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# Multi-fold Ground Penetrating Radar Imaging and Classification of Buried Targets for Environmental Applications

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## Abstract

We use an integration of Single Fold (SF), Multi fold (MF), i.e. multi offset, Multi Azimuth (MA) and Multi Component (MC) or Polarimetric Ground Penetrating Radar (GPR) configurations to identify, characterize and classify targets of environmental interest. The results obtained in real and controlled conditions are validated by numerical simulations and excavation and show that MF/MA/MC GPR methods are fit for target classification in complex subsurface conditions.

## Introduction

Ultra High Resolution (UHR) geophysical techniques are often used to study waste disposal sites, polluted areas, pipe leakages and brownfields in support of traditional invasive characterization methods based on sampling. Geophysical techniques provide information about physical properties of areas and volumes. This is their main advantage when compared with traditional invasive methods (TIM). TIM exploit chemical and physical analysis of samples obtained at the surface, or in boreholes and trenches, to provide information from single points in the area of study. Geophysical techniques can determine the characteristics of several physical properties over a grid, thus extending the areal significance of the TIM calibration. Ground Penetrating Radar techniques are well suited for site characterization in terms of vertical and horizontal resolution, depth of investigation and target identification capability. We tested GPR in several different environmental conditions and with different acquisition and analysis procedures. GPR is normally used only in Single Fold (SF) configuration, i.e. single offset. In this paper we use an integration of Multi Fold (MF), i.e. multi offset, Multi Azimuth (MA) and Multi Component (MC) or Polarimetric configurations for different environmental applications. In particular, we focus on the following common situations: 1) pipe localization, internal fluid characterization and pipe leakage detection; 2) waste disposal characterization; 3) industrial plant analysis.

## Methods

We used an ultra-wide band (UWB) Ground Penetrating Radar (Malå Geoscience) equipped with shielded and unshielded antennas in the range of 200-800 MHz. We performed single offset acquisition (SF) and multiple common-offset-data acquisition to obtain Multi-Fold sections with average 1200 % fold. The range of offset was usually between 40-200cm, according to the frequency of the used antennas. The offset increment step was 5cm for 500 and 800 MHz antennas and 10cm for 200 and 250 MHz antennas. We exploited also Multi Azimuth and multi offset acquisition and analysis at single surface positions to obtain more traces related with the same depth point. The offset for this kind of analysis was in the range of 40-70cm and the angular step increment was 10°. As for Multi Component acquisition, we performed multi offset and multi azimuth acquisitions at selected locations using co-pole and cross-pole antennas configurations.

We obtained several GPR datasets in the field and in a sandbox that is used as test site for experiments in controlled conditions. In the latter case we used a 2x2x1m box with homogeneous sand inside. We put plastic and metal pipes of different diameters in the sandbox and we filled them with air or fluids (fresh water, sea water, oil, gasoline). We also simulated a pipe leakage through the controlled injection of fluids in a cleft pipe. We validated GPR results by means of numerical simulations performed with a finite-difference time domain (FDTD) modeling algorithm.

We paid particular attention to preserve amplitude information and to define real position and shape of targets during data processing. On such purpose, we used true amplitude processing algorithms and avoided use of any time or space balancing. We tested different imaging solutions, including post/pre-stack time and post/pre-stack depth migration.

The velocity field was calculated using diffraction hyperbolas or semblance velocity analysis when planar reflectors were available. A further improvement in velocity-based material characterization can be achieved through velocity-depth macro-model reconstruction by means of layer-stripping or tomographic techniques. We use a combination of Deregowski and focusing techniques for the optimization of the macro-model and the related estimate of dielectric permittivity from radar wave velocities. These parameters were used in the synthetic model. 2D and pseudo 3D GPR data interpretation were done with the help of information deriving from other geophysical methods (resistivity and magnetometry) or from direct analysis (borehole stratigraphy and granulometric analyses).

## Results and discussion

The first GPR experiment in controlled conditions is based on the study of a plastic pipe (diameter 10 cm) buried in the sandbox at a depth of 30 cm and filled with different fluids (air, fresh water, salt water with different salinity, oil and gasoline). We then simulate a gasoline leakage that produces a saturated lens beneath the pipe. We use 800 MHz antennas with different offsets and configurations for data acquisition. Figure 1 shows a synthesis of results obtained in single offset mode with antennas TE axes perpendicular (1) and parallel (2) to the pipe.

