The European GIGA Project

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Synopsis
There is an increasing demand from Utility companies and No Dig operators for tools that can provide them with reliable information on underground objects and pipes when they have to deal with a new installation.
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.
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); it involves both end-users and GPR suppliers, thus combining bottom-up and top-down approaches in GPR innovative research.
In the following, the main axes of research and the activities completed to date by IDS-Ingegneria dei Sistemi are described.

Introduction
The worldwide demand for telecommunication links is increasing rapidly and as a consequence has also raised the need for new installations, especially for broadband connections to ISDN services (Internet, Cable TV, etc.).
Moreover, other utility providers (e.g. gas, electricity, etc.) are striving to minimise disturbance to people and to traffic caused by excavations.
In this respect, trenchless techniques are recognised worldwide for their ability to play a key role; at the same time, it is worthwhile underlining that the use of such equipment during excavations, can make a significant contribution to reducing emissions of greenhouse gases (GHG), such as CO2.
However, the general opinion is that one of the main technical problems with several trenchless applications is the detection and the mapping of the 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, which may generate subsequent service problems that are difficult and expensive to trace and which could produce 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 many 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, drilling contractors have been unable, so far, to rely totally upon GPR.

As a consequence, the main objective of the GIGA project is to enable 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

The use of electromagnetic waves for locating objects within the underground, was theorized in the early twentieth century in a German patent by Leimbach et Löwy, but a renewed interest in the modern era arose during the Vietnam war when American forces experimented with it to detect tunnels dug by the Viet Cong.

A Ground Penetrating Radar is an implementation of an "Ultra Wide Band" (UWB) Radar and its working principle is quite similar to the one of a conventional radar system, but with some specific differences.

First of all, a conventional radar has a range of several tens or hundreds of km, whereas a GPR is able to investigate up to tens of meters in depth.

Then, the resolution (i.e. the capability to distinguish close aircraft or ships) of a conventional radar is within tens of meters, while a GPR can allow a resolution of few centimetres (depending on the frequency of the antenna).

Moreover, high-power signals generated by conventional radars propagate in the air with very low attenuation; on the contrary, low power signals emitted by a GPR are subjected to very high attenuation due to the material characteristics.

Finally, inhomogeneities within material investigated by GPR generate a clutter level higher than the one affecting conventional radars; this interaction with the environment is, arguably, the major limitation on performance achievable by georadars.

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

Position and depth of the target are obtained just by reading coordinates of the hyperbolic shape within the radar map displayed in Figure 2. Nevertheless, it can be easily understood that, due to the presence of several and complex targets underground, the analysis of the data collected by the GPR can be very difficult.

