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Discrete Wavelet Transform to reduce surface scattering in GPR sections

Dora Francesca Barbolla[1*], Lara De Giorgi[1], Giovanni Leucci [1]

[1] *National Research Council –Institute of Heritage Science, Lecce, e-mail: dora.barbolla@ispc.cnr.it, lara.degiorgi@cnr.it , giovanni.leucci@cnr.it.*
**Corresponding author, e-mail: dora.barbolla@ispc.cnr.it*

***Abstract* – Ground-penetrating radar (GPR) is often a fundamental tool for cultural heritage preservation. However, under some conditions, coherent noise can occur in the radargram interfering with the useful signal. Reflections from above-surface objects, such as walls or vaults, and buildings, could be recorded in the radar sections and could hide subsurface reflections linked to the structures of interest. The problem of surface scattering can be addressed by using the Discrete Wavelet Transform analysis which decomposes the signal allowing the recognition of different anomalies coming from different targets.**

I. INTRODUCTION

Ground Penetrating Radar (GPR) is one of the most used geophysical methods for the exploration of the shallow subsurface, archaeological applications, and cultural heritage preservation. The GPR method allows the detection of electromagnetic discontinuities present in the investigated materials. Especially in the archaeological field, such discontinuities are mainly due to lithological changes, variations in the water content, fractures systems, or empty spaces present in the ground, such as tombs, and tunnels having different electromagnetic properties with respect to the surrounding environment [1]. The discontinuities that generate electromagnetic wave reflections are linked to changes in the dielectric properties of the investigated volume. GPR data are subjected to digital data processing, interpretation, and visualization techniques to emphasize significant anomalies in the raw data and understand their three-dimensional relationships.
In several geophysical techniques, there is the common practice to sum together data acquired with the same constant parameters in the same position. On GPR data this operation is obtained by acquiring more than one trace for each profile location, recording then just the mean trace for each position. [2]. This process can reduce random or incoherent noises while emphasizing the signal content and also the coherent noises present in the signals. In fact, under some conditions, coherent noise can occur in the radargrams interfering with the useful signal. The most relevant components of coherent noises are related to ringing phenomena and to undesired reflections (surface scattering).
Reflections or diffractions from above-surface objects, such as trees, power lines, fences, and buildings, could be recorded in the radar sections and could hide subsurface reflections. In fact, due to the much higher electromagnetic wave velocity in the air than in the ground, the reflections from the objects above the surface could be present in the time window of interest [3].
The problem of surface scattering is not negligible because it can severely degrade the visibility of interesting reflections or even, if not recognized, can be the cause of interpretation pitfalls.
The interpretation of radar data acquired inside buildings, where many important elements are above the surface, such as columns, statues, the ceiling, or the roof, could be very difficult. All those elements above the surface could create ambiguous anomalies.
In this work, we focus on how to reduce this type of noise through the application of the wavelet transform (WT).
Wavelet transform analysis was previously developed for seismic signal analysis (e.g., [4]), and then widely applied to many scientific disciplines: [5] introduced the discrete wavelet transform (DWT) to separate the regional and local contributions to the measured magnetic and gravity anomaly fields; [6] introduced the continuous wavelet transform (CWT) for potential fields using wavelets derived from the Poisson kernel; [7], recently introduced the CWT for the analysis of direct current resistivity data.
In particular, in this work, we simulate an acquisition under a sloping roof 3-5 meters above the surface to calculate how it interferes with the signal due to the target of the survey, a void 1-3 m deep. We simplify the model by considering the roof as a semi-horizontal body.

II. WAVELET TRANSFORM METHOD

The WT is a useful tool for the analysis of non-stationary signals such as the GPR signals: it is well-suited for filtering signals whose frequency content varies with time.