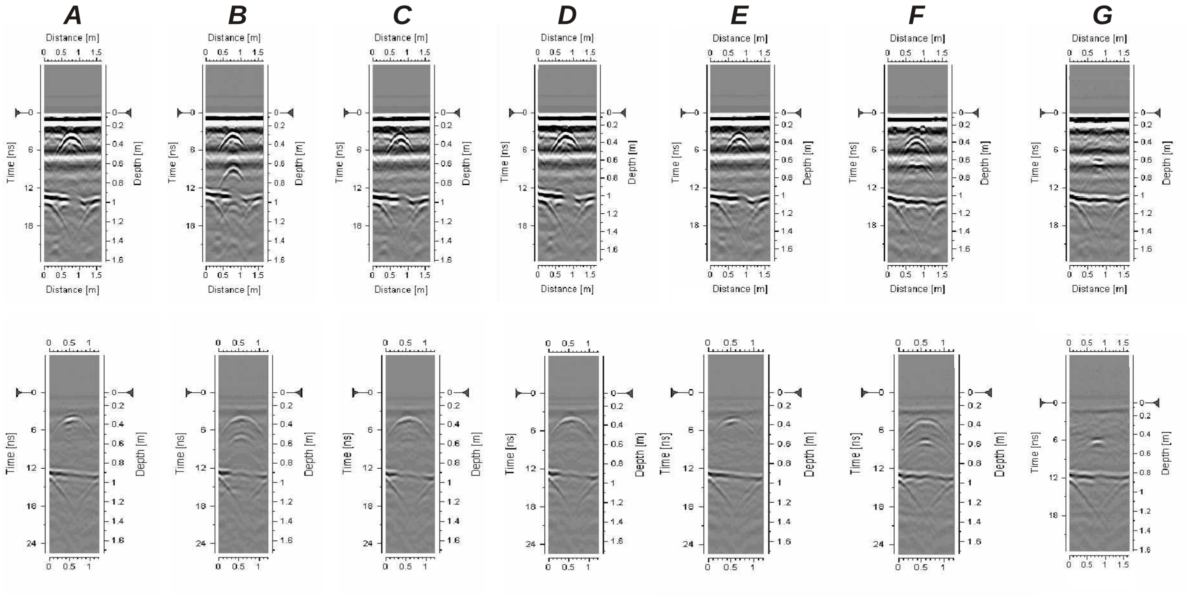

**Figure 1**. 800 MHz GPR profiles obtained with TE antennas axes perpendicular (1) and parallel (2) to a plastic pipe filled with: air (A), distilled water (B), salt water with 17g/l (C) and 35 g/l (D) of sodium chloride and gasoline (E). (F) shows the gasoline filled pipe with a lens saturated by the same fluid beneath the pipe, (G) shows only the saturated lens. See text for details.

The TE perpendicular configuration always shows amplitude greater than the TE parallel configuration, but the coherent noise is lower in the latter configuration. The strong reflector located at 13-14 ns (about 95 cm depth) represents the metallic base of the sandbox. In such conditions, a leakage can be easily detected, also without the pollution source (Fig. 1G). Pipe content cannot be characterized by using only single offset sections. Polarimetric multi offset and multi azimuth data allow a better definition and classification of pipe content. The graphs in Figure 2 show the amplitude of the diffraction from the top of the pipe as a function of azimuth for different antennas configurations and fluid contents. (A, B, C) and (D, E, F) are in co-pole and cross-pole antenna configuration respectively. A and D represent the air filled plastic pipe, B and E fresh water filled plastic pipe, C and F a metallic pipe with the same dimensions. The minimum amplitude, in the case of a dielectric fluid and co-pole antennas, occurs in TM configuration (90° in the graph). We observe the opposite in the case of conductors (B and C). The cross-pole antenna configuration shows a more complex behavior. In such a case air and water filled pipes show a similar trend, while the metallic pipe is remarkably different.

