The ORFEUS Project:

a step change in Ground Penetrating Radar technology to locate buried utilities

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Abstract

There is a serious issue associated with the inability to detect and accurately locate buried utility assets and, as a result, too many holes are dug in the road. This creates problems such as traffic delays, leading to unnecessary fuel usage, and quality of life issues related to air quality, noise pollution and lost time. This is not a single utility problem and needs to be addressed on a European basis, with utilities working together to provide appropriate solutions.

A EC funded Specific Targeted Research Project (STREP) has recently started with the aim to develop the next generation of ground penetrating radar (GPR) systems, by means of complementary GPR tools. Together they will raise the probability of detection of underground buried assets and, as a result, significantly ease their rehabilitation and/or replacement.

The project will last for 36 months and will cost €5.4 million.

Key issues

Industrial societies have grown to be dependent upon services that are delivered by infrastructure buried in the ground, principally in roadways. The economic, environmental and safety implications of disruption to these services can be critical.

Traditionally, work on buried plant and equipment involves digging a trench, completing the work, and reinstating the filled hole. In recent years, the use of trenchless technology has significantly increased because of the economic benefits, particularly a reduction in the number and extent of excavations. Whichever method is used – trench or trenchless – there is a need to understand the nature of the underground environment that will be disturbed when planning new installations or when excavating to maintain existing infrastructure.

Figure 1: A typical tangle of pipes and cables under our city streets that can result in expensive third party damage

Historically, location of underground plant and equipment has been based on record information held by utility companies. This information, even if it exists (and much of it does not) is often inaccurate, incomplete or out of date. It is 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.
Ground Probing Radar (GPR) is very attractive because, amongst the various state-of-the-art methods available, it is the only non-invasive technique capable of accurately locating both metallic and non-metallic buried objects, without prior knowledge of their position.
However, state-of-the-art GPR can provide unsatisfactory performance (especially in terms of investigation depth and sensitivity to smaller, dielectric targets) and without further research and development, this technology will remain of limited use.

On this respect, the Orfeus project is a European Commission funded collaborative research study with the following three major objectives:

- To provide a step change in the depth penetration and spatial resolution of GPR used for surveys carried out from the ground surface.
- To prototype an innovative GPR-based real-time obstacle detection system for steerable bore- heads of Horizontal Directional Drilling (HDD) pipe and cable laying systems so that they can operate more safely below ground.
- To increase knowledge of the electrical behaviour of the ground, by means of in-situ measurements to enhance understanding of the sub-soil electrical environment, and to provide information for scientifically based antenna design.

The consortium running the project comprises representatives of the major water and gas utilities across Europe one of the world's leading developer of GPR systems, designers and operators of one of the world's leading Horizontal Directional Drilling (HDD) companies, supported by a recognized authority in GPR technology and its applications.

The technology

RADAR is an acronym that means **RA**dio **D**irection **A**nd **R**anging, and it has been used since the 1930's for the detection of aircraft, ships, vehicles. birds, rainstorms and other above-ground objects. Many diverse applications have been developed, but all depend upon the transmission of electromagnetic energy, usually in the form of a pulse, and the detection of a small amount of that energy reflected from the target. The time delay of the reflection indicates the range of the target.

Buried objects may also be detected by radar methods and have been the subject of electromagnetic probing for longer than have above-ground objects. Work reported in the fifteen years after 1910 was devoted to the electromagnetic identification of underground regions of dissimilar conductivity (e.g.

ore deposits) or absorption compared with their surroundings, using non-pulsed methods. The first pulsed experiments were reported in 1926 when the depths of rock strata were determined by time-of-flight methods. It was noted that any dielectric variations, not necessarily related to conductivity variations, could give rise to reflections and that, further, it was easier to implement directional sources than was the case for seismic methods.

