ORFEUS Project: the Surface GPR System

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***Abstract* — A surface based GPR system for locating buried pipes and cables suitable for deployment in urban areas is under development within the ORFEUS (Optimized Radar for Finding Every Utility in the Street) project. Innovative technical solutions allow significant inherent limitations of conventional radar systems to be overcome.**

I. The Operative Scenario and GPR State of the Art

The congestion of buried infrastructures of our urban areas is increasing as new optical fibre broadband communications networks are installed. Efforts to drive down installation and maintenance costs by the use of innovative excavation techniques, such as trenchless technology, are compromised by the lack of reliable non-invasive systems for underground mapping. . A major issue is to provide precise information on the location and connections of assets.

At present, the only non-invasive means for locating buried non-metallic utilities (where no active tags are present [1]) is Ground Penetrating Radar (GPR) systems. Many underground networks consist of plastic cables with a small metal content (for example telecommunications networks), and concrete pipes are often employed in sewage networks. In these cases, detection systems that rely upon the presence of metal are of limited use.

Impulse GPR systems are widely used for mapping buried plant. Such radars are characterized by a central working frequency of several hundreds of megahertz, and feature a wide operational bandwidth useful to obtain range resolutions, in typical soils, in the order of tens of centimetres. The dynamic range of these devices is, typically, 60-70dB: this performance often limits the ground penetration capability, especially when clay is present in wet soils. This is usually the case in northern European countries.

GPRs based on impulse techniques have several advantages, among which are: compact size and light weight with optimal field operational capability, and reduced power requirements. For these reasons, great attention has been focused on such technique for developing GPR systems for exploration of extraterrestrial planets [2]. However, impulse techniques require the use of non-tuned broadband receivers which limits the achievable dynamic range of the radar.

II. One Step Beyond: the Orfeus Project

The importance of addressing the problem of non-invasive detection of buried infrastructures in the urban environment has led the European Commission to support, under the 6th R&D Framework Programme, the ORFEUS research project which is carried out by a Consortium of nine partners: OSYS Technology Ltd.(Coordinator), the European Gas Research Group (GERG), UK Water Industry Research Ltd., GDF SUEZ S.A, Ingegneria dei Sistemi (IDS) S.p.A., Tracto - Technik GmbH, University of Brno, Technical University of Delft and the University of Florence. The main goal of the project is to develop an advanced and innovative radar technology for the location of underground utilities. To this end, two complementary radar systems are to be designed.

A. The Surface Radar System

As conventional GPR systems, the developed sub-surface radar operates over the ground interface. However, innovative design solutions have been adopted in order to obtain better resolution of the radar image at great depths. This is of crucial importance to enhance the performance of aforementioned radar in buried asset surveys. In particular, the following scientific and technical issues have been addressed:

- development of a radar system characterized by an increased penetration depth in realistic urban scenarios and capable of performing rapid surveys;
- development of a hardware background canceller able to reduce the impact of soil reflections on the performance of the receiver [3];
- development of an ultra-wideband (UWB) antenna with stable circuital and radiation properties over different types of soil.

This radar system is described in the following paragraphs.

B. The Bore-head Radar System

A second radar system has been also developed for trenchless pipe and cable detection based on horizontal directional drilling (HDD) techniques.

In this case, the aforementioned surface radar will be employed for steering the drilling activity, while the radar system installed on the drilling head is used to avoid buried targets.

In this way, a significant reduction in the risk of striking and damaging underground services can be achieved, whilst also enhancing the safety level of machine operators.

III. Increased Penetration Depth

In order to increase the penetration depth of a radar system two objectives have to be pursued: an increased system dynamic range and a good range resolution.

A. Dynamic Range

The dynamic range of any GPR system is determined by the maximum input signal able to be handled by the receiver and its noise level. In general, the larger the bandwidth of the receiver, the higher will be the noise level. All GPRs require a large operational bandwidth, but pulsed systems also need broadband receivers.

If the frequency components of the radar signal can be transmitted sequentially, then a tuned narrow band receiver with a low noise level can be used. Such a technique, known as Continuous Wave Stepped Frequency (CW-SF), provides significant advantages in terms of low noise and good dynamic range, but it results in increased circuital complexity, size, weight and power consumption.

