Operational Radar to For Every drill string Under the Street

Grant agreement no: 308356

Bore-head Radar Requirements

Deliverable 1.7

Coordinators Signature: ____________________

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Dissemination level		
PU	Public	☒
PP	Restricted to other programme participants (including the Commission Services)	☐
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CO	Confidential, only for members of the consortium (including the Commission Services)	☐

Preface

This deliverable is prepared within the framework of ORFEUS project (Grant agreement no: 308356), supported by the 7th Framework Programme.

ORFEUS aims at progressing the prototype HDD bore-head radar technology that was developed under the preceding FP6 financed project entitled "Optimised Radar to Find Every Utility in the Street".

Horizontal directional drilling (HDD) offers significant benefits for urban environments by minimising the disruption caused by street works. Use of the technique demands an accurate knowledge of underground utility assets and other obstructions in the drill path. its aims is to design a prototype innovative ground probing radar (GPR) based real-time obstacle detection system to increase the safety margins of HDD to allow its use in the widest possible range of conditions.

Extensive testing and validation, as well as supporting the demonstration and exploitation of the final product, is proposed. The crucial testing and evaluation phase will assess the risks, confirm environmental benefits and increase end users' (public
authorities and industry) confidence, awareness and uptake of this new technology. Technology transfer, training and standardisation, in cooperation with European standards organisations, will also be a significant element of the project.

Consortium

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Abbreviations

GPR: Ground Probing Radar

TBD = To Be Defined (an item where the general requirement principle is established, but the actual values will be defined in the detailed design phase.

TBC. = To Be Confirmed (an item believed to be correct and to be used as a working value, but will require confirmation during later detailed design phases.

UWB: Ultra Wide Band (a technology that allows the transmission/reception of very short pulses of electromagnetic energy. GPRs are using this technology)

Unit of Measurement

This table contains the definitions of physical quantities, phenomena, and units, primarily in the International System of Units (SI) and the metres-kilogram-second (MKS) system.

Base Units		
Quantity or phenomenon (and symbol)	**Standard International unit (and symbol)**	**Alternate units (and symbols)**
displacement (*d*)	metres (m)	centimetres (cm) feet (ft)
mass (*m*)	kilogram (kg)	gram (g)
time (*t*)	second (s or sec)	hour (h or hr) mean solar day (dy) solar year (yr)
current (*I*)	ampere (A)	statampere (statA) abampere (abA)
temperature (*T*)	kelvin (°K or K)	degree Celsius (°C or C) degree Fahrenheit (°F or F) degree Rankine (°R or R)

Derived Units		
Quantity or phenomenon (and symbol)	**Standard International unit (and symbol)**	**Alternate units (and symbols)**
speed (*s*) velocity (*v* or **v**)	metres per second (m/s or m · s $^{-1}$)	centimetre per second (cm/s or cm · s $^{-1}$)
acceleration (*a* or **a**)	metres per second squared (m/s ^{2} or m · s $^{-2}$)	centimetre per second squared (cm/s ^{2} or cm · s $^{-2}$) gravity (g)
current density	ampere per metre squared (A/m ^{2} or A · m $^{-2}$)	ampere per centimetre squared (A/cm ^{2} or A · cm $^{-2}$)
electromotive force (emf) voltage (*V* or *E*)	volt (V)	statvolt (statV) abvolt (abV)
resistance (*R*)	ohm	statohm abohm
conductance (*G*)	siemens (S)	statsiemens (statS) absiemens (abS)
electric field strength (*E*)	volt per metre (V/m or V · m $^{-1}$)	microvolt per metre (µV/m or µV · m $^{-1}$)
permittivity	farad per metre (F/m or F · m $^{-1}$)	picofarad per metre (pF/m or pF · m $^{-1}$) microfarad per metre (µF/m or µF · m $^{-1}$)
power (*P*)	watt (W)	horsepower (hp) statwatt (statW) abwatt (abW)
permeability (*µ*)	henry per metre (H/m or H · m $^{-1}$)	microhenry per metre (µH/m or µH · m $^{-1}$)
electromagnetic field strength	watt per metre squared (W/m ^{2} or W · m $^{-2}$)	microwatt per metre squared (µW/m ^{2} or µW · m $^{-2}$)
angular speed angular velocity	radian per second (rad/s or rad · s $^{-1}$)	degree per second (deg/s or deg · s $^{-1}$)
angular acceleration	radian per second squared (rad/s ^{2} or rad · s $^{-2}$)	degree per second squared (deg/s ^{2} or deg · s $^{-2}$)
frequency (*f*)	hertz (Hz)	kilohertz (kHz) megahertz (MHz) gigahertz (GHz) terahertz (THz)

