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di Torino**

**Ground penetrating radar surveys for the screening of buildings and
infrastructures**

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1. Introduction

1.1 Background

Ground Penetrating Radar (GPR) is increasingly used to investigate existing buildings, especially when destructive testing is not acceptable. In masonry walls, concrete structures, and historical façades, GPR offers a practical way to explore what lies behind visible surfaces without altering or damaging the structure. This aspect is particularly relevant for heritage buildings, where preservation requirements strongly limit invasive inspections. In building diagnostics, GPR surveys are commonly employed to identify hidden elements such as metallic anchors, reinforcement bars, air cavities, and service pipes embedded within walls. These targets produce reflections when electromagnetic waves encounter contrasts in material properties, mainly related to changes in dielectric permittivity and electrical conductivity. The output of a GPR survey is typically a radargram, which provides a time-based image of the investigated structure and can be interpreted to infer the position and nature of internal features. Localized objects often generate hyperbolic diffraction patterns, while planar interfaces are generally visible as laterally continuous reflection events (Jol, 2009).

Despite its advantages, the interpretation of GPR data in built environments is often complex. Walls and façades are rarely homogeneous; they are typically composed of layers with different thicknesses and physical properties. Moreover, small objects such as nails or thin pipes may generate diffraction patterns that overlap with reflections from interfaces such as cavities or backing walls. As a result, similar radar signatures can sometimes be produced by different internal configurations, making interpretation uncertain if it relies only on field data. For this reason, numerical modelling represents a valuable support for GPR analysis. By reproducing simplified but controlled representations of structural elements, modelling helps clarify how specific features influence the recorded signal. Synthetic radargrams obtained from numerical simulations can be directly compared with experimental data, allowing the interpreter to test hypotheses and better understand the physical origin of observed reflections. Most modelling approaches are based on time-domain solutions of Maxwell's equations, commonly implemented through finite-difference schemes, which are well suited to GPR applications because they can represent broadband source pulses and strong material contrasts realistically. Previous studies have shown that air-filled cavities typically produce strong and continuous reflections due to the large contrast between air and surrounding masonry, while metallic objects may generate very strong responses and significantly attenuate or block the signal propagating beyond them. In contrast, non-metallic pipes (e.g., PVC) tend to produce weaker reflections and usually allow deeper parts of the structure to remain visible (Jol, 2009; Li et al., 2025).

The experimental activity of this thesis focuses on the front marble stone façade of the Chiesa di San Giuseppe, located in Turin (Italy), at Via Santa Teresa, 22h, 10121 Torino. GPR profiles were acquired on both the left and right portions of the façade wall to investigate the internal structure and to detect hidden elements such as metallic nails and internal cavities. In this context, the integration of experimental surveys with numerical modelling is adopted to strengthen interpretation and to support the screening of the façade in a fully non-destructive manner (Solla et al., 2012).



Figure 1. Facade of the church of San Giuseppe

1.2 Software and Computational Tools

All processing and modelling activities presented in this thesis were carried out using MATLAB, which provided a flexible environment for data handling, signal processing, visualization, and management of simulation workflows.

Within this work, MATLAB supported two complementary tasks. On the experimental side, it was used to process the GPR profiles acquired on the church façade. The processing workflow followed standard and conservative steps aimed at improving data readability while preserving the physical characteristics of the recorded signals. The main operations included time-zero correction, removal of low-frequency components, background removal to reduce horizontal banding and enhance localized anomalies, and the application of gain functions to compensate for signal attenuation with increasing travel time. The same processing strategy was applied consistently across profiles to maintain comparability between the left and right façade datasets.

MATLAB was also used to support the numerical modelling stage through dedicated simulation scripts. The modelling activity reproduced simplified wall configurations representative of the façade, including slab interfaces, metallic nails, internal cavities, and pipes with different material properties. The simulations produced synthetic radargrams that were later compared with the experimental radargrams to clarify the origin of reflection and diffraction patterns and to evaluate how different internal configurations affect the GPR response.

2. State of the art

2.1 GPR Method

Ground Penetrating Radar (GPR) is a non-destructive electromagnetic investigation technique based on transmitting short, broadband pulses into a medium and recording the energy that returns to the antenna after interacting with internal interfaces. The recorded signal is produced by reflections generated when the propagating wave encounters contrasts in electromagnetic properties. In building and façade diagnostics, these contrasts commonly occur at boundaries between construction materials, such as marble and masonry, at transitions between solid material and air (for example, cavities or voids), and at conductive targets such as metallic nails or steel pipes. The GPR signal is recorded as a function of two-way travel time. When the antenna is moved along a line on the investigated surface, each emitted pulse produces a radar trace, and the ensemble of traces forms a radargram, which provides a time-based representation of the internal structure along the survey profile.

In most building materials, magnetic effects can be considered negligible, and the GPR response is primarily controlled by relative dielectric permittivity ϵ_r and electrical conductivity σ . Relative permittivity governs wave velocity, while conductivity governs attenuation. In a low-loss, non-magnetic medium, the wave velocity can be approximated by

$$v \approx \frac{c}{\sqrt{\epsilon_r}} \quad (1)$$

where c is the velocity of the electromagnetic wave in free space. This relationship explains why the wave travels rapidly in air and more slowly in stone or concrete. Conductivity affects the loss of signal energy; as σ it increases, attenuation increases, and penetration depth decreases. This is particularly relevant in construction materials affected by moisture, salt content, or conductive inclusions, all of which can reduce the visibility of deeper reflections.

When an electromagnetic wave reaches an interface, part of its energy is reflected, and part is transmitted, and the relative amount of reflection depends on the contrast between the electromagnetic properties of the two media. Interfaces characterized by large contrasts—such as air versus masonry produce strong reflections that are typically easy to identify in radargrams. Interfaces with smaller contrasts, such as PVC versus masonry, tend to produce weaker reflections that may be more difficult to recognize. Conductive targets behave differently from dielectric contrasts: metallic objects produce very strong responses because of their high conductivity. In practice, they may also lead to signal shadowing, because a large fraction of the incident energy is reflected before it can propagate beyond the metallic element, reducing the detectability of deeper targets.

A fundamental aspect of GPR is the trade-off between resolution and penetration depth, which is mainly controlled by antenna frequency. Higher frequencies provide improved resolution but reduced penetration, whereas lower frequencies penetrate deeper but provide less detail. For façade investigations, where the targets are typically shallow and small, such as slab thickness, nails, cavities, and pipes, high-frequency antennas are commonly preferred. The relation between wavelength, velocity, and frequency is expressed by

$$\lambda = \frac{v}{f} \quad (2)$$

and the smallest detectable feature size (i.e., vertical resolution) is generally a fraction of the wavelength, often approximated as $\lambda/3$ to $\lambda/4$ depending on survey conditions. In dense building materials, this typically corresponds to centimetre-scale resolution for high-frequency surveys, which is consistent with the requirements of façade screening applications. GPR measurements are recorded in time (ns), and converting travel time to depth requires an estimate of wave velocity in the relevant medium. For a single homogeneous material, depth can be approximated as

$$d = \frac{vt}{2} \quad (3)$$

Where t is the two-way travel time. In layered structural systems, however, the conversion becomes more complex because the wave velocity changes between layers. This is particularly important in façade cladding systems where the wave may travel through stone and then through an air cavity, which has a much higher velocity. In such cases, applying a single velocity value to the entire travel-time axis may lead to incorrect depth estimates, and the layered configuration must be considered explicitly during interpretation.

In radargrams, different target geometries produce recognizable patterns. Laterally continuous planar interfaces, such as layer boundaries or the roof of an air cavity, tend to appear as continuous reflection events. By contrast, small or localized targets such as metallic nails or reinforcement bars produce hyperbolic diffractions because the antenna target distance changes as the antenna moves along the profile. Pipes may appear as hyperbolic diffractions when their diameter is small relative to the wavelength, or as broader curved reflectors depending on geometry, coupling conditions, and the size of the target. The material of a pipe strongly influences its response: steel pipes typically generate high-amplitude reflections and may obscure deeper interfaces, whereas PVC pipes usually produce weaker reflections and often allow deeper features to remain visible.

For historical façades, GPR offers important advantages: it provides rapid imaging, does not require physical intervention, and can reveal internal discontinuities and embedded elements that are not accessible through visual inspection. At the same time, limitations must be considered. Material heterogeneity and layering can produce overlapping reflections and interference that complicate interpretation, conductive targets can mask deeper features, uncertainty in velocity estimation affects depth conversion, and the acquisition on vertical surfaces may introduce coupling-related variability. Numerical modelling provides a controlled framework to assess how individual structural elements influence radar responses and to support more reliable interpretation in complex layered wall systems (Daniels, 2004).

2.1.1 GPR Acquisition

Ground Penetrating Radar (GPR) data acquisition represents a critical phase of any investigation, as the quality and reliability of the results strongly depend on the survey design and execution conditions. In structural applications, acquisition must be tailored to the expected target type and depth, the geometry of the investigated surface, and the material characteristics of the structure.

A key parameter in GPR acquisition is the antenna frequency, which controls the trade-off between spatial resolution and penetration depth. Higher-frequency antennas provide improved resolution and are therefore suitable for detecting small-scale or shallow features such as reinforcement bars, anchors, and near-surface cavities; however, penetration depth decreases as frequency increases. Lower-frequency antennas allow deeper penetration at the expense of resolution. For concrete and masonry investigations, intermediate to high frequencies are typically adopted to achieve centimetric resolution within the shallow depths of interest.

Survey geometry and acquisition parameters also influence the interpretability of radargrams. The spacing between consecutive traces defines the lateral sampling and must be sufficiently small to avoid spatial aliasing and loss of information, particularly when the targets are localized (e.g., nails or small pipes). Similarly, the time window and sampling interval must be selected to capture the relevant reflections while maintaining data quality. In addition, stable coupling between the antenna and the investigated surface is essential to minimize signal loss and ringing caused by air gaps or surface irregularities, which is especially important on vertical surfaces such as building façades.

Environmental and material conditions may further affect data quality. Moisture content, surface roughness, and material heterogeneity can increase attenuation, scattering, and distortion of the signal. For this reason, acquisition parameters are often checked and adjusted on site, and calibration using reference measurements can support more reliable depth estimation when needed. In building investigations, GPR data are commonly acquired along parallel profiles to support two-dimensional interpretation, while dense grids may be used when three-dimensional reconstruction is required. Profile-based strategies are particularly effective in complex masonry structures and historical façades, where invasive methods are undesirable and where repeated observations across adjacent profiles improve confidence in the identification of cavities, embedded elements, and discontinuities (Annan, 2009).

2.1.2 GPR Processing

Ground Penetrating Radar (GPR) data processing is a fundamental step in the workflow because the raw recordings collected in the field are rarely directly interpretable. In building and façade investigations, the measured signal typically includes not only reflections from internal interfaces, but also unwanted components such as the direct wave, antenna ringing, low-frequency drift, and site-related noise. In addition, electromagnetic attenuation causes a progressive reduction in amplitude with increasing travel time, which can mask deeper features. The purpose of processing is therefore to improve the signal-to-noise ratio, enhance the continuity of meaningful reflectors, and emphasize localized anomalies associated with elements such as nails, pipes, cavities, and material boundaries.

A first operation commonly applied to GPR datasets is time-zero correction (or start-time adjustment). Due to system delays and variations in antenna coupling, the first arrivals may not be perfectly aligned from trace to trace. Aligning the start time ensures that the same physical event occurs at the same time position along the profile. This step is particularly important when comparing multiple profiles and when converting time to depth, since small timing shifts can introduce significant errors in shallow structural assessments.

Raw GPR traces often contain a slow-varying component related to the acquisition system and the emitted wavelet baseline. To remove this component, a high-pass filtering step is typically performed. This operation suppresses very low-frequency trends, stabilizes the signal baseline, and improves the visibility of reflection events. After baseline stabilization, the dataset commonly benefits from background removal, a procedure used to attenuate horizontally continuous noise such as airwave energy and antenna ringing. Background removal is often implemented by subtracting the average trace (or a running mean) from all traces, reducing coherent horizontal banding and making localized features more evident. In building investigations, this step is especially effective in enhancing diffractions from discrete metallic targets and in improving the readability of internal discontinuities.

Filtering is another key component of GPR processing. Because antennas operate over a limited bandwidth, band-pass filtering is used to retain the portion of the spectrum that carries the most useful information while attenuating low-frequency drift and high-frequency noise. Filter limits are generally chosen according to the antenna bandwidth and the expected target dimensions. In materials such as concrete and masonry, where attenuation can be significant, filter selection must be conservative to avoid removing the useful signal content at later times.

As travel time increases, signal amplitude decreases because of geometric spreading and material attenuation related to electrical losses. For this reason, a gain function is usually applied to balance amplitudes and improve the visibility of deeper reflections. Gain may be implemented as linear or exponential time-dependent amplification, or through methods such as automatic gain control (AGC). When applied carefully, gain enhances the interpretability of later events without saturating shallow reflections or amplifying noise excessively.

Depending on the objective of the study and the clarity of the dataset, more advanced procedures may also be considered. Migration, for example, can be used to correct the geometric distortion of diffractions, repositioning reflected energy closer to its true subsurface location. Migration is especially useful when accurate localization of point-like targets is required, but it is strongly dependent on a reliable velocity estimate and may not always be necessary for qualitative interpretation.

Finally, processed radargrams recorded in two-way travel time can be converted to depth using an estimate of electromagnetic wave velocity. This time-to-depth conversion facilitates engineering interpretation and comparison with construction details. Velocity can be estimated through hyperbola fitting, calibration against known targets, or reference values. In layered façade systems, depth conversion should be applied with caution, since wave velocity can vary significantly between materials such as stone, masonry, and air cavities. Processing must be applied consistently to avoid introducing artefacts that could bias interpretation. This is especially important in historical façades, where modelling can help verify the physical origin of key reflections (Jol, 2009).

2.1.3 GPR Interpretation

GPR interpretation is the process of linking reflection patterns observed in radargrams to physical structures and materials within the investigated object. In building and façade investigations, interpretation is typically carried out by combining knowledge of electromagnetic wave behavior with information about construction geometry and expected materials. Unlike direct inspection methods, GPR does not provide a “photograph” of the interior; it provides a time-based response that must be translated into structural meaning by recognizing characteristic signatures such as continuous reflectors, diffraction hyperbolas, and zones of attenuation.

A first step in interpretation is the identification of the main continuous reflection events associated with planar interfaces. In façade systems, these interfaces often correspond to the air–stone surface, the boundary between a cladding slab and the backing material, or the roof and base of an internal cavity. Planar interfaces generally appear as laterally continuous reflection bands because the wavefront intersects an extended boundary over many traces. The strength of these reflections depends on the dielectric contrast between materials: interfaces involving air typically produce high-amplitude events, while contacts between materials with similar electromagnetic properties may generate weaker reflections.

Localized objects and small targets are commonly recognized through diffraction patterns. Metallic nails, anchors, and reinforcement bars are classic examples of discrete targets in structural GPR. When the antenna passes over such an object, the recorded arrival time varies with antenna position, producing a hyperbolic shape in the radargram. The apex of the hyperbola indicates the approximate position of the target along the profile, while the curvature is related to the velocity of the material outside the target. In practice, the diffraction hyperbolas do not carry any information about the material of the target, but the amplitude and sharpness of these hyperbolas are also influenced by object size, orientation, and conductivity.

Voids and cavities represent another key interpretative target in building diagnostics. Air-filled cavities typically generate strong reflections due to the high contrast between air and surrounding masonry or concrete. In some cases, both the upper and lower boundaries of a cavity can be detected, producing a pair of reflections; the travel-time separation between these events can provide an estimate of cavity thickness, provided that appropriate velocities are adopted for the relevant materials. In layered façade systems, interpretation must account for changes in velocity between stone, masonry, and air, since applying a single velocity to the entire time axis can lead to inaccurate depth estimates.

Pipes can generate different radar signatures depending on their geometry and material. Pipes with a small diameter may behave similarly to point targets and appear as hyperbolic diffractions if the radar profile is acquired perpendicularly to their elongation. Larger pipes or pipes located near strong planar interfaces may produce broader curved responses and complex interference with nearby reflections. Material properties strongly influence detectability. Metallic pipes, such as steel, produce very strong reflections and may generate multiple reverberations, often creating shadow zones where deeper interfaces become weak or disappear. Non-metallic pipes, such as PVC, usually generate weaker reflections because their electromagnetic properties are closer to those of surrounding materials; however, they generally allow wave energy to propagate beyond them, preserving information from deeper features such as cavities or backing walls.

Because building structures often include multiple layers and embedded elements, interpretation is rarely based on a single reflection event. Instead, it relies on consistency across profiles, coherence of reflectors, and the repeatability of localized anomalies. Changes in amplitude, continuity, and reflector geometry may indicate variations in material properties, thickness, or internal configuration. At the same time, interpretation must consider potential sources of ambiguity, such as overlapping reflections, multiples, and processing artefacts.

For these reasons, modern GPR interpretation in complex structural environments is often supported by numerical modelling. Forward simulations provide controlled reference cases that show how nails, cavities, and pipes of different materials are expected to appear in radargrams under similar acquisition conditions. This support strengthens interpretation reliability, especially when direct validation through destructive testing is not feasible, as is typically the case in historical buildings (Daniels, 2004).

2.2 Literature Review

2.2.1 heritage façade voids, high-frequency antennas

A recurring challenge in heritage diagnostics is that many deterioration features—such as voids, delamination zones, and hidden discontinuities develop within masonry. At the same time, the surface remains the only accessible part of the structure. Johnston et al. (2018) address this problem by testing whether high-frequency GPR can still produce interpretable radargrams when applied to a rough historic stone façade, and by comparing how different antenna frequencies affect what can (and cannot) be detected.

Much of the earlier heritage-focused GPR work tended to treat block masonry as single “important” stones, rather than as a connected system where decay may extend across several units. Johnston et al. explicitly try to move beyond this limitation by running their profiles across multiple blocks to see whether GPR can highlight features whose extent is larger than one stone. Another important pattern they engage with is the well-known resolution–penetration trade-off: higher frequencies image smaller defects but lose depth, while lower frequencies penetrate deeper but blur small targets.

Their comparison is straightforward but useful: the same wall section was surveyed using three Malå antennas (1.2, 1.6, and 2.3 GHz), run along two perpendicular test lines (vertical and horizontal) of about 80 cm. A major practical issue in wall surveys is coupling rough stone surfaces create air gaps and unstable antenna movement. To deal with this, they used a manufacturer’s plastic sheet (80 × 80 cm) to create a smoother surface. They also checked whether the small air gaps introduced by the sheet (about 0.5–1 cm) would distort the data; since the differences were negligible, they proceeded with the sheet as a field solution. For processing, they applied DC adjustment (to remove drift and bring the signal back to the zero line), followed by background removal using a FIR band-pass filter in Malå GroundVision. For depth/velocity interpretation, they used hyperbola matching in ReflexW.

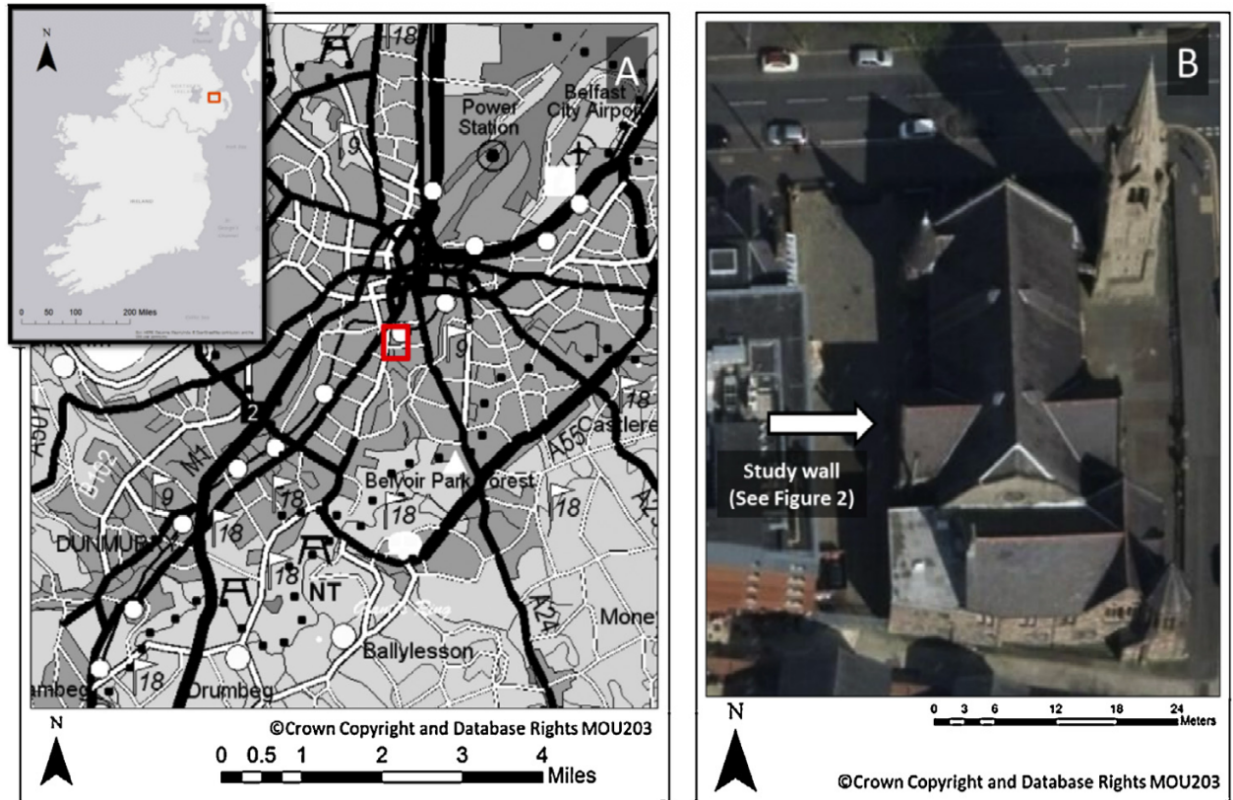


Figure 2. (A) Location of Fitzroy Presbyterian church within Ireland and Belfast, and (B) the location of the study wall section on the building (Johnston et al., 2018)



Figure 3. (A) Location of the perpendicular test lines, marked in red, on the study wall surface. (B) operation of the equipment on the study wall section (Johnston et al., 2018)

The outcomes clearly show how strongly frequency selection controls interpretation in masonry. The 1.2 GHz antenna reached the greatest depth and identified a layered structure consisting of a stone layer and an underlying rubble fill, with the interface located at approximately 16 cm. In their discussion, the authors report penetration to about 32 cm, though with reduced ability to resolve finer internal details. The 2.3 GHz antenna behaved oppositely: it did not reach the deeper interface, but it was more sensitive to near-surface anomalies (roughly 0–3 cm). It could highlight small-scale features that the 1.2 GHz antenna could not distinguish well. The 1.6 GHz antenna performed the worst in this specific context. The radargrams showed strong ringing, and even after background removal, the artefact remained significant. They also observed coupling/mismatch problems and anomalies that did not appear in the other frequencies, suggesting these were data-collection artefacts rather than real targets.

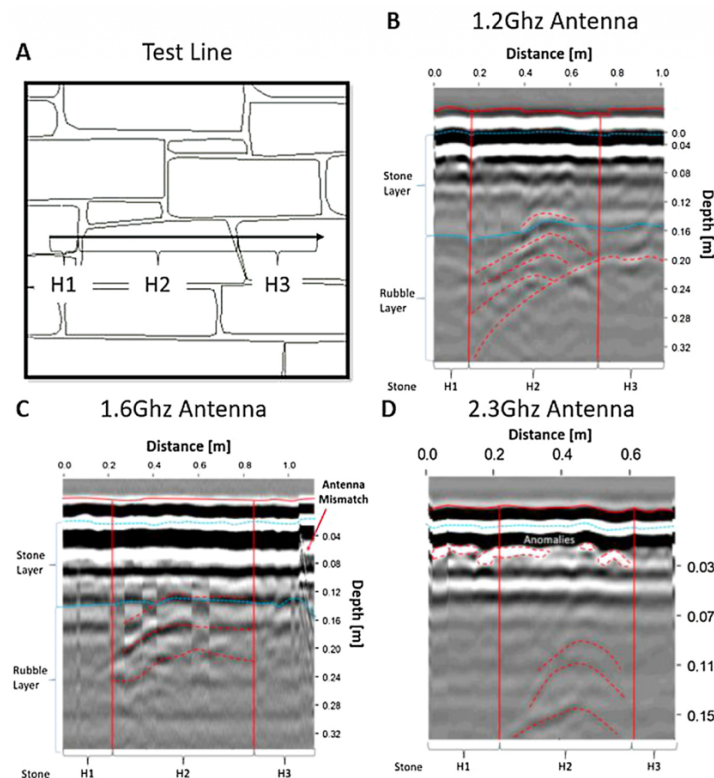


Figure 4. Annotated reflection profiles produced from running the three different frequencies of antennas, 1.2 GHz (B), 1.6GHz(C), and 2.3GHz (D), along the horizontal test line (A). (Johnston et al., 2018)

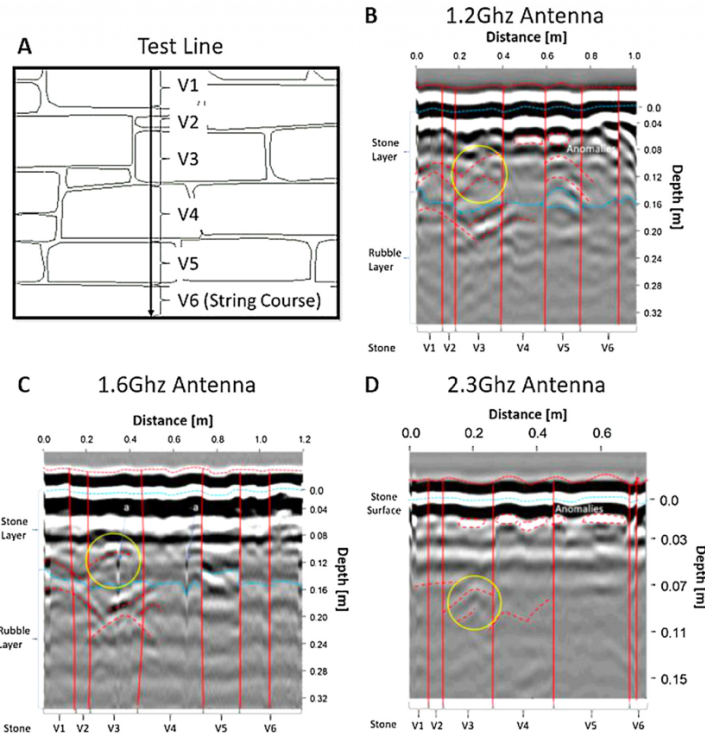


Figure 5. Annotated reflection profiles produced from running the three different frequencies of antennas, 1.2GHz (B), 1.6GHz(C), and 2.3GHz(D), along the vertical test line (A). Artefacts detected on the 1.6GHz radargram are marked with an 'a'. (Johnston et al., 2018)

A key limitation emphasized by Johnston et al. is non-uniqueness: even when anomalies are visible, GPR alone cannot confidently identify the feature (void, different stone type, clay clast, etc.) without additional information. They explicitly state that the method can indicate “something is there,” but it cannot confirm identity on its own. They also show that façade geometry itself can introduce misleading responses: as profiles crossed a string course, the topographic change created an anomaly that appeared in the radargrams and must be interpreted cautiously.