Over the next 50 years, radar pulsed techniques were developed for a range of specialised applications such as:

- ice thickness measurement
- fresh water depth measurement
- salt deposit thickness
- desert sand layer investigations
- buried plant location,

with the emphasis usually being on deep penetration sometimes up to a few kilometres. As a rule, deep penetration requires emissions at frequencies of a few MHZ or tens of MHz, with the consequent need for large antennas and the accompanying restriction of low resolution of the objects or interfaces detected. Shallow objects lying in, say, the first one or two metres of the earth's surface, which include those of most interest to utilities, may be detected by emissions at higher frequencies, up to 1000 MHz, for example. Systems typically intended to penetrate a few meters into the ground have become known by the term Ground Probing Radar (GPR).

Usually, the means of producing a transmit signal with the required frequency range useful for shallow probing is by means of an impulse generator based upon an avalanche diode. In this method, a short pulse is generated so that all of the frequencies within the range required are simultaneously transmitted. Although this is a cost effective means of producing a signal with usable characteristics, its physical mechanism is a random process that tends to produce noise and jitter. These processes limit the inherent dynamic range of the system.

The receivers for such systems are based upon the methods used in commercially available high frequency time domain sampling oscilloscopes which also have fundamental limits on their dynamic range. Even the best pulse based system has a dynamic range (from the maximum signal it can handle to its noise floor) which is unlikely to exceed 70 dB. All of this range, however, may not be available because of other system effects due to multiple reflections of energy between the microwave system components and between that antennas and the ground. These interactions are extended in time and define what is known as the 'Impulse Response' of the system. It is also known as the 'Clutter Profile' and it tends to obscure signals from wanted targets and further limits the effective dynamic range of the system.

Location and Mapping of buried utilities from the surface

The detection of buried utilities' plant imposes a particular set of constraints on the design of an effective GPR system. The majority of buried plant is within 1.5m 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 GPR 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 and good resolution of neighbouring plant, and some design compromises may have to be made.

Surprisingly, latest 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.