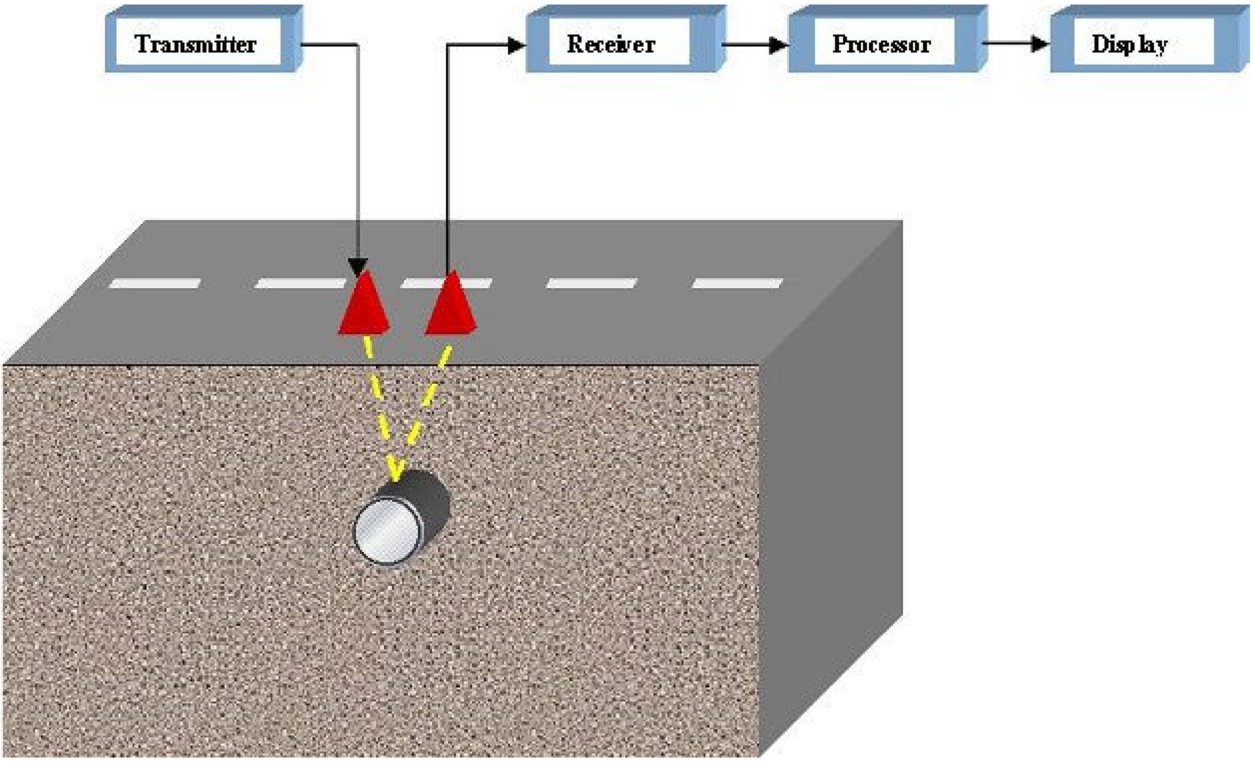

Figure 1: Basic GPR working principle

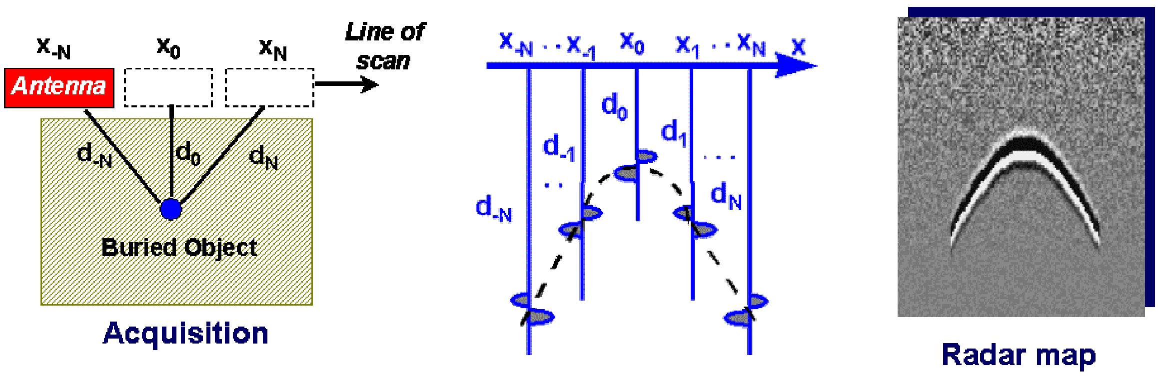

Figure 2: How a target is seen by a GPR.

However, the use of an array of antennas, lined up in the transversal direction with respect to the direction of movement, and operating simultaneously, can increase the detection rate and the accuracy achievable when looking for buried utilities.
This truly innovative solution was introduced by IDS in its GPR products since 1990, based on the idea of trying to implement in the georadar a similar scheme as the one used by “double threshold detection” radar.

In fact, in single threshold detection radars, when the operator has to decide on the presence of a target, something like a "peak detection decision" is performed; in other words, the output of the receiver is compared to some threshold or bias level.

This bias level, which can be due to the sensitivity of both the display and the human operator's visual perception, is related to the probability of false alarm and missed detection; in other words, when a noise pulse surpasses the bias level, the operator can mistake the noise for a signal and there is a "false alarm". Alternatively, when the radar mistakes a signal return for a noise pulse (which occurs when the signal return is below the bias level), there is a "missed detection".