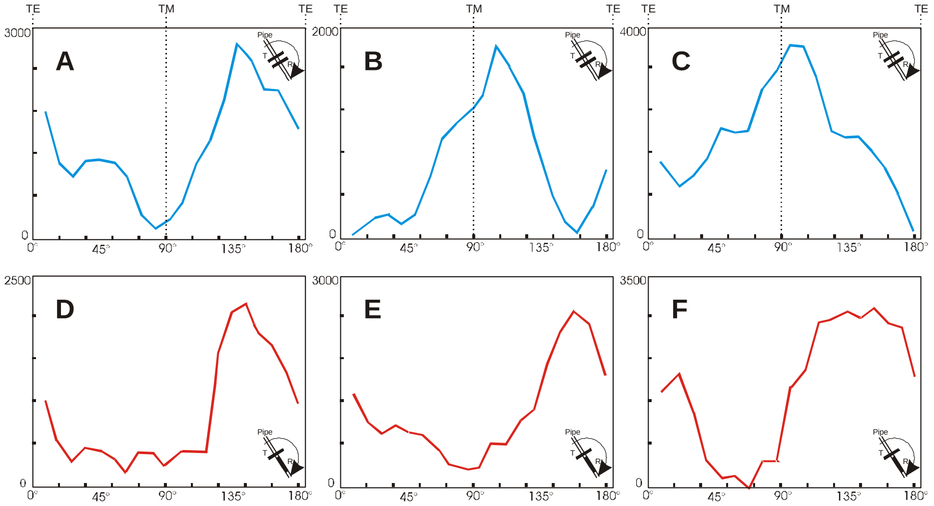

**Figure 2.** Amplitude vs. Azimuth analysis for different 800 MHz antenna configurations and pipe material and filling. A, B, C co-pole antennas; D, E, F, Cross-pole antennas. A, D air filled plastic pipe; B, E fresh water filled plastic pipe; C, F metallic pipe. In co-pole cases azimuth 0° represents TE broad side geometry; in cross-pole cases azimuth 0° represents the receiving antenna (R) parallel to the pipe.

This type of analysis allows to identify and localize the pipe and the leakage, but also to evaluate fluid characteristics. This procedure was validated by experiments in real conditions. Some problems occur with partially filled pipes, with mixed fluids or in very noisy environments.

In larger areas, without linear targets as pipes, the GPR approach is different. Waste disposal are a typical complex environment from the geophysical point of view, with vertical and lateral variations of physical properties. The same situation often occurs in industrial plants or brownfields. In these cases the main issue is not target localization, but the identification and definition of homogeneous zones. The definition of areas characterized by peculiar geophysical response is a very important task in terms of site analysis and management.

We tested a semi quantitative approach to determine homogeneous zones based on GPR and other geophysical datasets. Figure 3 shows an example obtained in a mixed urban and industrial waste disposal. The main problem was the localization of industrial ashes in a very large area. We performed a complete geophysical investigation on a 80x12m grid. We processed and analyzed the whole GPR dataset calculating also the instantaneous attributes of the signal by means of Wavelet Transform techniques, which provide enhanced results in noisy environments. We then performed an unsupervised classification of areas based on signal amplitude and instantaneous attribute characteristics. Localized and metal targets as well as GPR extended reflectors were interpreted and classified by the operator. The detailed velocity model definition was based on MF data analysis and direct borehole measures. We calculated dielectric permittivity and soil conductivity from such information. Depth, velocity and electromagnetic properties experimentally obtained were the input for numerical simulation by means of a finite-difference time domain (FDTD) modeling algorithm. Synthetic results and direct excavations confirm the geophysical interpretation. We obtain several homogeneous areas from GPR data analysis (Fig. 3 A, B, C, D and E). Figure 3 F shows the synthesis of results and the environmental interpretation: zones marked with “Mx” represent mixed zones with ashes, urban waste and debris; “As” zones are characterized by predominant amounts of industrial ashes. We tested different imaging solutions, including post/pre-stack time and post/pre-stack depth migration, on a GPR dataset obtained at an oil storage and refinery plant. Figure 4 shows a comparison between a multifold stack section (A) and the corresponding pre-stack time converted depth migration (B). Velocity optimized macro-model reconstruction was obtained by a recursive combination of Deregowski and focusing techniques. From this example we can notice that pre-stack migration algorithm allows a very good definition of complex targets such for example the well identified trench of figure 4 B.