2.2.2 Building phases of the Casa del Citarista (Pompeii, Italy) enhanced by GPR

Corradini et al. (2025) used Ground Penetrating Radar to investigate the Casa del Citarista in Pompeii, to support the reconstruction of building phases and hidden architectural elements without excavation. The paper treats GPR as a tool that becomes much more reliable when it is combined with architectural knowledge (plans, standing walls, known room functions, and previous archaeological information). Heritage buildings often produce complicated radar responses because they are built and modified over long periods. Floors, fills, reused walls, and later repairs can sit on top of each other, creating multiple reflections in the same area. In this setting, GPR is not just about detecting “anomalies,” but about understanding whether reflectors match plausible construction elements and phases.

A recurring result in the study is that broad and continuous interfaces (for example, floor levels) are usually easier to follow than small, discontinuous masonry remains. At the same time, features linked to water management channels, drains, or cavities often stand out clearly because their geometry and the physical contrast with surrounding materials generate strong reflections. In the Casa del Citarista, the survey supports the interpretation of drainage structures and the presence of a cistern, showing how GPR can contribute to both the layout and the functional understanding of the site. A key strength of this work is the use of a dense acquisition strategy: many closely spaced parallel profiles were collected so that the data could be interpreted in 3D, as separate 2D radargrams. This makes it easier to check whether reflectors are continuous and coherent when viewed from different directions.

They also used two antenna frequencies (nominally around 300 and 800 MHz). The higher-frequency antenna provides more detail at shallow depth, while the lower-frequency antenna supports deeper penetration and clearer recognition of larger structures. The authors also point out that the effective frequency content can shift because attenuation and coupling can alter what is transmitted and recorded in the field. Processing follows a structured workflow, including trace alignment and time-zero correction, filtering, gain, and migration, together with steps aimed at reducing acquisition artifacts and improving image clarity. The dataset is processed using MATLAB-based tools (Multichannel GPR) and then interpreted in 3D through slices and picked reflectors, which helps reduce the uncertainty that often appears when interpretation is done profile-by-profile only.

The paper is also clear about common practical limitations. Positioning can be problematic in archaeological courtyards and near standing walls, where GNSS signals are disturbed. This can introduce spatial distortions in depth slices if not corrected. Interpretation uncertainty is another challenge: some linear reflectors can be explained in more than one way (for example, channels, construction joints, or later modifications). The authors emphasize that, in some cases, excavation or targeted verification would still be needed to confirm the nature and chronology of certain anomalies. (Corradini et al., 2025)

2.2.3 Void detection behind tunnel concrete lining by an SH-Ultrasonic-assisted GPR method

Ground-penetrating radar (GPR) is extensively applied for non-destructive evaluation of reinforced concrete linings and structural walls, particularly for detecting voids, delamination, thickness variations, and hidden defects.

The method relies on the transmission of high-frequency electromagnetic (EM) waves and the interpretation of reflections generated at dielectric interfaces. In the referenced study, two antenna frequencies were employed: 900 MHz for high-resolution void detection in Test-1 and 600 MHz in Test-2 for deeper investigation of grout layer thickness variations and larger cavities. The choice of frequency directly controls the trade-off between resolution and penetration depth. At 900 MHz, vertical resolution is approximately $\lambda/2 \approx 0.1m$ in concrete, enabling clearer imaging of relatively small voids behind the lining. In contrast, the 600 MHz antenna provides greater

penetration depth but reduced vertical resolution, making it more suitable for detecting deeper water-filled cavities and evaluating layer thickness variations. (Wang et al., 2026)

GPR data in the study were acquired in common-offset (zero-offset) mode and processed through direct wave removal, de-wow filtering, band-pass filtering, gain control, background subtraction, and time-to-depth conversion. Depth conversion relied on assumed interval velocities of approximately 0.1 m/ns for concrete and 0.06 m/ns for grout. These values are relevant to façade investigations in dense stone materials such as marble, where comparable electromagnetic velocities may be assumed for first-order depth estimation.

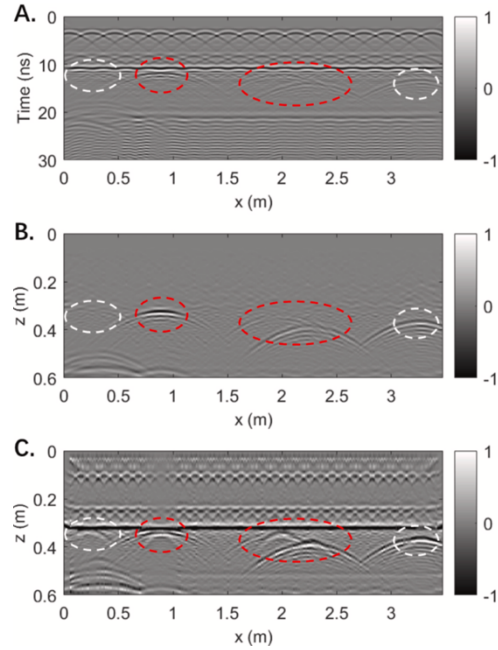


Figure 6. Example of data fusion. A. GPR data in time domain. B. Processed GPR data in depth domain. C. GPR and ultrasonic data fusion results. Red and white dash circles highlight water-filled and air-filled voids, respectively. (Wang et al., 2026)

The detectability of voids is governed by electromagnetic contrast and scattering behavior. The normal-incidence reflection coefficient is expressed as

$$r = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \quad (4)$$

Where ε_1 and ε_2 denote the relative permittivity of adjacent media. For typical concrete ($\varepsilon_r \approx 9$), air ($\varepsilon_r = 1$), and water ($\varepsilon_r \approx 81$), the magnitude of the reflection coefficient at both concrete–air and concrete–water interfaces is approximately 0.5. However, experimental evidence demonstrates that water-filled voids are significantly more detectable than air-filled voids, despite similar theoretical reflection amplitudes. This apparent contradiction is explained by differences in radar cross section (RCS), which quantifies scattering efficiency:

$$\hat{\sigma} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|E_s|^2}{|E_i|^2} \quad (5)$$

Where R is the antenna-target distance, E_s is the scattered field, and E_i is the incident field. For a cylindrical void at 900 MHz, estimated RCS values were approximately 0.37 m² for a water-filled cavity and 0.04 m² for an air-filled cavity. The much larger RCS and shorter wavelength in water (≈ 0.04 m) compared to air (≈ 0.33 m) make water-filled voids electrically larger and therefore more

reflective targets. Consequently, GPR at both 900 MHz and 600 MHz exhibits higher detection reliability for water-filled defects, while dry air-filled detachments produce weaker signatures and may be overlooked. (Wang et al., 2026)

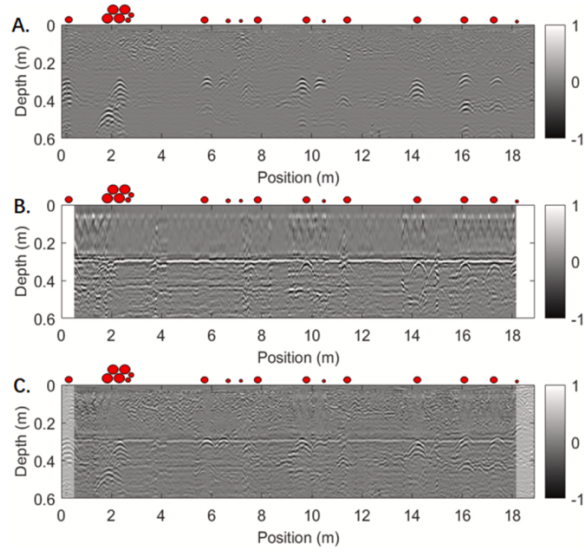


Figure 7. Platform model Test-1: Water-filled void imaging results. Red cycles are void locations. A. GPR results. B. Ultrasonic CMP stacked results. C. GPR-ultrasonic data fusion. Color maps include scale bars showing normalized amplitude (-1 to 1). (Wang et al., 2026)

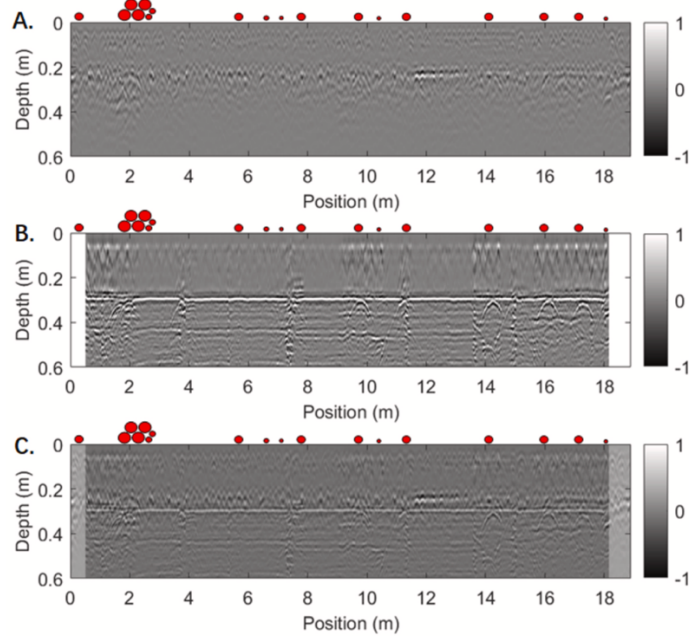


Figure 8. Platform model Test-1: Air-filled void imaging results. Red cycles are void locations. A. GPR results. B. Ultrasonic CMP stacked results. C. GPR-ultrasonic data fusion. Color maps include scale bars showing normalized amplitude (-1 to 1). (Wang et al., 2026)

Experimental validation of these physical principles was performed through two controlled test campaigns. In Test 1, a reinforced concrete lining containing artificial air-filled and water-filled voids was investigated using a 900 MHz antenna. The results showed that water-filled cavities generated strong, clearly defined hyperbolic reflections with a high signal-to-noise ratio, while air-filled voids produced weaker and less distinguishable signatures. Rebar interference further reduced the detectability of dry cavities. This test demonstrated the sensitivity of GPR performance to void-filling conditions and reinforcement density.

In Test 2, a lower-frequency 600 MHz antenna was employed to investigate deeper cavities and variations in grout layer thickness. The reduced frequency allowed greater penetration depth and improved imaging of deeper structural features, although at the cost of reduced vertical resolution. Reflections appeared broader and less sharply defined compared to the 900 MHz data. The experiment clearly illustrated the fundamental frequency trade-off: higher frequencies provide superior resolution for shallow anomalies, while lower frequencies enable deeper penetration but reduced spatial precision.

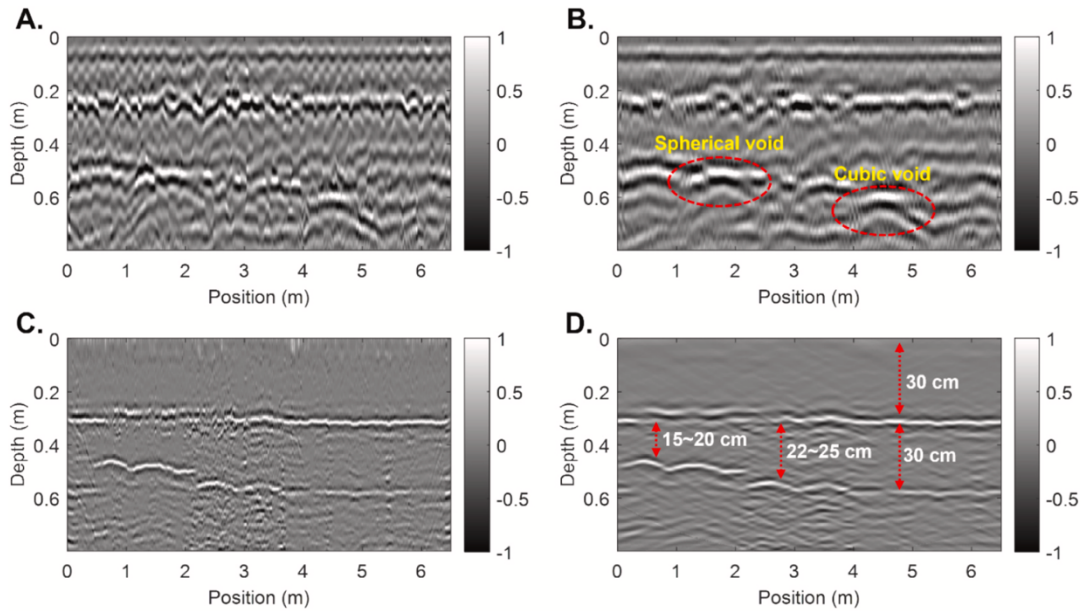


Figure 9. Platform model Test-2: Voids and grout layer imaging results. A. Raw GPR results. B. Processed GPR results. C. Raw ultrasonic CMP stacking results. D. Processed ultrasonic CMP stacking results. (Wang et al., 2026)

For façade investigations such as the marble slabs of the Church of San Giuseppe, this frequency-dependent behavior is highly significant. Marble cladding thicknesses on the order of 7–8 cm, anchoring depths of a few centimeters, and potential rear cavities of limited thickness require high-resolution imaging. Therefore, ultra-high frequency antennas (e.g., 1–2 GHz) are generally preferable for detecting shallow detachment zones and anchor positions. However, the limitations observed in the literature suggest that dry air-filled gaps behind marble slabs may still produce relatively weak reflections, particularly in the presence of metallic anchors. Consequently, careful

velocity calibration, amplitude analysis, and signal enhancement techniques are required for reliable façade diagnostics.

Environmental conditions further influence radar performance. Increased moisture raises dielectric permittivity and attenuation, reducing penetration but enhancing contrast at water-filled defects. Material heterogeneity, cracking, and surface roughness can introduce scattering effects that complicate interpretation. These factors are especially relevant in historic masonry façades, where aging, weathering, and restoration interventions introduce variability in material properties.

2.2.4 A Historical Building Information Modeling Data Modeling Approach for the Valentino Castle North Wing

The article positions itself within recent advancements in Heritage Building Information Modeling (HBIM), emphasizing a shift from purely geometric reconstruction toward a documentation-oriented approach. While HBIM has significantly improved heritage conservation through digital modeling and data integration, persistent challenges remain, including fragmented workflows, limited semantic interoperability, and the difficulty of balancing geometric accuracy with informational depth. In response, the authors propose a framework that prioritizes structured information management over high-resolution geometry, redefining HBIM as a comprehensive system for organizing, interpreting, and sharing heritage data across disciplines.

The proposed methodology is based on a six-stage workflow that combines both geometric and semantic processes, from knowledge structuring and data collection to modeling, enrichment, and interoperability. A significant contribution of the study is the introduction of a four-level information hierarchy: Building, Zone, Architectural Components A and B, which clearly links 3D geometry with external databases. This structure allows the model to serve not only as a visual representation but also as an information repository, supporting metadata integration, ontology alignment, and cross-platform data exchange. By applying BIM management principles such as information requirements and execution planning, the workflow improves coordination and standardization within heritage documentation projects.

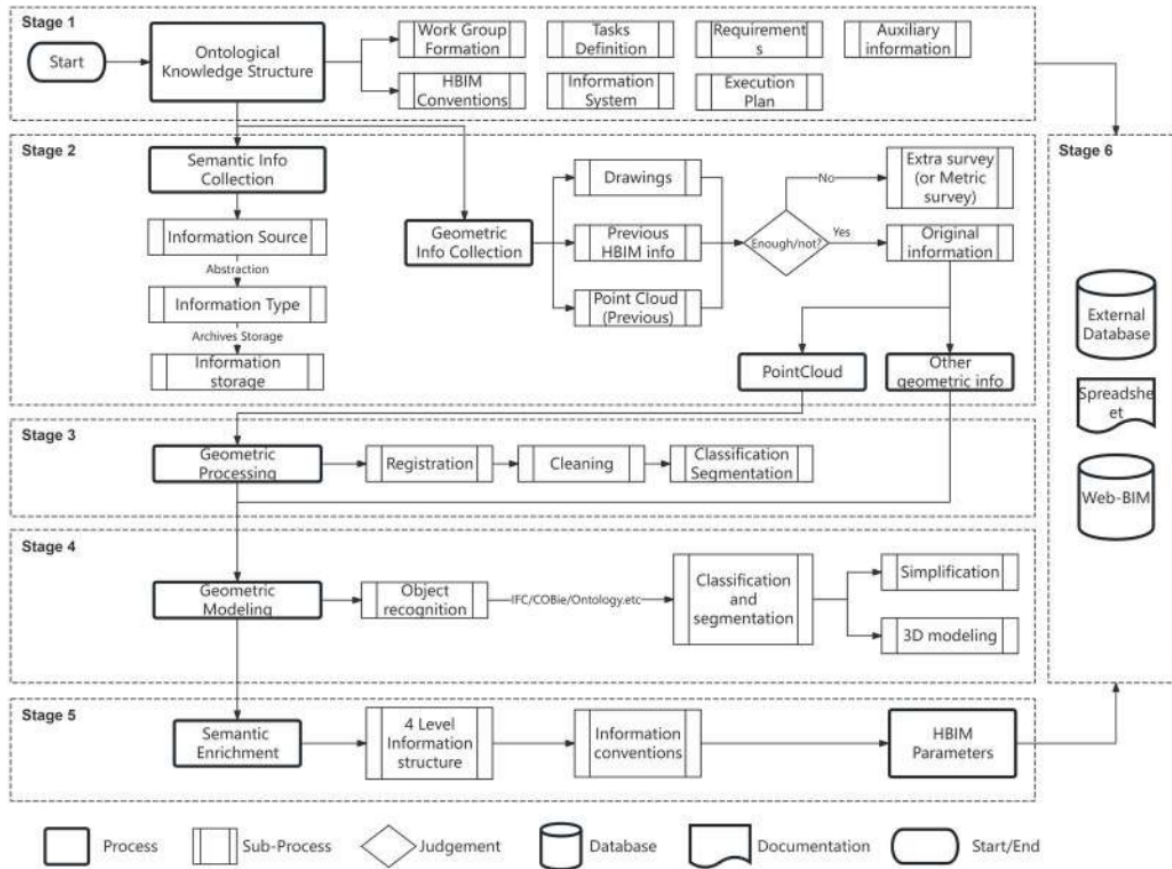


Figure 10. The documentation-oriented HBIM workflow in this project (Li et al., 2025).

Results demonstrate the effectiveness of this approach, particularly in handling complex and heterogeneous datasets. The integration of archival records, survey data, and point clouds allowed for a comprehensive understanding of the building, despite challenges such as incomplete or inconsistent datasets. Notably, the use of artificial intelligence tools facilitated the extraction and organization of information from large volumes of documentation, improving the efficiency of semantic data management. This highlights the growing potential of AI-assisted workflows in heritage documentation, especially for linking textual and visual data to digital models.

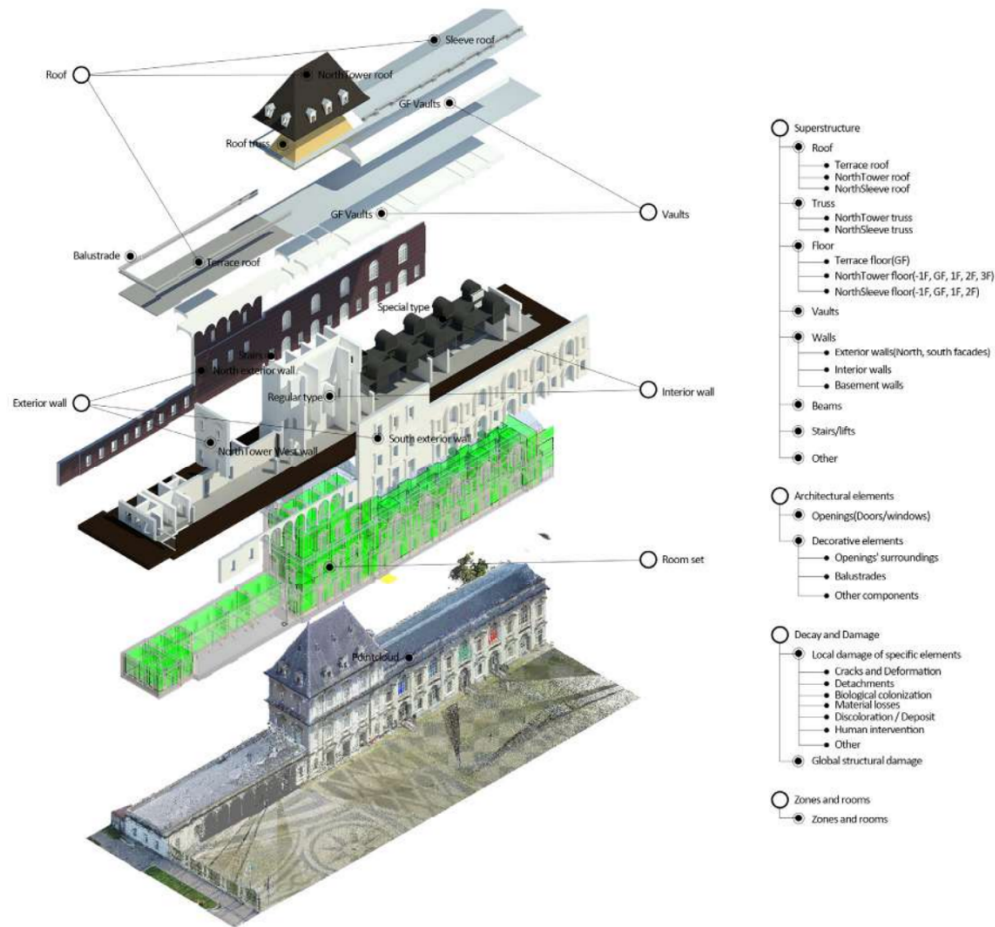


Figure 11. Explosion diagram of different types of architectural elements' geometric modeling in HBIM (Li et al., 2025).

From a geometric perspective, the study confirms that efficient documentation can be achieved without relying on highly detailed models. By reusing existing point cloud data and supplementing missing information through drawings and manual surveys, the authors developed a simplified yet coherent geometric representation. While global structural elements showed satisfactory accuracy, local architectural details exhibited greater deviations due to simplification. Nevertheless, this trade-off was considered acceptable, as the model successfully supported documentation, visualization, and information retrieval tasks.

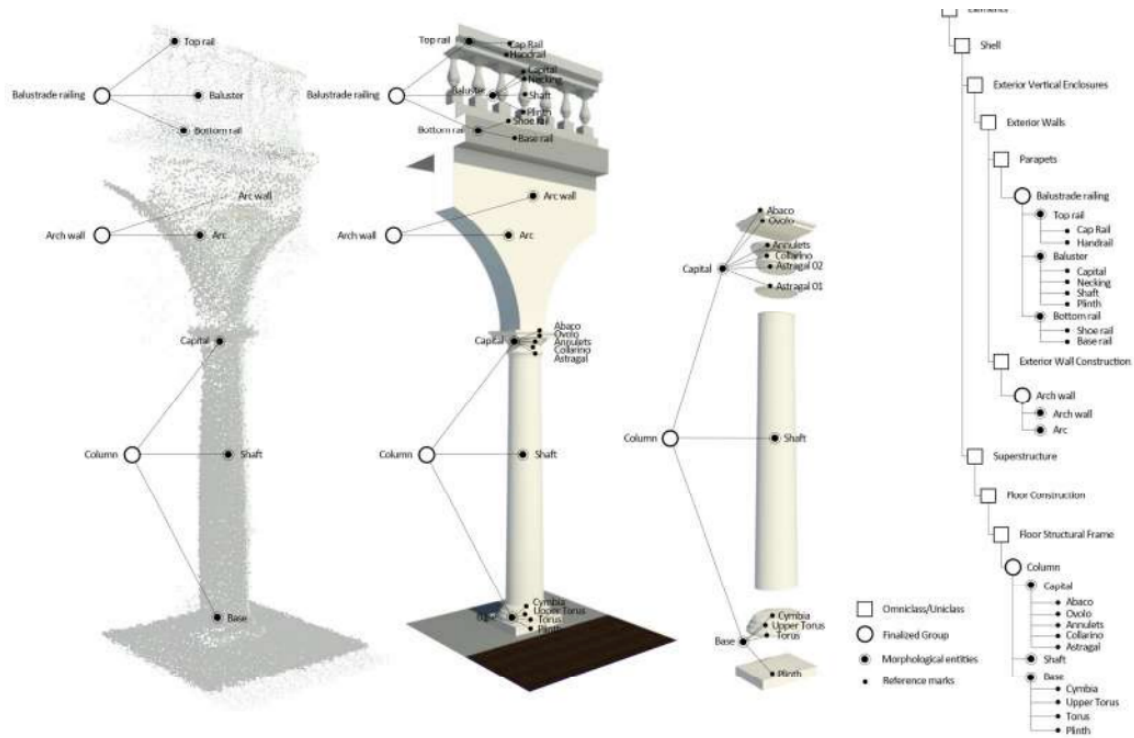


Figure 12. Three-dimensional graph providing a semantic description of a part of a terrace (ontology) and classification strategy of a column in the Valentino Castle project (Li et al., 2025).

Semantic enrichment process proved essential in enhancing the functionality of the HBIM model. The integration of structured metadata, damage classification systems, and database-linked information enabled effective monitoring, analysis, and management of the building over time. Despite some limitations such as software dependency, reduced geometric precision in detailed elements, and limited evaluation of AI performance, the study provides a valuable contribution to the field. It demonstrates that HBIM can evolve into a documentation-centered framework, where the integration of geometry, semantics, and interoperability supports more efficient and sustainable heritage management.

