Part II

NDT in masonry using Ground Penetrating Radar
6. Ground Penetrating Radar: a state of the art

In the last decades, the use of non-destructive techniques (NDT) increased significantly in scientific and technical communities such as engineering, geology and archaeology. Within the civil engineering community, the use of the so called NDT techniques increased with the knowledge acquired by the numerous successful results obtained, the wide range of applications and the continuous technological improvements that allow the availability of better and cheaper equipment. The technique called Ground Penetrating Radar (GPR) has been used for almost 30 years (Reynolds, 2002; Ulriksen, 1982). However, its use for the structural assessment of civil engineering structures appeared mostly in the last decade. Now, GPR has become a accepted technique in the wide range of non-destructive testing techniques that can be used to assess the integrity of civil engineering structures (Shaari et al., 2003).

Ground Penetrating Radar is a relatively new geophysical technique, which has experienced in the last ten years significant progress. The understanding of the physical phenomena that govern the propagation of radiowaves and the technology has reached a level of maturity, Annan (2002). Despite the fact that GPR entered in the field of remote probing, non-destructive testing and diagnosis when several other techniques were already present, its characteristics allowed it to rapidly reach a broad public. The Ground Penetrating Radar, as an electromagnetic method, was originality used for deep prospecting applications. Technical advances allowed this system to become more reliable and, at the same time, more portable and lower cost. Currently, the wide diversity of instrument configurations gives to Ground Penetrating Radar the most extensive set of applications of any geophysical technique (Reynolds, 2002; Daniels, 2004). For engineering purposes, this tool is mostly used in the inspection of concrete and wood structures, and highway layer assessment measurements. However, modern digital GPR systems are rapidly demanded in other fields such as quality assessment of repairs (Maierhofer et al., 2003b), quality control and design check (Barrile and Pucinotti, 2005). A more recent but also promising application of this technique is the inspection of historical structures.

Ground Penetrating Radar consists on the propagation of high frequency electromagnetic radiation in both natural (geological materials) and man-made environments (concrete, masonry, etc.), to detect subsurface and underground features. The radar application is based on the fact that the velocity of propagation of the electromagnetic energy and its reflection in the interfaces between different materials are affected by the electric and magnetic properties.
of these materials (Forde, 2004). GPR is generally considered the electromagnetic analogue of sonic and ultrasonic pulse-echo methods, which are successively used for the assessment of voids, cracks, delaminations and material heterogeneities in concrete structures (Clemeña, 1991).

### 6.1. Historical notes

The possibility to remotely detect features and objects behind opaque surfaces has fascinated mankind for years (Daniels, 2004). The use of electromagnetic waves for remote probing started in the beginning of the 20\(^{th}\) century by experiments that proved the possibility of transmitting electromagnetic waves through space as a beam of energy and receive the reflected signal from an airborne object in the path of the beam. Additionally, in the 1930’s, military use for the detection of planes was found to be very effective. During the Second World War, the technique was used for the detection of submarines from airplanes and for the precise planning of massive air bombings (Buderì, 1998). During this period, this technology experienced an intense development of the electronic circuits, enabling the accurate detection of planes, ships, clouds, etc. All these applications were made possible by realising that different objects have their own reflection properties with respect to electromagnetic waves. Such waves travel through air at a constant speed, close to the speed of light. Moreover, in the atmosphere, electromagnetic pulses travel with low attenuation so ships and airplanes can be detected many kilometres away. This technology was already well-developed in the 1940’s, which lead to the development of the modern detection systems, designated by RADAR, which is an acronym for RA\textit{dio} Detection And R\textit{anging} (Buderì, 1998).

Although the use of electromagnetic methods started as a military application, the potential of its use within the civil and scientific communities was foreseen rapidly. The first experiments with electromagnetic waves were carried out by Hulsmeyer, in 1904, and published by Leinback and Lowy in 1910. They attempt to remotely detect the presence of metallic objects buried in the soil by employing a continuous wave (CW) transmission device (Clemeña, 1991; Reynolds, 2002). Additional, experiments using pulsed radar for the investigation of buried features were performed by Hülsenbeck (1926). Pioneering works in the field of mineral and ore exploration in Sweden were carried out by Sundberg (1931) and structural mapping of hydrocarbon exploration was performed by Sundberg and Hedström (1934). The first Ground Penetrating Radar survey was performed by W. Stern in Austria in 1929 to sound the depth of a glacier. Historically, Ground Penetrating Radar was primarily focused on mapping structures in the ground. Since then, the technology was largely forgotten until the
late 1950’s (despite the fact that 36 patents were filed between 1936 and involving subsurface radar), when U.S. Air Force radars were seeing through ice as planes tried to land in Greenland but misread the altitude and crashed into the ice. Experiments in the early 1950’s showed that this technology was also applicable for transmission through solids such as rocks and soil. It was quickly understood that the speed and amplitude of the radiowaves varied significantly between materials taking into consideration the distance travelled, allowing the identification and profiling of geological features. This lead to the development of special radar systems, in the late 1960’s, which were called Ground-Probing or Ground-Penetrating Radar (GPR) due to their original intended applications. The fundamentals of this prospecting equipment are fully described in Daniels (1989; 2004). Early GPR work focussed on geological and permafrost soil applications but increased significantly in the 1960’s with the development of radio echo sounding of polar ice sheets and the probing of deep glaciological and geological features such as salt and fresh water deposits, desert sand, rock formation and coal (Annan and Davis, 1976). Application of radar to subsurface exploration did not become common until the 1980’s. GPR was broadened to include mapping of soil and rock stratigraphy (Davis and Annan, 1989), which can be used in mining applications (Scaife and Annan, 1991). Other applications included the profiling of contaminated water or wastewater (Benso on et al., 1984; Ulriksen, 1982).

Civil engineering applications of GPR started to appear in the mid 1970-80’s (Bungey and Millard, 1993; Forde and McCavitt, 1993), at a time where the technology allowed producing reliable, easy handling and more cost effective equipments. This led to an expansion of the range of applications, including building and structural non-destructive testing, archaeology excavations, road and tunnel quality assessment, location of voids and containers, mine, pipe and cable detection. Bertram et al. (1974) reported one of the very first studies on the use of GPR related to civil engineering, which dealt with the inspection of airfield for voids underneath pavements. In that period, the Geophysical Survey Systems, Inc. (USA) was also established, as the first company to produce commercial civil GPR equipments and, currently, one of the largest ground penetrating radar manufacturers internationally. Since then, many other specialized radar companies have appeared with similar products such as Måla GeoScience (Sweden), Era (UK), Sensors and Software (USA), IDS (Italy), etc. With the continuous progress of the technology and the growing experience of the scientific community (Olhoeft, 1998; 2000), more and better equipment is available. This will allow an increase of the already vast number of applications where the GPR system is able to provide reliable answers to existing problems of the civil engineering community. Continuous
research on processing algorithms (Dell'Acqua et al., 2004; Valle et al., 1999) with the final objective of producing more reliable data that generates adequate results, which can be easily readable for any operator not involved in NDT investigation has been carried out during the last decade (Binda et al., 1998), namely designers, architects, etc.

Currently, GPR is used to assess the integrity of civil engineering structures and retrieve information from structural elements that are not possible to obtain without the use of destructive methodologies, including: structural integrity of concrete structures, detection of reinforcement bars and voids (Taffe et al., 2003; Maierhofer, 2003a), delamination of cover concrete (Maierhofer, 2003b; Dérobot, 2003), assessment of tendon ducts in concrete bridge decks (Taffe et al., 2003; Hugenschmidt, 2002; Dérobot et al., 2002), pavement evaluation and road layer’s thickness assessment (Al-Qadi and Lahouar, 2005; Al-Qadi et al., 2003; Maser and Richter, 1993; Saarenketo, 1992; Van Leest, 1998). Non-destructive testing in laboratory for the determination of moisture content in concrete and water level during the curing of concrete, assessment of the moisture content and distribution has been pointed out by Maierhofer (1998c) and Weise (2003). GPR can also be used in the evaluation of the salt content and dielectric properties in bricks, masonry specimens (Maierhofer et al., 1998a, 1998b, 2001), concrete (Robert, 1998; Reppert, 2000; Stousos, 2001) and bituminous materials (Al-Qadi et al., 2001), or check in the ballast integrity in railways (Clark et al., 2001, 2004; Gallagher, 1999). Another field of application is the structural monitoring (Huston et al., 2000). Location and monitoring of the evolution of the infiltration of contaminants, contaminants leakage and toxic plumes was studied by Daniels (1995) and Castro (2003). GPR has been used to investigate the features of the material layers beneath pavements (Gordon et al., 1998; Hugenschmidt and De Whitte, 1998) and even to find archaeological remains (Goodman and Nishimura 1992). Other uses include the assessment of earthquake damaged towers in Italy (Binda et al, 2000; Flint et al., 1999; Colla et al., 1997). Forde et al. (1999) shown that GPR can also be used through fresh water to investigate potential scour holes in a non-saline river bed.