The CWT of $f(x) \in L^2(\mathbb{R})$ is defined as [8]

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(x)\, \tilde{\psi}\left(\frac{b-x}{a}\right) dx \qquad (1)$$

where $W(a,b)$ is the wavelet transform, ψ is the analyzing wavelet, *a* is the scale (or dilation), *b* is the position parameter, $\tilde{\psi}$ is the complex conjugate of ψ, and $L^2(\mathbb{R})$ denotes the Hilbert space of square-integrable functions. $\tilde{\psi}\left(\frac{b-x}{a}\right)$ is obtained by translating and dilating the mother wavelet ψ, according to the two parameters *a* and *b*, respectively.

In this work, we use DWT. The main difference between CWT (equation 1) and DWT is that for the CWT, the scaling and shifting factors *a* and *b* can have all possible values in ℝ, while, for the DWT, the scaling and shifting factors can only have power of two values [9]:

$$a = 2^j$$

$$b = ka$$

where *j* is the level at which the DWT is performed and $k \in \mathbb{Z}$.

The coefficients of the DWT are devided into two groups: the approximation coefficients, which are the high scale, low-frequency components of the signal f(x) and the detail coefficients which are the low scale, high-frequency components.

The DWT approximation coefficients of the signal *f(x)* at level *j* are expressed as follows:

$$A_j = \sum_{n=0}^{\infty} f(n)\phi_{j,k}(n) \qquad (2)$$

where is $\phi_{j,k}(n)$ the scaling function associated with the wavelet function $\psi_{j,k}(n)$.

The detail coefficients at level *j* are expressed as follows:

$$D_j = \sum_{n=0}^{\infty} f(n)\psi_{j,k}(n) \qquad (3)$$

.

Based on equations 2 and 3, the decomposition of the signal f(x) can be repeated as the number of levels increases. This procedure is also known as the multi-resolution analysis. As a result, a set of *j* approximations and details can be obtained through the various decomposition levels. First, the signal f(x) is split into an approximation A1 and a detail D1. Then, the approximation A1 is also split into a second-level approximation A2 and detail D2 and so on.

III. DWT ANALYSIS OF SYNTHETIC DATA

As said above, we simulate a GPR survey to detect a void in the soil, whose top is deep 1.5 m, considering a sloping roof above the investigated surface. We want to calculate how it interferes with the signal due to the target of the survey. We simplify the model by considering the roof as a semi-horizontal body.

A. Radargram simulation and data processing

The simulation of the electromagnetic wave propagation is performed using the finite difference (FD) method. The model (Fig. 1) consists of an area (-20 m <z< 0) m characterized by a dielectric constant ε=1 to represent air and an area (0 m <z< 20 m) with a dielectric constant ε=6.5 to represent a soil. The void is modeled by defining a circle with a radius r=1 m and the center 2,5 m deep, and the dielectric constant ε=1. The roof is modeled through a block with dimensions 16x1,5 m and slope 9°. The height of the bottom varies from 2,8 m to 5,8 m and the dielectric constant is set to ε=7.

In the input parameters we set the frequency to 200 MHz and the time window to 110 ns, using DeltaX=0.03 and DeltaT=0.05.

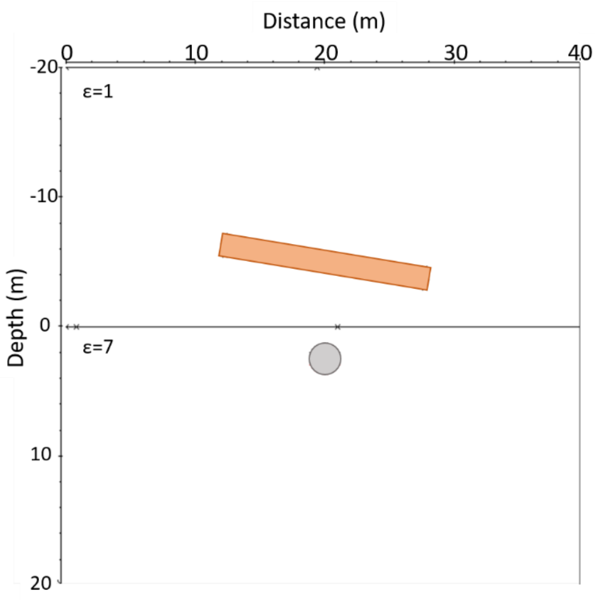

Fig. 1. Geometry of the model used for the GPR survey simulation.