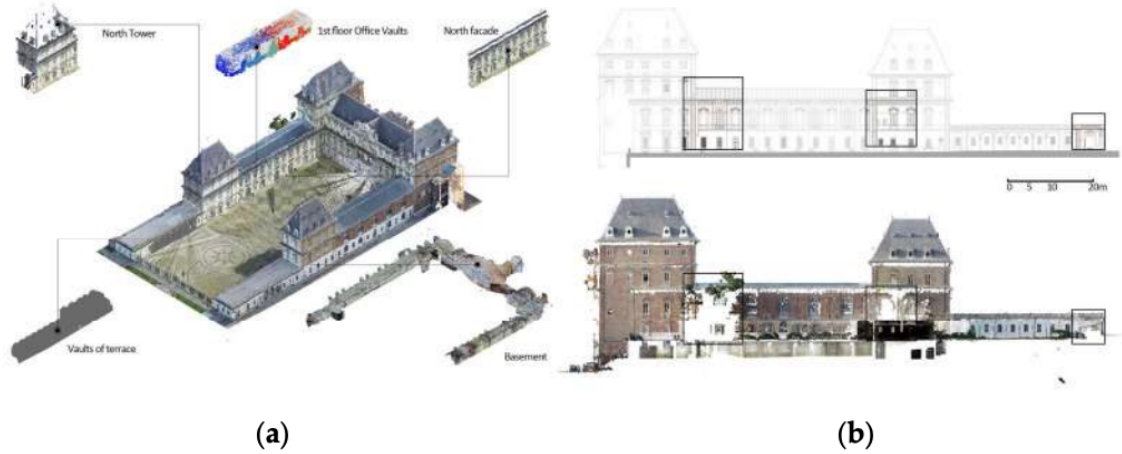


Figure 13. (a) Example of the different data integrated. (b) The missing point clouds in the north facade were supplemented by the scanned drawing information and other documents (black frame) (Li et al., 2025).

3. Modeling

3.1 Model Description

Numerical modelling was used to interpret Ground-Penetrating Radar data collected on the façade of the Chiesa di San Giuseppe in Turin. In built environments, GPR responses can be difficult to interpret uniquely because different internal configurations may generate similar signatures. A controlled numerical framework helps isolate the contribution of individual targets—such as metallic nails, air cavities, and service pipes and provides synthetic radargrams that can be compared with experimental profiles.

All simulations were implemented in the MATLAB environment through a two-dimensional (2D) representation of the investigated section (Irving & Knight, 2006). The geometry of the wall and embedded targets was discretized on a regular Cartesian grid, and each grid cell was assigned electromagnetic properties. In practice, the model domain is stored as property matrices, where the relative permittivity ϵ_r and electrical conductivity σ define the propagation velocity and attenuation of electromagnetic waves within each material. This matrix-based implementation makes it straightforward to introduce or remove elements (e.g., cavities, pipes, nails) by modifying the corresponding ranges of indices. The spatial discretization adopted for the simulations was $dx = dz = 0.01$ m. The time discretization was $dt = 0.02$ ns. At the beginning of each run, the code evaluates the maximum source frequency content and checks whether the chosen spatial and temporal steps satisfy numerical accuracy and stability requirements. In particular, the maximum stable time step is computed for the selected discretization, and the value $dt = 0.02$ ns was selected consistently with the stability limit reported by the code. This ensures stable propagation of the electromagnetic wavefield and avoids numerical artifacts that would affect the synthetic radargrams.

For low-loss dielectric materials (such as air, masonry/stone, and PVC), the wave propagation velocity can be approximated as reported in Equation 1. This relationship is useful to link the assigned permittivity to the expected travel times. In contrast, conductive materials (e.g., steel) are primarily governed by high electrical conductivity; they produce powerful reflections and can significantly attenuate the signal transmitted beyond them. For this reason, metallic inclusions are treated as conductors in the property assignment, and a meaningful propagation velocity inside the metal is not typically used in interpretation.

The modelling output is a set of synthetic traces organized in the same way as field GPR data, producing a time-versus-position radargram. This allows a direct qualitative comparison between simulated responses and experimental profiles after processing, supporting the identification of characteristic patterns such as hyperbolic diffractions (typical of point-like targets) and continuous reflectors (typical of planar interfaces or extended voids).

3.2 Material Properties

The electromagnetic properties assigned to the model were selected to represent the main components expected in the church façade configuration, with stress on contrasts controlling reflection strength: relative permittivity ϵ_r and electrical conductivity σ . The values adopted in this thesis are summarized in Table 3.1. For dielectric materials, an indicative velocity v is also reported $v \approx c/\sqrt{\epsilon_r}$. For steel, the material is treated as highly conductive; therefore, the concept of propagation velocity is not used in the same way as for dielectrics.

Table 1. Data for the modeling materials

Material	ϵ_r	$\sigma \left(\frac{S}{m}\right)$	$v \left(\frac{m}{ns}\right)$
Air	1	0	0.30
Stone / Concrete	4	0.001 $\rightarrow$ 0.007	0.15
PVC	3	0	0.17
Steel	$\rightarrow \infty$	$6 * 10^6$	≈ 0 (treated as conductor)

The wall material was represented with a relative permittivity around $\epsilon_r = 4$, consistent with masonry/concrete-like behaviour, and a low but non-zero conductivity to account for attenuation effects. The selected conductivity range (0.001 to 0.007 S/m) reflects the expected variability in real building materials due to moisture content, composition, and heterogeneity. PVC was modelled as a low-loss dielectric ($\epsilon_r = 3$, $\sigma \approx 0$), leading to weaker reflections than metallic pipes, while still producing detectable contrasts at the pipe boundaries depending on surrounding materials. Steel was represented as a highly conductive material ($\sigma = 6 \times 10^6$ S/m), which is expected to generate strong reflections and possible shadow zones beneath the target due to signal blocking and attenuation.

3.3 Simulation scenario

To support the interpretation of the experimental GPR profiles acquired on the façade of the Chiesa di San Giuseppe, four numerical scenarios were defined. The scenarios were designed in a progressive way: starting from a simplified configuration representative of the wall with shallow metallic elements, then introducing internal voids and pipes, and finally isolating the response of cavities and pipes by removing the slab and nails. In all cases, the same numerical framework described in Sections 3.1–3.2 was adopted, so that differences among outputs can be attributed to the presence or absence of specific targets rather than to changes in discretization or solver settings. Each scenario is stored as a dedicated MATLAB file containing the property matrices (relative permittivity and conductivity) that define the model geometry and materials.

3.3.1 Scenario 1 – Nails + Slab + Wall

This first scenario represents the baseline structural configuration used to reproduce the façade’s response when only the main wall body and shallow metallic inclusions are considered. The model includes the wall material and the external slab layer, together with two nails modeled as conductive point-like targets. The purpose of this scenario is to isolate the characteristic signatures generated by small metallic elements in the presence of a layered interface (slab–wall). In GPR data, nails typically behave as compact scatterers, producing diffraction patterns that can overlap with reflections from planar interfaces; therefore, this scenario is essential for establishing a reference response for metallic targets under simplified conditions.

3.3.2 Scenario 2 – Nails + Slab + Two Cavities + Two Pipes

The second scenario introduces a more complex internal configuration by adding two air cavities and two pipes to the baseline model, while keeping the slab and nails. This configuration represents a realistic case where multiple reflectors coexist within the wall and may generate overlapping responses. The objective is to evaluate how cavities (extended low-permittivity zones) and pipes (localized cylindrical targets) interact with the reflections and diffractions already produced by nails and layered interfaces. This scenario is particularly useful for understanding the potential ambiguity in interpretation when several targets lie within similar depth ranges, and their signatures interfere in the radargram. It also allows an initial evaluation of “masking effects,” where strong reflections from one element may reduce the visibility of deeper features.

3.3.3 Scenario 3 – Wall + Two Cavities + Two PVC Pipes

The third scenario removes both the slab and metallic nails, leaving only the wall body with two cavities and two PVC pipes. This simplified configuration was created to specifically study the detectability of non-metallic pipes in the presence of voids, without the additional scattering caused by shallow metallic targets. PVC is a low-loss dielectric material and generally produces weaker reflections than steel; therefore, the response of PVC pipes can be subtle, especially when nearby cavities generate strong and continuous reflections. For this reason, Scenario 3 provides a controlled setting to assess how clearly PVC pipes can be recognized in synthetic radargrams and how their signatures compare to those of cavities in the same wall material.

3.3.4 Scenario 4 – Wall + Two Cavities + Two Steel Pipes

The fourth scenario uses the same geometry as Scenario 3 (wall with two cavities and two pipes) but replaces PVC pipes with steel pipes. This scenario isolates the effect of high electrical conductivity on the radar response. Steel is expected to generate very strong reflections and can significantly attenuate or block the electromagnetic wave, potentially producing shadow zones beneath the pipes and reducing the energy available to illuminate deeper portions of the model. By comparing Scenarios 3 and 4, the role of pipe material on reflection strength, waveform character, and signal penetration can be evaluated under otherwise identical conditions. This comparison is directly relevant to structural screening problems, where different pipe materials may exist and must be distinguished based on their GPR signature.

4. Experimental data

4.1 Site and survey context

The experimental work presented in this thesis was carried out on the front façade of the Chiesa di San Giuseppe in Turin, located in Via Santa Teresa, 22h, 10121 Torino. The façade includes three large marble cladding slabs arranged in vertical groups on both sides of the main entrance portal. An inspection performed on 9 March 2023 highlighted a localized anomaly on the right-hand side of the portal: one marble panel appeared slightly out of plane compared with the adjacent slabs. The observed slab has approximate dimensions of 1.30 m × 1.30 m, with an estimated thickness of about 7–8 cm. It corresponds to the central element of three slabs positioned vertically one above the other on the right side. The misalignment is most evident at the base and is visible continuously along the lower edge, suggesting that the issue is not a minor surface defect but may be related to a discontinuity, detachment, voided zone, or internal feature behind the cladding.

To assess the internal condition of the wall behind the marble surface without damaging the structure, a Ground Penetrating Radar (GPR) survey was planned over the façade area. The survey design was based on a simple principle: investigate the anomalous slab on the right side while also

collecting measurements on a geometrically similar reference area on the left side of the portal. On the left-hand side, the façade presents three slabs arranged in the same configuration as on the right, but without any visible misalignment. This provided a useful “baseline” response, allowing the radar signatures observed on the right side to be compared with an area that appears structurally stable at the surface.

The GPR acquisition was organized as a set of parallel horizontal profiles measured directly on the marble surface. The profiles were spaced at regular 20 cm intervals, which is a practical compromise between coverage and survey time and provides sufficient lateral sampling to track changes in the response with height. In other words, the slab surface was divided into measurement levels at approximately 20, 40, 60, 80, 100, and 120 cm, referenced along the slab face, so that each radar profile represents a horizontal scan line at a known elevation. The same spacing concept was applied on both sides of the portal to ensure that the datasets are comparable and can later be interpreted consistently. In total, seven profiles were acquired on the left-side area and eight profiles on the right-side area. The right side was intentionally covered with one additional profile to provide denser sampling where the anomaly was observed and to reduce uncertainty in the localization of possible internal features associated with the misaligned slab.

Each profile was acquired along the width of the slab, so the expected profile length is approximately consistent with the slab dimension (around 1.30 m, allowing for small offsets depending on where the antenna started and stopped). This profile orientation is particularly suitable for identifying laterally localized anomalies (such as nails, cavities, or pipes) and for distinguishing them from broader, laterally continuous reflectors (such as interfaces between layers). The combination of multiple profiles acquired at different heights and the left–right comparison across the portal makes the dataset more robust for interpretation. Because the survey was repeated at regular 20 cm intervals, it is possible to check whether a reflection pattern is consistent across several heights, which may indicate a more extended interface or a larger internal zone, or whether it appears only in one or two profiles, which is more typical of localized targets such as nails or small inclusions. In addition, surveying both sides of the portal provides a built-in reference: the left side (no visible misalignment) represents a baseline response for a similar façade configuration, while the right side (misaligned slab) is the area of interest. Features that appear only on the right side, or that show systematic differences between the two sides, can therefore be interpreted with greater confidence as potentially related to the observed misalignment, rather than being normal construction details or acquisition artefacts.

4.2 GPR survey design and acquisition

A high-frequency GPR setup was selected to maximize resolution in the first decimeters behind the façade. The measurements were performed using an IDS K2 control unit coupled with an IDS Aladdin dual-polarization antenna with a 2 GHz central frequency. Using this frequency and adopting an indicative propagation velocity in marble of about 0.1 m/ns, the corresponding wavelength in the material is on the order of ~ 5 cm; with the usual resolution assumption of roughly $1/3$ – $1/4$ of the wavelength, targets with a thickness of approximately 1.5–2 cm can realistically be distinguished. This is consistent with the practical objective of detecting small

construction details such as anchoring elements, estimating the slab thickness, and assessing the backing condition immediately behind the slab.

To ensure a uniform coverage of each slab surface, the acquisition was organized as a set of horizontal profiles. In the reference report, six horizontal profiles were collected with a 20 cm spacing to cover the slab area, and two additional horizontal profiles were acquired across the upper and lower edges (i.e., straddling the top and bottom borders). In your dataset, the same “dense, evenly spaced” logic is reflected in the way the slabs were scanned on both sides of the portal (with 7 profiles on the left and 8 profiles on the right, according to your acquisition notes), which keeps the interpretation comparable between the “reference” slab and the slab showing the misalignment.

4.3 Processing workflow

To keep the experimental analysis consistent and comparable across the façade, all recorded GPR profiles were processed using a single, repeatable MATLAB workflow. The purpose of this approach was to transform raw radar records affected by system delay, ringing, and amplitude decay into sections that are easier to interpret in terms of reflections and diffraction patterns, while avoiding aggressive processing that could create artefacts. The processing parameters were kept fixed for the entire dataset so that differences observed between profiles can be attributed to real subsurface/structural variations rather than to changes in processing choices.

4.3.1 Data import and axis definition

The raw traces were first imported from the acquisition files and stored as a 2D matrix, where each column represents one trace along the profile and each row represents the recorded samples in time. The spatial axis was reconstructed from the trace spacing dx , while the time axis was obtained from the total recording time window T and the number of samples n , so that the sampling interval is:

$$dt = \frac{T}{n-1} \quad (6)$$

To allow interpretation in terms of depth, the two-way travel time was converted to depth using an assumed electromagnetic wave velocity v in the investigated medium:

$$z = \frac{v t}{2} \quad (7)$$

In this equation t is the two-way travel time.

4.3.2 Time-zero correction

The first processing operation after inserting the raw data was time-zero correction, which removes the system delay and ensures that the beginning of each trace corresponds consistently to the emission of the radar pulse. This was done by identifying the delay (direct wave onset) and removing the corresponding initial samples. The result is an aligned dataset where reflections can be compared across the profile without artificial time shifts.

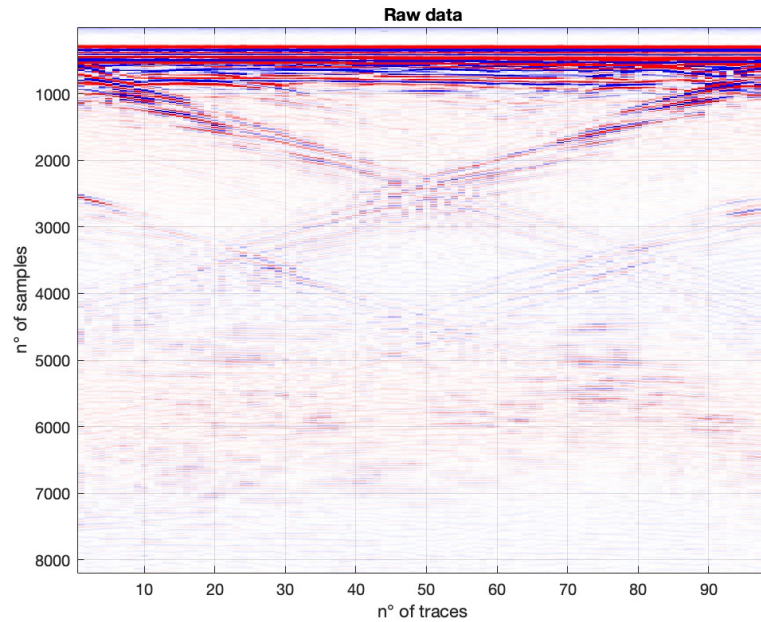


Figure 14. Processing workflow - Raw data

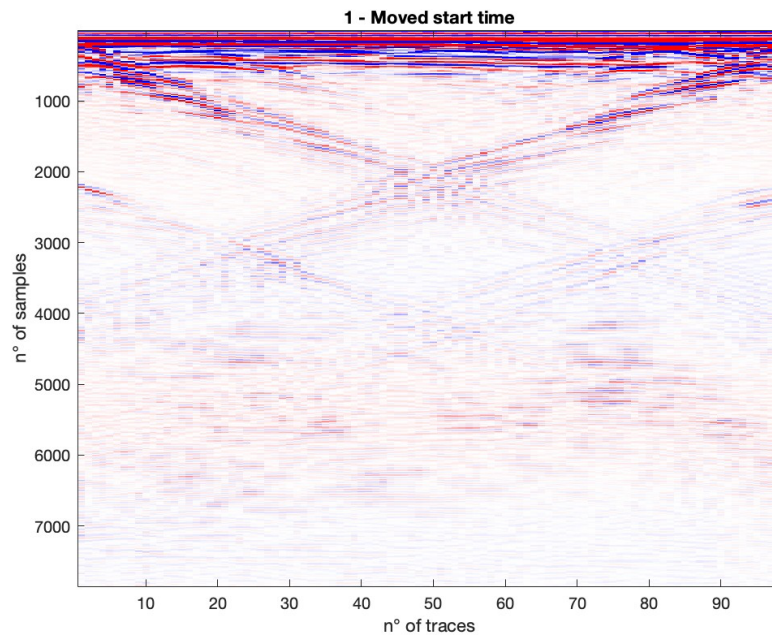


Figure 15. Time-zero correction

4.3.3 Background removal

GPR records often contain laterally continuous components such as antenna ringing, airwave effects, and other systematic horizontal banding that can mask weaker subsurface reflections. Background removal was applied by subtracting the mean trace (computed across all traces) from each trace. This step suppresses horizontally persistent energy and enhances localized reflections associated with discontinuities such as interfaces, inclusions, or void-like features.

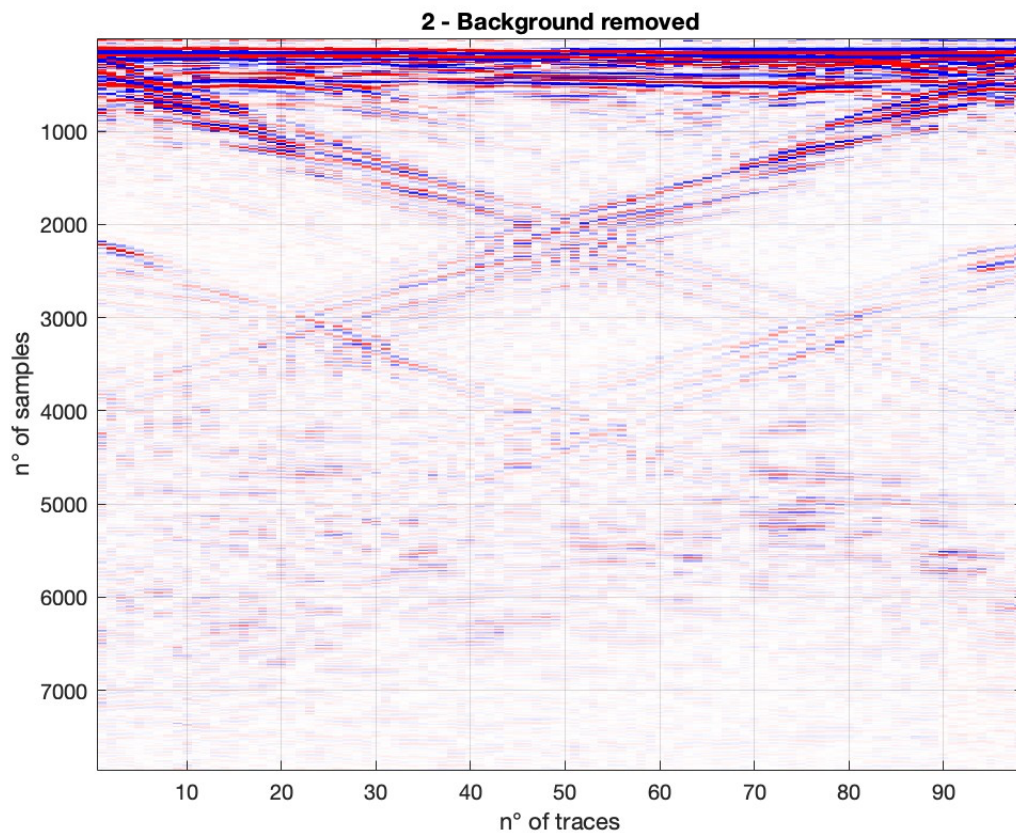


Figure 16. Background removal

4.3.4 Cutting Stationary Traces

The removal of stationary traces was not required in this dataset. Stationary traces typically occur when the antenna pauses during acquisition, producing repeated vertical traces that introduce artificial banding. The absence of this step indicates that the data acquisition was continuous and stable, with no duplicated or static traces affecting the radargrams.

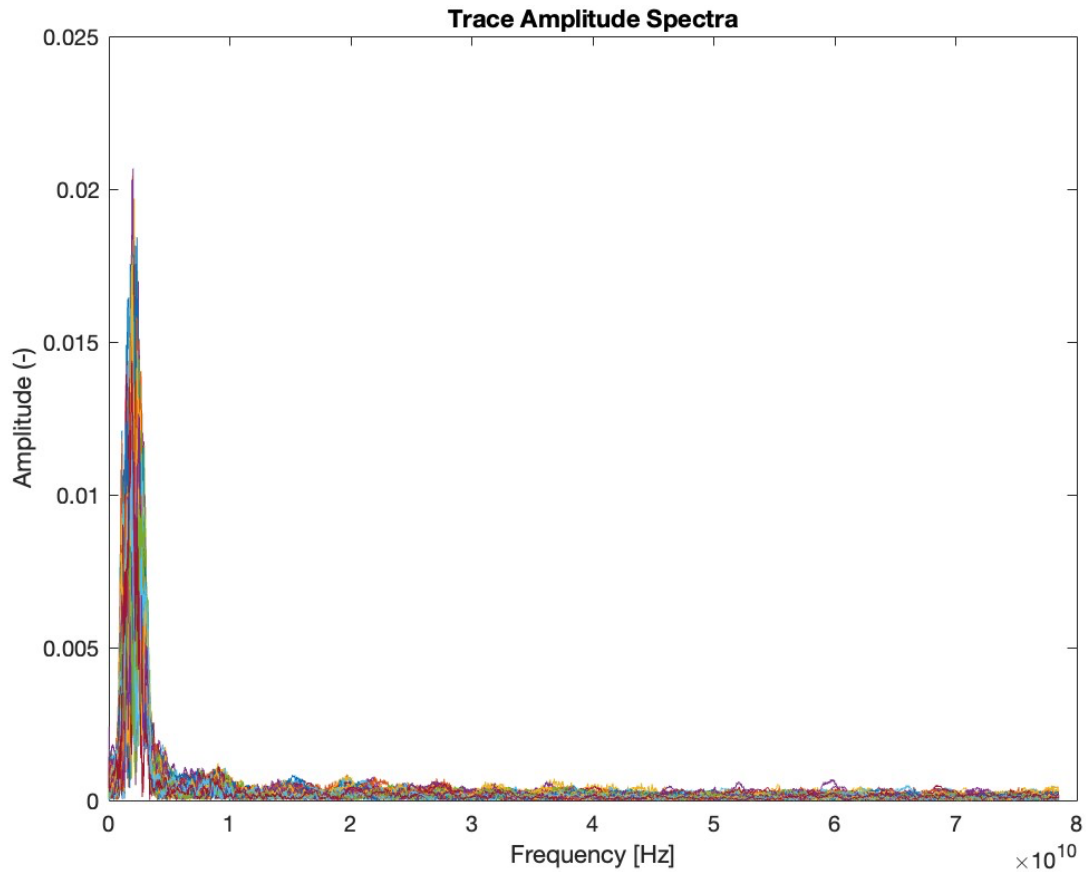


Figure 17. Trace Amplitude Spectra

4.3.5 Band-Pass Filtering

Band-pass filtering was not applied in the processing workflow. Although band-pass filters are commonly used to suppress low-frequency drift and high-frequency noise, this step was intentionally omitted to preserve the original spectral and amplitude characteristics of the signal. Maintaining the raw frequency content ensured that amplitude-based interpretations, particularly instantaneous amplitude analysis, remained physically meaningful and unaffected by artificial spectral modification.

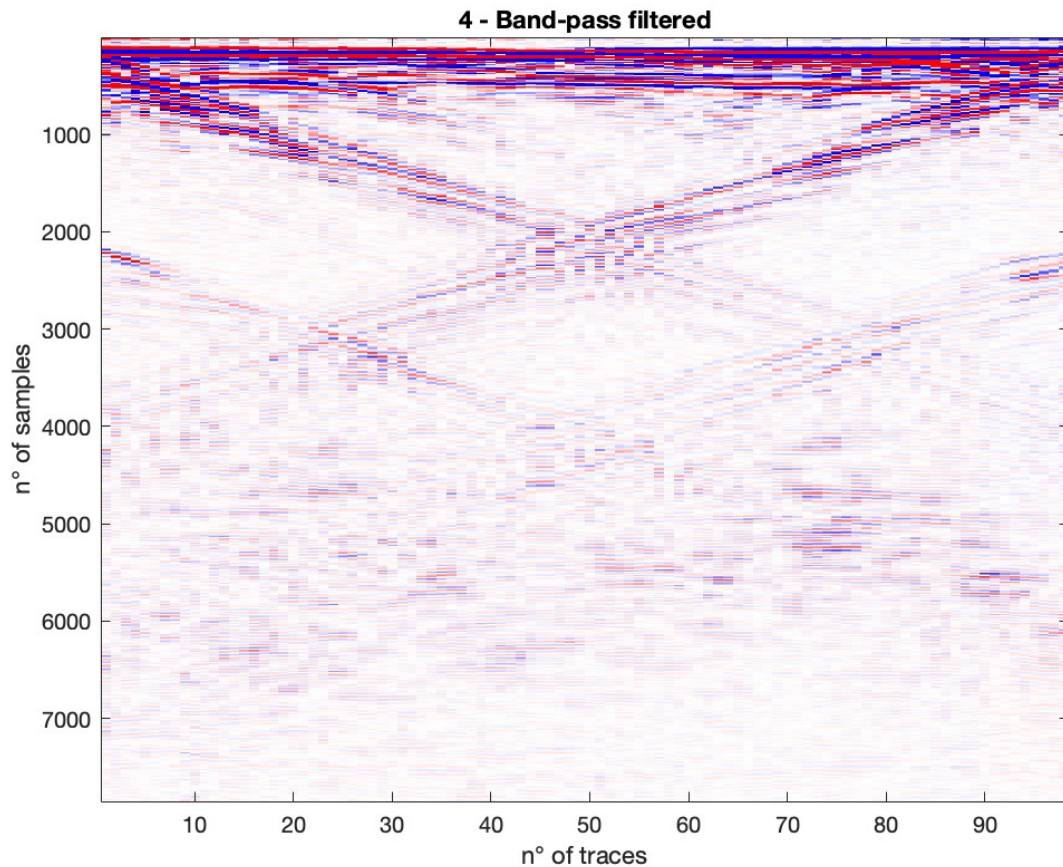


Figure 18. Band-Pass Filtering

4.3.6 Divergence Recovery

A linear divergence recovery gain was applied to compensate for amplitude decay caused by geometric spreading of the electromagnetic wave as it propagates through the materials. As wave energy disperses with increasing travel time, deeper reflections naturally appear weaker. The application of a linear gain function enhances these deeper signals proportionally to time, restoring amplitude balance across the radargram. This step improved the visibility of the slab-wall interface and deeper masonry reflections while maintaining relative amplitude relationships.

