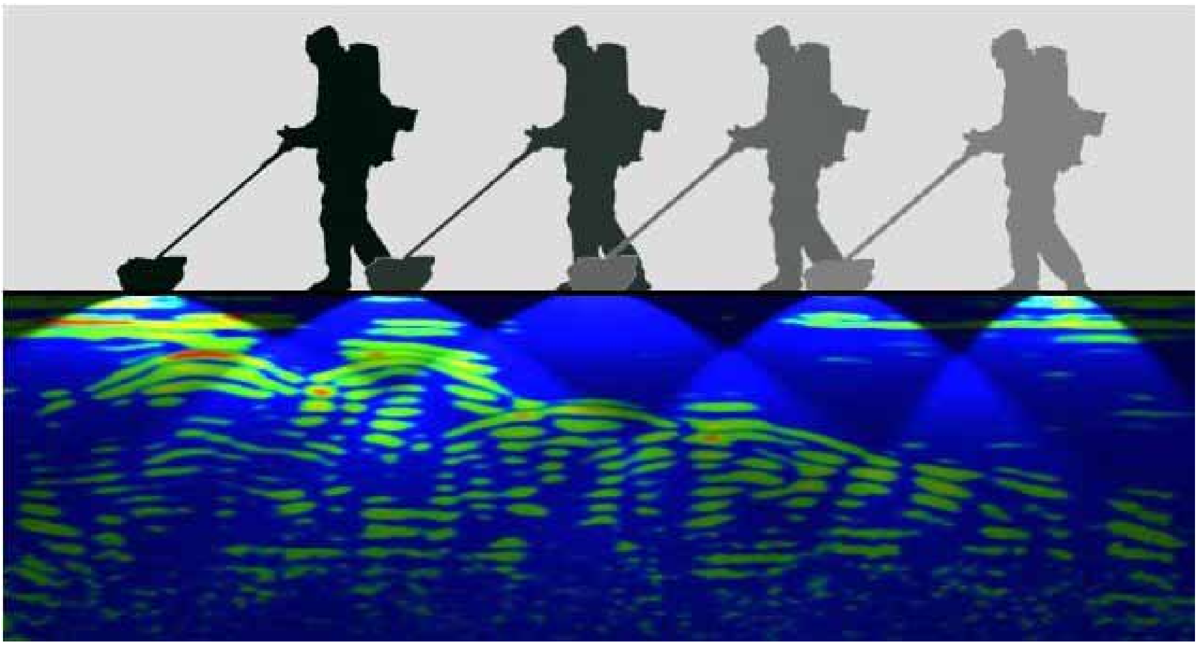
Optimised Radar to Find Every Utility in the Street



Surface GPR Radar Specification

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1 Introduction

1.1 Identification of the Contract

Contract name: ORFEUS

Customer and Contractors:
contract signed between the European Community, represented by the Commission of the European Communities, and

- OSYS Technology (UK), (OSYS)
- IDS INGEGNERIA DEI SISTEMI S.p.A (Italy), (IDS)
- GAZ DE FRANCE (France), (GdF)
- TRACTO-TECHNIK (Germany), (TT)
- UKWIR Ltd (United Kingdom), (UKWIR)
- EUROGAS-GERG (Belgium), (GERG).
- TECHNISCHE UNIVERSTIET DELFT, (TUD)
- UNIVERSITA DEGLI STUDI DI FIRENZE, (UNIFI)
- VYSOKE UCENI TECHNICKE V BRNE (BUT)

Contract number: FP6-2005-Global-4-036856
Contract signature date: 19-12-2006
Contract start date: 01-11-2006
Contract termination date: 31-10-2009

1.2 Purpose of the Contract

This project addresses the requirement for advanced technologies for locating, maintaining and rehabilitating buried infrastructures (area II.3.3). Specifically, it fulfils the requirement for locating buried assets. This project will use innovative techniques to provide a clear advance in the state-of-the-art in Surface Radar. It will also 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. This will require that new antenna designs be developed to provide a look-ahead capability and robust systems to be designed to protect against the hostile mechanical environment. In order to pursue these two objectives, an increased 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 is needed.