The synthetic data obtained are processed through two steps: move start time and background removal. Figure 2 shows the result of the simulation after the processing.

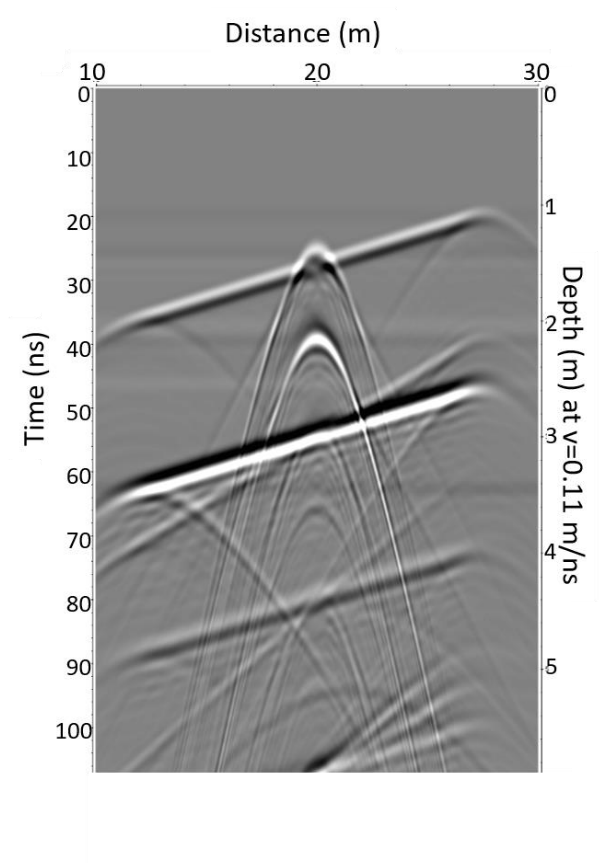

Fig. 2. Processed synthetic radargram.

The signal relating to the block above the surface can be clearly recognized.

B. DWT analysis to remove noise due to a body above the surface

Two-dimensional transforms, such as 2D WT, are useful for analyzing and filtering sloping features. The subdivision into horizontal, vertical, and diagonal panels at each level of the 2D multiresolution analysis, can be used for filtering unwanted features only in those panels in which they occur.

The choice of the mother wavelet, $\psi_{j,k}(n)$, is theoretically arbitrary but it is critical and important in practice: it affects the performance of the technique. In fact, the coefficients of the wavelet transform represent how closely the wavelet is correlated with the signal. Therefore, it is better to choose a mother wavelet similar to the incident GPR signal. In this work, we perform the DWT analysis using the Symlet order 6 (sym6) which, as shown by Baili [9] is very similar to the GPR signal. We use wavelet decomposition at level 3.

Figures 3, 4, and 5 show the results for several levels of decomposition. For each level the approximation panel is in the upper left quadrant, the horizontal detail in the upper right, the vertical detail in the lower left, and the diagonal detail in the lower right.