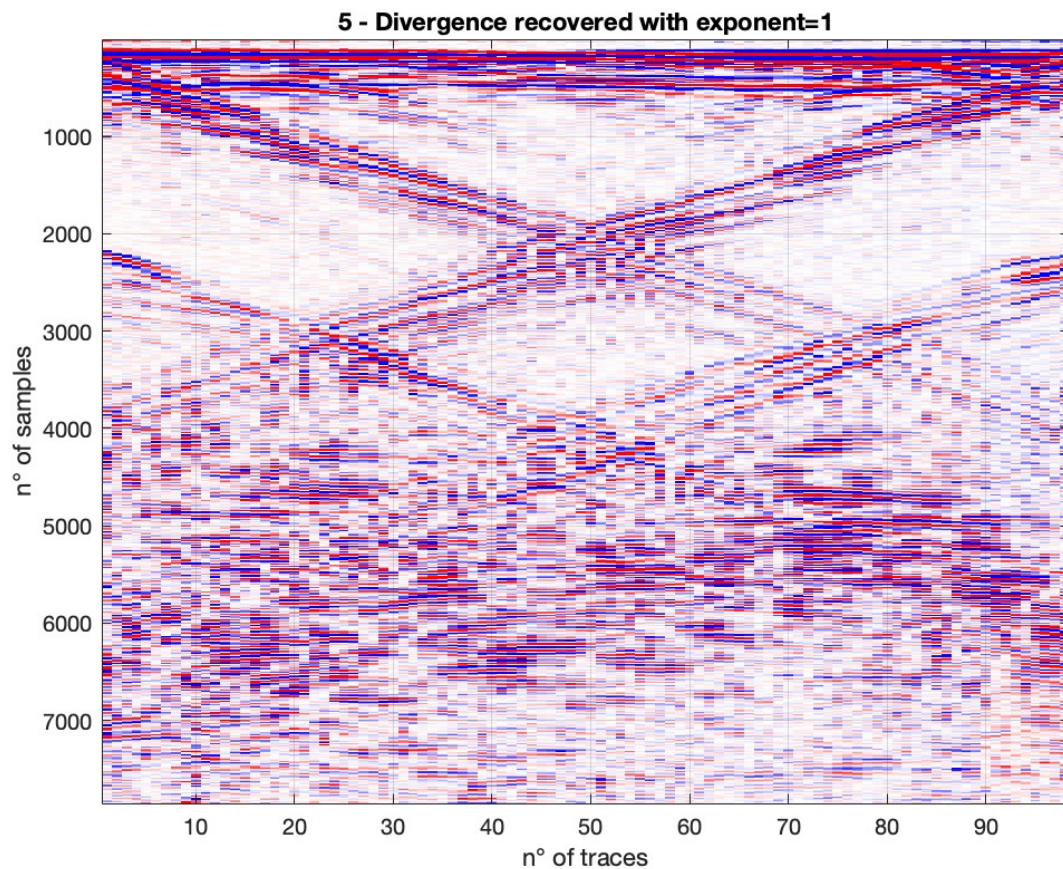


Figure 19. Divergence Recovery

4.3.7 Removal of Stationary Traces in Radargram

No traces were removed at the radargram stage. This confirms that the dataset did not contain redundant or corrupted traces requiring manual correction. The radargrams, therefore, represent continuous and structurally reliable acquisition lines.

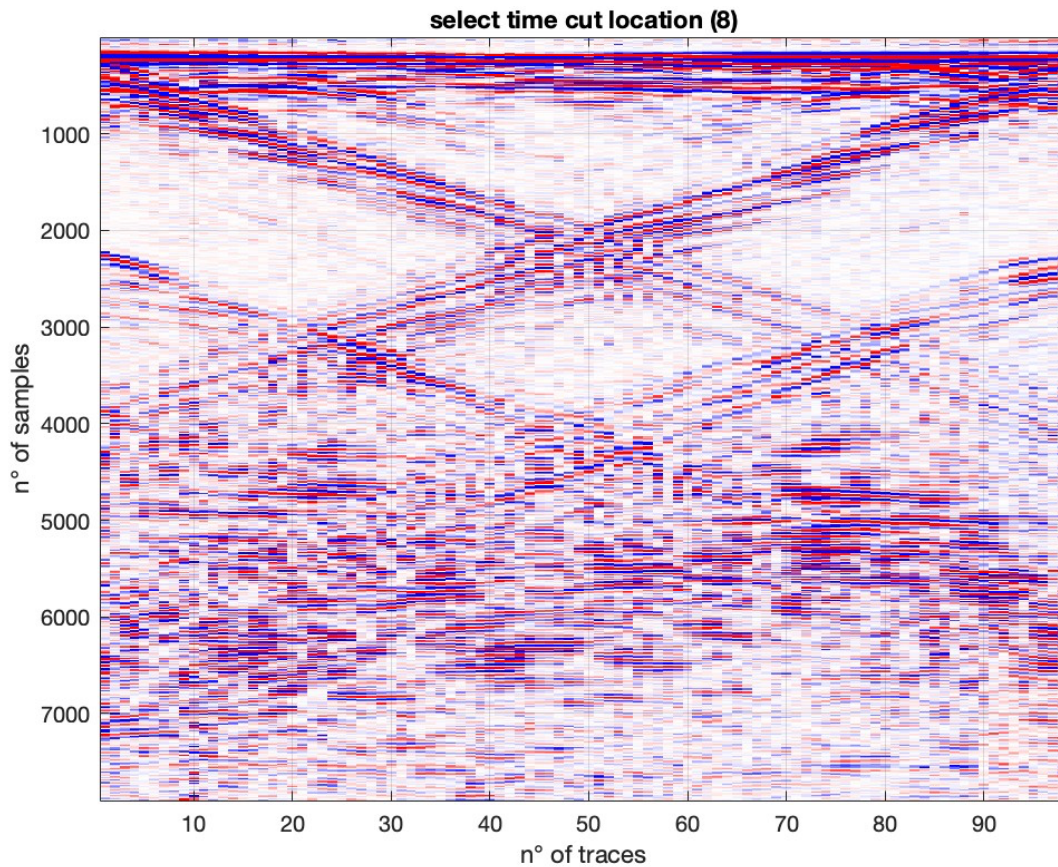


Figure 20. Selection for time cut

4.3.8 Time Cut

A time cut was applied to remove unnecessary late-time data beyond the depth of structural interest. Deep sections often contain low-amplitude noise and attenuated signals that do not contribute meaningful information to façade diagnostics. Truncating the time window improved visualization clarity, reduced noise clutter, and focused interpretation on the marble slab, air cavity, and upper masonry wall. In this example, the time cut was applied before 1.7m depth.

After the application of the time cut, both the processed radargram and the instantaneous amplitude image are limited to approximately the upper 0.9 m of depth, focusing the interpretation on the structurally relevant façade zone. In the processed radargram, the removal of deeper late-time data eliminates the chaotic and highly scattered masonry response, resulting in a cleaner section where the air-marble interface, the lower boundary of the marble slab, and the large continuous hyperbolic geometry produced by the slab edges are more clearly visible. Localized, smaller hyperbolas, likely associated with metallic anchoring elements, also become easier to distinguish due to the reduced background noise. In the instantaneous amplitude image, the strong shallow reflector is further emphasized as a high-energy band, while the slab-edge hyperbola appears more concentrated in terms of energy distribution. The deeper weak scattering is no longer present, improving contrast and structural clarity.

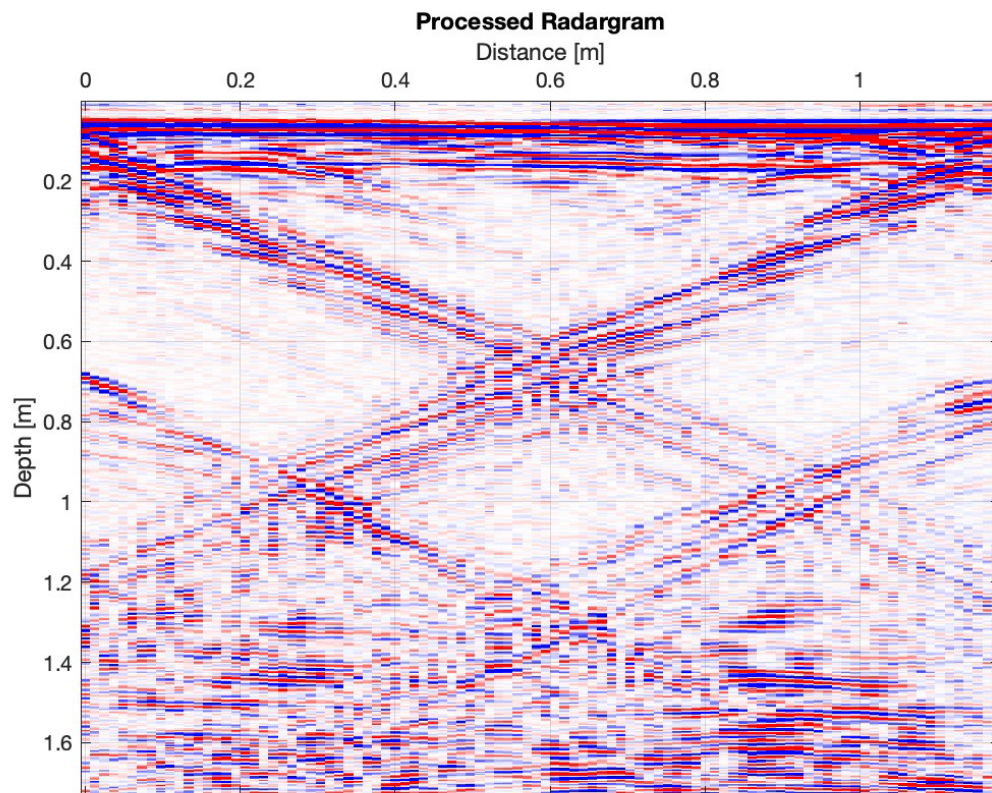


Figure 21. Processed Radargram

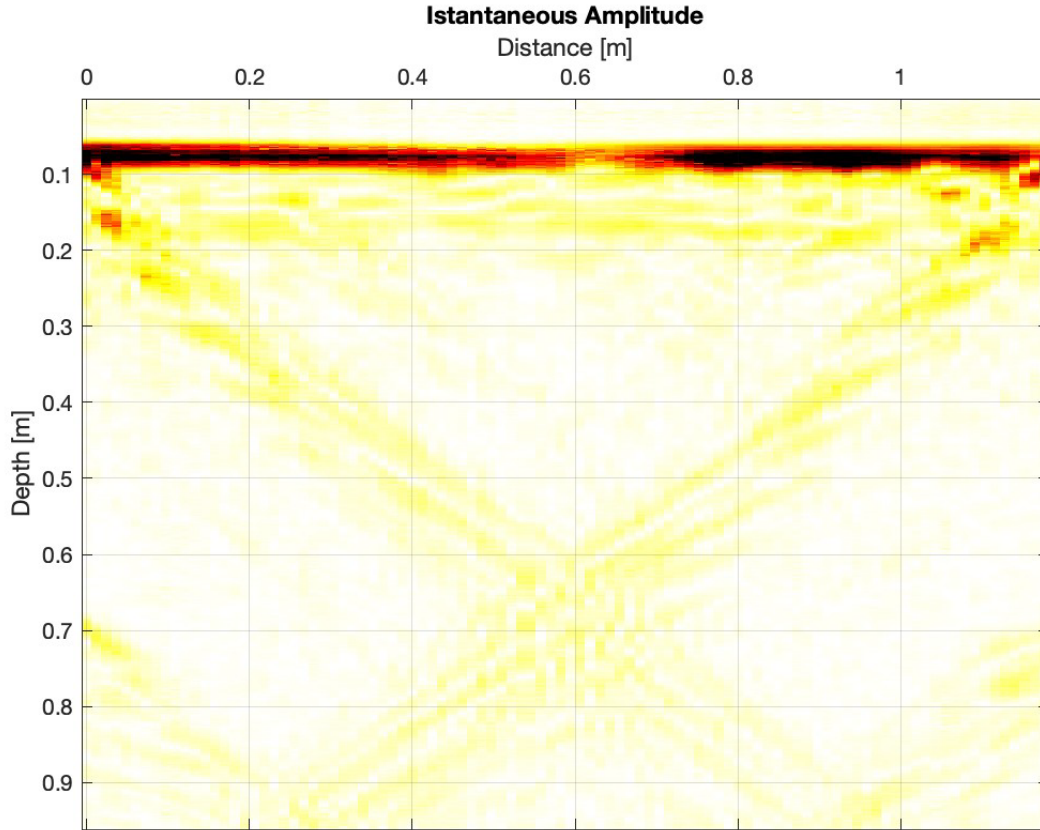


Figure 22. Instantaneous Amplitude

Structural and Electromagnetic Characterization of the Scanned Façade

The six GPR profiles consistently reveal a multilayer façade configuration composed of four main zones: the air region in front of the antenna, the suspended marble slab, an air cavity between the slab and the church wall, and the masonry wall itself. Each of these zones exhibits distinct physical and electromagnetic characteristics that control the radar response observed in the processed radargrams.

The uppermost zone corresponds to the air in which the antenna was installed during acquisition. Physically, this is a non-conductive and homogeneous medium with negligible attenuation. Electromagnetically, air has a relative dielectric permittivity of approximately $\epsilon_r \approx 1$, which allows electromagnetic waves to propagate at nearly the speed of light according to

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (8)$$

Because air presents the lowest possible permittivity, a strong reflection is generated when the wave encounters the marble surface below. This air–marble interface appears in all profiles as a continuous, high-amplitude reflector and represents the first major impedance contrast in the façade system.

Immediately beneath this region lies the marble slab, which forms the visible external architectural element. Physically, the slab is a compact, relatively homogeneous stone material mechanically suspended on metallic nails. Marble typically exhibits a relative permittivity in the range of $\epsilon_r \approx 6\text{--}8$, resulting in a reduced wave velocity compared to air and moderate signal attenuation. In the radargrams, the slab is characterized by two sub-parallel reflectors corresponding to its upper and lower boundaries. The internal portion of the slab shows limited scattering, confirming its structural uniformity. The clarity and lateral continuity of these reflectors across all seven profiles indicate a consistent slab thickness and intact material condition.

Below the slab, a distinct air cavity is identified between the marble and the masonry wall. Physically, this void represents a gap that separates the slab from direct contact with the structural backing wall. Electromagnetically, the cavity reintroduces a medium with $\epsilon_r \approx 1$, creating strong dielectric contrasts at both the marble–air and air–masonry interfaces. These contrasts generate pronounced reflections and enhance amplitude responses in the instantaneous amplitude attribute. The presence of this cavity confirms that the slab is mechanically suspended rather than bonded to the wall. Within this void zone, hyperbolic diffractions are consistently observed and correspond to metallic nail supports; their high electrical conductivity produces strong localized reflections and characteristic “smile-shaped” diffraction patterns.

The deepest zone corresponds to the masonry church wall. Physically, this structure is composed of heterogeneous historic materials, including stone, brick, and mortar, possibly with variable moisture content. Electromagnetically, the masonry exhibits higher effective permittivity and conductivity compared to marble, leading to increased attenuation and scattering of the radar signal. As a result, the radargrams show reduced reflector continuity and progressive amplitude decay with depth. This behavior reflects the heterogeneous internal structure of the wall and the natural energy loss of electromagnetic waves in more conductive materials.

5. Results

5.1 Modeling results

Quantitative Description of the Modelled Targets

To provide a more precise description, the approximate geometric dimensions of the modelled targets were quantified in terms of their cross-sectional areas within the numerical grid. These values provide additional information about the relative size of the different elements embedded within the wall model. The metallic nails were modelled as vertical rectangular inclusions embedded within the slab–wall system. Each nail occupies an area of approximately 0.0075 m^2 within the simulation domain. The nails are positioned symmetrically along the profile at horizontal positions corresponding to 0.3 m and 0.9 m , producing a center-to-center spacing of approximately 0.60 m . Due to their metallic nature and relatively compact geometry, these elements represent strong electromagnetic scatterers within the model.

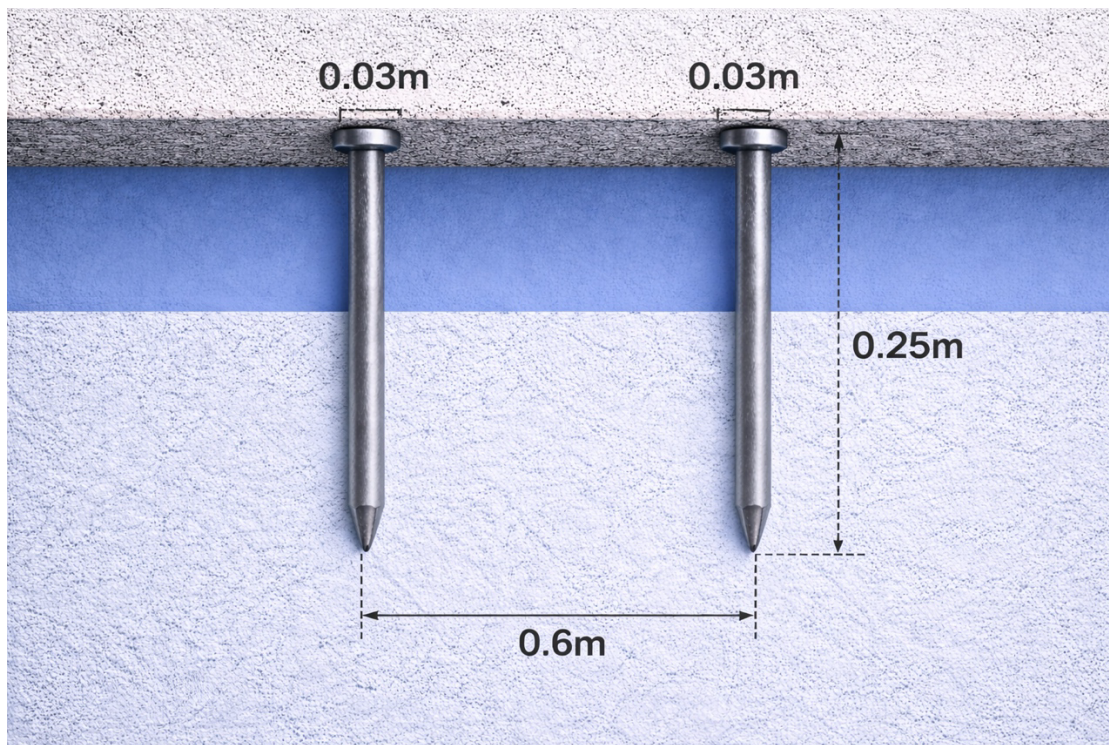


Figure 23. Steel nails and measurements

The model also includes two horizontal pipes, which represent possible service conduits embedded within the wall. Each pipe has an approximate cross-sectional area of 0.0606 m^2 within the simulation grid. Although the two pipes share the same dimensions, their joint positions differ, introducing slight geometric asymmetry in the model. The first pipe contains a joint located at approximately one-third of the total profile length measured from the left side of the model, whereas the second pipe contains its joint at approximately two-thirds of the profile length measured from the left side. This configuration allows the simulation to reproduce small structural discontinuities that may occur in real installations.

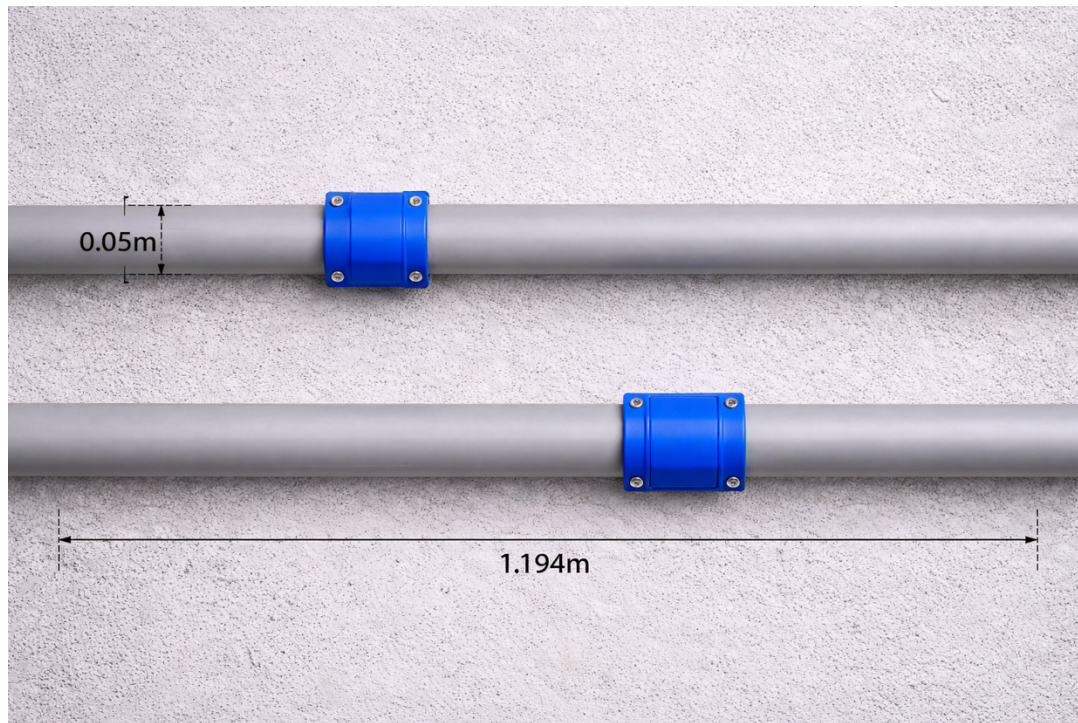


Figure 24. PVC or Steel pipes with couplings

Two air-filled cavities were also included to represent possible voids or detachments within the wall structure. The upper cavity, located above the first pipe, is relatively small and has an approximate area of 0.0012 m^2 . The second cavity is positioned deeper in the model, below the second pipe and toward the right portion of the domain. This cavity is larger, with an approximate area of 0.00222 m^2 . The presence of cavities with different dimensions allows the simulation to evaluate how cavity size influences the resulting radar response. Larger voids typically produce stronger reflections due to the greater dielectric contrast between air and the surrounding masonry material.

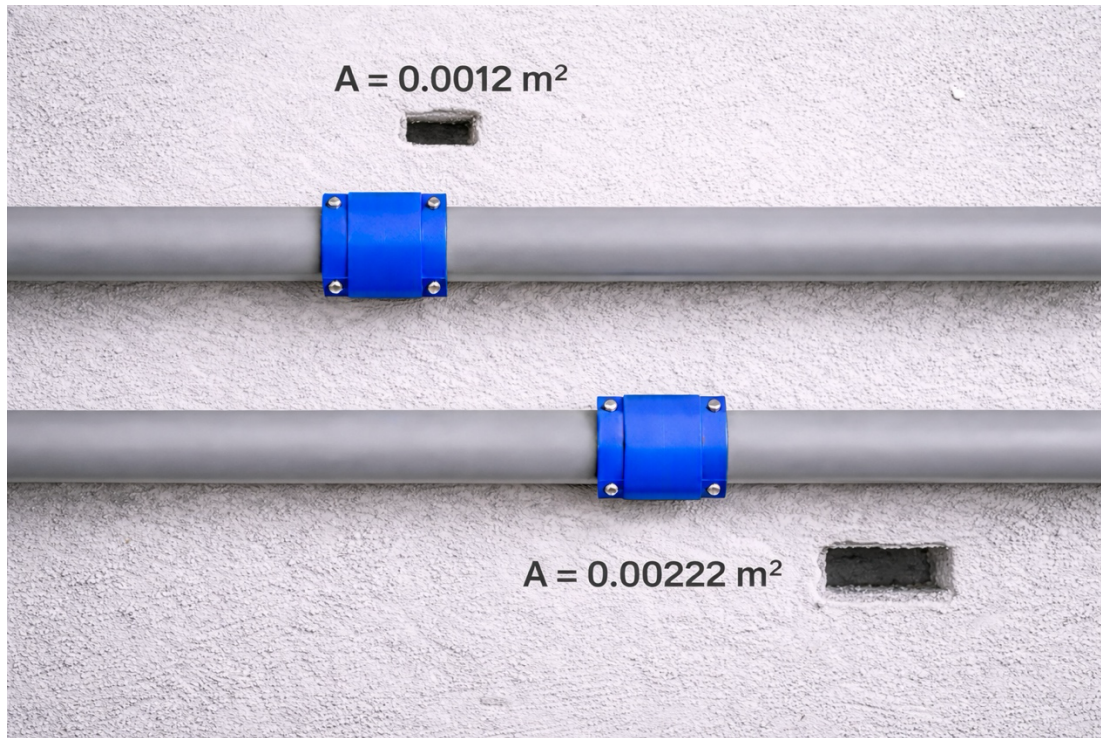


Figure 25. Cavities and pipes with couplings

The modeled targets are presented both as a conceptual schematic and as their numerical implementation in the simulation. Figure 22 shows a simplified representation of the physical scenario, highlighting the position and dimensions of the elements included in the model. The configuration consists of two metallic nails placed near the upper part of the wall, separated by a horizontal distance of 0.6 m and penetrating the wall to a depth of about 0.25 m. Deeper within the wall, two horizontal pipes are included in the model together with two air-filled cavities of different sizes. The first cavity is located above the upper pipe, while the second and slightly larger cavity is positioned below the lower pipe. This schematic view helps visualize how the different targets are arranged within the wall and clarifies the geometric relationships between them.