Ground penetrating radar is a recognized and trustful technique but a lot of research is still carrying out to increase its effectiveness in new and complex applications, and in the development of more powerful and effective software applications that process more easily and efficiently the data obtained from field acquisitions. New applications are starting to appear, for example, in humanitarian help. Since the Falklands conflict, in 1982, and due to the occurrence of other several armed conflicts in the last years of the 20th century, ground penetrating radar systems were used with the aim of locating thousands of plastic mines that
were thrown indiscriminately from the air and which remain invisible to metal detectors (Milisavljevic, 2003). Many companies developed specific products to help in this complex endeavour (Daniels, 2004). Moreover, forensic experts are also using GPR to detect buried human bodies in order to help criminal investigations. More recently, GPR’s potential is being studied for very diverse uses, such as for the detection of water on planet Mars (Olhoeft, 2001), detection of persons buried under rubble caused by natural catastrophes, earthquakes or avalanches due to snow.

6.2. Description and principles of operation of GPR

The ground penetrating radar is a non-destructive technique based on the propagation of electromagnetic radiation, also designated by electromagnetic waves or radiowaves, through the ground or other dielectric media. The media of propagation of radiowaves can be of quite variable nature since GPR surveys can be performed virtually in every material which permits the transmission of electromagnetic energy. Among them, numerous natural materials can be found such as dry soil, rocks, ice and water (only in certain conditions), and construction materials, like brick and stone masonry, concrete, asphalt, etc. The following sections give a brief insight into the typical hardware that constitutes a typical modern radar system and highlight the most important characteristics and operational conditions.

6.2.1. Basic instrumentation

A typical modern radar system is generally constituted by the following four components: control unit, radar antenna(s), visualisation unit and data storage device. These components are illustrated in Figure 6.1. The control unit of a radar system is an electronic device that is composed by a micro-processor, memory, mass storage medium to store setup and measurement settings, and, possibly, by field data. Modern GPR systems are digitally controlled. Data is usually recorded digitally for post-survey processing and display. The control unit is a frequency independent component, whose primary purpose is to generate electromagnetic pulses with short period and high voltage, and transmit them to the transmitter antenna, which, in turn, is responsible for radiating the investigation surface.
Radar antennas are complex electronic devices, which are specifically designed to optimize ground interaction (as they are used in contact with the surface). As illustrated in Figure 6.1, they are in charge of radiating the investigation medium with electromagnetic energy and of receiving the reflected energy caused by interfaces between materials of different dielectric properties during its propagation through the material under investigation. Typical antennas are constituted by transducers, or bow-tie elements, that convert electrical current on the metallic antenna elements into electromagnetic energy that is radiated towards the ground in the form of electromagnetic pulses. Inversely, these antennas also convert electromagnetic energy pulses into electrical current, acting as output of the electromagnetic radiation reflected back from the ground. Radar antennas are characterised by their central frequency, $f$. Currently, a broad range of frequencies are available, ranging from as low as 10 MHz to very high frequencies such as 2000 MHz and more. The choice of a particular frequency is dependent on the type of application, depth and dimensions of potential targets and field environment. Table 6.1 illustrates typical applications, expected resolution and depth of penetration for several common frequencies of radar antennas in favourable conditions.
<table>
<thead>
<tr>
<th>Central frequency</th>
<th>Depth of penetration</th>
<th>Resolution</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 MHz</td>
<td>50 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 MHz</td>
<td>30 m</td>
<td>Low resolution</td>
<td>Geotechnical, geological</td>
</tr>
<tr>
<td>50 MHz</td>
<td>10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 MHz</td>
<td>5 to 20 m</td>
<td>Low resolution</td>
<td>Geotechnical, environmental, mining</td>
</tr>
<tr>
<td>200 MHz</td>
<td>2 to 7 m</td>
<td>Low to medium resolution</td>
<td>Geotechnical, engineering and environmental</td>
</tr>
<tr>
<td>500 MHz</td>
<td>1 to 4 m</td>
<td>Medium to high resolution</td>
<td>Engineering</td>
</tr>
<tr>
<td>1000 MHz</td>
<td>0.5 to 1.5 m</td>
<td>High resolution</td>
<td></td>
</tr>
<tr>
<td>1500 MHz</td>
<td>0.5 m</td>
<td>Very high resolution</td>
<td></td>
</tr>
</tbody>
</table>

### 6.2.2. Operative mode

Ground penetrating radar systems are quite flexible and allow data to be collected in several ways, depending on the sort of information that the end-user is seeking, the nature of the investigation medium and the equipment. Three modes of deployment are usually considered with GPR: reflection mode, common-midpoint and transmission mode (or tomography). Each one of these acquisition modes has its particularities and differs considerably in terms of required equipment. Similarly, the results obtained are substantially different, being the reflection mode the most frequent method, as the simplest and fastest way of acquiring data with a radar system.

Performing GPR surveys using the reflection mode requires one or two antennas to be moved over the investigation medium along a specific direction by keeping constant the distance between transmitter and receiver. Generally, the transmitter and receiver are located in a common plastic container (monostatic antennas), which makes the distance between them known and constant.

The measurements consist of the phases indicated in Figure 6.1. Firstly, the control unit generates an electromagnetic pulse and sends it to the transmitter antenna that irradiates the investigation media with a broad beam of electromagnetic energy. That electromagnetic wave is then reflected by each interface between adjacent dielectric materials encountered during its propagation in the investigation medium and the reflected echoes are collected by the receiver.
Generally, the control unit generates not only one pulse at a time but several thousand of pulses per unit time, which results in a repetition rate of several kHz that are sent to the transmitter antenna (Reynolds, 2002). A usual value for the repetition rate is 50 kHz. This technique, illustrated in Figure 6.2, is a consequence of the current technology limitations, which requires a single transmit pulse for every sample to be recorded in order to produce a complete waveform (Stickley, 2000). Additionally, the operation of transmitting and receiving signals is not done simultaneously. Currently, the transmission of a single pulse is followed by a “dead time” in which the transmitter is closed and the receiver is opened to read the reflected signals. After that, the receiver is shut and the transmitter sends signals again and a similar cycle repeats until the transmission is stopped. The antenna is then dragged away into another position where the same steps occur, generally triggered by a distance survey wheel.

The system records the time taken by the radiowave to travel from the transmitter to the radar reflectors, and then back to the receiver, commonly designated by “Two-Way Travel-Time”, generally expressed in nanoseconds (ns). In each position, the system samples an entire trace (or waveform), which is a set of several samples collected during a certain time interval (in terms of nanoseconds) and then spans it over the configured maximum depth (time window). The traces are placed successively one after another and displayed in a monitor in the form of a continuous radargram, which represents a two-dimensional image of the variation of the dielectric properties of the materials located under the alignment of the profile. Figure 6.3a illustrates a typical situation where the radar is used to map an object buried in the ground and Figure 6.3b shows the corresponding radargram displayed in terms of variable area wiggle or, wiggle trace, which is a technique coming from the time when the radar systems were analog.
Today, digital recording systems display the amplitudes of the signals according to a grey scale or colour menu, with the strongest reflections being picked by the brightest colours, as illustrated in Figure 6.4.

![Figure 6.3](image1)

(a)

![Figure 6.4](image2)

(b)

Figure 6.3 – Radar reflection survey over a target. (a) Methodology and (b) resultant radargram displayed as wiggle traces.

Figure 6.4 – Display of a radargram in grey scale. Example taken from one of the walls that were tested during this research.