1.3 Purpose of this document

The ORFEUS project has three main objectives:

- Surface GPR: GPR for surveys carried out from the ground surface;
- Bore-Head GPR: GPR for surveys carried out from steerable bore-heads of Horizontal Directional Drilling;
- Ground Knowledge: knowledge of the electrical behaviour of the ground in order to improve antenna design.

The present document is intended to supply specifications for:

- synthesis of requirements;
- system and subsystem specifications;
- architecture draft;

relative to the first objective "Surface GPR" of the project.

The objectives "Borehead GPR" and "Ground Knowledge" are not considered here.

Inputs for the Surface GPR specifications will be derived from:

- Contractual requirements and constraints
- Surface GPR user requirements delivered by the ORFEUS end-user groups, and subsequent analysis of the performance requirements, reported in the following documents:
  - Document D4 - Surface GPR User Requirements;
  - Document D6 – Requirements summary for Surface GPR.

2 Reference documents

2.1 Documents written by the Customer

[1.1] ORFEUS CONTRACT : n° FP6-2005-Global-4-036856 signed on 19/12/06 and coming into effect on 1st November, 2006 between the European Community, represented by the Commission of the European Communities, and

- OSYS Technology LTD (United Kingdom), (OSYS)
- IDS INGEGNERIA DEI SISTEMI S.p.A. (Italy), (IDS)
- GAZ DE France (France), (GDF)
- TRACTO-TECHNIK (Germany), (TT)
- UKWIR Ltd (United Kingdom), (UKWIR)
- EUROGAS-GERG (Belgium), (GERG).
- TECHNISCHE UNIVERSTIET DELFT, (The Netherlands), (TUD)
- UNIVERSITÀ DEGLI STUDI DI FIRENZE, (UNIFI)
- VYSOKE UCENI TECHNICKE V BRNE (BUT)

2.2 Documents written by the contractors

[2.1] ORFEUS Proposal n° FP6-2005-Global-4-036856.
[2.2] ORFEUS Project, Annex I, Description of Work – Issue date: 16/10/2006.
[2.3] ORFEUS Project Consortium Agreement – Issue date: 23/10/2006

3 Executive Summary

This document reports the specifications for the development of the ORFEUS surface GPR.

The system *specifications* set the standard to which the final system design is required to perform; they came from the exhaustive and accurate analysis of all the requirements and set the ideal for the optimum performance of the system, given the current state of the technology.
Main system performance parameters are specified and a possible architecture identified; then, sub-system specifications and interfaces amongst the sub-systems are drawn.

The system specifications have been developed in order to minimise technological limits to the performance so that only physical limits due to the propagation of e.m. waves in the ground are relevant. In order to achieve this result a very innovative equipment design is proposed, strongly based on concepts of dynamic adaptivity to the ground characteristics and their change along the survey path.

Conclusions

This document constitutes the input for the development phase for the surface radar. A system architecture is proposed together with the description of main sub-systems and the specifications they will have to comply with.

4 Surface Radar System Specification

4.1 General

This chapter shows an outline of the system architecture and system specification for the surface GPR to be designed and developed in the ORFEUS project.
An important point is that the requirements include highly critical constraints, due to the need to detect smalls pipes buried in highly lossy soils. Namely, in order to assure 130dB dynamic range, no system characteristic should introduce a performance degradation through the whole dynamics. For instance thermal noise as well as phase noise, amplifiers linearity and synthesizer spurious contributions shall be kept low.

Moreover, external and physical limiting factors are present (as opposed to technological limits) which jointly decrease overall GPR detection performance:

- electromagnetic emission regulations impose an upper limit in GPR transmitted power;
- survey time constraints give an upper limit in energy impinging on and reflected by target;
- ground electromagnetic absorption gives an upper limit in received energy from target;
- ground properties variations in the bandwidth limit theoretical range resolution.

The design target is:

to minimise technological limitations and retain only external and physical ones.

It is clear that, in order to have a final performing prototype, a trade-off between some design choices and some other system performance must be considered.
An effective reasonable attempt of architecture scheme and modules specifications follows.