The numerical representation of this configuration is shown in Figure 23, which displays the spatial distribution of the relative permittivity (ϵ_r) is used in the MATLAB model. In this image, the simulation domain is discretized into a computational grid where different electromagnetic properties are assigned to the slab, the wall material, and the embedded targets. The variations in permittivity allow the nails, pipes, and cavities to be clearly distinguished within the model. By comparing the schematic illustration with the permittivity matrix, it is possible to verify that the geometry and position of the targets were correctly implemented in the numerical model. This representation forms the basis for the simulation of the GPR response discussed in the following section.

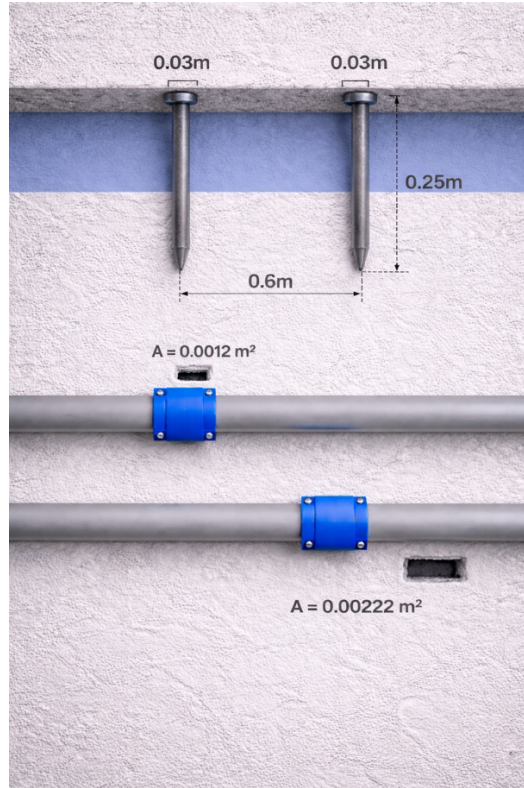


Figure 26. Conceptual schematic

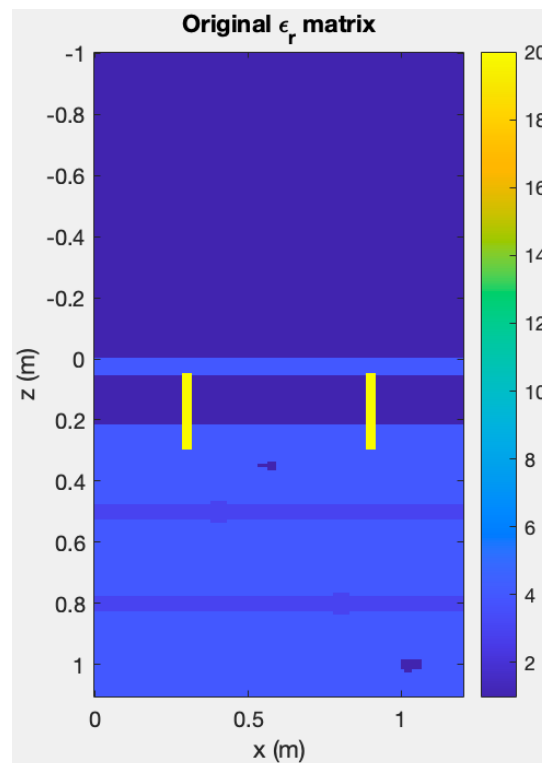


Figure 27. MATLAB ϵ_r matrix

The geometric characteristics of the modeled targets were defined to reproduce a simplified yet representative configuration of possible subsurface elements that may exist behind the façade. The model includes metallic nails, horizontal pipes, and air-filled cavities placed at different depths within the wall structure. Each element was assigned specific geometric dimensions and spatial positions within the simulation domain. Table 2 summarizes the main geometric properties of the modeled elements, including the material type, approximate area, depth range, and their relative position within the model. These parameters were used to construct the numerical model and ensure a consistent representation of the simulated targets.

Table 2. Modelled elements and their geometric properties

Element	Material	Area (m ²)	Depth	Details
Left nail	Metal	0.0075	Shallow (~0.05–0.30 m)	center at x = 0.3 m
Right nail	Metal	0.0075	Shallow (~0.05–0.30 m)	center at x = 0.9 m
Upper pipe	PVC / Steel	0.0606	~0.47–0.53 m	joint located at 1/3 of the profile
Lower pipe	PVC / Steel	0.0606	~0.77–0.83 m	joint located at 2/3 of the profile
Upper cavity	Air	0.0012	~0.33–0.36 m	located above the first pipe
Lower cavity	Air	0.00222	~0.98–1.04 m	located below the second pipe

As summarized in Table 2, the model includes two shallow metallic nails centered at approximately 0.3 m and 0.9 m along the profile. Two horizontal pipes are positioned at greater depths within the wall, while two air-filled cavities of different sizes are located above the upper pipe and below the lower pipe, respectively. This geometric configuration was designed to represent plausible subsurface conditions behind façade slabs and to generate distinct electromagnetic reflections that can be analyzed in the simulated GPR profiles.

5.1.1 Scenario 1- Nails + Slab + Wall

For the first simulation scenario, which includes only the slab, the wall material, and the two metallic nails, the numerical model was run using the same computational framework described in Chapter 3. The source pulse used in the simulation contains frequency components up to approximately 2.81 GHz, which is consistent with a high-frequency GPR signal suitable for detecting shallow targets and small embedded elements. Based on the material properties assigned to the model, the minimum wavelength in the computational domain was estimated as 0.0238 m. This value was used to evaluate the numerical discretization requirements of the grid.

The spatial discretization adopted in the simulation was $dx = dz = 0.01$ m, while the temporal discretization was $dt = 0.02$ ns. Before the beginning of the simulation, the code automatically checked the numerical stability condition and reported a maximum stable time step of

approximately 0.020217 ns for the selected grid. Since the adopted time step is slightly smaller than this limit, the simulation satisfies the stability condition and can be considered numerically reliable. The same preliminary step also verified the compatibility of the spatial discretization with the source wavelength and the electromagnetic properties of the materials included in the model.

The synthetic acquisition was performed along 119 source positions, producing a radar profile over a horizontal distance of approximately 1.2 m. For each source position, the wave propagation was simulated over 2501-time iterations, corresponding to a total time window of 50 ns. This time range is sufficient to record both the early reflections associated with the slab interface and the deeper diffraction responses generated by the metallic nails. The total computational time for the complete simulation was approximately 0.124 h, which corresponds to about 7.5 minutes.

The geometry of the numerical model for Scenario 1 is defined by the spatial distribution of the relative permittivity (ϵ_r), shown in Figure 28. The upper layer represents the marble slab, characterized by higher permittivity values, while the underlying region corresponds to the wall material with lower permittivity. Two metallic nails are embedded in the upper part of the wall at approximately $x = 0.3\text{m}$ and $x = 0.9\text{m}$, extending vertically from the slab into the wall. These elements introduce strong electromagnetic contrasts within the model, which generate reflections during wave propagation. The interpolated permittivity matrix shown in the lower panel represents the smoothed version of the original model used for the numerical simulation, ensuring a consistent representation of material boundaries within the computational grid. The interpolated permittivity matrix represents the grid-adapted version of the original model and is used by the numerical solver to ensure accurate representation of material boundaries within the discretized computational domain.

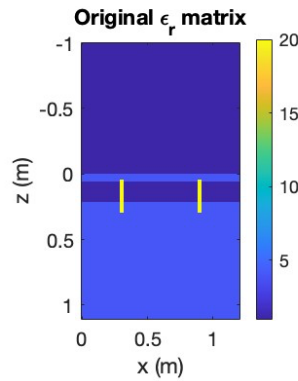


Figure 28. Relative permittivity (ϵ_r) - scenario 1

The relative magnetic permeability (μ_r) distribution of the model is shown in Figure 29. Both the original and interpolated μ_r -matrices present a uniform value across the entire domain, indicating that all materials in the model are assumed to be non-magnetic. In practical terms, this means that the magnetic permeability is approximately equal to that of free space ($\mu_r \approx 1$). As a result, no magnetic contrasts are introduced in the simulation, and the electromagnetic wave propagation is mainly controlled by variations in electrical properties such as relative permittivity and electrical conductivity. Consequently, the main reflections observed in the simulated radargram are related to dielectric contrasts between materials rather than magnetic effects.

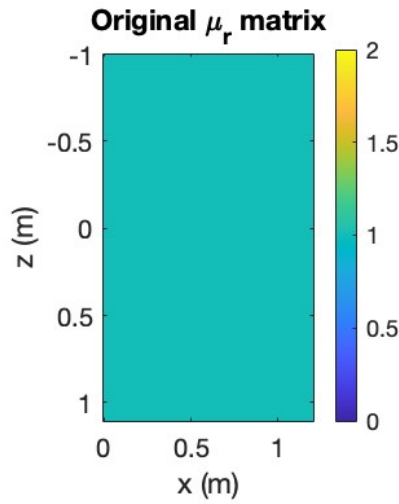


Figure 29. Relative magnetic permeability μ_r matrices – scenario 1

The electrical conductivity (σ) distribution of the model is illustrated in Figure 30. The matrices show the spatial variation of conductivity within the simulated domain, including the slab layer, the masonry wall, and the metallic nails. The metallic nails exhibit significantly higher conductivity values compared to the surrounding construction materials, which is consistent with their metallic nature. This strong conductivity contrast contributes to the generation of noticeable electromagnetic reflections during the simulation. The interpolated conductivity matrix closely resembles the original distribution, indicating that the interpolation step preserves the main material boundaries while adapting the values to the computational grid used in the numerical solver.

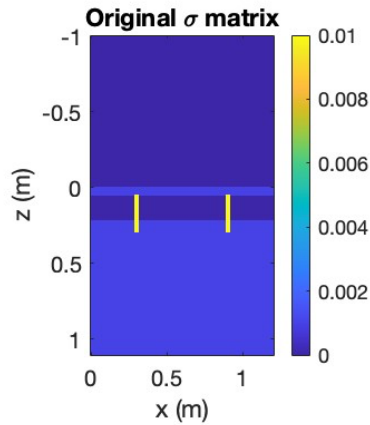


Figure 30. Electrical conductivity (σ) matrices – scenario 1

The propagation of the electromagnetic wave within the modeled structure is illustrated in Figure 31 through a snapshot of the electric field component E_y at $t = 50\text{ns}$. The figure shows how the emitted radar wave travels from the surface into the slab and the underlying masonry wall. As the wave encounters the metallic nails embedded in the slab, strong scattering patterns are generated due to the high electromagnetic contrast between the metal and the surrounding materials. These interactions produce circular wavefronts that radiate outward from the nails, clearly indicating their presence within the structure. In addition, a continuous reflection is visible along the slab–wall interface, representing the dielectric contrast between the slab layer and the underlying masonry material. The wavefield distribution, therefore, highlights the main reflection mechanisms that contribute to the formation of the simulated radar response.

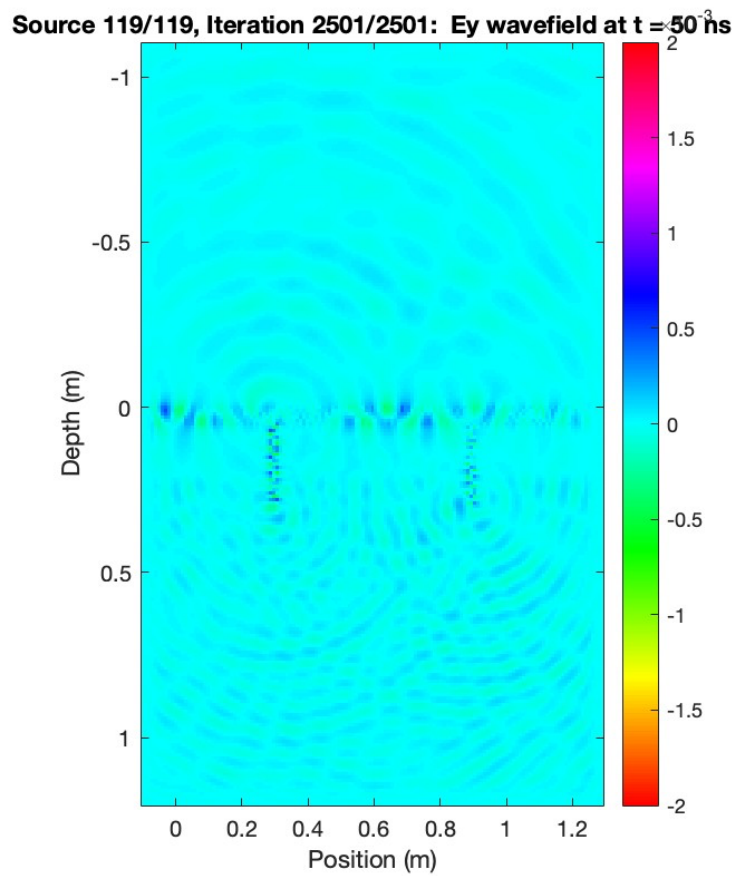


Figure 31. Snapshot of the simulated E_y wavefield – scenario 1

The synthetic radargram generated for Scenario 1 is shown in Figure 32. The image represents the simulated GPR response produced by the interaction of electromagnetic waves with the slab–wall system containing two metallic nails. The radargram clearly shows two characteristic diffraction hyperbola located approximately at 0.3 m and 0.9 m along the profile, corresponding to the positions of the left and right nails. These hyperbolic patterns are typical responses of point-like metallic objects in GPR data and result from the scattering of electromagnetic waves as the antenna moves along the surface. In addition to these diffractions, several continuous horizontal reflections are visible in the upper part of the radargram, representing the interfaces between the slab and the underlying masonry materials. At greater travel times, the signal amplitude gradually decreases due to attenuation within the wall material. Overall, the simulated radargram confirms that metallic nails embedded in the slab generate strong, identifiable reflections in the GPR response.

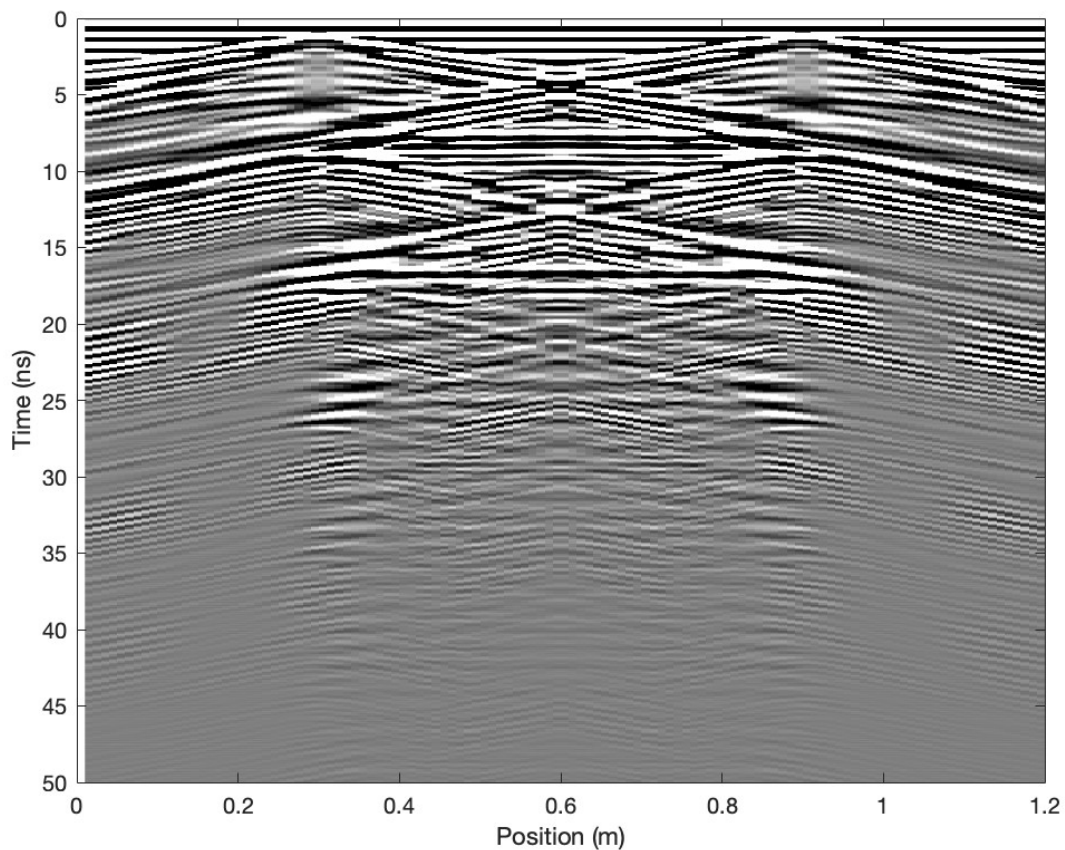


Figure 32. Synthetic radargram – scenario 1

The hyperbolic diffractions observed in the radargram correspond to the modeled positions of the nails (0.3 m and 0.9 m), confirming the consistency between the geometric model and the simulated GPR response.

5.1.2 Scenario 2 - Nails + Slab + Two Cavities + Two Pipes

The spatial distribution of relative permittivity (ϵ_r) is illustrated in Figure 33. Compared to the reference model, additional dielectric contrasts are introduced by the presence of two cavities and two horizontal pipes embedded within the masonry wall. The slab layer remains visible near the surface, while the metallic nails are represented by high-contrast elements extending downward from the slab. The cavities appear as localized zones of very low permittivity corresponding to air-filled voids, whereas the pipes create distinct anomalies due to the difference between their material properties and the surrounding masonry. The interpolated permittivity matrix closely follows the original distribution while adapting the material boundaries to the computational grid used in the numerical simulation.

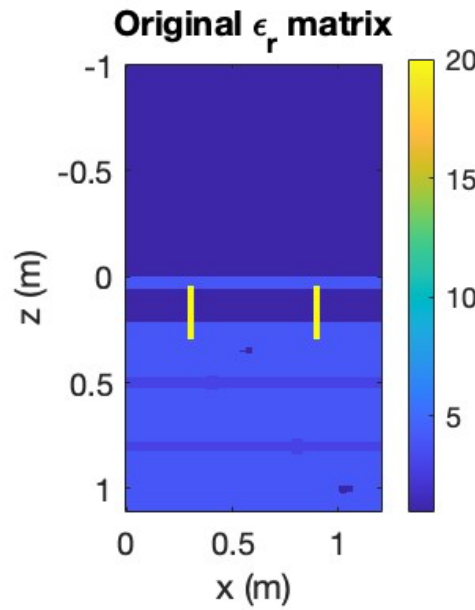


Figure 33. Relative permittivity (ϵ_r) - scenario 2

The relative magnetic permeability (μ_r) distribution used in Scenario 2 is shown in Figure 34. Like the reference model, the permeability remains uniform throughout the simulation domain with a value close to that of free space ($\mu_r \approx 1$). This indicates that all materials included in the model are considered non-magnetic. Consequently, magnetic permeability does not introduce significant contrasts within the model, and the propagation and reflection of electromagnetic waves are primarily controlled by variations in dielectric permittivity and electrical conductivity.

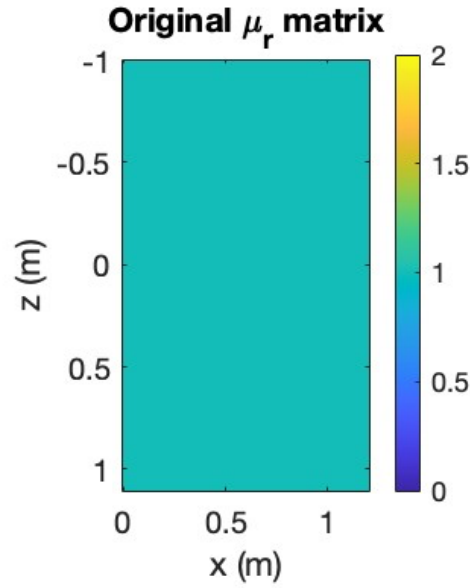


Figure 34. Relative magnetic permeability (μ_r) matrices – scenario 2

In Figure 35. The model includes different conductivity values corresponding to the slab, masonry wall, metallic nails, and the embedded pipes. The metallic nails appear as highly conductive elements compared to the surrounding materials, producing strong electromagnetic contrasts within the model. The cavities, representing air-filled voids, exhibit very low conductivity values, while the pipes introduce additional conductivity variations depending on their material properties. These contrasts play an important role in the generation of reflections observed in the simulated radar response.

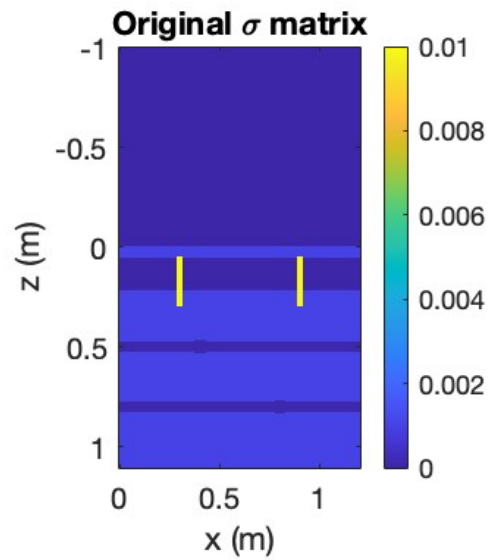


Figure 35. Electrical conductivity (σ) matrices - scenario 2

The propagation of the electromagnetic wave within the model is illustrated through snapshots of the electric field component E_y at two different time steps, $t = 28\text{ns}$ and $t = 50\text{ns}$. These snapshots provide insight into the interaction between the radar signal, and the subsurface targets present in Scenario 2.

At the intermediate stage ($t = 28\text{ ns}$) in Figure 36, the radar pulse has already reached the embedded features and begins to interact with the metallic nails, pipes, and air-filled cavities. Strong localized scattering is observed around the nails due to the high electromagnetic contrast between the metallic elements and the surrounding masonry. At the same time, the presence of pipes and cavities introduces additional diffraction and interference patterns within the model. The cavities disturb the propagation of the wavefront because of the strong dielectric contrast between air and the surrounding wall material, while the pipes generate broader scattering patterns related to their elongated geometry.

At the later stage ($t = 50\text{ ns}$) in Figure 37, the wave energy has propagated further through the model domain, and the reflected energy becomes more distributed. The interaction with the different subsurface features produces multiple overlapping wavefronts that propagate away from the targets. Compared with Scenario 1, the presence of pipes and cavities increases the complexity of the wavefield, generating additional scattering zones and interference patterns within the masonry wall. This behaviour demonstrates how multiple structural elements influence electromagnetic wave propagation and contribute to the formation of the synthetic radargram.

Source 7/119, Iteration 1401/2501: E_y wavefield at $t = 28\text{ ns}$

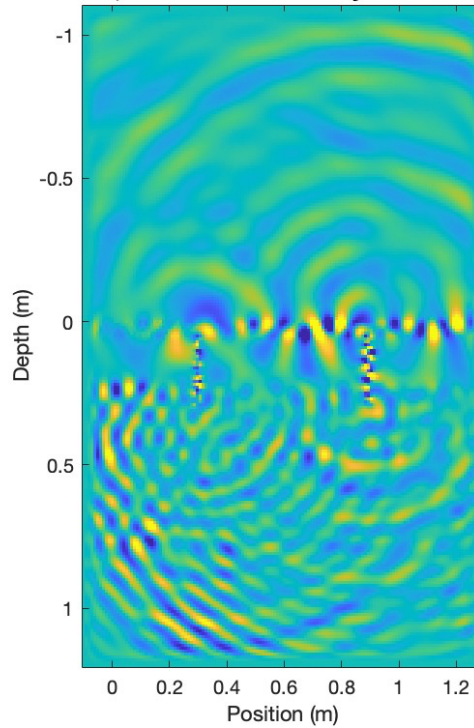


Figure 36. Simulated E_y wavefield $t=28\text{ns}$ - scenario 2

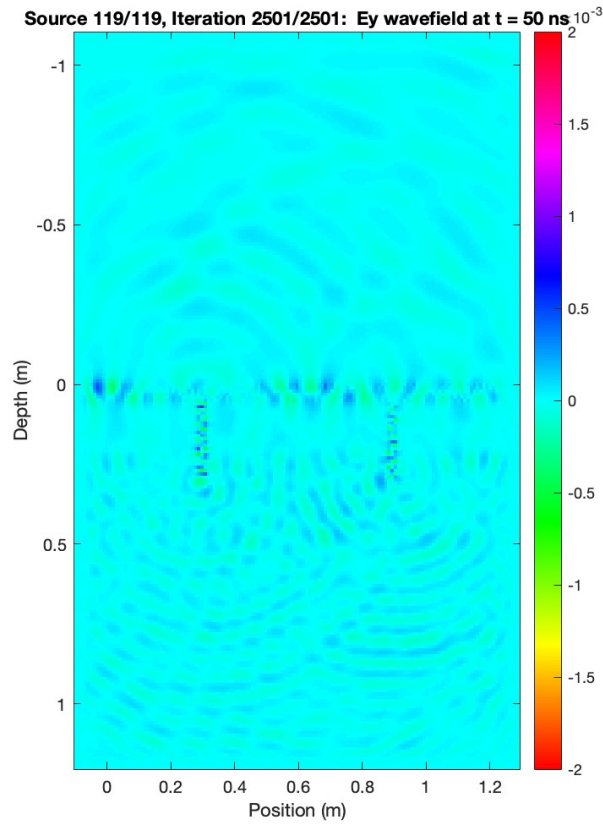


Figure 37. Simulated E_y wavefield $t=50\text{ns}$ - scenario 2

The synthetic radargram for Scenario 2 illustrates the simulated GPR response of the masonry wall containing nails, pipes, and cavities. Compared with the previous scenario, the radar response becomes significantly more complex due to the presence of additional subsurface features. While the metallic nails remain visible as distinct hyperbolic reflections near the shallow part of the radargram, the introduction of pipes and cavities produces additional reflection and scattering patterns. The pipes generate broader reflection zones that extend laterally along the profile because of their elongated geometry. In contrast, the air-filled cavities create localized disturbances in the reflected signal due to the strong dielectric contrast between air and the surrounding masonry.

At greater travel times, the radargram shows overlapping reflections and diffractions produced by the interaction of electromagnetic waves with multiple targets within the wall. These combined responses create a more irregular reflection pattern compared with the simpler configuration of Scenario 1, highlighting how additional structural elements influence the overall GPR signature of the model.