Derived Units		
Quantity or phenomenon (and symbol)	**Standard International unit (and symbol)**	**Alternate units (and symbols)**
wavelength	metres (m)	centimetre (cm) millimetre (mm) micrometre (μm or μ) nanometre (nm) Angström (Å)
data quantity	bit (b) byte (B)	kilobit (kb) megabit (Mb) gigabit (Gb) terabit (Tb) petabit (Pb) exabit (Eb) kilobyte (KB) megabyte (MB) gigabyte (GB) terabyte (TB) petabyte (PB) exabyte (EB)
bandwidth (signal)	Hertz (Hz)	kilohertz (kHz) megahertz (MHz)
bandwidth (data transfer rate)	bits per second (bps)	kilobit per second (Kbps) megabit per second (Mbps) gigabit per second (Gbps) character per second (cps)

TABLE OF CONTENTS

TABLE OF FIGURES

1 EXECUTIVE SUMMARY

Bore-head Radar Requirements Report
ORFEUS Deliverable D1.7 WP1 task 1.1

This document reports on the requirements the Bore-head Radar that will guide the final development of the system as specified in the contract with the EC.

Particularly, some of these requirements directly come from the former ORFEUS project that produced a fully working prototype; therefore, this document mainly focuses on features that were not implemented during that research with the over-all aim of producing a marketable system to be used in Horizontal Directional Drilling rigs.

Specifically, in the previous ORFEUS project, it was foreseen that following key aspects needed to be addressed before coming to the market:

1. Optimisation of antenna performance
2. Remote microwave source/receiver
3. Performance of the tilt angle sensor
4. Ruggedisation

In the following paragraphs, after a short overview of the application and a summary of end-user requirements determined from the previous ORFEUS project, the Bore-head Radar is described in terms of its main components the expected performance of which are specified.

Conclusion

The system specification included in this document sets the standard to which the final system design is required to perform and was developed from an exhaustive and accurate analysis of all the requirements. It describes the ideal design for the optimum performance of the system given the current state of the technology and realistic estimates of the environment in which it will operate

This report is therefore the reference document for the development phase of the ORFEUS Bore-head Radar.

A system architecture is proposed together with the description of the main sub-systems and their associated specifications.

2 OVERVIEW ON THE HORIZONTAL DIRECTIONAL DRILLING

HDD is a “trenchless” method for installing buried pipes and cables, of various sizes that minimises inconvenience to traffic and people living nearby. This technique is very powerful but, if used in an uncontrolled manner, it can cause significant damage to existing buried infrastructure. Clearly, before this type of system can be used, the operator must have an accurate knowledge of the utilities and other 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.

As Figure 1 clearly shows, the arrangement of existing underground pipes and cables can be complex and their exact position cannot be determined from maps. Surface GPR can help but, ideally, a GPR system should be mounted in the drilling-head that continuously scans the soil volume in front of and at the sides to locate all obstacles that can affect the path of the bore in order to avoid collisions and to ensure compliance with statutory clearance requirements between the pipe or cable being laid, and existing utilities.

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

The need to detect and be able to take action to avoid obstacles that may influence the optimum drill path during HDD operations is dictated by issues of and safety and economics.

Safety issues are, usually, related to the nature of the obstacle that may be encountered during operations. As a rule, buried infrastructure, statistically, represents the most frequently encountered hazards, particularly the risk of striking and damaging gas lines or high voltage electricity cables. Accidents of this nature raise safety of life issues both for the drill operator, other personnel and members of the general public.