Another way of presenting results of radar data is a three-dimensional display, which consist of placing 2D profiles in a three-dimensional block view. The accurate location of each trace is critical to producing accurate 3D displays. Normally, 3D block views are constructed and may then be viewed in a variety of ways, including as a solid block or as time slices (Binda et al., 2003; Lualdi and Zanzi, 2002; Taffe and Maierhofer, 2003; Valle et al., 1999). Obtaining a good three-dimensional display is a critical point on the interpretation of GPR data. Targets
of interest are generally easier to identify and to isolate on three-dimensional data sets than on conventional two-dimensional profiles.

Figure 6.5 – Example from an investigation on an historic villa where GPR profiles were performed in order to detect the position of wood beams embedded into the pavement (Binda et al., 2003). (a) Image of a time slice of 3D focussed data and (b) display of two beams as isosurfaces.

Finally, tomography is a rather distinct processing mode, which makes use of direct transmission acquisitions. It was originally developed in medicine and in several other fields with the aim to reproduce the internal structure of an object from measurements collected on its external surface. Formerly, it derives from the Greek *tomos*, which means “slice”. In this acquisition mode, the transmitter and the receiver antennas are separated and located successively in various positions in order to cover entirely the area under investigation with electromagnetic rays. In this case, transmitter and receiver are separated and the direct pulse is recorded. Figure 6.6 illustrates an example of the tomography of a column where, for each position of the transmitter antenna, the receiver is dragged along the remaining edges of the column in such way that the cross-section of the column covered with radiowaves is maximized. This methodology relies on the knowledge, at all times, of the relative position of the two antennas. As the distance between them is also known, it is straightforward to calculate the mean radiowave velocity of the appropriate ray path. Special inversion algorithms are used to calculate the velocity or attenuation distributions from the time travel or amplitude information, respectively. GPR tomography inversion algorithms allow the reconstruction of the interior of the column’s section (Colla and Binda, 1999). Because this testing technique gives a map of the velocity or attenuation distributions, it is particularly suitable for the detection of moisture and air voids. In fact, radiowave velocity and attenuation through these media differs significantly from most building materials.
6.3. Propagation of radiowaves in dielectrics

The GPR technique is based on a solid theoretical background. In order to understand how electromagnetic signals propagate, attenuate and reflect at material interfaces, a brief description of the most important properties is addressed in this section. In general, the properties that govern the propagation and loss of electromagnetic energy through natural and artificial materials are primarily associated to *dielectric properties* of those materials. These properties deal with the composition and water content of natural and artificial materials, namely geological and building materials.

6.3.1. Nature of electromagnetic waves

The nature of the electromagnetic field was described by the physicist James Clark Maxwell in 1864, which defined the basic principles of Electromagnetism by means of four fundamental expressions, known as *Maxwell’s Equations*. An electromagnetic wave consists of a disturbance in space constituted by an electric intensity ($E$) and a magnetic force ($H$) in a plane perpendicular to the direction of travel (polarized) and variable in time. An example is illustrated in Figure 6.7.
These electromagnetic waves have the particularity to propagate at the speed of light \(c\) (30 cm/ns) through space without the need of solid matter. In fact, electromagnetic radiation is characterized by the same properties as any periodic wave motion: frequency \((f)\), wave or pulse period \((1/f)\), wavelength \((\lambda)\) and amplitude, see Figure 6.8.

![Figure 6.8 – Partial sinusoidal wave indicating the main components of an electromagnetic wave.](image)

The velocity can be obtained by means of the frequency and wavelength by the following expression

\[
c = f \cdot \lambda \quad \text{(6.1)}
\]

The velocity of electromagnetic waves through vacuum is not the same as when they propagate through solid matter, being denoted as \(w\), and given by the relation

\[
w = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \quad \text{(6.2)}
\]

where the constant \(\varepsilon_0\) represents the permittivity of free space \((8.854 \times 10^{-12} \text{ F/m})\) and \(\mu_0\) the magnetic permeability of free space \((4\pi \times 10^{-7} \text{ H/m})\). F/m (Farad per meter) and H/m (Henry per meter) represent the SI units to measure, respectively, the permittivity and the permeability. The frequency range of electromagnetic radiation is very wide, ranging from lower than 10 Hz (atmospheric micro pulsations), through radar bands \((10^8\) to \(10^{11}\) Hz\) and up to \(10^{16}\) Hz (X-rays and gamma-rays), see Figure 6.9.
6.3.2. Dielectric properties of natural and artificial materials

The ground penetrating radar technique was made possible due to favourable electric properties that characterise a great number of natural and artificial materials and that allow the propagation of electric and magnetic waves. At the atomic level, these properties result from the interaction between the electrons of the matter and the electric and magnetic fields of the electromagnetic wave generated by the radar system. In particular, the contents in iron elements and amount of water strongly influence dielectric properties. The dielectric properties of materials constitute a dimensionless measure that defines the capacity of a material to store an electrical charge when placed in an electric field. Dielectric properties include the complex electrical conductivity ($\sigma^*$), the magnetic permeability ($\mu$) and the complex permittivity ($\varepsilon^*$) of materials (Clark, 2004). These properties constitute fundamental parameters and can influence the way radio waves propagate, reflect and attenuate through different earth and construction materials. The magnetic properties are solely relevant where magnetic materials are present. Therefore, in most common geological and building materials, such as concrete and masonry, the value of the magnetic permeability is equal to the permeability of free space.

Moreover, usual building materials such as concrete and masonry are characterised by a relative permittivity or relative dielectric constant ($\varepsilon_r$), which is described by

\[
\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}
\]
where \((\varepsilon)\) represents the complex electric permittivity and \((\varepsilon_0)\) the permittivity of free space of the particular material. Materials that allow the propagation of an electromagnetic field are designated as dielectrics, and are defined as poor conductors of electricity, but efficient supporters of electrostatic fields.

However, despite the term “constant” in the definition of \(\varepsilon_r\), the value of the relative dielectric constant of building materials depends on physical properties (bulk weight and porosity), water content and on the proportion of its constituents. Table 6.2 shows typical values of dielectric constant for geological and common building materials. Dielectric constant can reach values of 30 in most dry materials, but rarely exceeds 11 in the case of building materials. The dielectric constant of other building materials such as masonry, brick and asphalt are scarce in the literature, but approximate values of 6 for brick masonry (Clark et al., 2003a), 4 for brick (Clark and Crabb, 2003b) and 3-5 for asphalt have been pointed out (Reynolds, 2002).


<table>
<thead>
<tr>
<th>Material</th>
<th>Relative dielectric constant ((\varepsilon_r))</th>
<th>Electrical conductivity (mS/m)</th>
<th>Radiowave velocity (x 10^8) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
<td>3.00</td>
</tr>
<tr>
<td>Fresh water</td>
<td>81</td>
<td>1</td>
<td>0.33</td>
</tr>
<tr>
<td>Seawater</td>
<td>81</td>
<td>(4.10^3)</td>
<td>0.33</td>
</tr>
<tr>
<td>Sand</td>
<td>3-6 (dry)</td>
<td>(10^{1.1}) (dry)</td>
<td>1.20-1.70 (dry)</td>
</tr>
<tr>
<td></td>
<td>25-30 (wet)</td>
<td>1-10 (wet)</td>
<td>0.55-0.6 (wet)</td>
</tr>
<tr>
<td>Clay soil</td>
<td>3 (dry)</td>
<td>1-10 (dry)</td>
<td>1.73 (dry)</td>
</tr>
<tr>
<td></td>
<td>8-15 (wet)</td>
<td>(10^2-10^3) (wet)</td>
<td>0.70-1.10 (wet)</td>
</tr>
<tr>
<td>Granite</td>
<td>4-5 (dry)</td>
<td>(10^3) (dry)</td>
<td>1.20-1.50 (dry)</td>
</tr>
<tr>
<td></td>
<td>7-8 (wet)</td>
<td>1 (wet)</td>
<td>1.06-1.12 (wet)</td>
</tr>
<tr>
<td>Concrete</td>
<td>4-6 (dry)</td>
<td>1 (dry)</td>
<td>1.30 (dry)</td>
</tr>
<tr>
<td></td>
<td>11-12 (wet)</td>
<td>10-50 (wet)</td>
<td>0.9 (wet)</td>
</tr>
</tbody>
</table>

Generally, dry building materials are primarily influenced by their dry bulk density and geometry. In partially and fully saturated materials or soils (particularly argillaceous soils), the value of the relative dielectric constant becomes mostly influenced by the water content, salinity and porosity. The presence of water increases significantly the value of the relative dielectric constant because the dielectric constant \((\varepsilon_r)\) varies from 1 in air and increases significantly to 81 in water, and is fully described in Wensink (1993). Thus, a small amount...
of moisture within the material pores can cause a large increase of the relative dielectric constant, and, consequently, a considerable decrease of the speed of propagation of electromagnetic waves. Additionally, the presence of soluble salts or saline water in materials, especially in marine environments, increases the electrical conductivity of the materials. This result in a significant increase of the loss of the radiowaves energy and limits greatly the possibility of conducting a radar survey. Thus, when conducting GPR surveys, one of the most important parameter to consider should be the moisture content present in the materials.