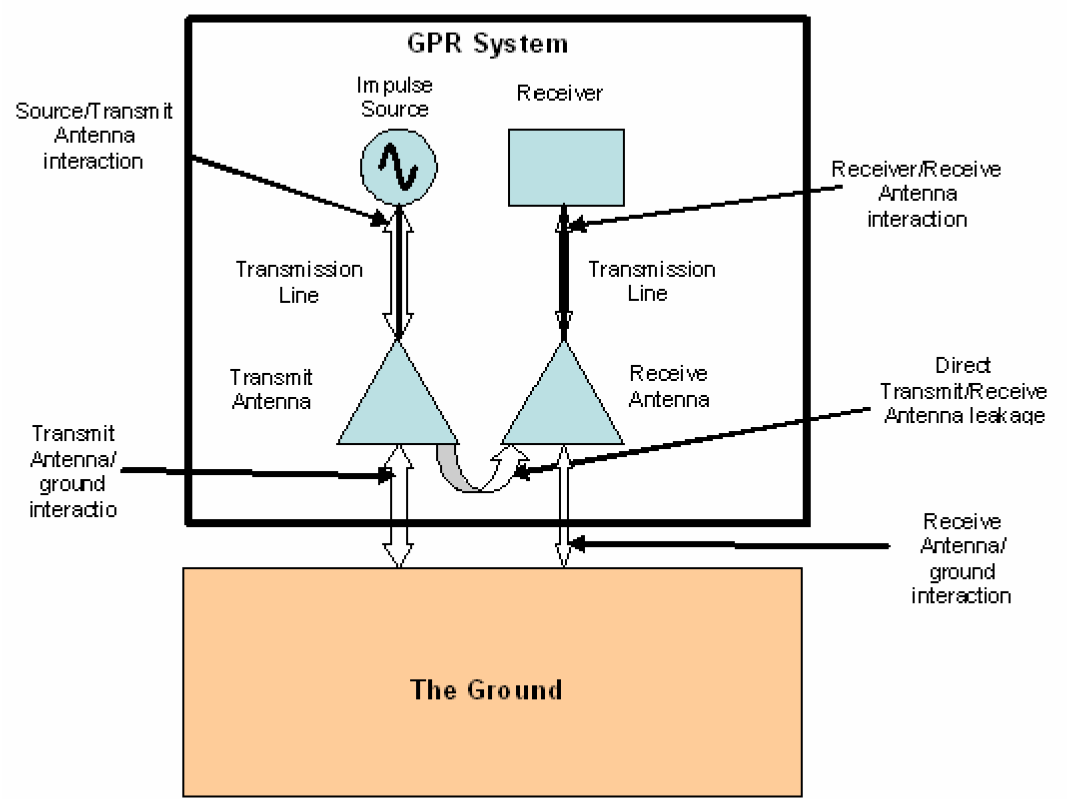

Figure 2 Impulsive GPR Schema and major signal interaction paths

As the current GPR technology (impulse based) has been extensively developed over many years, it is unlikely that future developments in themselves will lead to any significant improvement in the performance of ground penetrating radars.

For this reason, ORFEUS seeks to introduce Stepped Frequency Continuous Wave (SFCW) technology into GPR systems as an alternative to the present one. In theory, stepped frequency microwave sources possess superior dynamic range and stability compared to pulse systems, and permit the control of the frequency range, thus allowing an improvement in the penetration performance.