In economic terms, the hazard of communications cables entails a risk of extremely high compensation costs if high value services are interrupted by drilling operations. Lower down the scale, if obstacles are encountered that prevent further progress of the operation, then unplanned costs will be incurred in re-routing the bore path. Finally, society as a whole benefits from the efficiency and relative lack of disturbance (compared to open trenching) of HDD methods.

Prior to drilling operations, as much information as possible on the buried infrastructure is gathered from various sources, sometimes including surface operated Ground Probing Radar (GPR). The performance of such systems is not yet adequate to provide a complete knowledge of obstacles lying in the drill path, although it is anticipated that the proposed new generation of stepped-frequency GPRs will provide a step improvement. Additional information, obtained from a radar located in the drilling-head, should be able to provide real-time indications of obstructions in the drill path so that they may be avoided.

3 SUMMARY OF BORE-HEAD RADAR USER REQUIREMENTS

The purpose of the bore-head radar is to provide the drill rig operator with sufficient advance warning of obstacles present in the vicinity of the pilot bore. Such information may necessitate a change in direction, either to avoid the detected object or to provide sufficient clearance from the pilot bore for later operations, such as back-reaming, or pulling in the new pipe into its underground position. In terms of the radar penetration required to fulfil this objective, the distance needed is usually less than is the case for surface based radars used for location purposes. The actual values in the specification are dictated by the physical parameters related to the drilling speed of the process and the time and distance required by the operator to decide upon and take avoiding action

It is required both to detect objects that lie in the path of the pilot bore and those that may be present in the volume of a cylinder surrounding the pilot bore. This means that the radar must possess look-ahead and radial detection capabilities. Objects to be detected include pipes and cables (both parallel to and crossing the direction of the pilot bore), other man-made artefacts such as old building foundations, inspection holes, etc), and naturally occurring objects (such as stones and boulders or changes in ground consistency or geological situation).

In addition to fulfilling the primary detection role, the radar is also expected to provide information not only on the presence of objects likely to cause problems for the drilling and subsequent pipe-laying operation, but also on their angular position and distance from the drilling head, and whether there is one, or more than one, object.

Following paragraphs summarise the end-user specifications as established during the previous ORFEUS project (Contract n° FP6-2005-Global-4-036856, Deliverable D6a).

3.1 PERFORMANCE SPECIFICATION SUMMARY

3.1.1 DETECTION

3.1.1.1. Mandatory detection requirements

i. Plastic, clay, concrete, polymer concrete and fibre pipes and cables

ii. Metal and reinforced concrete pipes and cables

3.1.1.2. Optional detection requirements

iii. Interfaces between different clay soils, humid / wet clay

iv. Underground cavities

v. Other buried artificial plant

3.1.1.3. Target detection percentage in absorptive soil conditions

Minimum **95%** of all real targets up to **0.5 m** distance from the bore-head must be correctly detected.

3.1.1.4. False target generation percentage

False target generation may not exceed

i. **1%** of the correctly located real targets up to a distance of **0.5 m** from the bore-head in axial direction,

ii. **1%** of the correctly located real targets up to a distance of **1.0 m** from the bore-head in radial direction.

3.1.2 CLASSIFICATION

3.1.2.1. Objects to be detected

i. Empty pipes and filled pipes

ii. Electricity and data cables

iii. Natural and artificial elements (e.g. gravel, rubble, debris, boulders, foundation remains).

3.1.2.2. Soil conditions for bore-head radar operations

Bore-head GPR must be usable in all natural and artificial soils types typical for Europe (The geographical scope of ORFEUS is limited to Europe, but there is no reason to suppose that equipment designed to cope with the full range of European conditions would not find application in a global market)

3.1.3 PENETRATION DISTANCES

3.1.3.1. Penetration on Bore-sight

i. Minimum **0.5 metre**

ii. Preferred **1 metre**

3.1.3.2. Penetration in Azimuth

i. Minimum **1 metre**

ii. Preferred **2 metres**

3.1.4 LOCATION ACCURACY (DISTANCE AND ANGLE)

3.1.4.1. Bore-head radar distance measurement accuracy

The accuracy, both in axial and radial directions, must be a minimum of:

i. **50 mm at 0.50 metres** distance from the bore-head

ii. **100 mm at 1.00 metres** distance from the bore-head

3.1.4.2. Roll angle (measured by a mechanical sensor)

+/-9° (+/- 2.5% of 360°). The roll angle will be measured with reference to a defined angular datum.