4.2 System Architecture and Composition

System architecture, composition and connections are shown in Fig. 4-1. The ORFEUS Surface GPR will be divided in four Subsystems:

- LOG SUBSYSTEM - Surface GPR Data Logger
- CON SUBSYSTEM - Acquisition, Frequency-Time Conversion & Adaptivity Control
- SEN SUBSYSTEM - Adaptive Stepped Frequency Sensor
- ANT SUBSYSTEM - Adaptive UWB Antenna
- 1 accessory survey wheel

Main connections between subsystems will be:

- USB/Ethernet
- Analogue Sensor Data
- RF cables
- Sensor Timings
- Real Time Sensor Adaptivity Control
- Off Line Sensor Parameters Control
- Off Line Antenna Adaptivity Control
- Survey Wheel position cable

Minor components and connections are not displayed but, for on site test purposes, the equipment will be provided with:

- an autonomous power source (battery pack):
- a mechanical support that will allow:
  - an efficient scan of the antenna on the ground
  - a suitable accommodation of subsystems

The system will be directed only toward the demonstration of challenging GPR performance. It will not be rated by IP levels, for protection against water, dust or mechanical vibrations. These aspects, as well as cables connections, power absorption, weight and cost, will be faced in a following stage (design to market) in which the product will be developed.

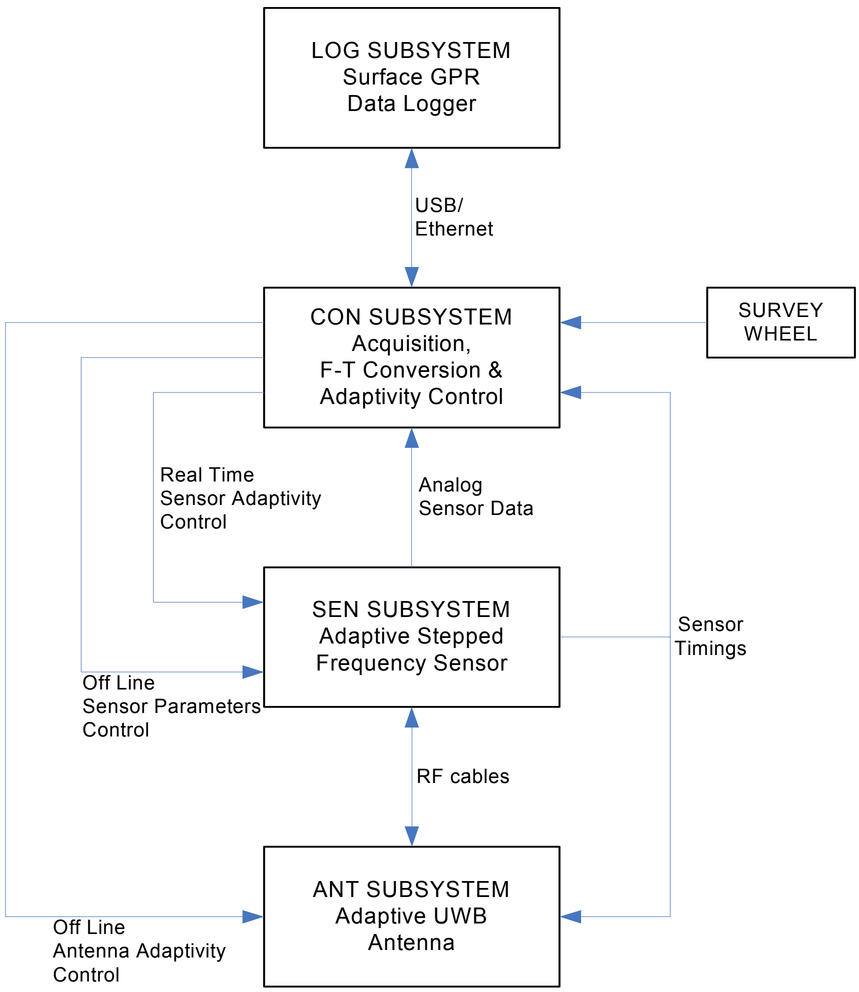

Fig. 4-1: System architecture of the surface GPR

4.3 System main specification

4.3.1 General

a) System Main Objectives

System mission: To detect and localize buried structures in ground by a surface survey. Accuracy and reliability in detection and location of buried utilities up to 1.5m in highly attenuating soils is needed.