6.3.3. Radiowaves’ speed of propagation

As given above, the speed of radiowaves in air is equal to the speed of light in air, namely, 30 cm/ns. However, when a radiowave propagates through a solid material, the velocity \( w_m \) is given by (Neal, 2004)

\[
\frac{c}{\sqrt{\left(\varepsilon_r \mu_r \frac{\sigma}{\omega \varepsilon} \right)^2 + 1}}
\]  

(6.4)

The expression \( w_m \) for the speed of propagation can be simplified when the radiowaves propagate through a low-loss material at radar usual frequencies, such as construction materials and most dry soils. This means that the material’s conductivity \( \sigma \) is very low and close to zero. Consequently, the term \( \frac{\sigma}{\omega \varepsilon} \), designated by “loss factor”, is considered to be null. Moreover, the relative magnetic permeability \( \mu_r \) is a dimensionless value, defined as the ratio between the magnetic permeability \( \mu \) and the constant of magnetic permeability of free space \( \mu_0 \). In non-magnetic materials, \( \mu_r \) is equal to one. Thus, the general expression for wave velocity can be further simplified for low-loss materials by using (Clark, 2003b)

\[
\frac{c}{\sqrt{\varepsilon_r}}
\]  

(6.5)

6.3.4. Transmission and reflection coefficients

During GPR surveys, the propagation of electromagnetic waves is modified according to the properties exhibited by the materials crossed by the radiowave, their relative shape and configuration. Each material has its own characteristic reflection towards electromagnetic waves and, depending on its dielectric properties, some materials can be completely transparent to radiowaves or either absorb or reflect the radiowaves to such an extent that they can be totally opaque to electromagnetic waves (Reynolds, 2002). On the other hand, steel
and other metallic materials reflect the totality of the incident electromagnetic energy. As the radiated pulses travel through the material under investigation different reflections will occur at interfaces that represent a change in dielectric properties. When an electromagnetic wave comes to an interface that separates two media with different electromagnetic properties, the incident energy will be partially reflected and partially transmitted, depending on the contrast between the relative dielectric constants of adjacent material layers. This process is illustrated in Figure 6.10 and its theoretical origin was based on the laws of Optics as the light is an electromagnetic wave. The angles of transmission and reflection are given by the Snell’s Law (Optics), whose corresponding expression is presented in Figure 6.10. It correlates the relative dielectric constant $\varepsilon_r$ with the angles of the incident and transmitted waves.

The proportion of energy reflected is given by the value of the amplitude reflection coefficient, denoted $R$. This coefficient is determined, basically, by the contrast between the values of the relative dielectric constants of the adjacent materials or as the ratio between the intensity of the reflected energy and the incident energy. $R$ is dimensionless and its magnitude lies between -1 and +1. The transmission coefficient, $T$, that characterises the amount of energy that is transmitted through the subsequent material layers, can be approximately derived from the reflection coefficient through $R + T = 1$, with the hypothesis that no other losses occur. Thus, it is supposed that the total incident energy is both reflected and transmitted. The values of the reflection and transmission coefficients are given by (Clemeña, 1991; McCavitt, 1993),

$$ R = \frac{\sqrt{\varepsilon_{r_1}} - \sqrt{\varepsilon_{r_2}}}{\sqrt{\varepsilon_{r_1}} + \sqrt{\varepsilon_{r_2}}} \quad T = \frac{2\sqrt{\varepsilon_{r_2}}}{\sqrt{\varepsilon_{r_1}} + \sqrt{\varepsilon_{r_2}}} \quad (6.6) $$
where $\varepsilon_{r1}$ and $\varepsilon_{r2}$ are the relative dielectric constants of material layers 1 and 2, respectively, and considering that layer 2 is deeper than layer 1 as illustrated in Figure 6.10. This expression assumes that no considerable losses occur and is limited to normal incidence of radiowaves on a planar surface.

6.3.5. Penetration depth

The penetration depth of a particular radar system is, generally, site related (materials and environment), and rather difficult to estimate before the inspection is actually performed. It is also affected in a certain extent by the equipment. Generally, depth can be estimated accordingly to values obtained in field or laboratory measurements, widely available through literature (Reynolds, 2002; Daniels, 2004), the experience of the operator and even through the data provided by the manufacturers of radar systems.

Several properties of materials allow the operator to estimate how good will be the signal penetration, but the most important property is the conductivity. The conductivity depends, essentially, on the water content of the materials. In general, the electrical conductivity determines how far through a material the radiowave signal penetrates, while contrasts in relative permittivity govern the proportion of energy transmitted and reflected at material boundaries. According to Clark (2004), the higher the electrical conductivity of the material, the greater is the attenuation and the lesser is the depth of penetration of the electromagnetic signal.

Before the measurements, a time window is, generally, fixed according to the expected depth of the objects and features that are to be resolved. This time window corresponds to the time taken by the signal to reach a reflector and then to come back to the receiver. This is a very important parameter because it will instruct the control unit only to read reflections during that period, with two consequences: firstly, it will avoid collecting unnecessary data; secondly, if not set up properly, the survey may fail to resolve targets located beyond the time window limits. That time, also designated by two-way transit-time or two-way travel-time, and denoted $\tau$ (ns), depends on the frequency and on the properties of the materials crossed by the radiowaves. The time window $\tau$ can be computed through

$$\tau = \frac{2h}{v_{mat}} \quad (6.7)$$
which is based on the maximum depth ($h$) that the user expects to achieve, and on the radiowave’s velocity ($v_{\text{mat}}$) through the respective material. Values for the velocity can be found in literature or through preliminary experimental measurements.

Limiting the transit time of the radiowave is necessary for limiting the amount of data collected by the system, avoids the recording of unnecessary data and speeds up field measurements. For example, when measuring a masonry wall ($v_{\text{mat}} \approx 12 \text{ cm/ns}$) with a thickness of 60 cm for quality purposes, $\tau$ is calculated as the time for the signal to reach the opposite side and come back, that is, 120 cm, which results in a travel time of 10 ns. Equation (6.7) can also be used after radar surveys to estimate approximately the depth of features that were present in radargrams.

### 6.3.6. Energy loss and attenuation

In Section 6.3.2 the electrical properties that govern the propagation of electromagnetic waves through materials have been described. They are electrical conductivity ($\sigma$), magnetic permeability ($\mu$) and relative permittivity ($\varepsilon$). During the propagation of radiowaves through sub-surface media, several factors result in a decrease of the signal’s strength and the electromagnetic signal will experience attenuation. The most significant loss mechanism is associated with material loss, which causes the electrical energy to be converted into heat energy. But, several other factors contribute to attenuate the radiowave’s energy. Figure 6.11 illustrates the most important factors that cause the decrease of the signal’s strength.

![Figure 6.11 – Factors that lead to the reduction of the signal’s strength. After Reynolds, 2002.](image-url)
Material absorption is considered to be the most significant loss mechanism, and causes the conversion of electromagnetic energy into heat energy (Clark, 2004). This phenomenon happens generally in conductive materials or in materials in which one of the constituents has an elevated electrical conductivity such as sea water, clay, wet bricks and stones (Clark et al., 2003a). The moisture content of materials is an important cause of absorption loss, whose presence, even in small amounts, can cause strong energy losses in frequencies above 1 GHz.