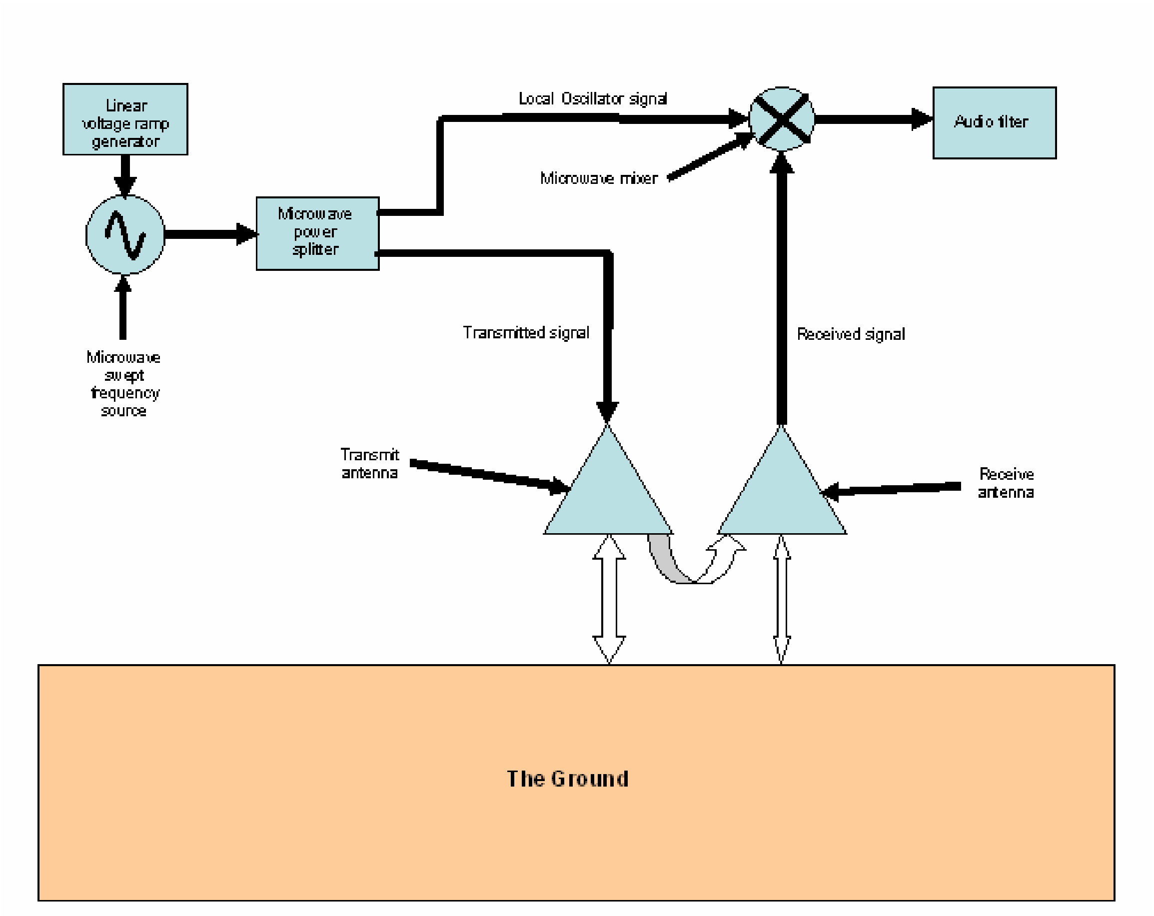

Figure 3 Continuous wave (CW) radar schematic diagram

A Stepped Frequency radar is similar to a CW radar with the main exception concerning the fact that the frequency can be changed in discrete, highly repeatable and stable, steps to cover the desired bandwidth. The phase and amplitude of the received tone is then sampled and the equivalent time-domain sweep reconstructed via a digital Fast Fourier Transform.
Although the peak power transmittable by the SFCW radar is some 20 dB lower than that of the impulse one, the receiver noise is greatly reduced due to the extremely narrow band filter used for receiving the tones, thus the dynamic range is largely increased.
However, the potential advantages of the SFCW transmit and receive system, in terms of superior dynamic range, have not been realised yet. This is because of some technical limitations (e.g. the slow repetition rate of the frequency generator) and due to related implementation costs.
Moreover, other measures are necessary to suppress internal reflections and match the antenna to the ground characteristics in order to optimise the propagation of the radar signal into the ground.

All these aspects will be analysed and hopefully solved along the project’s course; if so, these improvements will lead to an improvement in the ability of GPR operating from the surface to penetrate the ground and detect deeply buried targets.

Utilities avoidance from the underground

The Horizontal Directional Drilling (HDD) method for installing pipes and cables of various size, is very powerful technique but its uncontrolled use can cause great damage to existing buried infrastructures. Clearly, before this type of system can be used the operator must have an accurate knowledge of utilities and other potential obstructions in its path. Hazards include energised power cables, telecommunications lines (wire and fibre optic), steel and plastic gas piping, potable water and sewer lines made from various materials including clay and concrete. Striking one of these assets can be extremely dangerous for the safety of the operators, but can also cause huge economic losses due to the interruption of public services.

On this respect, the second task for Orfeus is the study of a GPR-based real-time obstacle detection system for steerable bore- heads of HDD pipe and cable laying systems so that they can operate more safely below ground.
The bore-head radar will have the capability to look in the forward and sideways directions and to detect objects which come within the cones of the antenna radiation patterns. Information from the radar will be passed to the operator on the surface so that he may steer around and thus avoid objects that would otherwise be struck.