3.1.5 RESOLUTION (MINIMUM DISTANCE BETWEEN OBJECTS)

The Bore-head GPR shall be able to determine the presence of multiple objects when they are separated by more than **300 millimetres (mm)**.

3.1.6 MINIMUM SIZE OF OBJECTS TO BE LOCATED

3.1.6.1. Linearly Shaped Objects

Minimum Size **10 mm** across the longest cross section

3.1.6.2. Amorphously Shaped Objects

Minimum Size **300 mm** across the longest cross section

3.1.7 SURVEYING

a. The minimum surveying and processing speed must provide real-time results at the operational drilling speed (maximum **0.30 m/sec**. - average operational speed approximately **0.1 m/sec**.)

b. The roll angle sensor must provide real-time results up to the maximum rotation speed of the drill rig (**200 rpm**)

3.1.8 MECHANICAL AND ENVIRONMENTAL

The mechanical and environmental requirements for the bore-head GPR are extremely demanding and, in summary cover the following items:

a. Material specifications for bore-head, bore-head GPR housing, shock protection and drill rods

b. Geometrical dimensions and mechanical properties of drilling-head and bore-head GPR housing and drill rods

c. Power supply from HDD drill rig to bore-head radar

d. Vibration (shock) protection for bore-head GPR electronics

e. New geometrical arrangements in the bore head geometry in order to relocate the fluid channel and the existing navigation system. Avoidance of inference between the GPR and the navigation equipment.

3.1.9 TRAINING LEVEL OF USERS

The training and educational level of the users must be such that they are to be able to work reliably and independently. As a minimum, they should fulfil the following requirements:

a. Have, at least, a secondary modern school qualification
b. have received training in a technical job or have several years experience in civil engineering, mining, drilling or metal working
c. have valid driver's license
d. be able to read, and understand, simple technical drawings and plans (3D imaginative capability).
e. ideally, have experience in HDD drill rigs (assisting operators, etc.)

3.1.10 MANUFACTURING COSTS

The costs for the production of an operational unit was given in deliverable D6a of Contract n° FP6-2005-Global-4-036856.

4 INTRODUCTION TO BORE-HEAD RADAR DESIGN SPECIFICATIONS

During the former ORFEUS project (Contract n° FP6-2005-Global-4-036856) the requirements listed in the previous Chapter 3 were exhaustively analysed; on that basis, a complete set of system and sub-system technical specifications were developed and used during the development phase (ref. deliverable D7 of Contract n° FP6-2005-Global-4-036856).

The prototype developed under that framework (hereinafter referred as FP6-Proto) was then tested and found capable of fulfilling most of those specifications; there were, however, aspects not considered in the design, essentially due to the prototypic nature of the system being developed. Thus, as explained in the Description of Work (DoW), the current ORFEUS project will address these features and the novel system is being re-designed according to the following guidelines:

1. Optimisation of the antenna bandwidth to further improve GPR resolution.

2. Engineering review of the design to :
   - further reduce the antenna dimensions (while optimising the required frequency bandwidth) to minimise the impact of the installation on the drilling equipment
   - decrease the manufacturing and assembly costs
   - properly select the materials used for filling the cavity (that contains the antenna) and for protecting against wear caused by friction: both of these materials can, in principle, modify the radiation beam and efficiency and this effect must be minimised

3. Optimisation of the antenna design, considering the possible effect of the drilling fluid on the electrical properties of the soil.

4. Integration of the antenna transmitting/receiving electronics with the timing circuit to reduce costs by housing only the cheap radiating elements in the drill-tip (that is a disposable item of the drilling equipment).

5. Optimisation of the antenna layout in order to improve the detection performance by using polarisation phenomena that are correlated to obstacles' shape, orientation and dimensions.

6. Design review and ruggedisation of the tilt sensor which is currently installed in the prototype developed during the previous research. This could be necessary particularly for improving the high vibration rejection capability of the sensor.

7. Ruggedisation of the whole electronic system, including printed circuit boards, cables, connectors, after assembly and connection of the redesigned subsystems

Items 1 to 5 in the list above, relate to the design of the antenna and its transmitter/receiver circuitry, item 6 relates to the tilt sensor, and 7 to the whole system.