It can be easily understood that missed detection and false alarm are subject to trade-off; it means that the number of false alarms (missed detection) may be decreased (increased) as the bias level is raised, and vice-versa; therefore bias level is a primary parameter in the radar's design.

For solving problems related to the human operator, “double threshold detection” radars have been introduced. Such systems impose detection criteria whereby the threshold of the first detector must be exceeded several times in a defined period of time before a target is certified; therefore, performance of these equipments is less affected by sensitivity of human operators (Figure 3).

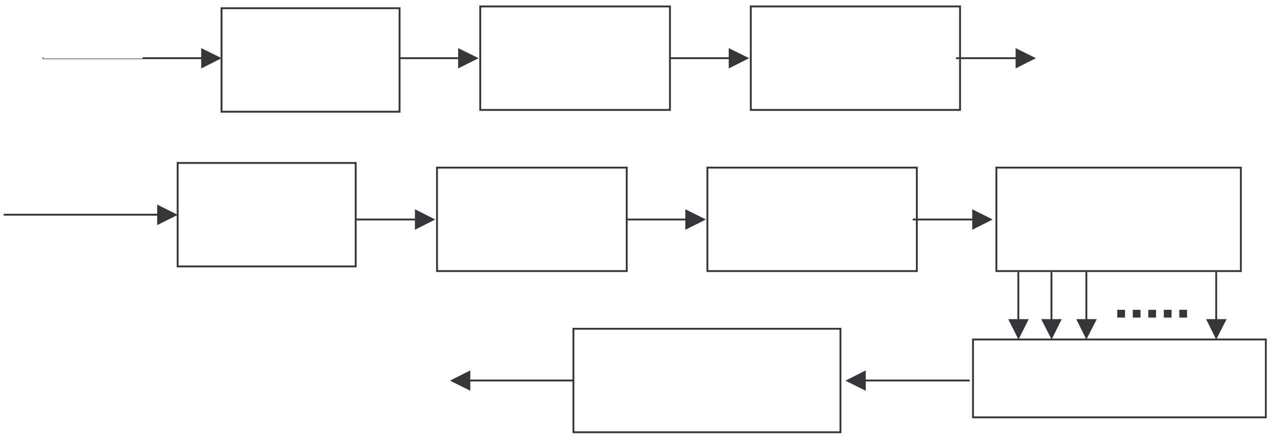

Figure 3: Simplified radar detection process (single or double threshold)

In GPR, the use of the array aids 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 data windows; 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.

