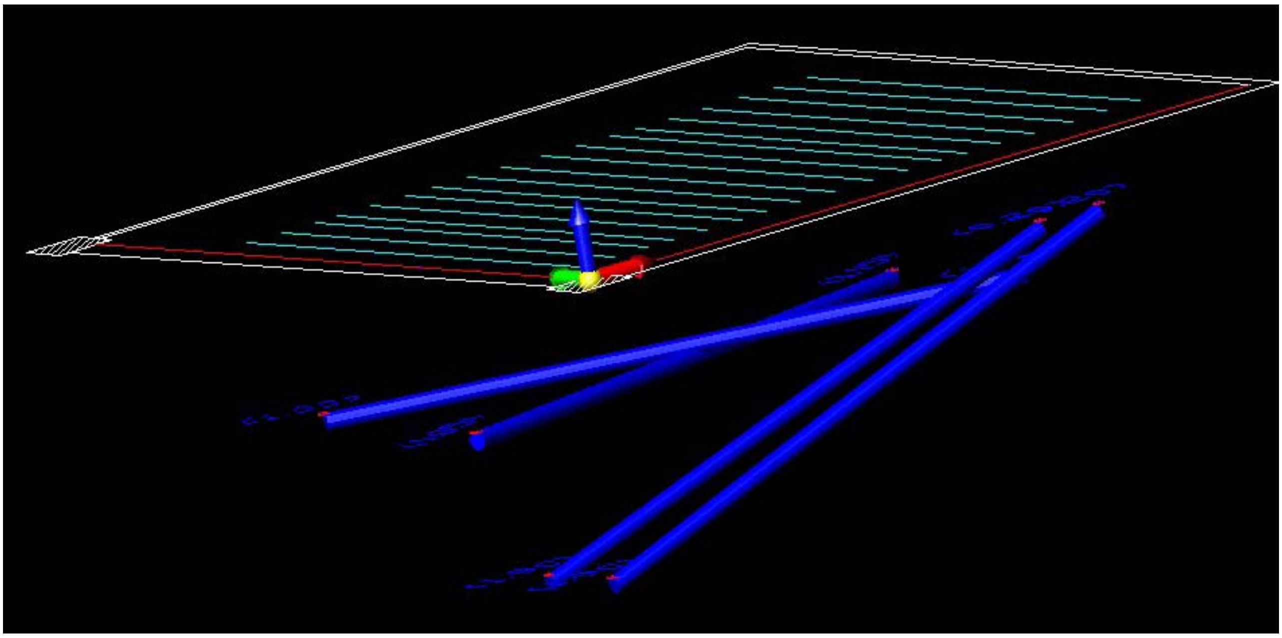

Figure 10: example of a 3D CAD map

Long Term research

In a longer term, the main objective of GPR design is to achieve a clutter-free dynamic range that is as large as possible, specifically to increase the range depth.

A secondary objective is to control the frequency range so that it closely matches the requirements of target detection and antenna characteristics. This conflicts, of course, with practical constraints such as cost, speed of operation and ease of implementation.

Commercial systems that are available now use conventional time domain sampling techniques and relatively inexpensive signal sources based upon avalanche transistor technology. This is tried and trusted technology that is convenient to manufacture. Its main limitations are a restricted dynamic range and, sometimes, a lack of stability with respect to time.

In GIGA, the use of stepped frequency sources, and receivers based upon homodyne detection and balanced mixers, has been studied. Such systems are generally known as “Frequency Modulated Continuous Wave” (FMCW) but, in this case because discrete frequency intervals are used, it is known as “Stepped Frequency Continuous Wave” (SFCW). Such systems theoretically possess superior dynamic range and stability compared to pulse systems and also allow control of the frequency range. At present, the main drawback to this approach is the high cost of the microwave sources. It is possible, however, that the particular requirements of GPR may allow a relaxation of the specification of a stepped frequency microwave source which could offer significant cost reductions.

The output of FMCW systems is, by definition, in the frequency domain, thus necessitating a transformation into the time domain. This is most often carried out using Fourier Transformations and the resulting output of this process is equivalent to that of a time domain sampling system with much wider dynamic range and stability.

Thus, in the longer term, it seems reasonable to assert that a Stepped Frequency Continuous Wave GPR will constitute a further step to addressing and possibly overcoming the remaining limitations of the technique.

Conclusions

GIGA is a research study, which was established to inform and enable the design and build of a new, dependable Ground Probing Radar (GPR). Its eventual objective is a GPR specifically designed to provide the precision and high resolution required for no-dig installation of gas pipelines by means of Horizontal Directional Drilling (HDD), in the belief that this approach to digging can both contribute to better protection of the environment and ensure a better quality of life for citizens.

A detailed knowledge of the sub-surface layout is essential before excavation or directional drilling is employed, if one is to eliminate both damage to buried plant and the potential for injury to personnel.
On the assumption that an improved GPR will be available, GIGA has estimated the potential for a reduction in the cost of installing gas pipelines and telecommunications networks. In addition, there is potential for further investment cost saving by using trenchless directional drilling, in association with GPR, when compared with classical trench digging, not to mention the considerable social, environmental and quality of life benefits from reductions in streetworks..

GIGA’s innovative approach came from the assessment of range depth, detection rate and accuracy required both by HDD operators and utility companies, and from research activities by following both top-down and bottom-up methodologies.

Over the two-year course of the project, valuable results have been obtained; amongst them, a meticulous assessment of the performance achievable by a GPR at the “state-of-the-art” and the important issues that need to be addressed, in both the short and long term; these are penetration depth and the detection of small diameter plastic pipes (and, perhaps, other small, non-metallic targets) particularly when deeper than 0.5 m and where the ground consists of material that is not sand.

The design of a new GPR equipment that will be capable of satisfying, in the short term, most of the End-user requirements has been proposed; by using multi-frequency antennas, such a system is believed to be suitable for extending the penetration depth to more than two metres in most circumstances.

Moreover, the key requirement of depth measurement in absolute terms has been met as a by-product of the algorithm for automatic detection.

In the longer term, it is likely that a Stepped Frequency Continuous Wave system could allow optimal frequency adaptation to the environment, providing further performance improvements in terms of penetration depth and the range of soil types and conditions in which GPR can operate.

Indeed, these encouraging results mean that GIGA will be followed by a second, medium-long term project to design, develop and test a new, specific GPR demonstration prototype.

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