Following chapters in this document report on the system/sub-system specifications and analyse those that are new or significantly modified with respect to the former project (ref. deliverable D7 of Contract n° FP6-2005-Global-4-036856).

5 SYSTEM'S DESCRIPTION AND OVERALL SPECIFICATIONS

The over-all architecture of the system to be developed in this project is similar to the one of FP6-prototype. Figure 2 below shows its composition in schematic form, and includes main sub-systems and I/O interfaces to the control computer.

Essentially, the Bore-Head Radar will integrate the following sub-systems:

- a transmitting and a receiving UWB antenna hosted in the drilling head to look-ahead
- a transmitting and receiving UWB antenna hosted in the drill rod to provide the side looking capability
- the microwave source and receiver for both the antennas hosted in the drill rod
- a radar control board, including
    - the multi-channel timing circuit for controlling the circuitry of both the antennas
    - the A/D conversion circuitry
    - a data processor
    - interface circuitry to the modem to be developed in the framework of Work-Package 3.
    - a power supply module for generating all the voltages, and currents, needed by the electronics
- a tilt angle sensor

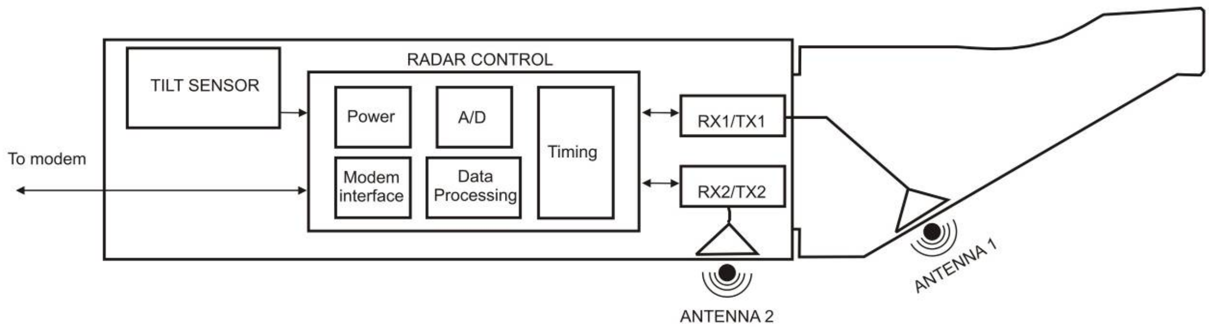

Figure 2: System architecture

Overall specifications for the system are as follows.

System mission:	To produce advance warning of obstacles present in the vicinity of the pilot bore
System directional detection capabilities:	in range and in the azimuth plane with respect to the drilling direction
System technology:	Impulsive Ground Penetrating Radar
Sensing device:	Ultra Wide Band GPR antenna
Dimensional constrains:	The underground equipment must be implemented in or behind the drilling head

Interface to drill head modem unit:	Ethernet connection, UDP protocol (4 wires)
Maximum power consumption:	< 2 A @ 12 V
Power supply voltage range:	10-15 V
Environmental:	all the electronic circuits will be potted to protect them against moisture. The radar control unit and the tilt sensor shall be housed in a water-proof enclosure.
Vibrations:	The unit must withstand the vibrations typically encountered during operations
Working temperature:	-10°C – 50°C
System minimum dynamic range:	40 dB
System clutter decay rate:	> 4dB/nsec

6 SUB-SYSTEMS TECHNICAL SPECIFICATIONS

6.1 ANTENNA

Technology:	Ultra Wide Band (UWB) dielectrically loaded dipole
Dimensions (radiating dipole) (LxW):	< 40x35 mm
Antenna bandwidth (-10 dB):	> 1 GHz
Antenna working centre frequency	≤ 2 GHz
Antenna position:	in front of the bore-head and/or on the drilling rod
Antenna dipoles orientation:	Parallel, broadside
Antenna directional capability:	side-looking and forward-looking
Antenna-3 dB beamwidth in E [1]plane:	< 90°
Antenna -3 dB beamwidth in H plane:	< 120°
Antenna impedance:	about 100 Ohm Ω
Dimensions of each radiating element (electronics included) (LxWxH):	<40x35x30 mm
Antenna protection	Dielectric window
Dielectric window relative permittivity	in the range 3 to 5
Dielectric window loss tangent	in the range 0.0001 to 0.001
Interface with other sub-system:	Wired to TX/RX electronics