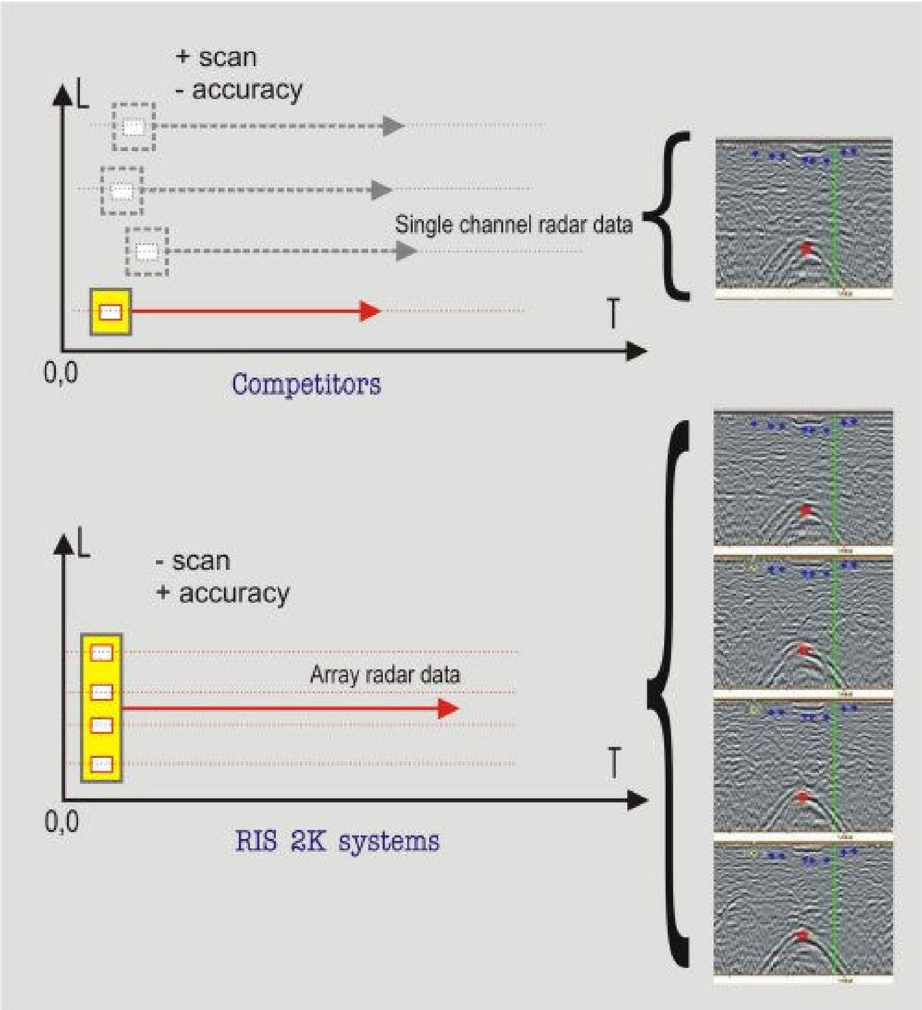

Figure 4: Benefits from the use of the antennas array

Overview of GIGA project

The GIGA project's main objective is to design 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.

The consortium running the project, includes both end-users (GERG, Gaz de France, Tracto-Technik and OSYS Technology) and GPR experts (TAD - Thales Air Defence and IDS Ingegneria dei Sistemi), thus combining bottom-up and top-down approaches in GPR innovative research.

Within this framework, the European Gas Research Group - GERG (which represents 10 European countries) is responsible for the dissemination of the results of this research within the European gas companies and other utilities, thus participating in the effort to strengthen the creation of European Research Area.

The main activities of the GIGA project have been planned to try to overcome some “intrinsic” limitations of currently available GPRs; latest developments in GPR technology elsewhere seem to be oriented towards visualisation improvement. Enhancements such as 3-dimensional plots and GPS positioning have been developed 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.

On the contrary, GIGA's innovative approach comprises three main research axes:

- Radar technology improvements;
- Multi-parameter/multi-configuration data fusion and data processing - based on flexible GPR measurements in close relationship with modelling and simulations;
- Specific radar data and signal processing algorithms to improve the discrimination between the object to be detected and interfering signals.

The project's work plan included three steps; first, a survey of 170 European utilities (gas, water, telecom, electricity, etc.) and European directional drilling companies was executed in order to collect and evaluate the requirements specification of GPR end-users. Gaz de France, Tracto-Technik and OSYS Technology managed this activity.

The second step, that is presently in progress, aims at gathering and understanding data from the physical phenomena involved, especially in complex situations (e.g. detection of plastic pipes, ground characteristics, etc.), when most currently available GPRs fail; it requires the execution of some measurements in experimental test areas, by using:

- "state-of-the-art" technology, thus providing a short-term performance reference and a bottom-up research approach (activity led by IDS);
- an experimental and flexible multi-parameter/multi-configuration GPR measurement tool, to acquire an optimal knowledge of the "environment", for the medium-long term, through a top down research approach (activity led by Thales Air Defence -TAD).

Analysis of collected data and the development and use of simulation/modelling tools will allow addressing the design of an enhanced GPR system by identifying the specifications for

- main radar characteristics (wavelength, bandwidth, power, antenna, etc.),
- signal and radar data processing algorithms.

The third and final step includes an end-user analysis of the new technical solution with reference to the requirements specification as drawn up at the end of the first step; again, Gaz de France, Tracto-Technik and OSYS Technology will handle it.

GIGA, valued at about 3 M€, will be completed at the end of 2003. If successful, it will be followed by a second medium-long term project to design, develop and test a new, specific, GPR demonstration prototype.

IDS' mission within GIGA

IDS-Ingegneria dei Sistemi is an Italian company that has been involved since 1990 in the development and manufacture of specialised GPR systems to be used for specific applications, in place of the more traditional "*general purpose*" radar systems, in order to overcome their intrinsic limitations.