The attenuation of the electromagnetic signal’s energy, which is material dependent too, is a complex function of the electric and magnetic properties of the medium through which it is travelling. In fact, not all the materials attenuate the electromagnetic signal in the same way. Table 6.3 reports examples of artificial materials that attenuate the signal in a much different way. The attenuation coefficient is generally expressed in terms of decibels per meter (dB/m) or in Nepers per meter (Np/m). The higher the attenuation, the faster the signal will be lost.

<table>
<thead>
<tr>
<th>Material</th>
<th>Attenuation, $\alpha$ (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>asphalt</td>
<td>13.90</td>
</tr>
<tr>
<td>air</td>
<td>0</td>
</tr>
<tr>
<td>masonry</td>
<td>23.97</td>
</tr>
<tr>
<td>water</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Attenuation depends on the electric conductivity ($\sigma$), magnetic permeability ($\mu$) and permittivity ($\varepsilon$) of the material under investigation through which radiowaves propagate. A mathematical definition of the attenuation coefficient is given by

$$\alpha = \omega \sqrt{\frac{\mu_0 \varepsilon}{2} \left(1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}\right)^{\frac{1}{2}} - 1}$$

(6.8)

This is limited to non-magnetic materials, that is, with $\mu_r = 1$, where $\sigma$ is the bulk electrical conductivity at the given frequency, $\varepsilon$ is the dielectric permittivity ($\varepsilon = \varepsilon_0 \varepsilon_r$), $\mu_0$ is the magnetic permeability of free space and $\omega$ the angular frequency ($\omega = 2\pi f$). The attenuation is also frequency dependent. In fact, $\alpha$ is directly proportional to the signal’s frequency and, therefore, a higher attenuation of the signal is expected when using GPR systems with high frequency antennas.
The attenuation of the radar signal gives rise to the concept of skin depth ($\delta$), which was defined by Sheriff (1991) as the depth reached by the signal when its amplitude decreases by $1/e$, that is, approximately, 37% of its initial value $A_0$. The amplitude decrease of the electromagnetic signal at the particular depth $\delta$, denoted $A_\delta$, is defined by (Neal, 2004)

$$A_\delta = A_0 e^{-\alpha \delta}$$

(6.9)

The skin depth is inversely proportional to the attenuation, thus the higher the attenuation of a particular signal, the lower penetration reached. The skin depth is defined by (Reynolds, 2002)

$$\delta = \frac{1}{\alpha}$$

(6.10)

The skin depth only gives an estimation of how well the electromagnetic energy penetrates into a medium but does not define the absolute depth of penetration. A simplified formula of the skin depth is given by (Reynolds, 2002)

$$\delta = \frac{2}{\alpha} \sqrt{\frac{\varepsilon}{\mu}}$$

(6.11)

This equation is limited to cases where the signal propagates in low-loss materials. In the case of dry building materials, which are characterised by a low conductivity value, the simplified form of the skin depth can be used with the majority of GPR antennas. A realistic estimation of the depth to which a conductor would give rise to detectable electromagnetic anomaly would be $\delta/5$ (Reynolds, 2002).

Moreover, electromagnetic energy can be lost by geometrical spreading of the energy. The radar’s signal is transmitted as a conical shaped beam with an angle of 30° to 45°. As the signal travel away from its source, it spreads within a larger area, causing a reduction of the energy density. This reduction increases at a rate of $1/r^2$, where $r$ is the distance travelled by the signal and corresponds to the radius of the radiation in a spherical pattern, as illustrated in Figure 6.12. This loss mechanism increases with the increase in depth of the signal but generally, in shallow measurements, this loss can be neglected.

Another important factor of energy loss is energy scattering. When an electromagnetic wave hits an object part of its energy is reflected. If there are objects with dimensions of the same order as the signal’s wavelength, these objects will cause the electromagnetic energy to be
scattered or diffused in a random order (Reynolds, 2002) causing high levels of clutter (signal disorder) and loss. The amount of clutter is influenced by the frequency of the signal (Moorman, 2003) and by the conditions of the investigation medium. That way, a short wavelength (high frequency) will scatter a great amount of waves when radiated through an incoherent medium such as sand or a soil with stones, that is, with a significant amount of objects with dimensions close to the wave’s wavelength. Additionally, when the radiowave hits an interface between two adjacent materials with different dielectric properties, reflection and transmission mechanisms also result in energy losses (Reynolds, 2002).

![Diagram of geometrical spreading](image)

Figure 6.12 – Loss of power due to geometrical spreading.

Finally, energy losses can also occur due to the equipment electronics and efficiency. Generally, this occurs at two levels: in the antennas of the radar system, due to the inefficiency of the antennas to transmit and receive the totality of the signal, and due to ground coupling effects. GPR antennas are mostly used in direct contact with the ground, so, they are specifically designed to optimize the ground interaction in order to transmit the maximum electromagnetic energy into the investigation media. However, during the transmission of the radiowave, losses occur between the air and the ground, due to an insufficient coupling between the antenna and the surface.

This phenomenon largely modifies the radiation pattern of the antenna. All antennas have directional properties, which result in not radiating power equally in all directions. Thus, the electromagnetic field is irradiated in the subsoil with a radiation aperture smaller than in free space. For example, Shaari et al. (2003) showed that the beam width, or angular spread, of the radiowave’s signal in concrete was reduced to 60% of the value found in air.

A second consequence from ground coupling is that the radiated signal frequency experiences a translation of the spectrum towards lower frequencies relatively to the spectrum exhibited in free space (Forde, 2004; Shaari et al., 2003). The signal emitted by the antenna is a spectrum
of frequencies, where the peak corresponds to the central frequency of the antenna. When coupled to the ground surface, this peak frequency is shifted downwards, lowering the overall frequency of the signal. In that way, water, earth soil and any manmade material seem to force a shift of the entire spectrum towards lower frequencies due to the fact that the wavelength changes as the permittivity of the material changes. Figure 6.13 illustrates an example of the frequency spectrum from an antenna with a central frequency of 900 MHz when propagating through air, concrete and water. Shaari et al. (2003) concluded that the peak frequency decreases to 400 MHz when the signal propagates through concrete or water while in air the peak frequency is located at 900 MHz.

![Figure 6.13 – Frequency spectrum of signals in air, concrete and water. After Shaari et al., 2003.](image)

6.4. System design characteristics

6.4.1. Noise

When conducting a GPR survey, the signals that are recorded may incorporate data that is not directly connected to the investigation purposes, causing unwanted effects that can significantly degrade or even cover totally the signal from desired targets. That extraneous data is commonly designated by noise, and may come from different sources, such as natural events or manmade structures and materials. Despite their diverse nature, the most important sources of noise that may affect GPR are: vehicles, electric cables, telecommunications systems, GSM cell phones, pipes and natural electric and magnetic phenomena (Reynolds, 2002). Figure 6.14 illustrates the effect of the presence of a high level of noise.
Thus, any GPR survey should be carefully prepared to avoid acquiring unnecessary noise that can mask the important signals of the investigation. Besides the sources of noise described, other objects can interfere significantly in the radar signals. These are usually described as passive noise, which can partially hide the signals from the real targets. Therefore, it is wise to clean the area from metallic and other potentially detectable objects as they might appear in the radargram with reflections and diffractions. Such objects can be as diverse as metallic scaffolding and electric cables. Additionally, existing or unexpected objects within the investigation area can also give rise to disturbances in the radargram, such as underground pipes.

Several techniques are available to decrease the influence of noise into the radar data and to increase the Signal-to-Noise ratio. Firstly, the use of shielded antennas, which are antennas that contain a metallic envelope around the bow-tie elements, helps to prevent, or minimise, the effects of noise on radar data. This metallic enclosure works in both ways: firstly to prevent external radiowave from disturbing the investigation and, secondly, to prevent the radar signal to be irradiated on air and, possibly, disturb telecommunication systems or add noise after diffractions or reflections by neighbouring objects. Another possible technique to reduce noise influence consists in summing the effects of several traces acquired at very close locations, commonly designated by trace stacking. By doing so, the noise levels tend to cancel to some extent, so reducing its overall effect while the important signals are enhanced. Finally, the Signal-to-Noise ratio can be improved through the use of filters included in processing software packages, such as: pass band filters, DC removal, Automatic Gain Control (AGC).
6.4.2. Radar resolution

When performing a GPR survey, one of the most important questions to be answered is if the signal will be able to reproduce the layers, features and objects present in the investigation sub-surface region in order to recognise the signals from the targets among the other signals. The resolution of a particular antenna defines the minimum feature that can be successfully resolved, and, generally, it depends essentially on the central frequency of the antenna. Even if it is widely accepted that resolution increases with increasing frequency, the nonlinearity of the medium in which the electromagnetic waves propagate demands that additional considerations must be made, which are related to hardware characteristics and radiowave properties.