b) System main technologies

System technology: Stepped Frequency Continuous Wave GPR.
Sensing device: Ultra Wide Band GPR antenna.
System main composition: LOG Subsystem: Surface GPR Data Logger
CON Subsystem: Acquisition, F-T Conversion & Adaptivity Control
SEN Subsystem: Adaptive Stepped Frequency Sensor
ANT Subsystem: Adaptive UWB Antenna
Survey wheel
Survey output: Real-time B-scan visualization of underground range profiles.

c) Unaddressed objectives

The system will be directed only toward the demonstration of challenging GPR performance, so the following aspects will be neglected in the prototyping stage and will be faced in a following one (design to market) in which the product will be developed:

- Cost-effectiveness: Cost-effective technologies will be used, but the prototype will not be influenced by this constraint
- Power absorption: The prototype will not be optimised for extensive continuative surveys
- CE certification: It will not be pursued.
- Environmental: No protection against dust, water and high or low temperatures will be certified
- Mechanical: No protection against shock and vibrations

4.3.2 Performance

The system specifications list, by which contractual requirements can be achieved, is:

SP SYS1 Penetration depth: 1.5m in ground with 50dB/m two way attenuation (increased by 50% with respect to pulse GPR technology)
SP SYS2 System minimum dynamic range: 130 dB
SP SYS3 System clutter decay rate: > 10dB/nsec
SP SYS4 Detection rate:~90% with a ~90% confidence level
SP SYS5 Spatial resolution: Nominal 17cm
SP SYS6 Adaptivity: Antenna and Sensor adaptivity to ground

4.3.2.1 Rationale

The system composition will be:

- LOG Subsystem - Surface GPR Data Logger
- CON Subsystem - Acquisition, Frequency-Time Conversion & Adaptivity Control
- SEN Subsystem - Adaptive Stepped Frequency Sensor
- ANT Subsystem - Adaptive UWB Antenna
- Plus 1 accessory survey wheel

The SEN Subsystem will be responsible for signal synthesis, transmission and reception and will be connected to the ANT Subsystem which will couple GPR to ground. A survey wheel (packed up within or near ANT Subsystem) will provide CON Subsystem with information about the position of the survey. CON Subsystem will carry out three distinct duties:

- it will provide ANT and SEN Subsystems with adaptivity control signals
- it will digitize video I/Q analogue signals from the Sensor Unit
- it will perform the frequency-time conversion on acquired data, making them available to the LOG Subsystem.

The LOG Subsystem will consist of a Man/Machine interface by which the end user will be capable to set-up GPR acquisition parameters and visualize survey processed information in a suitable way.

As stated in the ORFEUS proposal document, the main system objective is to provide an improved performance compared to commercial pulsed GPRs. For this reason, SFCW design and development will be oriented toward the achievement of this objective, which in turn will assure a successful GPR, useful and suitable for a subsequent marketing.

4.4 Sub-systems specification - Surface GPR Data Logger

4.4.1 LOG Description

The Data Logger (LOG Subsystem) will implement the following services:

- Man Machine Interface (MMI)
  - Control: the user will be able to select an acquisition or survey type from a graphical user interface. The LOG subsystem will provide the other subsystems with the parameters corresponding to the chosen survey type.
  - Display: The LOG subsystem will display acquired and processed data, matching signal dynamics with man sight dynamics.
- Data Storage: The LOG subsystem shall save acquired raw or processed data, for further analysis.
- Data Processing: The LOG subsystem will execute data processing algorithms (filtering, background removal, gain function, horizontal filtering, etc.) to permit suitable data display.

The LOG subsystem objective is to implement the MMI and to process data in exactly the same way as a commercial pulsed GPR does.
While performance enhancement comes from data acquired by the sensor and the antenna, the usefulness of the LOG is to enable comparison between pulsed GPR and SFCW GPR, in order to estimate performance enhancement. For this reason processing and display techniques will be derived from IDS products, so a direct comparison shall be carried out.