As a result of the company's expertise, IDS was selected to manage the bottom-up research phase of GIGA; in other words, starting from the measurement of performance achievable by using its current technology, IDS will address the specifications that can be executed in the short-medium term.

In this activity, simulation tools that have been specifically developed, can aid the analysis because of the possibility to evaluate accurately the behaviour of the GPR when varying the environment and target characteristics.

Completed activities and results achieved to date by IDS

To evaluate the performance achievable with IDS' state-of-the-art equipment, an intensive survey was carried out during autumn 2002 in the trial area established by Gaz de France in Saint Denis (Paris – France). This area, which has no equivalent in the world, includes different ground materials and a selection of metal and plastic pipes of various diameters, buried at various depths; in this way, 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.

To perform these tests, five equipment configurations were selected as the most suitable from those currently manufactured or designed by IDS; in detail, the following set-ups have been implemented and used during the survey:

- RIS 2K-MF, Multi-frequency array, integrating 200 and 600 MHz dipoles;
- RIS 2K-S-S, Single-frequency array, integrating dipoles at 600 MHz;
- RIS 2K-S-D, Single-frequency array, integrating dipoles at 200 MHz;
- RIS 2K-0-LD, Single antenna configuration, capable of collecting a single profile at 100 MHz;
- RIS 2K-PM, Polarimetric module at 400 MHz.

Figure 5: Data collection with the RIS 2K – MF configuration at the GDF test site

Figure 6: Data collection with the RIS 2K – 0 - LD configuration

The analysis of the huge amount of data collected during the trial was completed during spring 2003; it provided an evaluation of the performance that can be guaranteed at present when using the IDS GPR for detecting buried utilities. It's encouraging to see that some interesting and promising results have been obtained when using innovative processing techniques such as 3-D migration and polarimetric processing.

IDS' equipment performed well, even if some limitations in detection rate and range depth were encountered in the presence of highly conductive soils; however, in these areas tested configurations were found able to detect more than 70% of the existing pipes, mainly as a result of the combined use of high and low frequency antennas. At the same time, it was possible to get the full performance (100%) in pits with lower signal attenuation and where traditional buried pipe layouts were simulated.

Data analysis also showed a remarkable accuracy both in determining horizontal and vertical position of pipes; for instance, averaged error in determining utilities' depth was, most of time, smaller than 25 mm, in good agreement with the relevant end-user requirements.