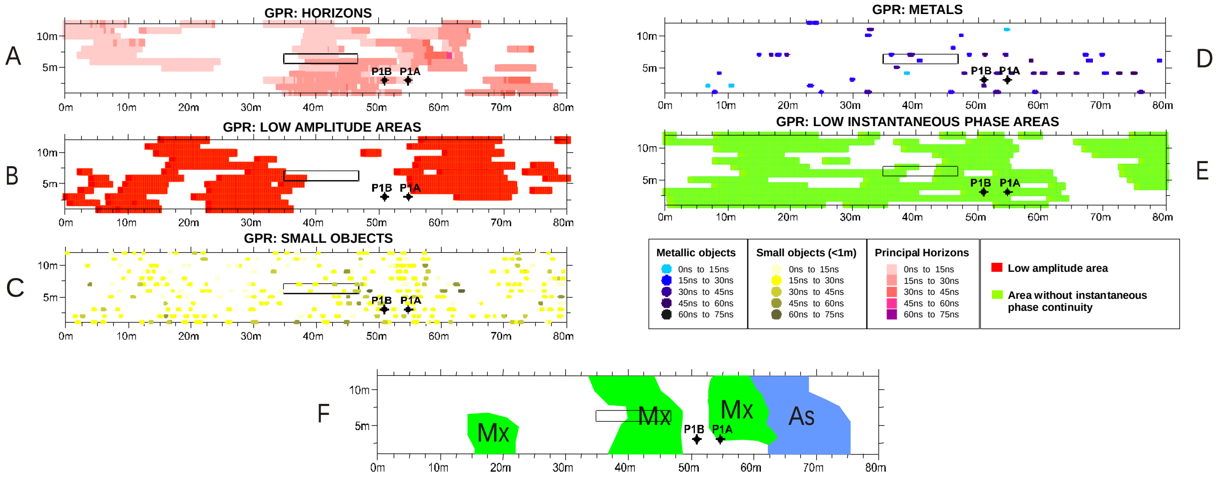

**Figure 3.** Homogeneous GPR zones (A, B, C, D, E) and interpretation of results of a mixed waste disposal (F). "Mx" indicates mixed zones with industrial ashes, urban wastes and debris; "As" indicates zones with predominant industrial ashes content. See text for details.

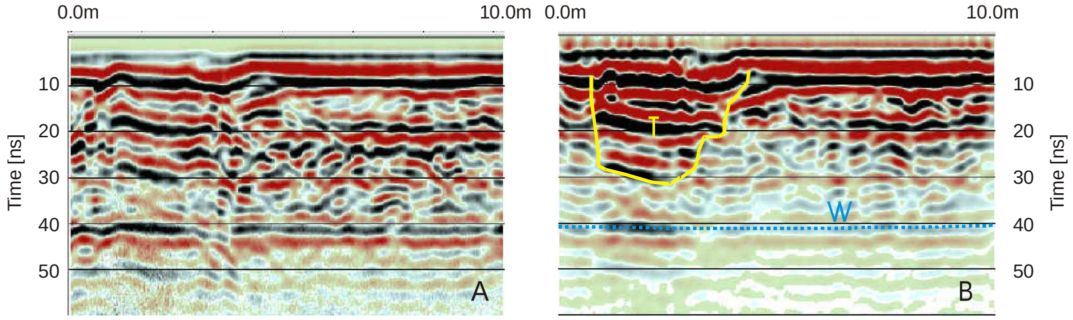

**Figure 4.** Example of 250 MHz stack section (A) and pre-stack time converted depth migration (B). In (B) the definition of lateral and lower limit of the trench "T" is better imaged than in (A). "W" indicates the water table position.

## Conclusions

We tested Single Fold (SF), Multi-Fold, Multi-Azimuth and Multi-Component (MFAC) GPR methods in controlled conditions (sandbox) and at different sites of environmental interest with different targets and background characteristics. The results show that processing and analysis of MFAC data allows enhanced discrimination of volumes characterized by homogeneous radar response also in conditions where conventional single-fold techniques fail to provide exploitable information. In most cases, amplitude variations with offset and azimuth demonstrate to be highly sensitive to subsurface physical properties variations and provide a robust tool for target classification. Finite-difference time domain (FDTD) modeling and pre-stack time and depth migration algorithms are often very useful and allow a more accurate interpretation and geophysical target localization.

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