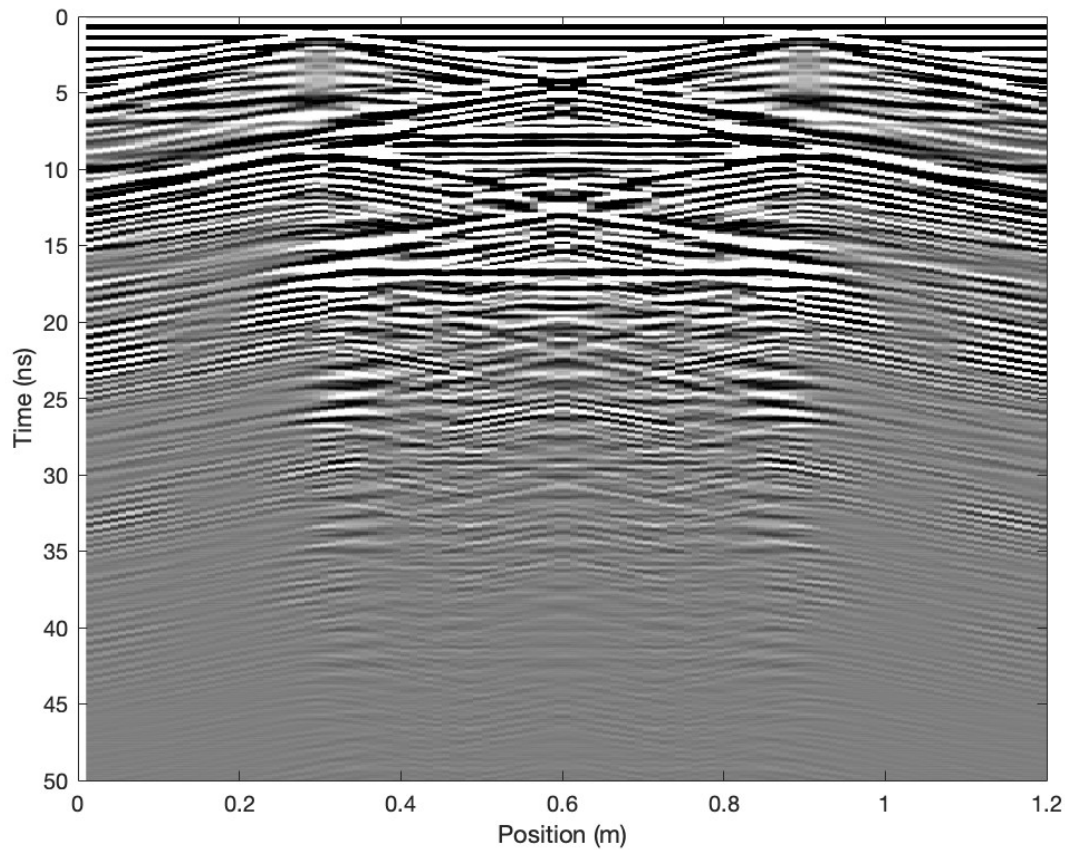


Figure 38. Synthetic radargram - scenario 2

5.1.3 Scenario 3 - Wall + Two Cavities + Two PVC Pipes

The distribution of relative permittivity (ϵ_r) for Scenario 3 is presented in Figure 39. In this configuration, the model consists of the masonry wall containing two horizontal PVC pipes and two air-filled cavities, while the metallic nails and the slab considered in the previous scenarios are no longer included. The masonry wall forms the main background medium with relatively uniform dielectric properties. The PVC pipes appear as elongated zones with slightly different permittivity compared to the surrounding material, while the cavities are represented by small regions of very low permittivity corresponding to air. These contrasts in dielectric properties define how the electromagnetic waves propagate through the model and play a key role in generating the reflections observed in the simulated radar response.

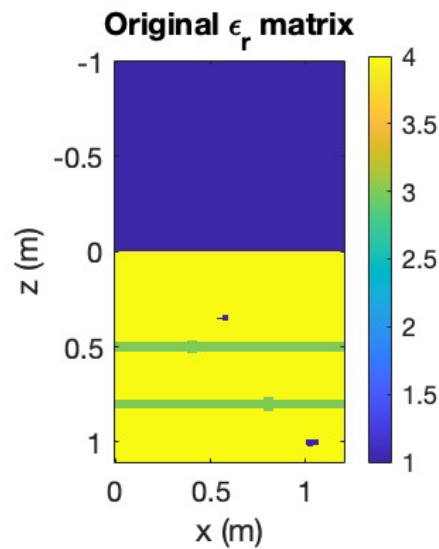


Figure 39. Relative permittivity (ϵ_r) - scenario 3

Figure 40 presents the spatial distribution of the relative magnetic permeability (μ_r). The magnetic permeability is constant throughout the entire computational domain, with a value of $\mu_r = 1$. This reflects the assumption that all materials included in the model, such as masonry, PVC pipes, and air-filled cavities, behave as non-magnetic media.

Because no magnetic contrasts exist within the model, the μ_r parameter does not contribute to reflections or scattering of the electromagnetic waves. For this reason, both the original and interpolated μ_r matrices appear uniform and identical. The wave propagation observed in the simulation is therefore mainly controlled by variations in dielectric permittivity and electrical conductivity rather than magnetic permeability.

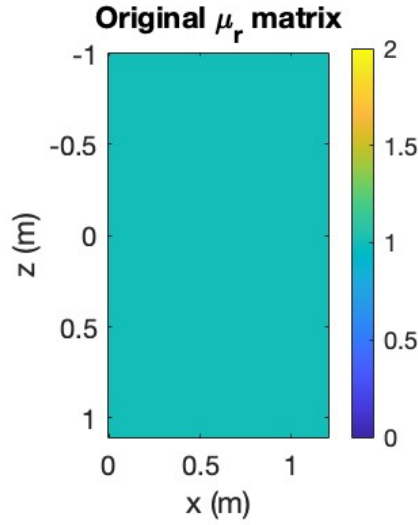


Figure 40. Relative magnetic permeability (μ_r) matrices - scenario 3

Figure 41 shows the electrical conductivity (σ) distribution used in the model for Scenario 3. The masonry wall is characterized by a relatively low but uniform conductivity, representing the typical electrical behavior of dry masonry materials. In contrast, the air region above the wall exhibits nearly zero conductivity, reflecting its non-conductive nature.

Within the wall, the PVC pipes appear as elongated zones with very low conductivity, since PVC is an insulating material. Similarly, the cavities are modeled as air-filled voids and therefore also present negligible conductivity values. These low-conductivity inclusions create clear contrasts with the surrounding masonry, which influence the attenuation and reflection of the electromagnetic waves during propagation.

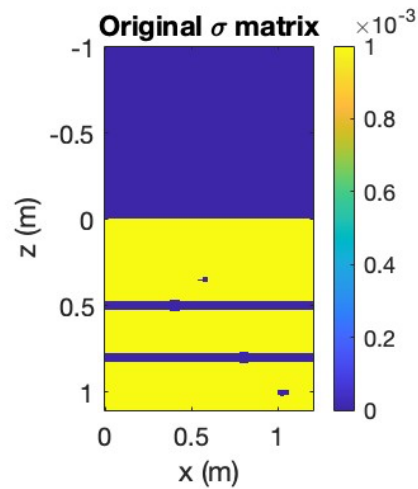


Figure 41. Electrical conductivity (σ) matrices - scenario 3

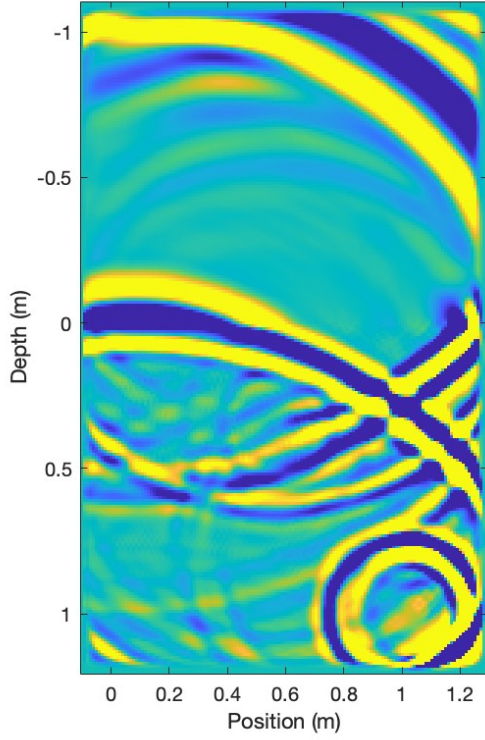
The evolution of the electromagnetic wave propagation within the model is illustrated through several snapshots of the electric field component E_y at different times ($t = 11$ ns, 17 ns, 21 ns) together with the final state at $t = 50$ ns. These images show how the radar signal progressively interacts with the subsurface features included in Scenario 3. (Figure 42)

At $t = 11$ ns, the emitted wavefront begins to penetrate the masonry wall and spreads radially from the source position. The first interactions occur at the air–wall interface, producing strong reflections due to the significant dielectric contrast. As the wave continues to propagate downward, the initial disturbances associated with the internal targets begin to appear. At $t = 17$ ns, the interaction between the electromagnetic wave and the internal structures becomes more evident. The presence of the PVC pipes generates clear curved reflection patterns due to their cylindrical geometry. These reflections produce localized zones of high amplitude, indicating the positions where the wave encounters dielectric contrasts between the pipe material and the surrounding masonry. At $t = 21$ ns, the wavefront penetrates deeper into the model and multiple scattering effects develop.

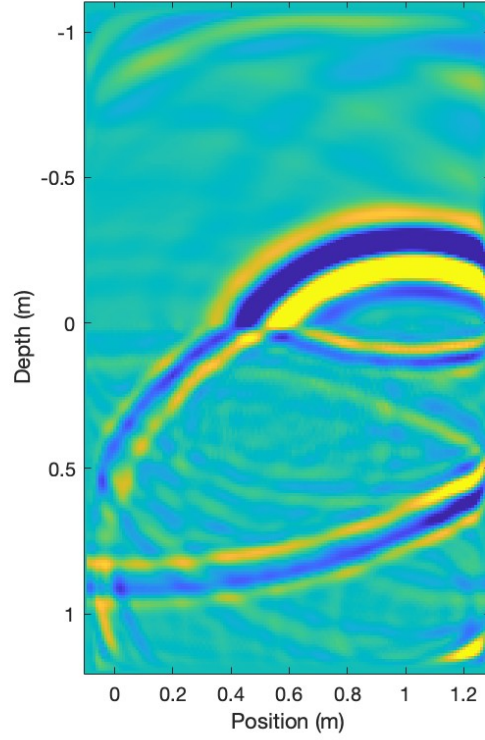
Reflections from the pipes interact with secondary reflections from the surrounding masonry layers, producing more complex interference patterns. The cavities also contribute to localized disturbances in the wave propagation due to the strong dielectric contrast between air and the surrounding material.

Finally, the wavefield at $t = 50$ ns represents the late stage of the simulation, where most of the energy has propagated through the model and undergone multiple reflections and scattering events. Compared with the earlier snapshots, the wavefield appears smoother because the energy has dispersed throughout the computational domain, and part of it has been absorbed by the model boundaries. Nevertheless, the cumulative effects of the subsurface targets are embedded in the recorded signals that form the synthetic radargram.

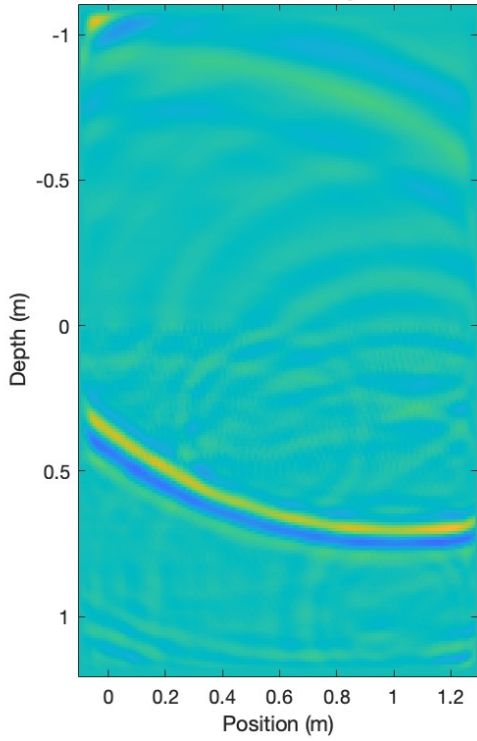
Source 8/119, Iteration 551/2501: Ey wavefield at t = 11 ns



Source 5/119, Iteration 851/2501: Ey wavefield at t = 17 ns



Source 6/119, Iteration 1051/2501: Ey wavefield at t = 21 ns



Source 119/119, Iteration 2501/2501: Ey wavefield at t = 50 ns

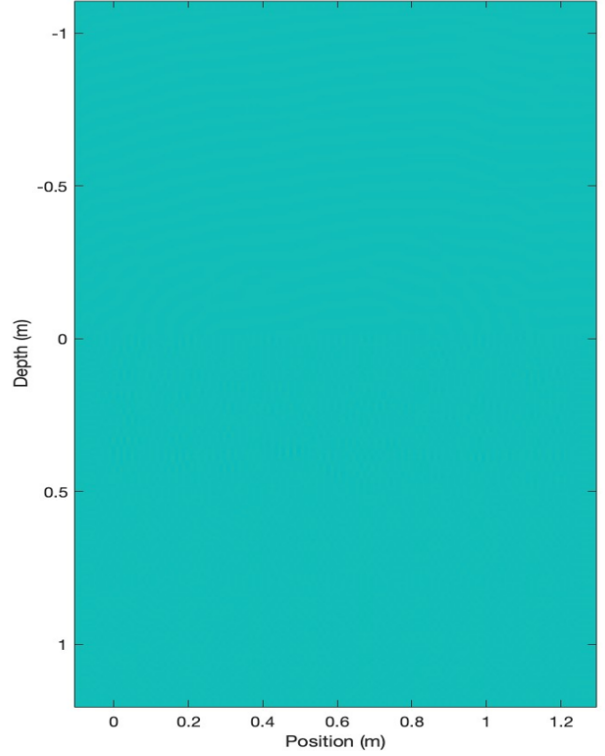


Figure 42. Snapshots of the simulated electric field component E_y at different times ($t=11$, 17, 21, and 50 ns) showing the propagation of the electromagnetic wave within the model – scenario 3

The synthetic radargram obtained for Scenario 3 illustrates the reflections produced by the internal structures within the masonry wall when scanned by the simulated GPR system. The first strong and continuous reflection visible near the top of the radargram corresponds to the air–wall interface, which generates a high-amplitude signal due to the large dielectric contrast between air and masonry. This reflection appears as a nearly horizontal event extending across the entire profile. (Figure 43)

Below this interface, additional reflections appear as curved and slightly hyperbolic patterns, which are mainly associated with the presence of the PVC pipes embedded within the wall. Because the pipes have a cylindrical geometry and a dielectric contrast with the surrounding masonry, they produce characteristic reflection signatures that vary along the horizontal scanning direction. The upper pipe generates a broader reflection event around the early time window, while the deeper pipe produces another curved reflection at slightly later times. These features are typical of elongated subsurface objects detected by GPR. In addition to the pipe reflections, weaker disturbances can be observed within the radargram, which are related to the air-filled cavities present in the model. Due to their small size and lower dielectric contrast compared to metallic objects, the cavities generate weaker and more localized reflections. As the radar signal penetrates deeper into the model, the amplitude gradually decreases due to attenuation and energy dispersion within the masonry material, resulting in a smoother and less distinct signal at later times.

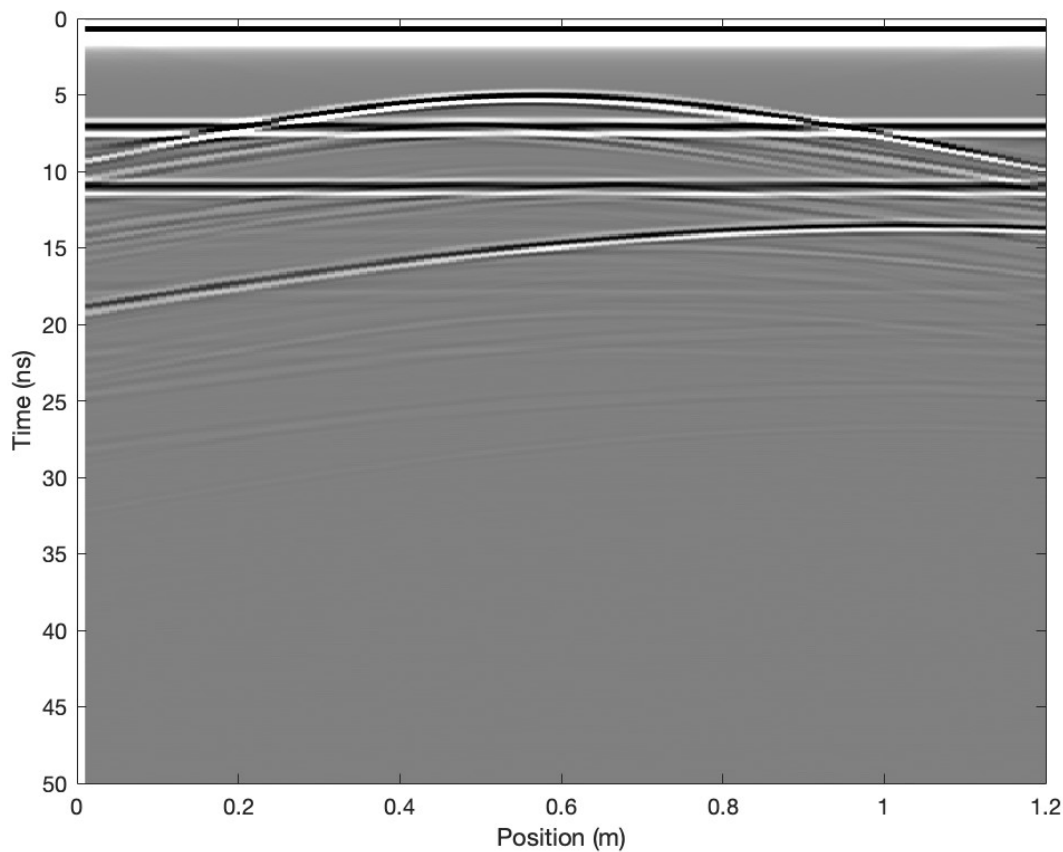


Figure 43. Synthetic radargram - scenario 3

5.1.4 Scenario 4 - Wall + Two Cavities + Two Steel Pipes

Figure 44 shows the relative permittivity (ϵ_r) distribution used for Scenario 4. In this configuration, the model consists of the masonry wall containing two steel pipes and two air-filled cavities embedded within the structure. The masonry wall forms the main background medium and is characterized by a relatively uniform dielectric permittivity. Above the wall, the air region is represented by a much lower permittivity value, producing a clear contrast at the air–wall interface.

Within the wall, the steel pipes appear as elongated horizontal features, while the cavities are represented by small regions of very low permittivity corresponding to air-filled voids. These contrasts in dielectric properties create discontinuities within the medium that strongly influence the propagation of electromagnetic waves. As in the previous scenarios, the interpolated matrix represents a refined version of the original permittivity grid, allowing the material boundaries to be better adapted to the numerical discretization used in the simulation while preserving the overall geometry of the model.

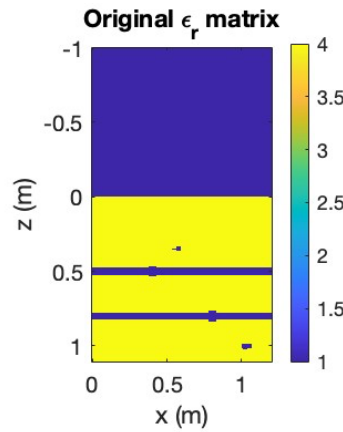


Figure 44. Relative permittivity (ϵ_r) - scenario 4

Figure 45 shows the distribution of relative magnetic permeability (μ_r) used in Scenario 4. The magnetic permeability is uniform across the entire computational domain, with a constant value of $\mu_r = 1$. This assumption indicates that all materials included in the model, masonry, steel pipes, and air-filled cavities, are treated as non-magnetic in the simulation.

As a result, no magnetic contrasts are introduced within the model, and the propagation of the electromagnetic waves is not influenced by variations in magnetic properties. Consequently, the original and interpolated μ_r matrices appear completely homogeneous and identical. The wave behavior observed in the simulation is therefore primarily governed by variations in dielectric permittivity and electrical conductivity rather than magnetic permeability.

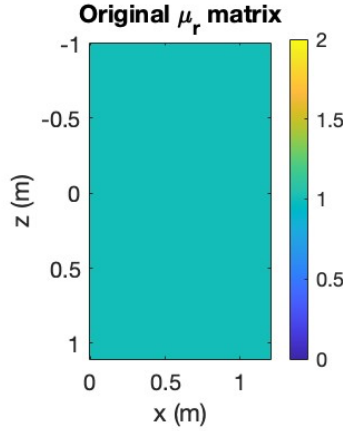


Figure 45. Relative magnetic permeability (μ_r) - scenario 4

In this model, the masonry wall is characterized by relatively low electrical conductivity, representing the typical electrical behavior of dry masonry materials. The air region above the wall exhibits nearly zero conductivity, consistent with its non-conductive nature. (Figure 46)

The steel pipes embedded within the wall appear as horizontal zones with extremely high conductivity values compared to the surrounding masonry. This strong electrical contrast reflects the highly conductive nature of steel and significantly influences the interaction between the electromagnetic waves and the subsurface structures. As a result, the steel pipes are expected to generate strong reflections and scattering during the simulation.

The air-filled cavities are represented by regions of very low conductivity, like air, producing additional contrasts within the model. As in the previous parameter maps, the interpolated matrix represents a refined version of the original conductivity distribution used to match the spatial discretization of the numerical simulation while preserving the geometry and location of the modelled features.

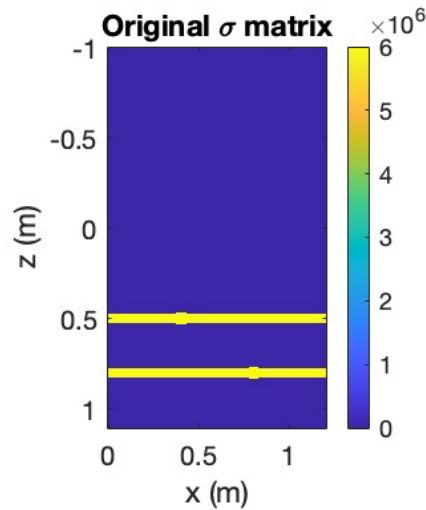


Figure 46. Electrical conductivity (σ) distribution - scenario 4

The sequence of wavefield snapshots shows how the electromagnetic wave propagates through the masonry wall containing two air-filled cavities and two steel pipes. At the earliest stage ($t = 5$ ns), the emitted wave begins to spread from the source and interact with the air-wall interface. Because of the strong contrast between the air and the wall material, part of the wave is reflected while the rest penetrates the masonry. At this moment, the wavefront is still relatively smooth, although small disturbances start to appear as the wave approaches the first internal structures. (Figure 47)

As time progresses ($t = 11$ ns and $t = 16$ ns), the wavefront reaches the embedded objects, and the interaction becomes more complex. The steel pipes produce very strong reflections due to their high conductivity, generating intense wavefronts that propagate both upward and downward within the wall. At the same time, the air-filled cavities slightly distort the wave propagation, creating diffraction patterns and localized scattering. By $t = 25$ ns, most of the main reflections from the pipes and cavities have already formed and continue to travel through the medium. The wavefield becomes more irregular as multiple reflected waves interact with each other, producing interference patterns inside the wall. These effects are stronger than in the previous scenarios, mainly because the steel pipes create much stronger reflections than less conductive materials.

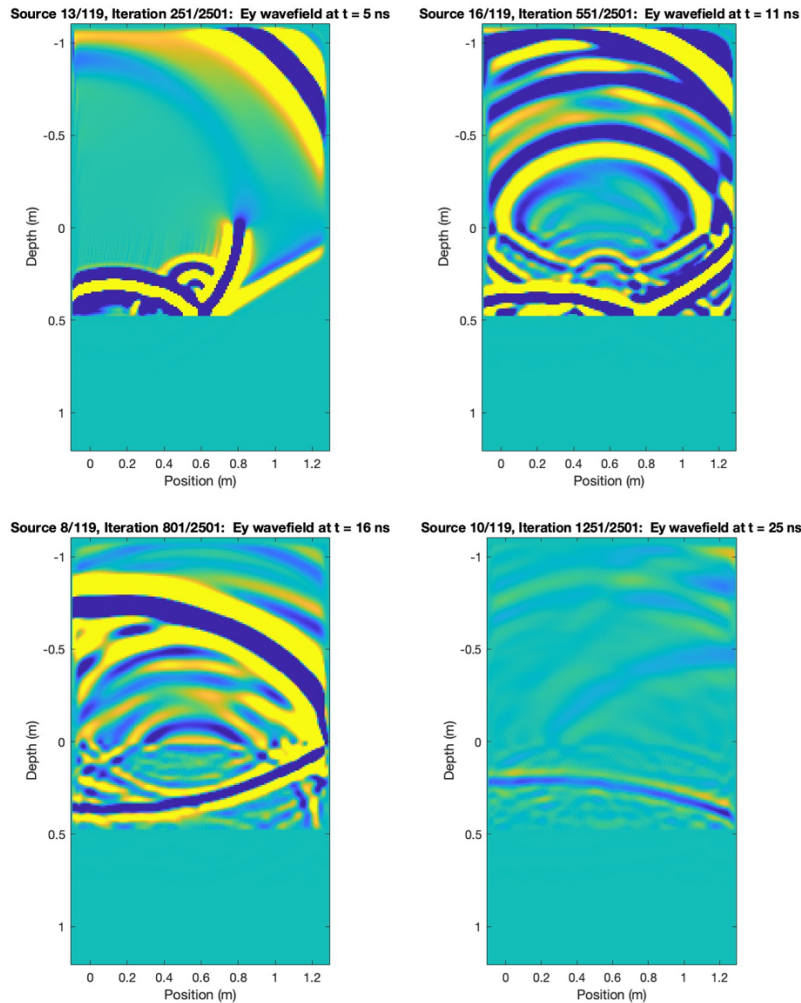


Figure 47. Snapshots of the simulated electric field component E_y at different times ($t=5, 11, 16$, and 25 ns) showing the propagation of the electromagnetic wave within the model - scenario 4

The final snapshot at $t = 50$ ns shows the wavefield after most of the reflections and scattering events have propagated through the model and gradually attenuated. Compared with the earlier snapshots, the strong wavefronts generated by the interaction with the steel pipes and cavities are no longer clearly visible. Most of the energy has already traveled away from the main interaction zones or has been dissipated within the medium. (Figure 48)

In the earlier stages (5–25 ns), the wavefield was dominated by strong reflections and complex interference patterns produced by the highly conductive steel pipes and the air-filled cavities. These structures generated intense scattered waves that propagated in multiple directions inside the wall. By $t = 50$ ns, however, these reflected waves have spread and weakened, resulting in a much smoother and more uniform field distribution. Only faint residual wave patterns remain visible, indicating that the main wave interactions within the model have already occurred at earlier times.