The LOG subsystem will be operative on a laptop computer, suitable for GPR data rates and processing speeds. A solution derived from the IDS GPR product line would be preferable, in order to optimise on-site comparison between SFCW and pulsed GPRs.

4.4.2 LOG Specifications

SP LOG1 MMI – Control: The following acquisition modes will be available:

- Sensor Bias Calibration
- Sensor Gain Calibration
- ABC Calibration
- Antenna Calibration
- Survey Acquisition, with the following parameters:
  - Frequency Bandwidth
  - Frequency Step
  - Pulse Repetition Frequency
  - Survey Wheel Sampling
  - Antenna Configuration

SP LOG2 MMI – Display:

- B-scan

SP LOG3 Data storage: It will be possible to save to disc both survey acquisition data and calibration data, in IDS GPR derived formats.

SP LOG4 Data processing: Available algorithms:

- Space equalisation
- Horizontal filtering
- Vertical filtering
- Background removal
- Dynamic equalisation
- Power
- Dynamic range estimation

SP LOG5 Interfaces: The LOG and the CON subsystems will be linked by USB or Ethernet interface. A serial interface with the following 3 subsystems will also be available for debug purposes.

- CON (Acquisition, F-T Conversion & Adaptivity Control)
- SEN (Adaptive Stepped Frequency Sensor)
- ANT (Adaptive UWB Antenna)

4.5 Sub-systems specification - Acquisition, F-T Conversion & Adaptivity Control

4.5.1 CON Description

The Acquisition, F-T Conversion & Adaptivity Control (CON Subsystem) will carry out the following operations:

- Analogue to digital Conversion
  The CON subsystem will carry out the analogue to digital conversion, making GPR data available for the LOG subsystem. Data will be acquired in frequency domain, I/Q format, i.e. In-Phase and Quadrature samples will be acquired for each frequency tone. Intermediate frequency sampling (as alternative to baseband sampling) can be used, thus reducing analogue sampling channels from two to just one.
  Both signal amplitude and phase must be acquired with high accuracy, so, in order to achieve a system dynamic range of 130dB, digital dynamics will be raised from a 16bit precision A/D converter (typical for commercial GPR pulsed systems) to a 24bit precision A/D converter.
  An SFCW radar has a larger set of data types to manage compared to a standard pulsed GPR.
  In particular, the CON subsystem will acquire:
  - Sensor Bias Calibration Data on each frequency
  - Sensor Gain Calibration Data on each frequency (i.e. system Transfer Function)
  - ABC Calibration Data on each frequency (i.e. ABC vectorial response)
  - Antenna Calibration Data on each frequency (S11 and/or S21 parameters)
  - Survey Acquisition Data on each frequency

- F-T Conversion
  The CON subsystem will carry out frequency to time conversion, in order to supply the LOG subsystem with time-domain GPR data, homologous to commercial pulsed GPR data but with higher accuracy. Frequency – time conversion consists of:
  - Survey Acquisition Data correction using Calibration Data
  - Windowing and subsequent inverse Fast Fourier Transform for the actual conversion.

- Antenna Adaptivity Control
  The Con subsystem will manage antenna adaptivity in the following two ways:
  - S11 parameter comparison.
    The S11 parameter is an indicator of the fraction of power which the transmitter effectively channels through the antenna. If, through antenna analysis, simulation and measurement, the antenna efficiency is known, an indirect esteem of the power radiated through the ground can be derived from S_{11}, also depending on the antenna configuration.
  - Survey Data analysis
    Depending on the antenna configuration, antenna coupling parameters change together with energy radiated into the ground, which can be evaluated, so best antenna configuration can be chosen. Many factors have to be considered (such as antenna beam width, Tx/Rx coupling) but two main effects can be identified:
    - Energy reflected corresponding to the same range bin, from two different configurations, and
    - The depth corresponding to the transition of reflected signal beneath system noise level.

    The best configuration can be chosen, on the basis of such principles.