Generally, the resolution in depth is taken as a function of the frequency of the antenna and can be defined as the minimal distance between two reflectors that can be resolved. Generally, an object is resolvable if its dimensions are greater than ¼ of the wavelength (λ) of the incident radiation (Padaratz and Forde, 1995), when considering favourable conditions of propagation. However, it must be noticed that smaller objects can also be detected, such as small metal reinforcement in concrete structures or masonry bed joints, even if nothing can be said about their size. A direct result of this formula is that higher frequencies ensure a better resolution by having a smaller wavelength than lower frequencies. For example, the values of the wavelengths for several typical nominal frequencies used in GPR systems are listed in Table 6.4 as well as the expected resolution, when propagating in air.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Wavelength (cm)</th>
<th>Resolution (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>300</td>
<td>75</td>
</tr>
<tr>
<td>250</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>500</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>900</td>
<td>33.3</td>
<td>8.3</td>
</tr>
<tr>
<td>1000</td>
<td>30</td>
<td>7.5</td>
</tr>
<tr>
<td>1500</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

In reality, when propagation is performed through a solid medium such as soil, concrete, or masonry, the resolution decreases because it is affected by the complex nature of the source waveform, material characteristics and ground responses. Thus, the formula of a quarter of the wavelength in air is not applicable in solid materials, as the central frequency does not
Ground Penetrating Radar

correspond anymore to the nominal frequency. Studies by Padaratz and Forde (1995) showed that the wavelength of the electromagnetic signal decreases with the central frequency and dielectric constant of the investigated material. Thus, the joint influence of the decrease of the speed of propagation and the decrease of the peak frequency affect negatively the resolution of radar measurements. Values close to the theoretical resolution value have already been achieved in some laboratory experiments in controlled environments such as in the case described by Clark et al. (2003a), where the intrados and extrados of a 10 cm thick masonry arch were perfectly detected with a very high frequency antenna, which is the double of the expected resolution for the same frequency in air. Therefore, some authors suggest using an immediate value of half wavelength (\( \lambda/2 \)) as a basis for the choice of the antenna that fits the investigation requirements (Forde, 2004). Forde (2004) also suggests to take \( \lambda/3 \) as the depth of the first detectable target, which is useful when targets are located at shallow depths, such as in problems like material detachments, superficial cracks, and thin layered materials. To solve those problems, it is necessary to use an antenna with a very high frequency such as 1.5 to 2 GHz. However, these antennas are characterized by a rather low penetration.

The resolution of features located at the same depth can be defined as the minimum distance between two scattering targets located at the same depth that can be resolved. In this case, the electromagnetic signal is considered to travel from the transmitting antenna in a cone of radiation, with a finite-sized footprint (Figure 6.11 and Figure 6.12), defined by the directivity pattern of the antenna. The first Fresnel zone defines the area of the illuminated points inside the radiation cone that will not be individually discriminated because they contribute constructively to generate the same signal return since they produce signals that are separated less than half a wavelength during the total travel time. The radius \( r \) of the first Fresnel zone is given by (Pearce and Mittleman, 2002)

\[
r = \sqrt{\frac{\lambda^2}{16} + \frac{\lambda z}{2}}
\]  

(6.12)

For a depth \( z \) much superior to the wavelength (\( \lambda \)) of the propagating radiowave, a simplified equation is given by (Pearce and Mittleman, 2002)

\[
r = \sqrt{\frac{\lambda z}{2}}
\]  

(6.13)

The area of the first Fresnel Zone is related to the antenna’s frequency wavelength (\( \lambda \)), thus, the higher the wavelength, the larger the Fresnel zone. As a consequence, high frequency
antennas are characterised by smaller Fresnel areas, and, consequently, high spatial resolution due to their better capacity to distinguish closely positioned objects, relatively to lower frequencies antennas.

### 6.4.3. Signal sampling

The electromagnetic pulses that are received by the antenna are digitally stored, that is, the analogue signal is digitised, or sampled, at discrete intervals of time, through an A/D converter. An example of analogue and sampled signals is illustrated in Figure 6.15. In order to have a sufficient number of samples to reconstruct the real signal, samples must be collected at a specific frequency, called sampling frequency ($f_s$).

![Figure 6.15 – Example of (a) analogue and (b) sampled signals.](image)

If an insufficient number of samples are collected, at a frequency lower than the minimum sampling frequency, events could be missed during the investigation and the resulted signal would be different from the expected one. This is known by aliasing and can result in the loss of important high frequency information as well as in the introduction of “false” lower frequency data. Figure 6.16 illustrates an example of aliasing phenomena, where the real frequency is more than twice the reconstructed signal.

![Figure 6.16 – Aliasing phenomena due to an inadequate or too low sampling frequency.](image)
Therefore, the sampling frequency must be chosen adequately. Generally, aliasing phenomenon can be avoided if the Nyquist-Shannon sampling theorem is followed to quantify the sampling frequency (Lualdi et al., 2003; Annan, 1999a). This theorem states that the sampling frequency must be greater than twice the highest frequency of the input signal in order to reconstruct the original analogue signal flawlessly from the sampled version, as

\[ f_S > 2f_{\text{max}} \]  

(6.14)

As a result, the highest frequency that can be correctly reconstructed from the sampled signal is half the sampling frequency and is known as the Nyquist frequency \( f_N \) as reported by (Kak and Slaney, 1988; Utsi, 2003)

\[ f_N = \frac{1}{2} f_S \]  

(6.15)

The Nyquist criterion is also used to ensure that no elements are missed along the radar profile. The \( \Delta x \) interval between consecutive traces must be smaller than \( \frac{1}{4} \) of the minimum wavelength contained in the radar signal, defined by (Kak and Slaney, 1988; Doerkson, 2002)

\[ \Delta x < \frac{1}{4} \lambda_{\text{min}} \]  

(6.16)

The wavelength \( \lambda_{\text{min}} \) is obtained dividing the radiowave velocity \( (w) \) in the investigation media by the maximum frequency, \( f_{\text{max}} \), of the broadband pulse.

Considering that the maximum frequency is, approximately, 1.5 times the central frequency \( (f) \), with an antenna with a central frequency of 1 GHz, the sampling frequency \( f_S \) should be at least 3 GHz. These sampling requirements do not represent an insurmountable problem because, in modern GPR systems, sampling frequencies much superior to the ones required by the Nyquist criterion may be selected. Millimetre trace intervals can be selected to ensure a good digital description of the radar signal. Generally, the accuracy of radar data is limited by the equipment’s own characteristics. From the author own experience, a sampling frequency of 10 GHz and a trace interval of less than 5 mm may be taken when performing acquisitions with the 1 GHz nominal frequency antenna without influencing severely acquisition times.

### 6.4.4. Predicting GPR exploration depth

To determine the total exploration depth that can be achieved by the radar signal, additional factors must be taken into consideration in addition to those related with the sub-surface
media through which the electromagnetic waves travel and which are described in section 6.3. These additional factors are normally associated with radar equipment. Thus, to estimate the exploration depth, it is usual to use the Radar Range Equation (RRE) analysis, which consists in predicting the losses that affect the electromagnetic signal during its path from the transmitter to the receiver antennas. This path can be made of up to five steps, which correspond to the losses that occur to the signal: antenna losses (transmitter and receiver), transmission losses between air and the ground (efficiency of the antenna’s ground coupling), losses due to geometrical spreading of the energy beam, attenuation due to the investigation media properties and losses due to the scattering of the radar signal from the target itself (Reynolds, 2002). The flowchart illustrated in Figure 6.17 describes the losses that affect a single radar pulse. The electromagnetic pulse leaves the source with a power $P_S$, which, it should be noted, is limited by the regulations that control electromagnetic pollution, such as the Federal Communications Commission (FCC) in the United-Sates of America and the European Telecommunications Standards Institute (ETSI) in the European Community.