B. Range resolution

The range resolution of the radar system implicitly determines the relevant penetration depth which is bounded by the range resolution cell size. By using a very high resolution it is possible to minimize the range resolution cell size and, consequently, to reduce the clutter cell dimension. This approach is particularly useful in urban environments where the soil is very inhomogeneous and mainly composed of inert materials.

For these reasons, a primary goal is to improve the range resolution compared with conventional radar systems, by increasing the operational bandwidth. Since the lowest operating frequency is 100MHz, the operational bandwidth can only be increased by using the higher frequency band. Unfortunately, the radar performance at higher frequencies is selectively affected by the soil attenuation, which tends to impose a limitation on the effectiveness of the technique.

The ORFEUS radar system operates in the 100MHz - 1GHz frequency range. In this way it is possible to maximize both the penetration depth and the range resolution.

In particular, by adopting the SF-CW technique it has been possible to develop an ultra-wideband system characterized by a range resolution that is more than three times greater than that featured by low-frequency pulsed GPR systems.

IV. Fast Scan

It is highly desirable that GPR surveys in urban areas do not hinder normal road operations. For this reason the developed radar system should be able to perform fast surveys, at least at walking pace.

A CW-SF based radar does not fully meet this requirement because of the need sequentially to transmit radio signal packets at equally spaced frequencies. In order to avoid a defocusing effect in the FFT (Fast Fourier Transform) processing used to determine the range profiles, each frequency tone used to assemble the synthetic impulse should be transmitted at the same position. For this reason, the radar system should, ideally, be stationary during each frequency scan. Since frequency tones are sequentially transmitted, this is a serious problem to address. Moreover, such an approach does not maximize the spectral efficiency.

On the other hand, it is extremely hard to design a radar system able to manage all the CW signals (multi-frequency CW) simultaneously because of the very large number of tones (in the order of some hundreds). Also there are severe intermodulation problems that affect the receiver when it is subject to hundreds of equally frequency-spaced CW radio signal components.

For this reason, the proposed surface radar is based on a conventional stepped frequency technique. However, since the fast survey capability is an important requirement, the temporal efficiency expressed (for each scan) as the ratio between the integration time and the time necessary for the frequency scan has to be maximized. It is clear that, in order to maximize such parameter, the frequency hopping time should be reduced by designing an agile, UWB synthesizer.

The UWB frequency synthesizer has been developed in such a way that the CW-SF radar system is able to provide a temporal efficiency equal to one. This is a challenging task since available synthesizers are usually based on the Digital Direct Synthesis (DDS) technology, which is not directly suitable for UWB applications.

Off-the-shelf DDS chips are able to synthesize bandwidths of several hundreds of megahertz. Moreover, since this class of devices is severely affected by numerical distortion [4], a portion of the operational frequency band cannot be used for high dynamic range GPR operations. On the other hand, UWB frequency synthesizers can also be based on PLL technology employing UWB voltage-controlled oscillators (VCOs). However, such solution requires control loops that are, typically, too slow for the considered radar application.

To overcome previously described limitations, the proposed synthesizer architecture combines DDS and VCO-based PLL technologies in such a way that the requirements in terms of ultra-fast frequency hopping and extreme UWB operation can be met. In this way it has been possible to develop a radar system able to perform frequency scans at a rate of 200 scan/s.

V. UWB Antenna System

The antenna requirements are very demanding in terms of broadband characteristics, good efficiency, compact size combined with low frequency operation, stable antenna transfer function over different grounds (needed for time-domain pulse synthesis via IFFT) and light weight. No antenna designs capable of fulfilling such requirements have been reported in literature.

Investigations into the most suitable antenna with characteristics invariant with respect to the electrical properties of the ground has led to the selection of an ultra-wideband cavity-backed resistively loaded bow-tie design