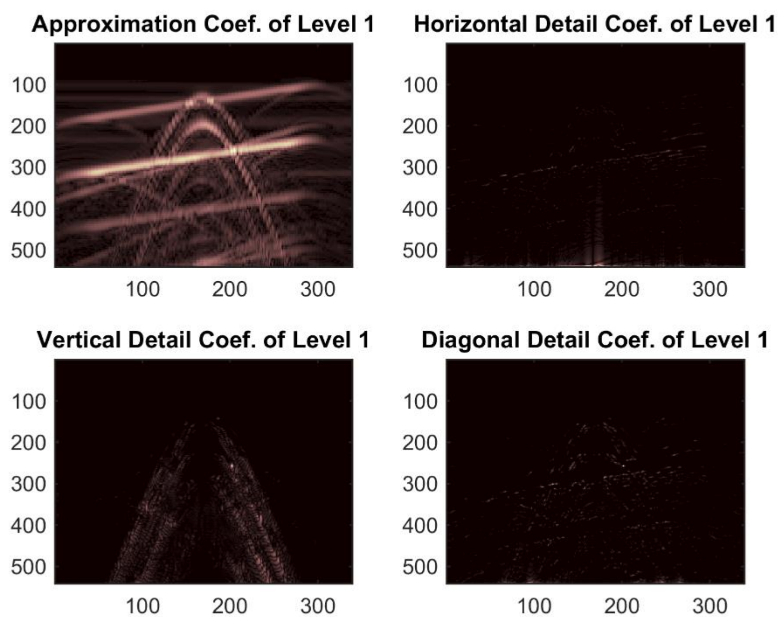

Fig. 3. Wavelet decomposition of level 1

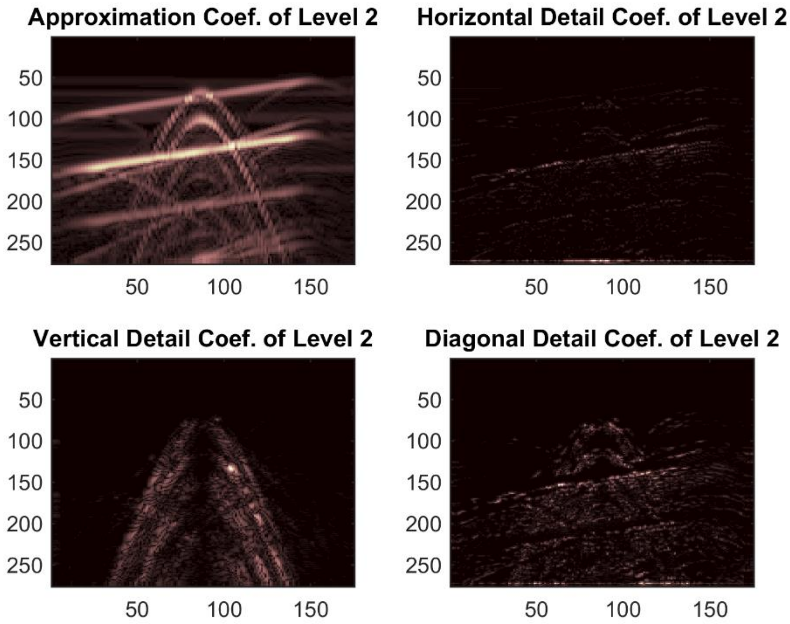

Fig. 4 *Wavelet decomposition of level 2*

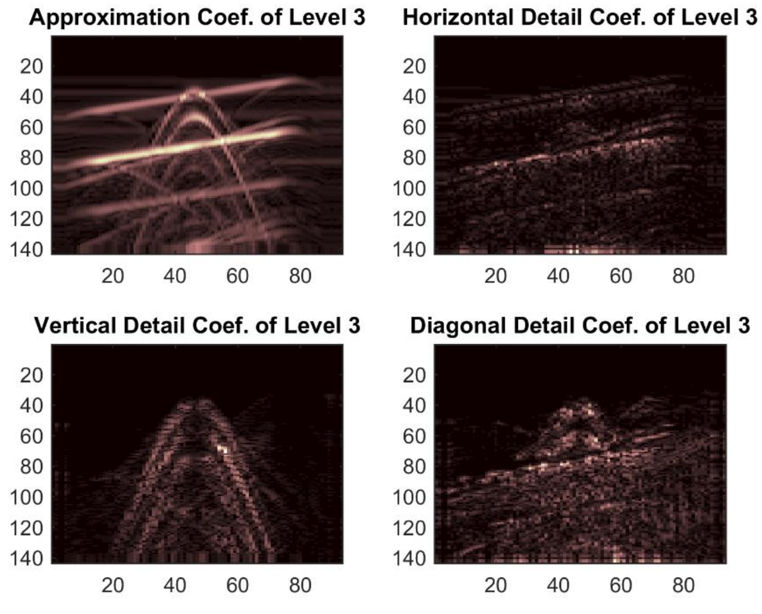

Fig. 5 *Wavelet decomposition of level 3*

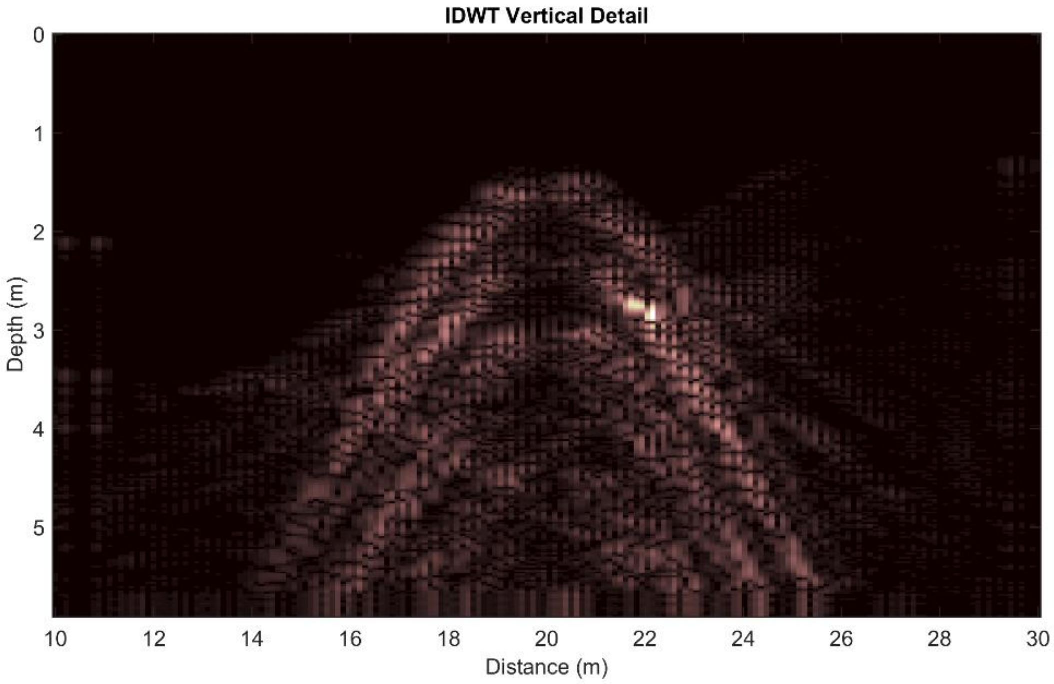

Fig. 6 Signal reconstruction performed by IDWT of the vertical detail coefficients of the level 3.

The dipping lines relating to the block above the surface are visible in the diagonal and horizontal panels, especially at the third level of decomposition (Figure 5). The anomaly related to the void is visible in the vertical panel.

We transform the signal back based on V(3) obtaining the result in Figure 6, which clearly identifies the void whose top is at a depth of 1.5 m, in correspondence with the vertex of the hyperbola.

IV. CONCLUSIONS

We have successfully applied the DWT to the radar signals managing to recognize the various anomalies present in the radargram. In particular, the decomposition of the signals has allowed us to recognize the anomaly due to the void in the subsoil, which is evident on the vertical panel and that due to the block above the surface in horizontal and diagonal panels.

Preliminary data from the first tests show that DWT is a useful tool for clearly distinguishing anomalies related to buried structures from those related to objects above the surface.

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