Source 119/119, Iteration 2501/2501: E_y wavefield at $t = 50$ ns

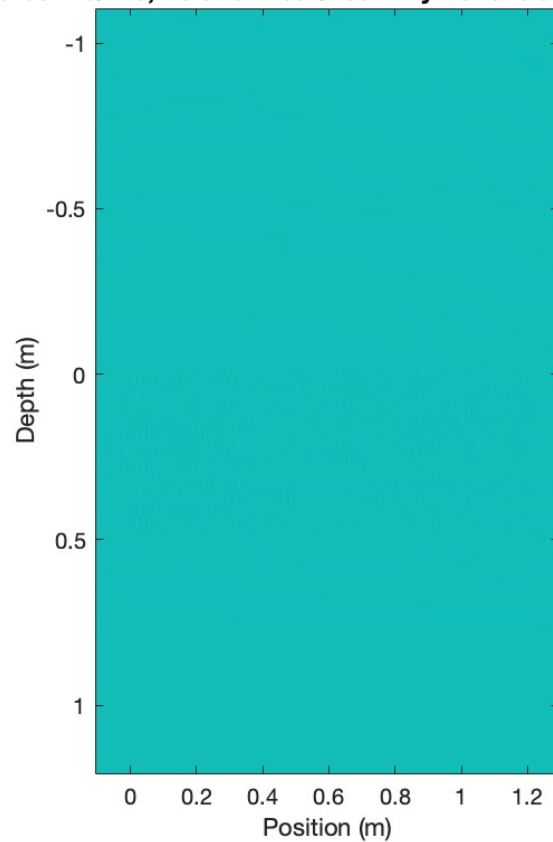


Figure 48. Simulated E_y wavefield $t=50$ ns - scenario 4

The synthetic radargram shows the reflections generated by a masonry wall containing two air-filled cavities and two steel pipes. The first strong and continuous reflection visible near the top of the radargram corresponds to the air–wall interface, where the electromagnetic wave encounters the boundary between air and the masonry material. This interface produces a clear and laterally continuous reflector across the entire profile. Below this boundary, several high-amplitude reflections appear due to the presence of the steel pipes embedded in the wall. Because steel is highly conductive, these pipes generate very strong reflections that appear as pronounced hyperbolic patterns in the radargram. These hyperbolas are clearly distinguishable and dominate the radargram response compared to other subsurface features. (Figure 49)

The air-filled cavities also contribute to the radargram signature. They produce additional diffraction patterns and localized reflections that slightly distort the surrounding wave reflections. However, their response is generally weaker and more diffuse compared to the reflections produced by the steel pipes. At greater times (deeper sections of the radargram), the amplitude of the reflections gradually decreases due to wave attenuation and energy dispersion within the medium. Overall, the radargram clearly highlights the presence and position of the steel pipes, while the cavities introduce secondary anomalies that modify the reflection pattern within the masonry wall.

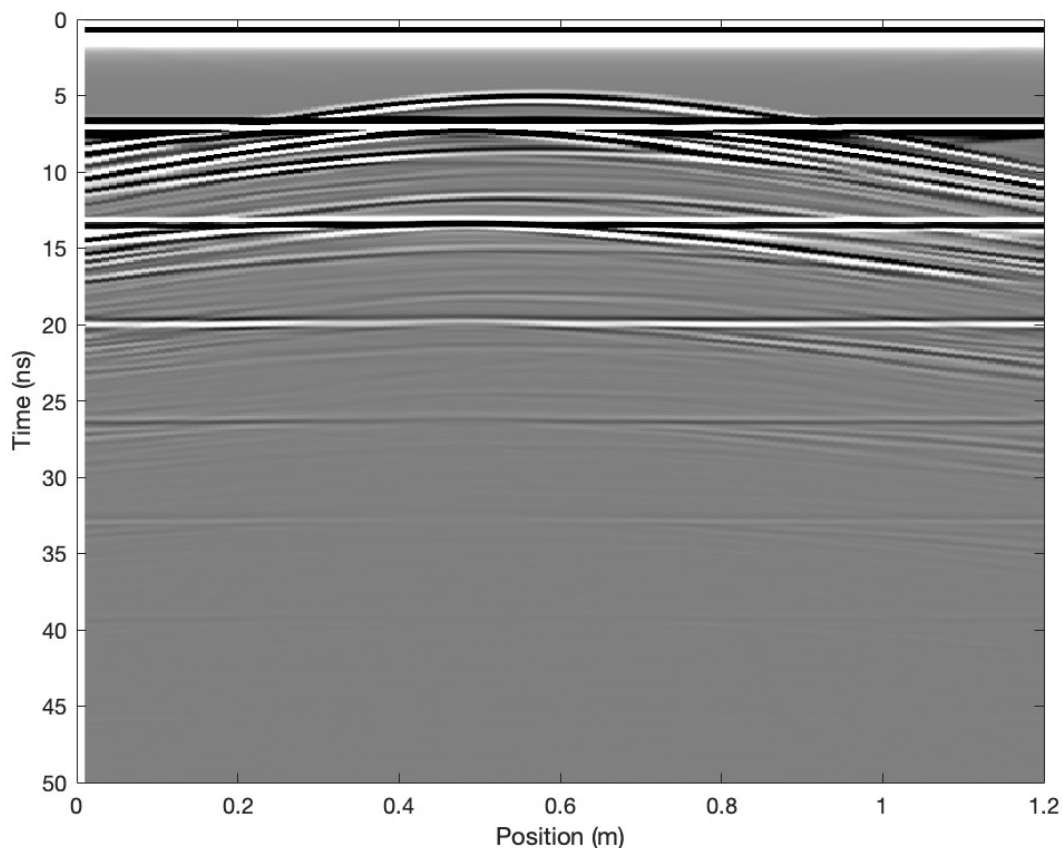


Figure 49. Synthetic radargram - scenario 4

5.2 Experimental results

5.2.1 Left side profiles

Profile 1

The first GPR profile acquired on the left side of the church façade (20 cm spacing) clearly delineates the suspended marble slab and the backing masonry wall. At shallow depth, a strong and continuous horizontal reflector marks the air–marble interface, generated by the high dielectric contrast between air and marble. A second parallel reflector below it defines the lower boundary of the marble slab, allowing the slab thickness to be determined.

At the beginning of the profile, two distinct hyperbolic diffractions are visible near the upper part of the radargram. These “smile-shaped” features correspond to metallic nail supports, as confirmed by their strong amplitude concentration at the hyperbola apex. Their geometry reflects the typical diffraction response of localized conductive targets.

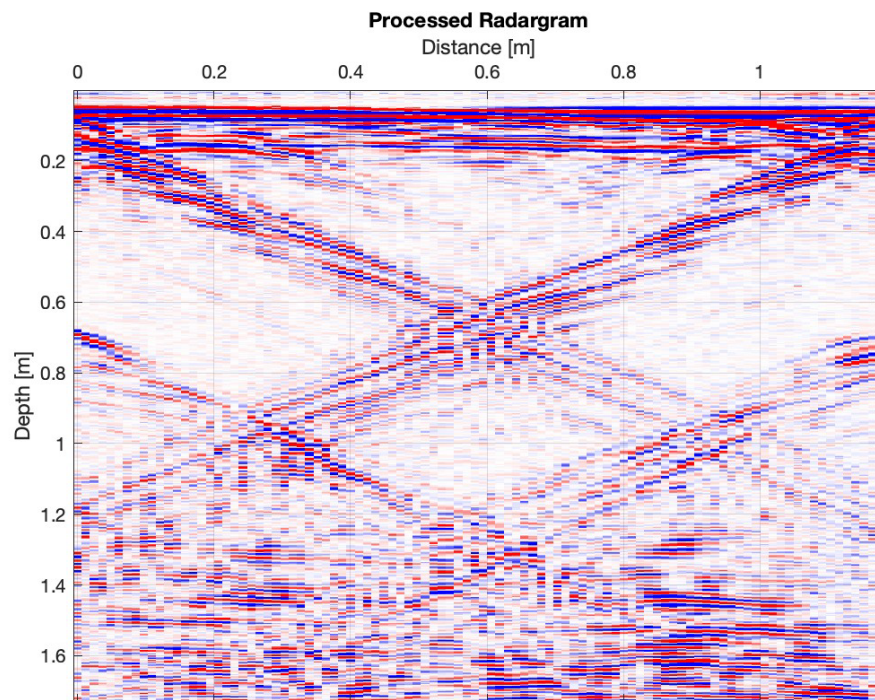


Figure 50. Processed Radargram for profile 1

The most prominent feature in the central portion of the profile is a continuous X-shaped diffraction pattern, representing overlapping reflections from both sides of the marble slab and its anchoring system. This confirms the mechanical suspension of the slab and the symmetric positioning of support elements. Below the slab–cavity region, the signal transitions into a more irregular and attenuated pattern corresponding to the masonry church wall. Reduced reflector

continuity and increased scattering reflect the heterogeneous nature of the historic masonry, while progressive amplitude decay indicates material attenuation with depth.

Profile 2

Processed Radargram Interpretation

The second profile acquired at 40 cm from the previous line confirms the same structural configuration observed in Profile 1. A strong and continuous shallow reflector marks the air–marble interface, produced by the high dielectric contrast between air and marble. Immediately beneath it, a second parallel reflector defines the lower boundary of the marble slab, allowing clear identification of slab thickness. In the central region of the radargram, a prominent, continuous X-shaped diffraction pattern is observed. This feature results from overlapping hyperbolic responses generated by metallic nail supports anchoring the slab. Compared to Profile 1, the hyperbolas appear slightly broader, which may reflect small lateral variations in nail position or slight differences in antenna alignment.

Below the slab and cavity region, the radar response becomes progressively more irregular and scattered. This transition marks the onset of the masonry church wall, where reflector continuity decreases, and signal attenuation increases due to the heterogeneous composition of the historic wall materials.

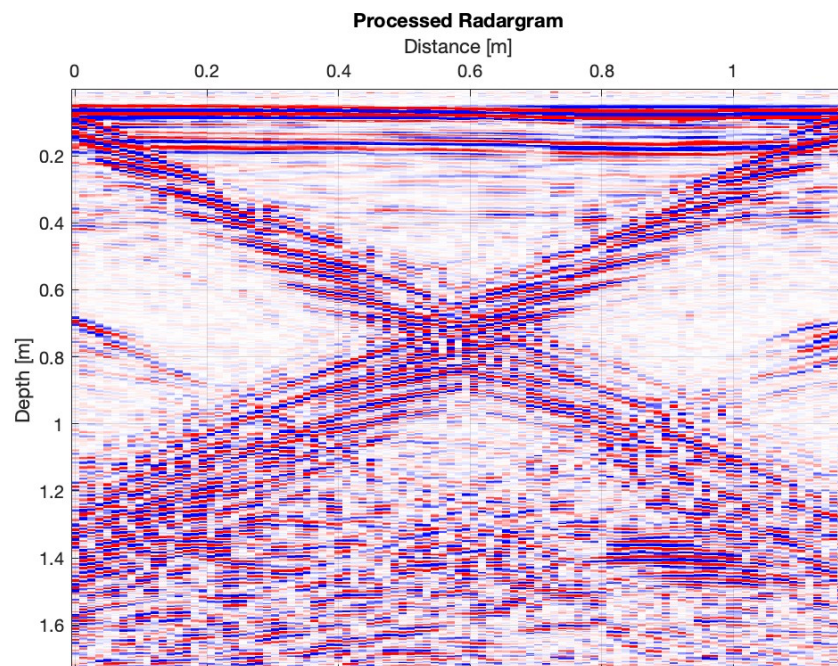


Figure 51. Processed Radargram for profile 2

Profile 3

The third profile, acquired at 60 cm spacing, confirms the structural configuration identified in the previous profiles. A strong and continuous shallow reflector marks the air–marble interface, while a second parallel reflector defines the lower boundary of the marble slab, allowing clear identification of slab thickness and confirming its lateral continuity.

In the central part of the radargram, a distinct X-shaped diffraction pattern is visible, produced by overlapping hyperbolic responses from metallic nail supports within the air cavity. Although the hyperbolas appear slightly more diffuse compared to earlier profiles, the concentrated apex response confirms the presence of highly reflective metallic elements and the mechanically suspended configuration of the slab.

Below the slab and cavity region, the radar signal becomes increasingly irregular and attenuated, indicating the transition into the masonry church wall. Reduced reflector continuity and enhanced scattering at greater depth are consistent with the heterogeneous composition of the historic wall materials.

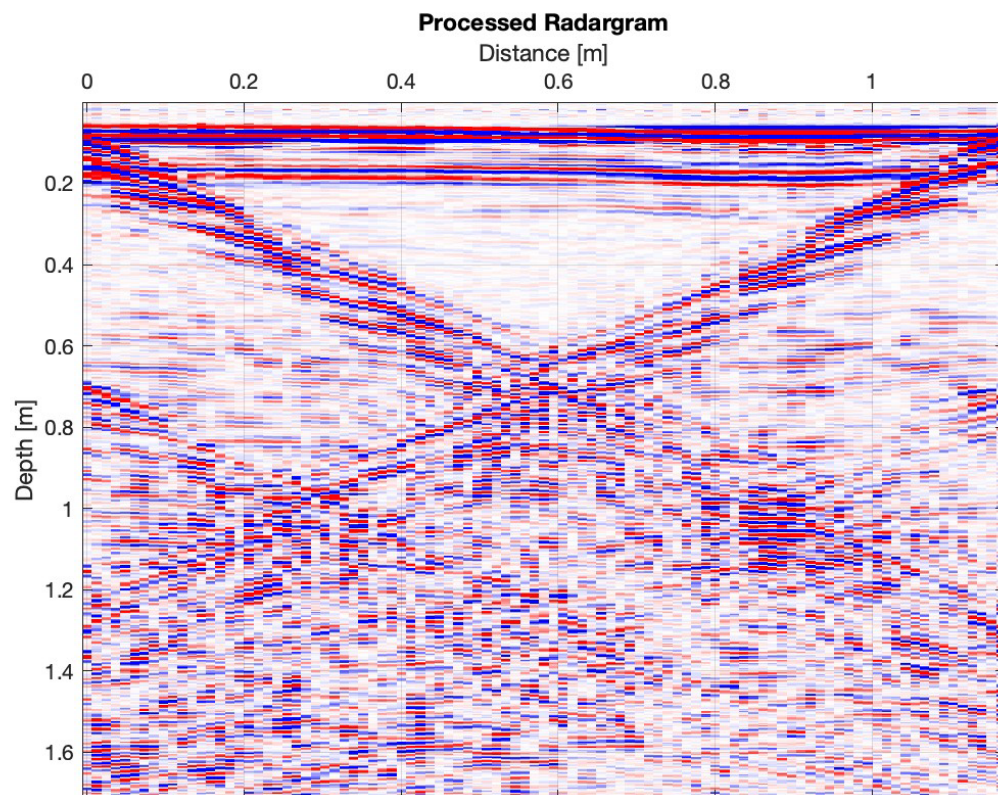


Figure 52. Processed Radargram for profile 1

Profile 4

The central X-shaped diffraction pattern, associated with the metallic nail supports, appears more geometrically defined and symmetrical, indicating improved diffraction resolution and slightly stronger reflector coherence at this position. The air–marble interface and the lower boundary of the slab also appear smoother and more laterally continuous than in Profile 3, where minor undulations were more evident. Additionally, the deeper section (approximately 0.9–1.2 m) shows slightly better reflector visibility and marginally reduced scattering compared to the previous profile, suggesting minor lateral variations in masonry composition or attenuation properties. Importantly, these differences do not indicate structural change; rather, they reflect natural lateral heterogeneity within the façade system while confirming the continuous presence of the suspended marble slab, the persistent air cavity, and the metallic anchoring elements.

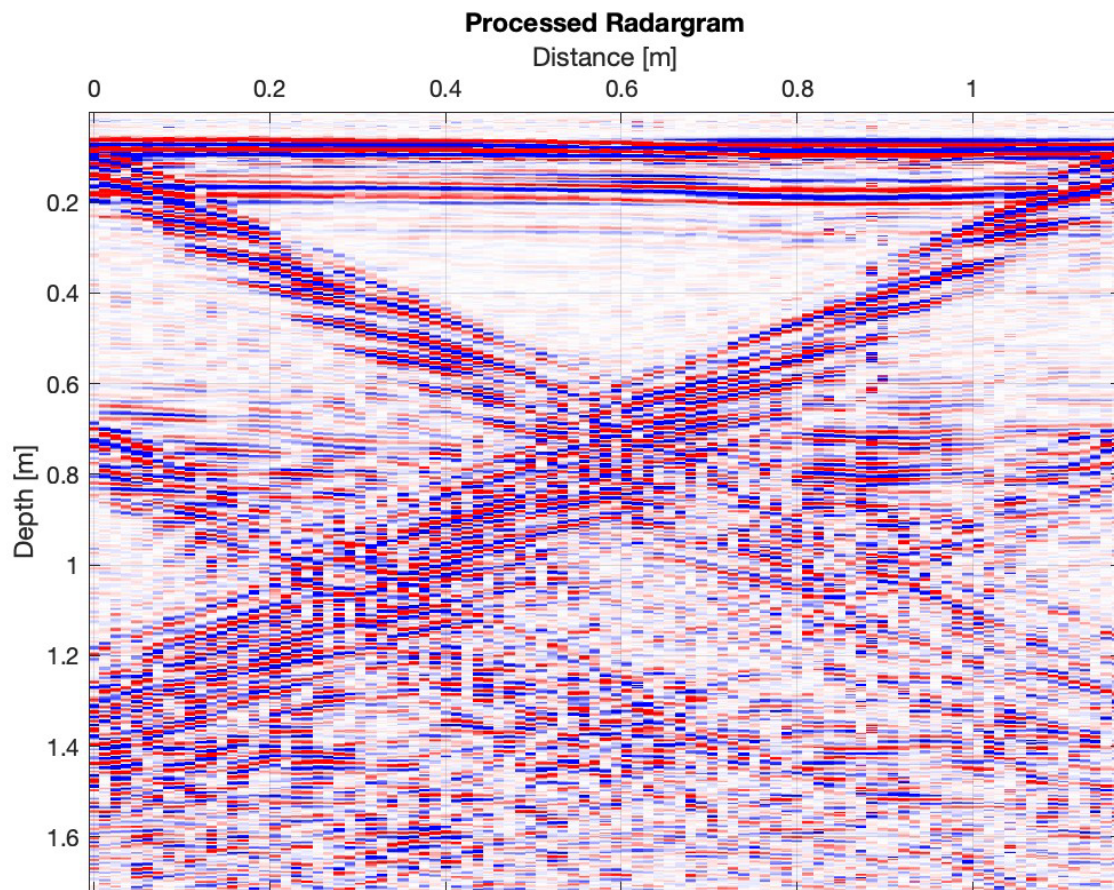


Figure 53. Processed Radargram for profile 4

Profile 5

The shallow section shows a strong, continuous reflector corresponding to the air-marble interface, followed by a second parallel reflector marking the lower boundary of the slab. Slab thickness remains consistent and laterally continuous.

Metallic nails do not produce the prominent X-shaped feature in the central portion of the radargram but instead represent the continuous overlapping halves of a larger hyperbolic response generated by the two edges of the marble slab. As the antenna moves laterally, the slab edges behave as geometric discontinuities, producing broad hyperbolic reflections. The apparent X shape results from the intersection of these two symmetric edge responses. This confirms the lateral limits and geometry of the suspended slab.

Near the beginning/right side of the profile (around 1.00 m horizontal distance), smaller and more localized hyperbolic diffractions are visible between approximately 0.4–0.7 m depth. These are distinct from the large slab-edge hyperbola and likely correspond to metallic nail supports or discrete anchoring elements within the air cavity. Below approximately 1.0 m depth, the signal becomes increasingly irregular and attenuated, marking the transition into the masonry church wall. Reflector continuity decreases and scattering increases, consistent with heterogeneous historic masonry. In this profile, the deeper section appears slightly noisier than Profile 4, suggesting localized variations in attenuation or material composition.

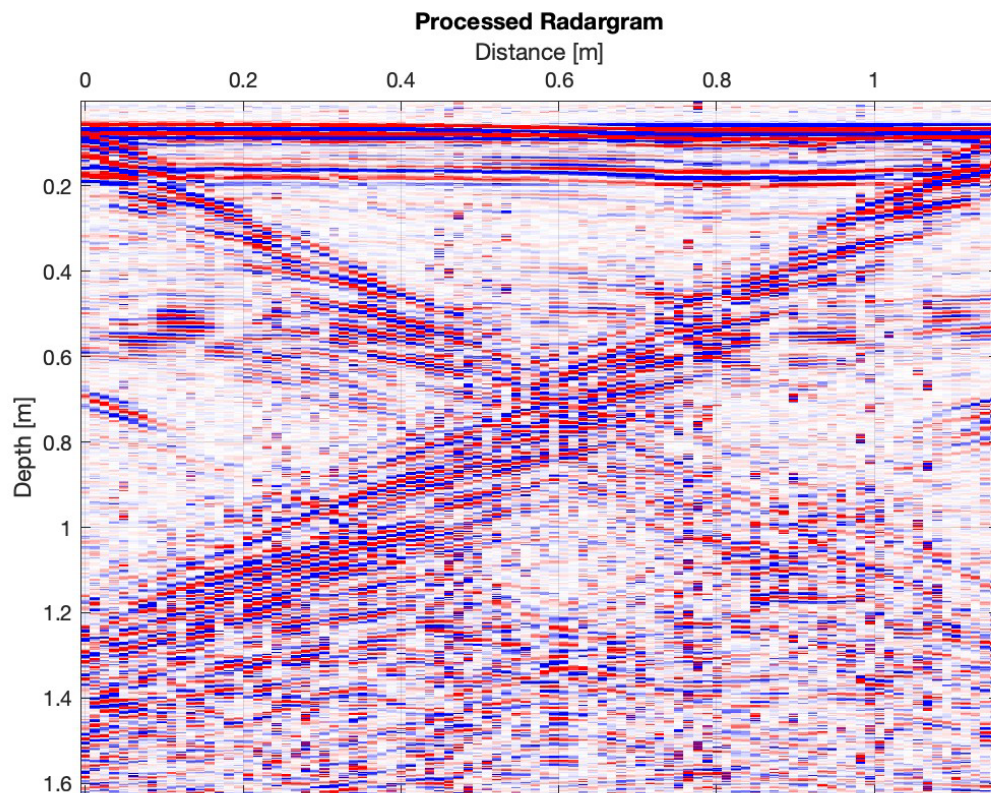


Figure 54. Processed Radargram for profile 5

Profile 6

Near the upper portion of the radargram, two faint hyperbolic diffractions can be observed just beneath the slab. These are difficult to recognize but likely correspond to metallic nail supports within the air cavity. Their weaker definition suggests minor attenuation effects, smaller reflector size, or slight changes in antenna–target alignment.

In the middle of the profile, an additional reflective zone appears around mid-depth. Unlike a clear point-source hyperbola, this reflection seems more distributed, possibly indicating local structural heterogeneity rather than a discrete metallic element.

Below approximately 1.0 m depth, the signal becomes more scattered and attenuated, marking the transition into the masonry church wall.

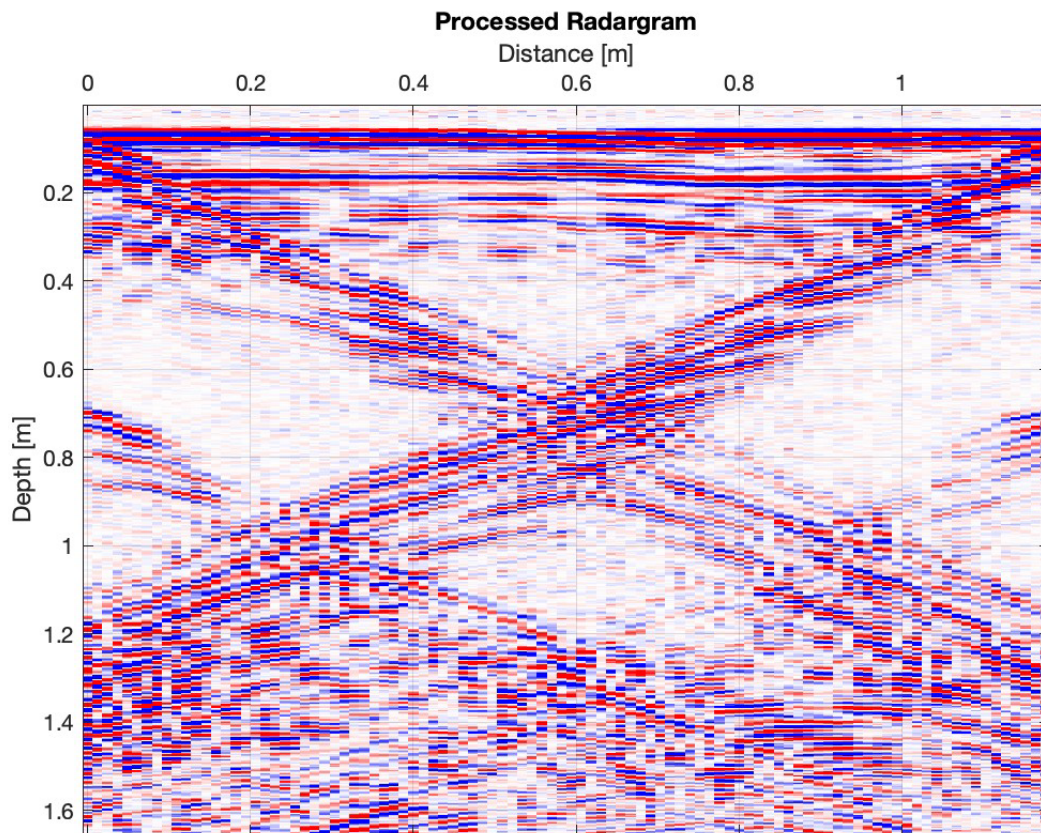


Figure 55. Processed Radargram for profile 6

5.2.2 Right side profiles

Profile 1

Starting from the top of the radargram, a strong and continuous reflector at approximately 0.08–0.12 m depth marks the air–marble interface, produced by the high dielectric contrast between air and the marble slab. Immediately below it, a second sub-parallel reflector defines the lower boundary of the marble slab, confirming consistent slab thickness. Within the upper portion of the cavity zone, approximately 0.15–0.30 m depth, several localized hyperbolic diffractions are visible, particularly in the circled areas. Their sharp curvature and concentrated apex reflections are characteristic of metallic nail supports embedded within the air cavity. These hyperbolas are narrower and more localized than the broader geometry generated by the slab edges, supporting their interpretation as point reflectors.