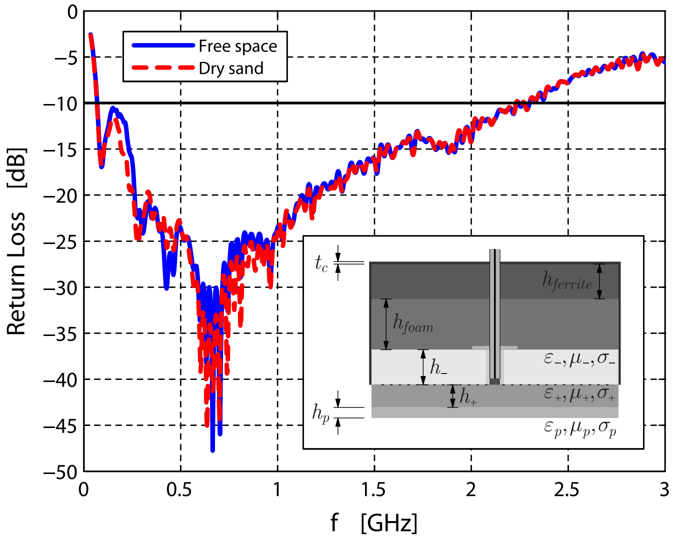

Fig. 1 Frequency behaviour of the input reflection coefficient of the cavity-backed resistively-loaded bow-tie antenna in free space, and over dry sand elevated to a height $h_a = 4\ cm$. The cross-sectional view of the structure is also shown

A sketch of the antenna geometry is shown in the inset of Fig. 1. The radiating structure features two slotted circularly-ended flairs, printed on a circular dielectric substrate, having diameter $D_c = 52\ cm$, provided with a protective coating that increases the mechanical and environmental durability of the structure. In order to prevent late-time ringing phenomena, which could, potentially, mask of buried targets, the flairs of the proposed antenna are resistively loaded [5]. This loading reduces spurious reflections between the antenna open ends and the feed point, so increasing the operational bandwidth of the radiating structure. The resistive loading of the antenna is technically realized by multiple equally-spaced concentric slots bridged with chip resistors. A cylindrical metallic cavity, filled with a ferrite absorbing layer is used to reduce the back-radiation and achieve a good impedance match over the whole operating frequency band. Moreover, a suitable foam panel is used to reduce the parasitic loading of the antenna board due to the proximity effect of the ferrite material.

The circuital characteristics of the antenna with the specified loading profile have been measured both in free space and over dry sand ($\varepsilon_{r_g} = 2.4$) at an elevation $h_a = 4\ cm$ from the air-ground interface. As it can be observed in Fig. 1, the antenna is well matched to the feeding line in the frequency band between $f_- = 66.5\ MHz$ and $f_+ = 2.3\ GHz$, resulting in a fractional bandwidth $FBW = 189\%$ that is only slightly affected by widely varying operational conditions.

The direct coupling between transmit and receive antennas, which determines the dynamic range of the radar, is below $-28\ dB$ over the whole operational bandwidth.

VI. Radar System Development

The prototype surface radar has been developed in order to achieve the following characteristics: modular architecture, easy access to each sub-module, robust mechanical assembly for reliable field operation.

The RF assembly is based upon sub-modules supported on two metal frames folded back to back by means of two hinges (Fig. 2). In this way the mechanical arrangement is reduced in size to fit inside a metal box measuring 50x60x25cm.

An additional frame hosts the acquisition and control unit which is based upon a DSP board. The system is controlled by a portable PC connected via an Ethernet link.

Finally, the radar system is installed on a tray that allows measurements to be carried out in field environments: the tray also hosts the survey wheel and the antenna system (Fig. 3).

The transmitter is able to operate employing a transmitted power of 0dBm (1mW), while the system transfer function is calibrated in hardware way in order to equalize the amplitude and phase response of the system.

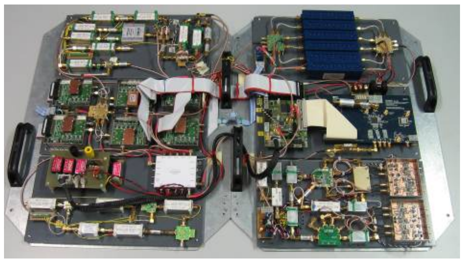

Fig. 2 Surface ORFEUS GPR foldable electronic assembly

Fig. 3 Surface ORFEUS GPR mechanical arrangement

VII. Laboratory Performance Assessment

In order to simulate realistic operational conditions where at least one strong reflection is experienced, a preliminary assessment of the radar performance has been performed, without the antenna sub-system, by using attenuated RF cables to model the effect of the target [6].

Fig. 4 shows the range profile when a single target scenario (coaxial cable) is considered. The measured result is compared to the theoretical one (with Hanning windowing) in order to evaluate the performance of the radar.

The comparison shows that:

- *range resolution* is consistent with theoretical predictions;
- *clutter decay* fits theoretical predictions up to -95dB;
- *flat clutter* (due to the noise) is 100dB below the peak level of the signal.