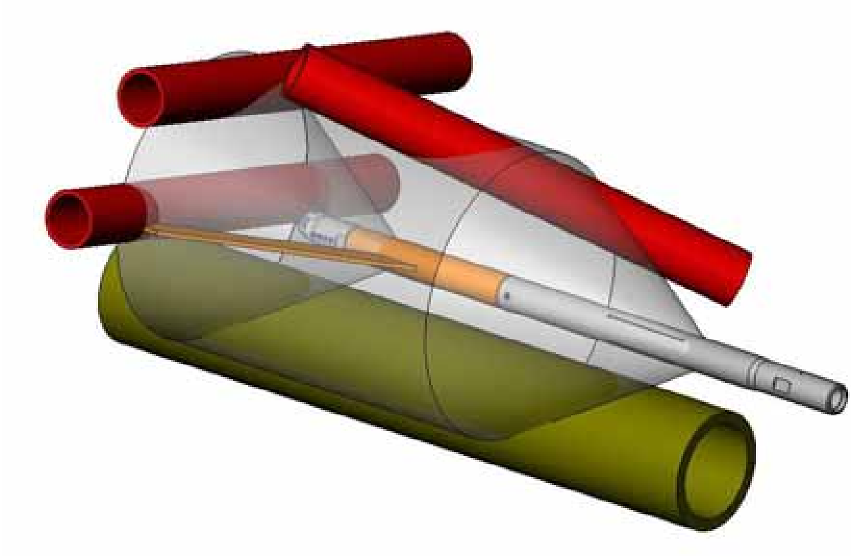

Figure 4: Examples of objects parallel, orthogonal and angled to the bore-head

Most of the scientific and technological issues to be addressed during this part of Orfeus, will concern the antenna design; in fact, the required performance in terms of range and sensitivity are mainly related to the antenna radiation pattern, which is primarily governed by its shape and dimension and these are constrained by the drilling rig size.

Furthermore, reflections from internal components (i.e. ringing) could cause a significant degradation of the antenna performance so that the detection of non-metallic targets (that produce a weaker echo) may be problematic.

Another significant scientific concern of the project is related to the radar data processing method. From this point of view, the overall requirement is to set a suitable strategy for highlighting the data that are really of relevance for the HDD operator (i.e. objects too close to the drill path), in order to allow the immediate interruption of the drilling before hitting underground utilities. Besides that, data processing has to be executed in real-time or in near real-time, which is a further demanding objective.

Finally, other critical, technical issues will have to be solved during the project; these comprise the environmental characteristics and the robustness of the packing for the electronics, the heat dissipation, the vibration damping and the transfer of the data from the bore-head to the operator seat.

Nevertheless, a successful outcome of the projectbore-head radar will encourage the use of trenchless pipe laying methods, with the consequential benefits to society. Moreover, the additional information from a borehole GPR, which should be able to detect exactly what is near to the bore-head, will provide a complete map of the local underground situation that hitherto has not been available.

Characterisation of Underground Environment

The third task for Orfeus concerns the development of reliable methodologies for the in situ measurement of soil characteristics relevant to the GPR; these measurements will also be used as an input for the other research activities as they will to provide useful information on the fundamental limits of GPR detection and to guide equipment design decisions.

In fact, the characteristics of GPR antennas depend strongly on the ground conditions; this phenomenon has a direct effect on GPR penetration depth and has not been extensively studied nor have practical solutions been implemented to improve performance.

In Orfeus a predictive model will be developed to provide the optimisation routine for adaptation of Moreover, by combining electromagnetic characterisation, at GPR frequencies, with geo-technical investigations and supplementing them with regional geological settings history information, a reliable characterisation of the ground will be obtained.

It provides an indispensable service for geotechnical applications of surface GPR as well as bore-head GPR in HDD technologies. The successful combination of these complementary sources of information will lead to the necessary knowledge for building a GPR applicability map of Europe.

Conclusions

The ORFEUS project addresses the requirement to improve the technology used to locate utilities buried infrastructure so that excavation cost will be lowered, economic no-dig technologies will be able to be used with confidence and leakage, specifically from pipes that transport water, will be located more easily than is possible with present technology.

This will be achieved by implementing a radical change in the fundamental technology used in GPR systems designed to carry out location surveys from the ground surface and by studying a new radar system capable of being deployed in the bore-head of no-dig equipment to provide advance warning of obstacles in the drill path.

Moreover, a programme of measurements to establish the range of soils electrical parameters over which the GPR’s will operate will underpin the scientific development work of the project.

This is high-risk research, and the outcome is critically dependent upon resolving several severe technological and scientific issues. However, a successful project outcome would increase the safety of directional drilling equipment used to install new utilities by reducing the probability of causing damage to existing buried plant. This will benefit the safety of the operators and communities and will help to avoid the consequential compensation costs associated with loss of services, reduce unnecessary excavations and so maintain fuel efficient traffic flow in congested urban areas.

Acknowledgment

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