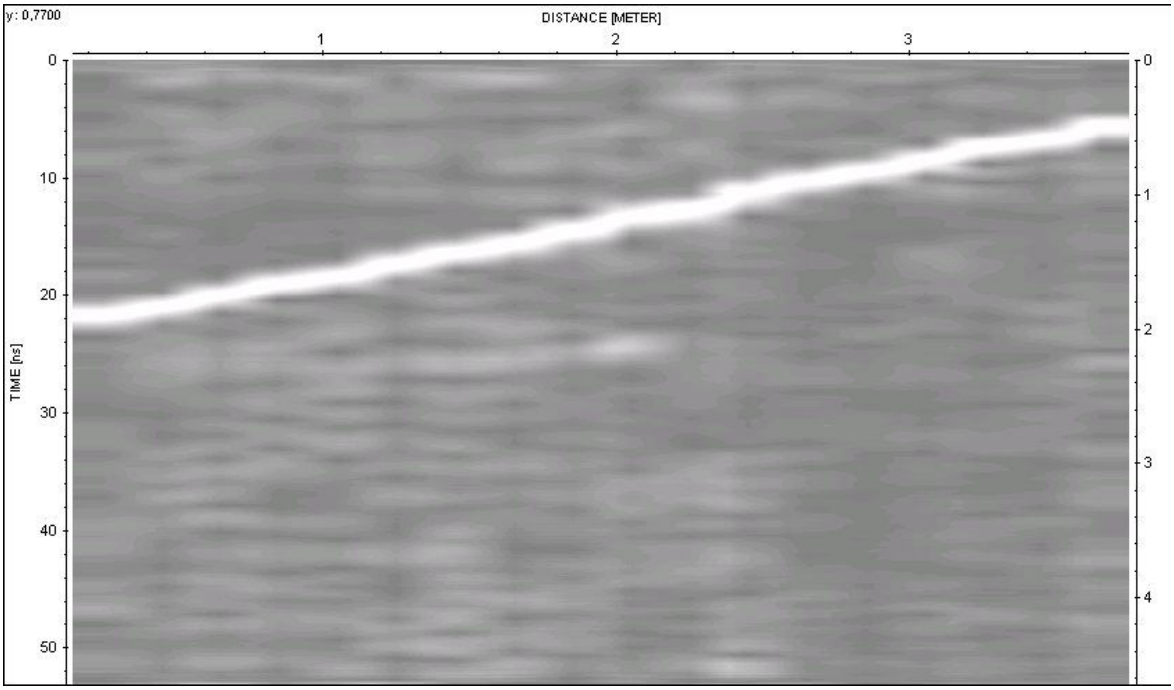

Figure 7: Imaging of a sloping pipe buried in the GDF test site

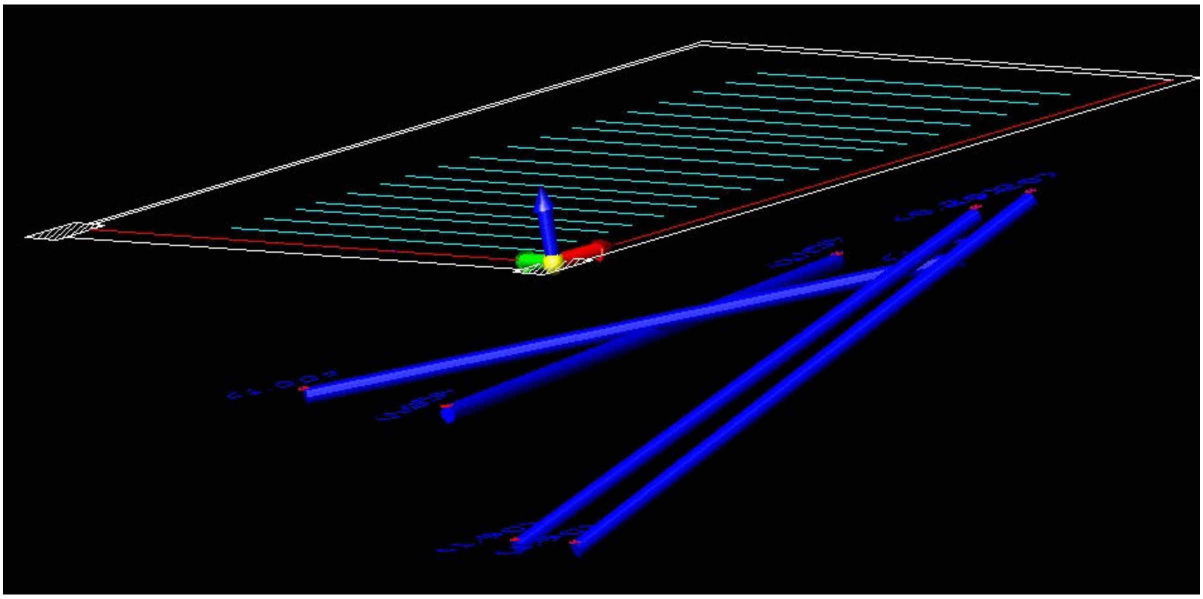

Figure 8: 3D CAD map of a pit

Simultaneously, IDS worked on the definition and the development of software tools capable of accurately simulating both the propagation of the electromagnetic signal through the ground and the scattering produced by buried targets.

Amongst several time-domain simulation methods available to date, it was decided to use and adapt Transmission Line Matrix Modelling (TLM) for reproducing typical GPR scenarios.

TLM is an innovative 3D simulation technique based on the analogy between the propagation of an electromagnetic 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. Therefore, it is a simple and explicit method for the modelling of wave propagation through a medium.

Different materials, including the ground, can be modelled according to their electromagnetic properties via judicious choices in the values of the inductance, capacitance, and admittances of the transmission lines in the modelling process. TLM can therefore model features such as lossy dielectrics and finite conductivity.

TLM has been well validated and applied to many areas of work, including antenna radiation patterns, antenna coupling problems, antenna EMC issues, RCS, screening performance of novel materials, etc.