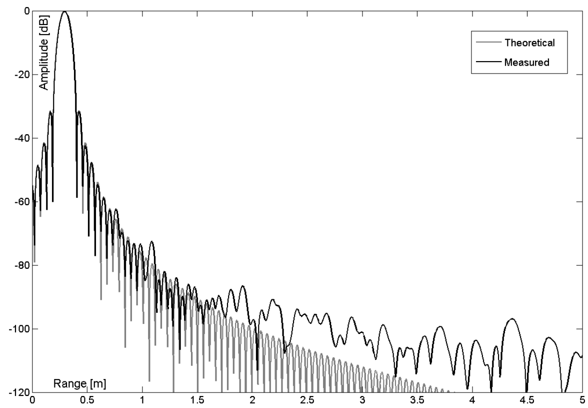

Fig. 4 – Comparison between real and theoretical range profile

VIII. PRELIMINARY COMPARISON WITH PULSED GPR

A preliminary comparison has been carried out between ORFEUS and two pulsed GPR systems operating at 200MHz and 600MHz (centre frequency), respectively. In order properly to evaluate the performance of the proposed electronic sub-system, a comparison has been made by connecting the ORFEUS GPR to a pair of bow-tie antennas similar to those used in the pulsed GPR.

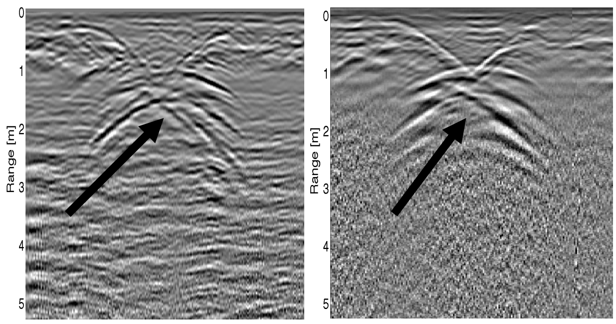

Fig. 5 – B-scan: comparison between ORFEUS GPR (left) and 200MHz pulsed GPR (right). Detection of several pipes at about 1m dept.

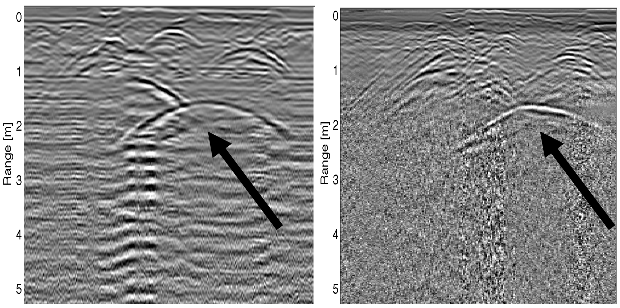

Fig. 6 – B-scan: comparison between ORFEUS GPR (left) and 600MHz pulsed GPR (right). Detection of a 1.5m deep sewage pipe.

In Fig. 5 the ORFEUS and pulsed GPR B-scans are shown. In both images, at about 1metre depth, several pipes are detected, however due to superior UWB capability, the ORFEUS B-scan exhibits better resolution and lower thermal noise.

In Fig. 6 a comparison with a 600MHz pulsed GPR is made using as a target a sewer pipe (under other targets) at a depth 1.5m. It can bee seen that the ORFEUS B-scan exhibits better resolution, lower noise level, and hence better target detection.

IX. FURTHER EXPERIMENTAL PROGRAMME

GDF SUEZ, as partner of the project, is making available a well documented, well maintained test site that has been widely used in previous EC-sponsored research projects [7] to evaluate the performance of different GPRs in realistic operative scenarios. This site has been recently updated and customized to test radar systems to the requiremements of the ORFEUS project. Emphasis will be placed on a comparison between ORFEUS GPR, equipped with the UWB resistively loaded bow-tie antennas described in paragraph V, and state-of the-art pulsed GPRs.

X. CONCLUSION

The main goal of the work presented in this paper is to develop a GPR with an increased penetration depth compared with state-of-the-art pulsed systems. To achieve this, an architectural solution has been developed to resolve critical issues that limit the performance of GPR. As a result, a SFCW radar has been developed. The combined DDS and VCO-based PLL technology allows scanning of the frequency band from 100MHz to 1GHz within 5ms and a receiver dynamic range of about 100dB. A dedicated antenna system provides consistent coupling of EM energy into the ground regardless of its conditions. The first experimental results have confirmed effectiveness of the radar design.

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