[1] For a linearly-polarised antenna, this is the plane containing the electric field vector and the direction of maximum radiation. The electric field or "E" plane determines the polarization or orientation of the radio wave. For a planar dipole antenna, the E-plane coincides with the antenna plane. The H-plane is perpendicular to the E-Plane.

6.2 MICROWAVE SOURCE (TX)

Technology:	Surface Mounted Device (SMD)
Dimensions of TX board (LxW):	< 20x30 mm
....	
Pulse repetition frequency (PRF):	400 KHz
Pulse generation technique:	Avalanche transistor
Pulse rise time:	< 150 psec
Jitter (rms)	< 5 psec
Pulse amplitude (peak to peak, at the antenna feed point)	>50 V (measured over a 100 Ω impedance)
Power consumption:	< 1W
Interface with other sub-system:	2 Coaxial cables to the antenna timing circuit
....	1 Coaxial cable to the antenna

6.3 MICROWAVE RECEIVER (RX)

Technology:	Surface Mounted Device (SMD)
Dimensions of RX board (LxW):	< 20x30 mm
....	
RF Sampling frequency:	400 KHz
Sampling technique:	diode sampling gate
RF max input voltage:	0.2 V (peak)
Sampler aperture width:	< 400 psec
Bandwidth:	> 2.5 GHz
RF noise figure:	< 20 dB
Power consumption:	< 0.6 W
Interface with other sub-system:	4 Coaxial cables to the antenna timing circuit
....	1 Coaxial cable to the antenna

6.4 RADAR CONTROL BOARD

Max Dimensions of the whole board (LxW):	600x35 mm
Total power consumption:	<10 W
Mechanical:	Housed in a water-proof container equipped with vibration damping mechanism
Interface with other sub-systems:	Coaxial cables to TX/RX Ethernet link to the communication modem

Power supply: 2 wires

6.4.1 TIMING CIRCUIT

Technology of the timing circuit:	Digital generation of triggers by means of DDS (Direct Digital Synthesizer) circuits
PRF:	400 kHz
Range:	min. 20 ns
Number of connectable antennas:	max 2
Multiplexing:	Time Division

6.4.2 A/D CONVERTER AND DATA PROCESSOR

Sample per trace:	minimum 256
Audio sampling clock:	200 kHz
A/D sampling depth:	16 bit
Total scan rate (2 channels):	< 3 msec
Maximum throughput:	3 Mbit/s
Data Processor	Microcontroller with built-in memory for data indexing and interfacing with the tilt sensor

6.4.3 MODEM INTERFACE

Data interface:	TCP/IP Embedded Ethernet Controller
Data protocol:	UDP
Data buffer:	16 KByte

6.4.4 POWER SUPPLY

Technology:	DC/DC converter
Available power:	1A@5VDC, 250mA@+12VDC, 250mA@-12CDC, 40mA@150VDC

6.5 TILT ANGLE SENSOR

Maximum dimensions of the board (LxW):	70x35 mm (stand alone or integrated within the radar control board)
Mechanical:	Housed in a water-proof container equipped with vibration damping mechanism

Technology:........	Surface Mounted Device (SMD) with processing and communication capabilities. Sensing with high shock rejection capability
Power consumption:	< 2 W
Angular range:....	0° to 360°
Maximum angular rate:	1200 °/s
Maximum shock survivability:	> 300 g
A/D sampling resolution:	12 bit
Angular sampling period:	< 4 msec
Maximum throughput to Radar Control Board:	16 kbit/s

6.1 BORE-HEAD AND HOUSING

Outside diameter of GPR-housing:	<= 85 mm
Space for GPR-electronics (diameter):	<= 36 mm
Maximum torque:	6500 Nm
Length of GPR-housing:	< 600 mm
Maximum flow pressure:	> 100 bar