- ABC control
  The CON subsystem will be able to control ABC in two ways:
  - ABC Calibration: The receiver will be switched off, ABC will be properly activated and Calibration Data collected, on each frequency.
  - Survey ABC Activation: In a Survey Acquisition, the CON subsystem will evaluate ABC control parameters from acquired data to let ABC signal follow ground unevenness.

- Space equalisation
  It will be possible to acquire data in the following ways:
  - without equalization
  - equalization with decimation: acquisition of a single scan for each DX (where DX is the survey resolution chosen for the wheel; typical values are 0.5 scan/cm 1 scan/cm or 2 scan/cm)
  - equalization with average: average of each scan acquired within 1 DX

4.5.2 CON Specifications

SP CON1 Analogue to Digital Conversion:
Number of channels: 2
Sampling Frequency: ≥40KSps per channel
Sampling depth: 24bit
Dynamic Range: ≥100dB

SP CON2 Frequency-Time Conversion:
Conversion Speed: Real Time
IFFT Repetition Frequency: 200 complex ifft/s (IQ)
Samples per IFFT: ~200 samples/ifft
Samples depth: 24bit

SP CON3 Antenna adaptivity control:
Control Speed: Offline
Control phases:
i. Calibration – Each configuration is measured
ii. Selection – The best configuration is selected
iii. Acquisition – Survey Data are acquired

SP CON4 ABC adaptivity control:
Control Speed: Run Time
Data rate: ≥40KSps

SP CON5 Space equalisation:
Equalisation speed: Real time
Equalization Types:
1. with decimation
2. with averages

SP CON6 Interfaces: The CON and the LOG subsystems will be linked by USB or Ethernet interface. The CON and the SEN subsystems will be linked by two analogue IQ lines which will carry the GPR signals to be acquired, one analogue line which will control the ABC in the sensor and some digital lines which will supply the CON and the ANT with timing signals. A serial interface will link CON with ANT subsystem.

- CON (Acquisition, F-T Conversion & Adaptivity Control)
- SEN (Adaptive Stepped Frequency Sensor)
- ANT (Adaptive UWB Antenna)
-

4.6 Sub-systems specification - Adaptive Stepped Frequency Sensor

4.6.1 SEN Description

The Adaptive Stepped Frequency Sensor (SEN subsystem) will carry out the following operations:

- Frequency Synthesis: SF waveform generation, with high frequency accuracy and stability to permit the dynamics and resolution needed for the GPR and with suitable speed for an adequate survey velocity.
- Transmission: Linear and flat signal amplification in whole bandwidth.
- Reception: High linearity and low Noise Figure, in order to allow project requirements fulfilment.
- Calibration: a calibration channel will allow bias and transfer function calibration of the system across the whole bandwidth, in order to optimise system resolution.
- ABC: analogue dynamic improvement system.
- S_{11} Measurement: for antenna configuration performance estimate

ORFEUS Surface GPR main objectives are to provide a “step change” in both penetration depth and spatial resolution of the survey, with respect to the state-of-the-art pulsed GPR. The SEN subsystem specifications which contribute the most to the aforementioned objectives are respectively:

- Penetration Depth
    - Rx analogue linearity (characterises the upper limit of Dynamic Range)
    - ABC accuracy (characterises the upper limit of Dynamic Range)
    - Rx Noise Figure (characterises the lower limit of Dynamic Range)
    - ABC Noise Figure (characterises the lower limit of Dynamic Range)
    - Waveform phase noise
    - Waveform generation speed
    - Sampling stability
- Spatial Resolution
    - Waveform frequency accuracy
    - Harmonics and spurs contribution

Analogue flatness in RF and Video bandwidth

4.6.2 SEN Specifications

SP SEN1 Sensor type: Stepped Frequency Continuous Wave

SP SEN2 Synthesizer technology: PLL + DDS

- Bandwidth: 100MHz÷1000MHz
- Frequency Step: in the range 5÷10MHz
- Maximum number of frequency steps in scan: >100
- Pulse repetition frequency (PRF): >20 KHz
- Scan repetition frequency (SRF): ~200 Hz