![Figure 6.17 – Block diagram of Radar Range Equation, which provides a means of estimating exploration depth.](After Reynolds (2002), Annan (2001) and Zanzi (2001).)
The transmitting antenna does not transmit the entire signal’s energy towards the investigation medium. In fact, only a fraction of the source power is radiated, depending on the efficiency of the antenna ($E_{Tx}$), which is, generally, associated with mechanical and electronic aspects of the antenna and ground coupling effects. Then, the energy fraction radiated towards the target is affected by a gain coefficient ($G_{Tx}, G_{Rx}$), as it is considered that the antenna does not irradiate homogeneously in all directions. During the propagation of the radiowave through the investigation media, the signal energy is reduced by attenuation coefficients ($K_{Tx}, K_{Rx}$), given by

$$K_{Tx}, K_{Rx} = \frac{e^{-\alpha z}}{4\pi z^2}$$

(6.17)

where, $z$ is the distance to the target and $\alpha$ is the attenuation coefficient. The denominator of $K$ corresponds to the total loss of the signal due to spherical divergence phenomena and numerator of $K$ represents material absorption.

When the signal illuminates the targeted objects, or any scattering object, a portion of the incident energy will be scattered depending on the cross-sectional area ($F$) of that object and its dielectric properties. Consequently, the object must be able to return part of the energy received from the incident radiowave in order to be detected. The scattering of electromagnetic energy only happen if the object has dimensions in the order of the signal wavelength. Once more, a gain coefficient ($g$) is given to estimate the energy reflected from the target towards the receiver, as the energy is not reflected homogeneously in all directions.

Finally, the energy arriving at the receiver will be collected by the antenna according to its effective area ($A$) and gain ($G_{Rx}$). The efficiency ($E_{Rx}$) of the receiver is the last term that contributes to reduce the effective power collected by the system.

The final Radar Range Equation is described by

$$P_R = P_0 \frac{E_{Tx} E_{Rx} G_{Tx} G_{Rx} v^2 (gF) e^{-\alpha z}}{64\pi^3 f^2 z^4}$$

(6.18)

where $v$ is the radiowave velocity through the investigation material. Possible targets at a particular depth will not be resolved if the value of $P_R$ drops too close to zero.
7. GPR and masonry structures: standard and advanced data processing

The effectiveness of the georadar in the structural assessment of historical structures will be demonstrated in the examples described in the following sections. The constitution of structural elements in historical buildings is often complex, being composed by several different and heterogeneous materials, like multiple-leaf masonry walls with mortar, stone, brick and rubble infill. Additionally, masonry structural elements include frequently other materials such as wood beams or iron elements (anchors, ties, etc.). These characteristics are important because to estimate the conservation state of structural elements it is necessary to determine the nature of the materials as well as their geometrical constitution (Binda, 2005). Thus, a series of georadar investigations were carried out in the present work, most of them in the framework of an European project (ONSITEFORMASONRY). These tests took place in several historical monuments that exhibit damage and require diagnosis, and in laboratory specimens specially designed for calibration purposes. Part of the GPR surveys was carried out in Portugal, in two historical monuments and in one laboratory specimen.

The results obtained from the laboratory specimen built at the University of Minho will be firstly presented, followed by the second laboratory specimen. Afterwards, the results obtained in historic monuments will be presented, with a particular focus on the presentation of radar data as usable images of the investigated elements. With respect to the investigation carried out in the monuments, the problems most frequently requested were to assess the material and geometry information from structural elements, to detect and locate steel and non-steel elements, voids, cracks and moisture content of materials. When necessary, the advantage of processing the data in 3D rather than solely in 2D will be highlighted (Binda et al., 2003), as well as the use of radar tomography (Saisi et al., 2001).

To process the GPR signals, software developed under ONSITEFORMASONRY European project will be used (RADARPOLI2D for typical 2D processing, GPR3D for 3D reconstruction and TOMOPOLI to process transmission acquisitions). For details about the processing techniques used in the present work the reader should consult the Annex C.

7.1. Main objectives of the ONSITEFORMASONRY project

The EC funded research project ONSITEFORMASONRY aimed at providing improved methodologies for the evaluation of historic masonry cultural heritage based on non-
destructive (NDT) and minor-destructive (MDT) testing techniques. The main final objective of the research project was to improve the cost/benefit ratio for investigation and diagnosis, based on the following goals:

- Improvement of current non-destructive techniques for better analysis, prediction and early prevention of damage as well as for the diagnosis and quality control of the intervention.
- Methodologies that allow more frequent assessments at lower costs.
- Use of the results for structural analysis.
- Definition of standards and guidelines.

For onsite testing and evaluation of methodologies, specific pilot sites have been selected and laboratory specimens were built in a way that a multitude of typologies and parameters were represented. General aims were:

- Clear up construction details.
- Understand the construction principles.
- Find and distinguish moisture distribution and content.
- Calibrate NDT and MDT methods.

The present work reports the results from the project with respect to Ground Penetrating Radar. The experimental work was carried out in the following locations: Pisece castle (Pisece, Slovenia); Altes Museum (Berlin, Germany) and OBELIX stone/brick masonry specimen (Berlin, Germany) built in the Federal Institute for Materials Research and Testing (BAM).

### 7.2. Stone masonry walls

Two stone masonry walls, illustrated in Figure 7.1, were built in the University of Minho with the objective of assessing the effectiveness of GPR to detect the geometry and characteristics of the masonry leaves. Additionally, the investigation aimed at detecting the elements embedded in the infill using several techniques. In this section, the geometrical details (thickness of masonry leaves and infill) and the embedded features (wood beam, polystyrene prism) will be evaluated with GPR.
7.2.1. Description of the specimens

The walls were constructed with three different kinds of masonry typologies with very weak lime mortar in order to simulate different but typical historic masonry typologies. Two different materials were used for the infill. A void was simulated with a polystyrene prism in one of the specimens and a wood beam was placed in the other wall. The detailed design drawings are shown in Figure 7.2.

Both walls are made with three-leaves, constructed on top of a small 5 cm thick concrete slab, cast only with the purpose of rectifying the ground surface. At the top of each wall, a thin layer of concrete was laid in order to protect the interior of the walls from rain and dust. A small slope was provided to facilitate rainwater drainage. The dimensions of the walls are, 122 cm in height by 260 cm in length. The thickness of the eastern wall (Wall 1) is 68 cm and 56 cm for the western wall (Wall 2). See Figure 7.3 for construction details.
Figure 7.3 – Examples of the construction phases of Wall 2. (a) Small 5 cm thick concrete slab for ground rectification, (b) starting of the construction of the wall over the thin slab and (c) protective thin concrete layer on top.

The masonry typology adopted in the walls is constituted, in the western side, by a rubble stone masonry with lime mortar joints with a thickness of 20 cm (Figure 7.4a). In the eastern side, two different masonry typologies were used: a 20 cm thick panel of regular masonry with unfilled joints (Figure 7.4b) and a panel of irregular stone masonry with lime mortar, with an average thickness of 20 cm (Figure 7.4c).

The infill was different for each wall. In Wall 1, the infill was constituted by rock and brick fragments, sand, pebbles and clay, in order to simulate a bad quality infill or a heterogeneous material of low strength. In Wall 2, the infill is constituted by gravel, with 2-3 cm of diameter and almost no cohesion. Two different objects were placed in the centre of the infill layer: a small high density polystyrene prism with dimensions of 9.5×8×40 cm, placed vertically in Wall 1, close to the top of the wall at about 80 cm from the ground (Figure 7.5), and a wood
beam with dimensions of 6.5×6.5×100 cm, placed vertically in Wall 2, but covering nearly the entire height of the wall (Figure 7.6).

Figure 7.5 – Construction of Wall 1 and location of the polystyrene prism. (a) Wall with a height of 80 cm and (b) position of the polystyrene prism (40 cm) close to the maximum height of the wall.

Figure 7.6 – Construction of Wall 2 and location of the wood prism. (a) Start of the construction with the prism in contact with the base and (b) top of the wood prism close to the maximum height of the wall.