In the central region of the profile, at around 0.5–0.8 m depth, a larger continuous hyperbolic geometry appears, forming an X-like pattern. This feature corresponds to the diffraction response of the marble slab edges, not metallic nails. The intersecting branches represent the antenna crossing the lateral limits of the suspended slab. Below approximately 0.9–1.0 m depth, the signal becomes increasingly irregular and scattered, marking the transition into the masonry church wall. Reflector continuity decreases and attenuation increases, consistent with the heterogeneous composition of the historic wall materials.

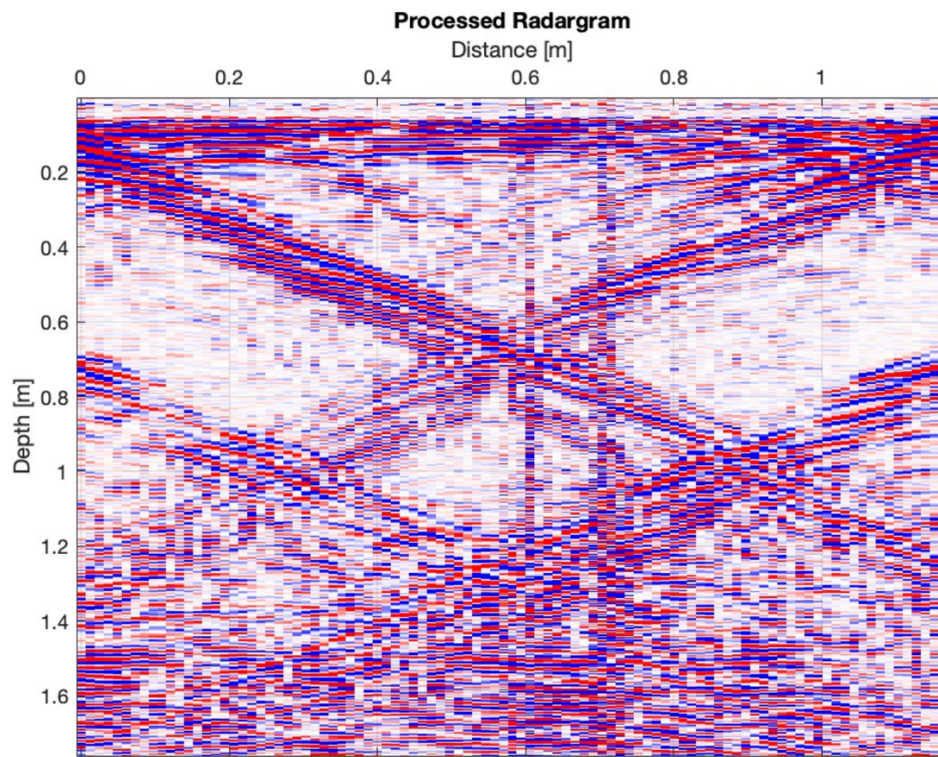


Figure 56. Processed Radargram for profile 1

Profile 2

At approximately 0.08–0.12 m depth, a strong and continuous reflector marks the air–marble interface, followed by a second sub-parallel reflector defining the lower boundary of the marble slab, confirming consistent slab thickness at this 40 cm position. In the upper cavity zone (~0.15–0.30 m depth), two faint and barely distinguishable hyperbolic diffractions can be observed. These are likely metallic nail supports, although their weak curvature and reduced apex concentration make them less clear than in the 20 cm profile. Their low visibility may be due to the slight lateral displacement of the nails relative to the antenna line or minor attenuation effects.

In the central portion of the radargram (~0.4–0.8 m depth), strong and continuous hyperbolic branches are visible. These correspond to the diffraction response from the lateral edges of the marble slab, forming a broad X-like geometry. The reflections are particularly strong along the slab sides, indicating clear geometric discontinuities at the slab boundaries. Below approximately 0.9–1.0 m depth, the signal becomes more irregular and scattered, marking the transition into the masonry church wall. Increased attenuation and reduced reflector continuity are consistent with heterogeneous historic masonry materials.

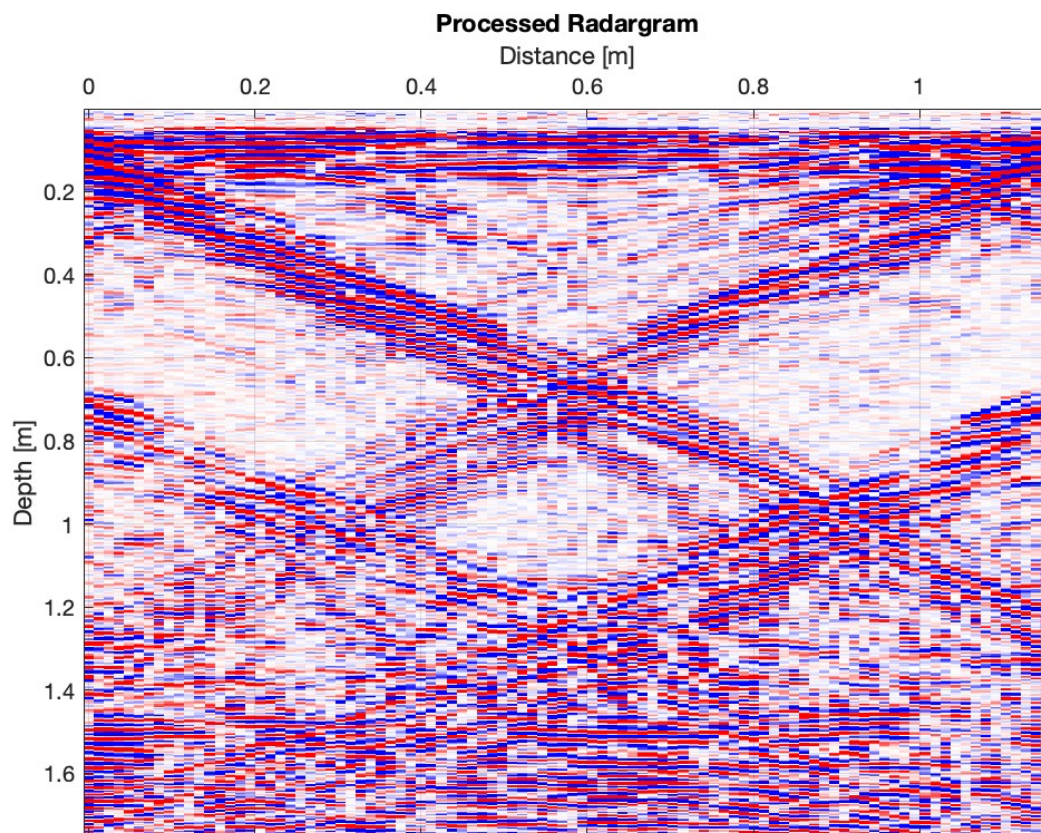


Figure 57. Processed Radargram for profile 2

Profile 3

At approximately 0.08–0.12 m depth, a strong and continuous reflector marks the air–marble interface, followed by a second sub-parallel reflector defining the lower boundary of the marble slab, confirming stable slab thickness at the 60 cm position. In the upper cavity zone (~0.15–0.30 m depth), hyperbolic diffractions are present but are less distinct than in the 20 cm profile. These subtle curved reflections likely correspond to metallic nail supports, although their reduced sharpness suggests a slight lateral offset from the antenna line or minor attenuation effects.

In the central portion of the radargram (~0.4–0.8 m depth), a pronounced and continuous X-like geometry is visible. This feature represents the diffraction response from the lateral edges of the marble slab, not metallic elements. The symmetry and continuity of these branches confirm the geometric limits and suspended configuration of the slab.

Below approximately 0.9–1.0 m depth, the signal becomes progressively irregular and scattered, indicating the transition into the masonry church wall. Increased attenuation and reduced reflector continuity are consistent with the heterogeneous composition of the historic wall materials.

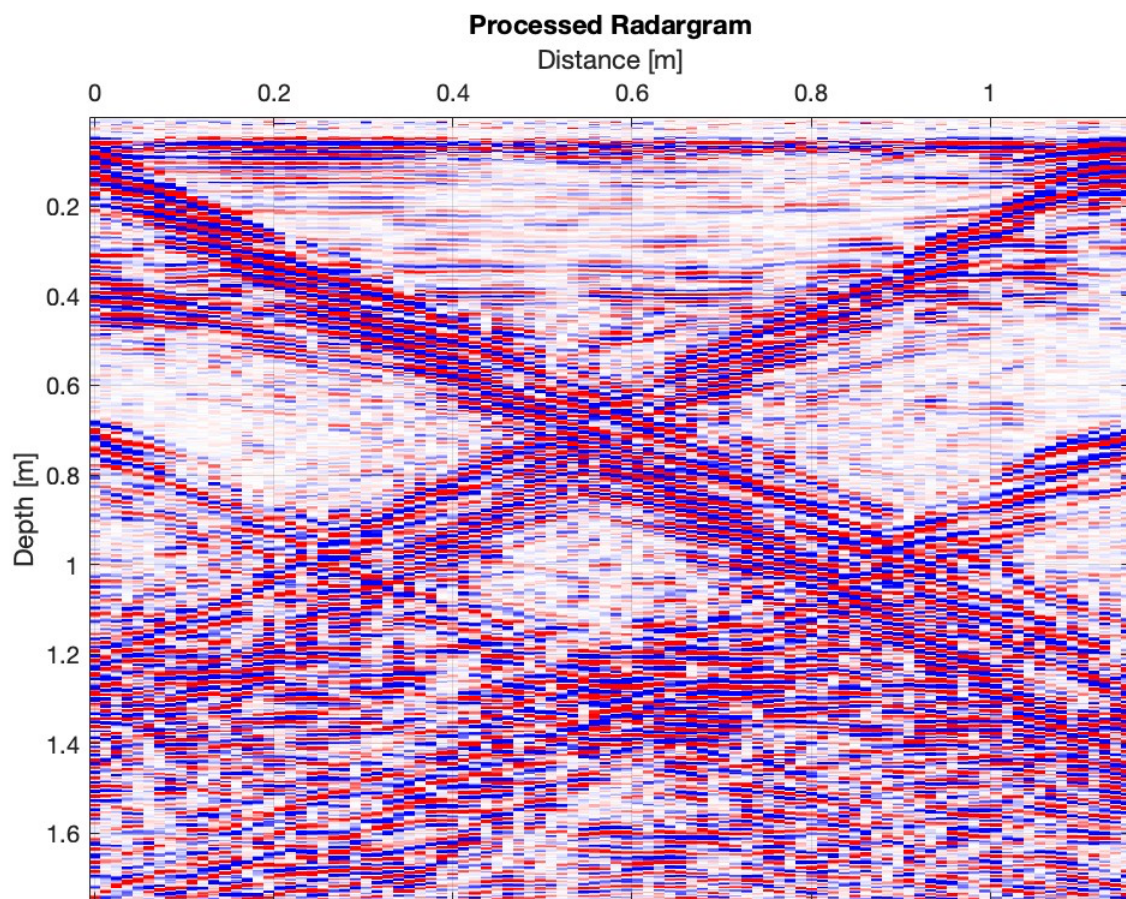


Figure 58. Processed Radargram for profile 3

Profile 4

At approximately 0.08–0.12 m depth, the strong and continuous reflector marking the air–marble interface remains clearly visible. A second sub-parallel reflector defines the lower boundary of the marble slab, confirming that slab thickness remains consistent at the 80 cm position. In the upper cavity zone (~0.15–0.30 m depth), hyperbolic signatures are present but are difficult to isolate due to the high density of reflections. Possible metallic nail supports may be present; however, their curvature is partially masked by overlapping reflections and wave interference.

The central portion of the radargram (~0.4–0.9 m depth) shows a strong and continuous X-like hyperbolic geometry produced by the lateral edges of the marble slab. Compared to earlier profiles, this region appears more complex, with multiple intersecting reflection branches. The increased reflection density suggests stronger wave interference between slab-edge diffractions and cavity reflections. Below approximately 1.0 m depth, the signal becomes highly irregular and scattered, indicating the transition into the masonry church wall. The deeper section shows significant attenuation and heterogeneity, making interpretation more challenging.

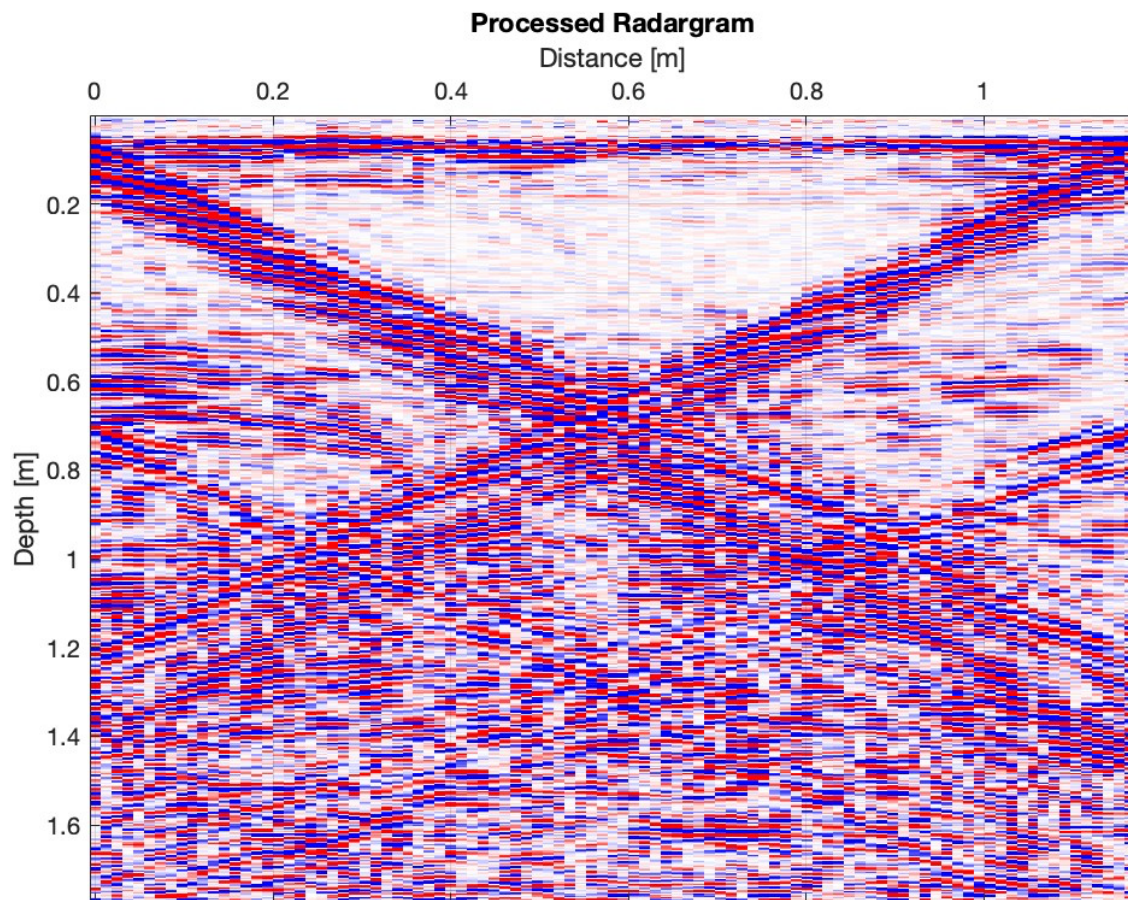


Figure 59. Processed Radargram for profile 4

Profile 5

At approximately 0.08–0.12 m depth, the strong and continuous reflector marking the air–marble interface remains clearly visible. The second sub-parallel reflector defining the lower boundary of the marble slab is also identifiable, confirming consistent slab thickness at the 100 cm position. In the upper cavity zone (~0.15–0.30 m depth), hyperbolic signatures are present but are difficult to isolate due to the high density of overlapping reflections. Possible metallic nail supports may be present; however, their curvature is partially masked by interference from adjacent reflections and slab-edge responses.

In the central region (~0.4–0.9 m depth), a pronounced and continuous X-like hyperbolic geometry is visible, corresponding to the diffraction response of the lateral edges of the marble slab. Like Profile 4, this area shows strong overlapping branches and increased reflection complexity, suggesting intensified wave interaction within the cavity zone. Below approximately 1.0 m depth, the signal becomes highly irregular and scattered, indicating the transition into the masonry church wall. The deeper section exhibits strong attenuation and heterogeneous reflectivity, making detailed interpretation more challenging.

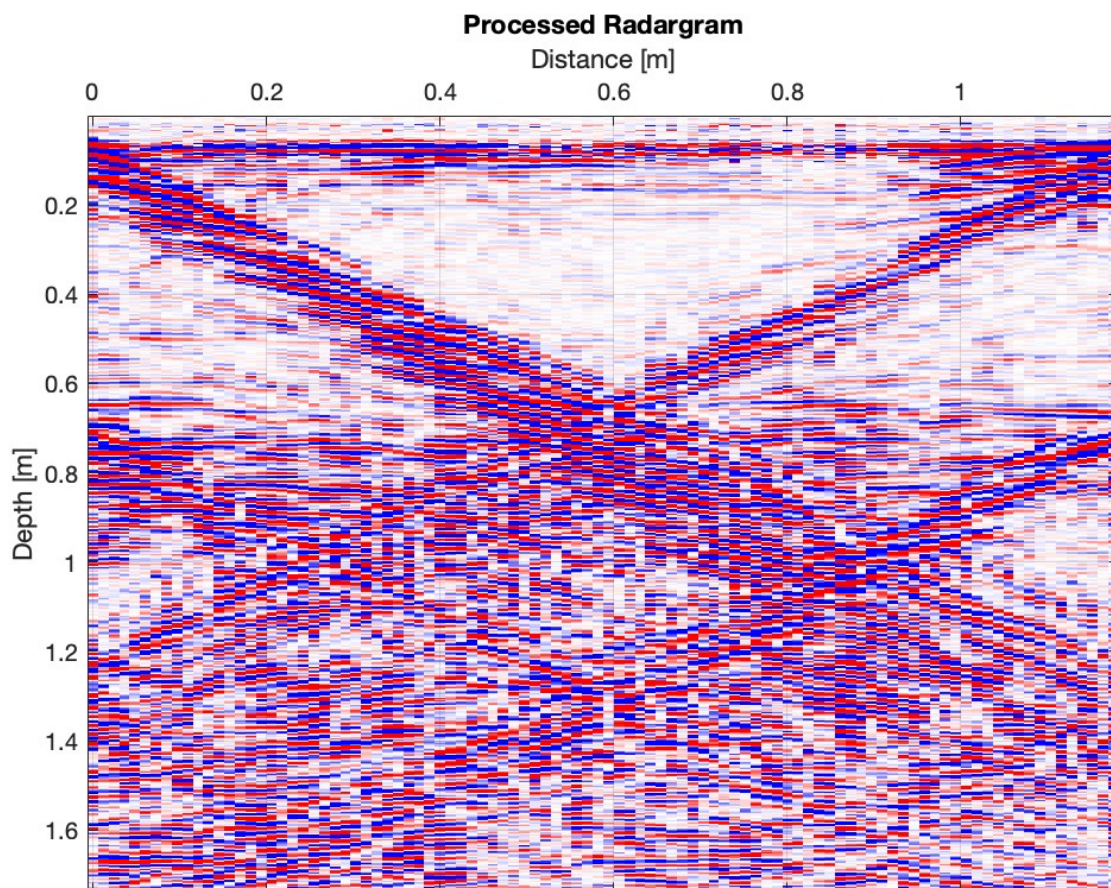


Figure 60. Processed Radargram for profile 5

Profile 6

At approximately 0.08–0.12 m depth, the strong air–marble interface is clearly visible, followed by the reflector marking the lower boundary of the marble slab, confirming consistent slab thickness. At a horizontal distance of approximately 0.2 m and a depth of ~0.15–0.30 m, a strong, well-defined hyperbola is observed, characteristic of a metallic nail support within the air cavity. Its sharp curvature and concentrated apex indicate a clear point reflector.

In the central region (~0.4–0.9 m depth), the continuous X-like geometry is consistent with diffraction from the slab edges, confirming the suspended configuration. At ~0.6–1.1 m depth, stronger reflections appear compared to previous profiles, likely related to interaction at the air–masonry interface or local wall heterogeneity. Below approximately 1.0 m depth, the signal becomes irregular and attenuated, marking the transition into the masonry church wall.

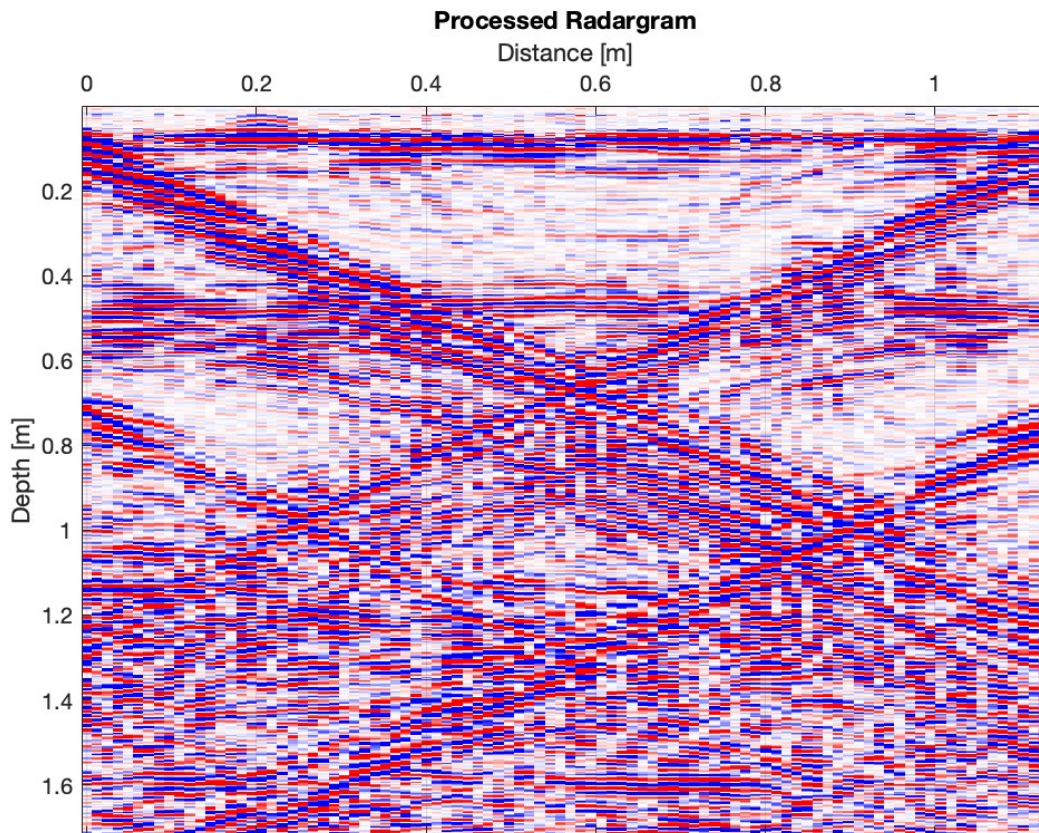


Figure 61. Processed Radargram for profile 6

6. Conclusion

This study examined the potential of Ground-Penetrating Radar (GPR) to identify hidden features within the façade wall of the Chiesa di San Giuseppe through numerical simulation. A series of controlled scenarios was created in MATLAB to better understand how different subsurface conditions affect electromagnetic wave propagation and radar responses. The models included combinations of masonry walls with air-filled cavities and embedded pipes made of various materials, enabling a step-by-step analysis of increasingly complex situations.

The results demonstrate that variations in material properties such as relative permittivity, electrical conductivity, and magnetic permeability strongly influence the behavior of electromagnetic waves within the wall. Air-filled cavities create clear dielectric contrasts with the surrounding masonry, producing diffraction patterns and localized reflections in both the wavefield snapshots and the synthetic radargrams. Pipes embedded in the wall also generate distinctive responses, although the strength and clarity of these reflections depend largely on the material properties of the pipes.

In particular, the simulations show that highly conductive materials such as steel produce very strong reflections and scattering effects, which dominate the radargram signature. In contrast, materials with lower conductivity, such as PVC, generate weaker reflections that are still detectable but less pronounced. The comparison between the different scenarios highlights how conductive targets can significantly modify the wavefield and create clear hyperbolic signatures in the radargrams, making them easier to identify.

The time-domain wavefield snapshots provided additional insight into the physical processes behind the radar responses. By observing the propagation of the electromagnetic waves at different time steps, it was possible to track how reflections, diffractions, and interference patterns developed as the wave interacted with internal structures. These intermediate visualizations help explain the features observed in the final synthetic radargrams and demonstrate how complex subsurface geometries influence the recorded signals.

The simulations confirm that GPR is a powerful non-destructive technique for investigating hidden structures within masonry walls. The numerical modelling approach adopted in this work proved particularly useful for understanding how different materials and geometries affect the radar response. Such simulations can therefore support the interpretation of real GPR surveys in historical buildings, where accurate identification of internal features is essential for conservation, restoration, and structural assessment.

Future research could expand this study by applying the developed modelling approach to the long-term structural assessment of historical buildings. Ground Penetrating Radar combined with numerical simulations can be used to monitor the internal condition of masonry structures and identify potential risks such as hidden cavities, cracks, voids, or other structural irregularities that may compromise the stability of the building. Repeated surveys over time would also allow researchers to observe changes occurring after different seasons and climatic conditions, since temperature variations, humidity, and weathering processes can gradually affect construction materials and lead to structural deterioration.

In addition, integrating this methodology with artificial intelligence and machine learning techniques could significantly improve the interpretation of GPR data. AI-based systems could assist in automatically identifying patterns, anomalies, and subsurface features within radargrams, reducing interpretation uncertainty and increasing analysis speed. Such integration would make the method more accurate and efficient, offering a valuable tool for structural monitoring, cultural heritage conservation, and preventive maintenance of historical constructions.

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