The tool that has been developed and tuned according to the purposes of the GIGA project is really capable of producing radargrams very similar to the ones truly collected in the field; for that reason, it will be helpful for validating any eventual and future development in georadar technology and for understanding specific behaviour in presence of particular targets and ground, whatever their characteristics.

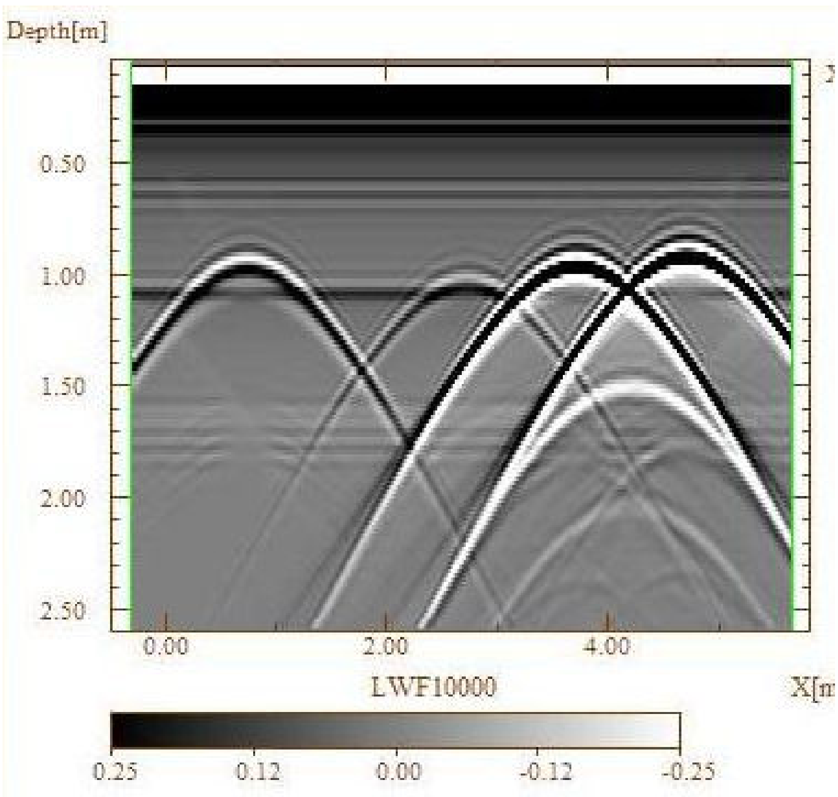

Figure 9: Example of simulated radargram

At the same time, TAD has worked on antenna and soil models to be used for running some behavioural simulations; this technique uses the optical propagation laws and then the Descartes and Huygens laws, instead of solving Maxwell equations. In this way, computational load is reduced and the behavioural simulation of a 3D scenario can run in few minutes instead of some days.

The combined use of this tool, which is particularly suitable for simulating Stepped Frequency Continuous Wave (SFCW) radars, and of the one developed by IDS, will help

- to fix the real physical limit of the pipe detection by executing an accurate analysis of the environment, the propagation and the buried objects;
- to choose both antenna and radar's main characteristics, for being able to match the operational requirements as stated by the end-users in term of detection rate, depth range and resolution.

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.

GIGA's innovative approach comes from the assessment of range depth, detection rate and accuracy required both by HDD operators and utility companies, and from research activities by following a top-down and a bottom-up methodology.
It involves IDS in the short-medium term as one of the leading GPR manufacturers, and Thales Air Defence-TAD for the medium-long term activities; in fact, trial measurements described above, have been executed also by using a flexible GPR tool based on a network analyser and developed by TAD. Said tool shall be able to collect all the data needed for providing an optimal knowledge of the environment and of the physical phenomena involved.

At present, IDS and TAD are working on the specifications for an enhanced GPR system capable of partially (in the short term) and fully (in the medium-long term) matching the demanding requirements of the survey carried out at the beginning of the project; nevertheless, based on the preliminary results achieved to date, it seems reasonable to assert that an enhancement of the state of the art is possible, in order to supply HDD operators and utility companies with reliable underground mapping tools.

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