SP SEN3 Transmitter:
- Transmitted power: ~100mW

SP SEN4 Receiver:
- Receiver technique: Heterodyne
- Receiver channels: I & Q
- Noise Figure: < 20 dB
- Receiver bandwidth: 100MHz÷1000MHz
- Analogue dynamic range: ≥100dB

SP SEN5 Calibration path: Alternative path to and from antennas.
- Path Bandwidth: Flat in amplitude and linear in phase over 100MHz÷1000MHz
- Path isolation: ≥40dB

SP SEN6 ABC:
DAC depth: 24bit
DAC dynamic range: ≥100dB
DAC data rate: ≥20KSps

SP SEN7 S_{11} Parameter Measurement path: Amplitude Measurement
- Measurement range: -20dB < $|S_{11}|$< 0dB

SP LOG6 Interfaces: The CON and the SEN subsystems will be linked by two analogue IQ lines which will carry the GPR signals to be acquired, one analogue line which will control the ABC in the sensor and some digital lines which will supply the CON and the ANT with timing signals.
- CON (Acquisition, F-T Conversion & Adaptivity Control)
- SEN (Adaptive Stepped Frequency Sensor)
- ANT (Adaptive UWB Antenna)

4.7 Sub-systems specification - Adaptive UWB Antenna

4.7.1 ANT Description

- *Adaptivity to ground characteristics*
  The antenna unit will be responsible for coupling between the radar front-end (Tx & Rx) and the ground. In the bandwidth of interest, the antenna unit should provide a flat response, i.e. a series of parameters should be fairly constant from 100MHz up to 1000MHz. If an antenna characteristic varies strongly with bandwidth, this will provoke a greater degree of system performance degradation. For instance non-flat antenna beam width, gain or return loss could affect both GPR resolution and detection sensitivity.

- *Antenna features flatness in bandwidth (beam width, gain, return loss)*
  Moreover, in order to maximise the detection probability of the system, the antenna unit should adapt its characteristics to the type of ground present in each circumstance. The antenna will have from a minimum of 4 up to a maximum of 9 configurations, each with different characteristics. The basic principle which will be used for this kind of adaptivity will be that of optimising S11 (reflection) and S21 (transmission) parameters of the antenna.

These parameters can be measured by the GPR itself on the survey site, so the best antenna configuration can be chosen, depending on soil type and antenna measured parameters.

- *Sub-bands*
  Under certain circumstances, it could be useful to work on a sub-band of the system (for instance when the survey focuses on deep pipes, and shallow depths can be ignored). In this case, S parameters can be chosen optimising antenna performance for just the selected sub-band, thus enhancing the adaptivity of the system.

- *Balun*
  A key component in the antenna unit is the Balun, which carries out signal transformation from unbalanced to balanced and vice versa. A Balun will be present at the inputs of both Tx and Rx antennas and it will inevitably affect antenna characteristics. A flatness of Balun characteristics in the whole bandwidth is needed to avoid a reduction in antenna performance.
  Other technologies are available, beside the Balun, in order to perform the balanced/unbalanced transformation from antennas to sensor. It will be chosen the solution which fits better with the ORFEUS requirements.

4.7.2 ANT Specifications

Antenna design is characterised by and high degree of innovation. A study is ongoing in order to define achievable objectives and technical solutions. Therefore the following antenna specifications must be considered preliminary and non complete.

SP ANT1 Technology: Ultra Wide Band RC loaded bow-tie with MEMS

SP ANT2 Desirable Dimensions (radiating dipole): < 80x40x40 cm

SP ANT3 Antenna bandwidth (-10 dB):>100MHz ÷ 1000MHz

SP ANT4 Antenna dipoles orientation: Parallel, broadside

SP ANT5 Antenna-3 dB beam width in E plane: ~80°

SP ANT6 Antenna -3 dB beam width in H plane: ~80°

SP ANT7 Coupling between Tx / Rx antennas: ~-25dB

SP ANT8 Antenna impedance: 50÷200Ohm

SP ANT9 Interfaces:
- 2 RF Coaxial cables (Tx/Rx) Vs. SEN
- 1 Serial I/O line Vs. CON