7.2.2. GPR results

7.2.2.1. Velocity analysis

The investigation on these masonry walls was carried out with the RAMAC/GPR system from MALA Geoscience, which was constituted by high frequency antennas: 1 GHz (Figure 7.7a) and 1.6 GHz (Figure 7.7b). The triggering and positioning system used with the 1 GHz antenna was composed by a digital hip chain and is illustrated in Figure 7.7c. It was preferred over the survey wheel due to the irregularity of the surface of the walls. The antenna was
positioned in the centre of the masonry panels oriented towards east, with a steel plate placed over the opposite surface. Figure 7.8 illustrates the radargram of the acquisition in time performed in Wall 2, where the signal took 9.1 ns to cross a 58 cm thick wall. An average radiowave velocity around 12.0 cm/ns was obtained from acquisitions in time in both walls.

Figure 7.8 – Time depth of the opposite side of the wall in the Wall 2 and equation to estimate average velocity.

7.2.2.2. Horizontal profiles from the eastern sides of the walls

The horizontal profiles were firstly performed on the eastern sides of both walls, which are constituted by two different types of masonries (regular and irregular). The different methodologies for the acquisition with the two antennas resulted in different profile’s lengths. Generally, the length of profiles is between 225 and 230 cm. The first profile was acquired at 9 cm from the concrete base and further horizontal profiles were separated by 15 cm.

Figure 7.9 represents a radargram from Wall 1 in the upper part of the wall acquired with the 1.6 GHz antenna. The data has been filtered and a gain function was applied to enhance the
diffractions. It is possible to recognize the regular masonry panel by the horizontal signal it has produced at the beginning of the profile (at 3.5 ns), while the second panel is detected via the hyperbolas that spread in the first nanoseconds. The interface between the first leaf and the infill material was clearly defined at an average depth of 3.5 ns, characterized by a strong reflection due to air voids caused by the deficient contact between stone and infill. The construction of these walls followed a traditional way, thus, no compaction was done to the infill, with the consequence of a high probability of occurrence of voids. Taking the velocity found earlier (12 cm/ns) the final thickness of the stone layer was estimated in 21 cm (error of 5% relatively to the design thickness). However, the no clear radargram was obtained showing clearly the signal from the polystyrene prism, even with the 1 GHz antenna.

With respect to Wall 2, the results were more satisfactory. The interface between the first stone panel was detected (see Figure 7.10a), with a clear distinction between regular and irregular masonry, at 100-110 cm from the beginning of the profile. Afterwards, the irregularity of the signal indicates an irregular interface. In this case, the wood beam was correctly detected, although a rather weak signal was obtained. The removal of the background signal, illustrated in Figure 7.10b, enhances further the hyperboles from the wood beam. The signal from the opposite surface was detected. However, the second interface (infill/masonry) was not detected.

The radargram in Figure 7.11 shows the wood beam acquired with the 1.6 GHz antenna, which showed a slightly better resolution than the 1 GHz antenna. The wood beam placed within the infill was correctly detected by a rather strong diffraction at approximately 110 cm from the beginning of the profile and at 5-6 ns of depth (26-30 cm). The better resolution of this
antenna can be assessed by the shape of the diffraction that corresponds to the wood beam. While in the first case, only a simple diffraction occurred, with the 1.6 GHz antenna, the other interface of the wood beam can be slightly perceived, as the diffraction is bigger. Nevertheless, the signal from the opposite surface was detected, but the second interface (infill/masonry) was still not detected. A slight error was observed when comparing the location of the wood beam in the radargrams relatively to the original design position.

![Figure 7.10](image_url)  
(Figure 7.10 – Radargram at 39 cm from the concrete base. (a) Simple signal filtering was applied in the dataset. (b) Background removal was additionally applied additionally.)

![Figure 7.11](image_url)  
(Figure 7.11 – Radargram at 29 cm from the concrete base with the 1.6 GHz antenna.)
7.2.2.3. Horizontal profiles in the western side of the walls

Additional horizontal profiles were carried out in the very irregular surface of both walls. The methodology was the same as before but only the 1 GHz antenna was used for this purpose. Because of the rough surface, the radargram exhibit strong irregularities, especially related with the signal from the acquisition surface and with the interface between the acquisition panel and the infill. This interface is not perceived very well. Figure 7.12 illustrates that fact with two radargrams of the same profile from the Wall 1 but processed differently. In the second case (Figure 7.12b), the background signal was removed and it was possible to observe numerous hyperbolas, characteristic of the irregular masonry material. However, no signals from the second interior interface or from the polystyrene prism were found, and only the signal from the opposite surface appears.

![Figure 7.12](image)

Figure 7.12 – Radargram from Wall 1, at 99 cm from the concrete base. (a) Filtering and SEC gain. (b) Filtering, background removal and AGC. Antenna of 1 GHz.

The information is similar in the case of Wall 2. Figure 7.13a shows one profile where the opposite side can be clearly distinguished through a horizontal signal. Numerous hyperbolas due to irregular joints and voids in the masonry panel are evident, consequence of removing the background signal. At 6 ns a very weak signal is observed. To improve its visibility, the background was removed, and resulted in the radargram showed in Figure 7.13b. A first hypothesis is that the observed weak signal is the diffraction that corresponds to the wood beam, as no other event appears around. The distance from the centre of the diffraction to the end of the profile was estimated in 88 cm. When adding 25 cm for the survey wheel, the total
length is 113 cm, which corresponds almost to the distance found in the radargrams carried out from the opposite side (with regular masonry).

Figure 7.13 – Radargrams from the Wall 2. (a) Profile at 69 cm from the concrete base (filtering and 5 ns AGC). (b) Profile at 39 cm from the concrete base (filtering and background removal).

7.2.2.4. Cross-section tomography

2D radargrams were extremely useful in the detection and location of the timber beam and the polystyrene prism embedded in the masonry walls. However, in order to assess the nature and shape of these objects, transmission measurements will be carried out in the area where those objects were detected. Transmission measurements result in velocity and attenuation tomograms that can help to identify more accurately the nature and shape of the embedded elements. This topic is currently being developed and improved in the frame of the European project Sustainable Bridges.

The measurements were carried out in both walls with two 1.6 GHz antennas. The investigation area was selected around the location of the embedded element that was estimated from the 2D radargrams. With respect to Wall 1 (with the polystyrene prism), the section of interest was located 40 cm below the top of the wall and consisted in an area of $100 \times 68$ cm$^2$ illustrated in Figure 7.14a. The transmitter was sequentially fixed in eleven stations separated by 10 cm while the receiver was performing eleven continuous profiles in the opposite side of the wall. WinTomo software (proprietary of MALA Geoscience) was used to process the radar data and to obtain the final velocity and attenuation tomograms.

The final velocity tomogram obtained from the investigation in Wall 1 is illustrated in Figure 7.14b. It shows that the major part of the tomogram exhibits an average velocity smaller than
12 cm/ns. The borders of the tomogram are characterised by a substantial number of artefacts and other side effects, which were not taken into consideration. Only the central area of the tomograms was considered for interpretation. A small area exhibiting a very high velocity, around 18 cm/ns, is located in the centre of the tomogram. Its position corresponds to the position of the polystyrene prism. The speed of propagation of radiowaves within polystyrene is close to the velocity in air (which is why this material is often used for air substitution when simulating air voids inside structures).

Figure 7.14 – Results from the transmission tomography. (a) Grid of measurements in Wall 1 and (b) resultant velocity tomogram.

With respect to Wall 2 (with the wood beam), the section of interest was located 30 cm below the top of the wall and consisted in an area of 80×58 cm² illustrated in Figure 7.15a. The transmitter was sequentially fixed in nine stations separated by 10 cm while the receiver was performing nine continuous profiles in the opposite side of the wall. The final velocity tomogram obtained from the investigation in Wall 2 is illustrated in Figure 7.15b. The major part of the tomogram exhibits an average velocity around 14 cm/ns. The borders and interior of the tomogram are characterised by a substantial number of artefacts and other side effects that affect quite severely the quality of the data. The area that was interpreted as being from the wood beam correspond well to its geometrical location and exhibits a very high velocity,
around 19 cm/ns, slightly higher than in polystyrene, which reveals that the radiowave velocity is similar in both materials.

![Figure 7.15](image)

Figure 7.15 – Results from the transmission tomography. (a) Grid of measurements in Wall 2 and (b) resultant velocity tomogram.

As it can be seen, the tomograms reproduce rather accurately the spatial position of the embedded elements in the masonry walls. However, the shape and area of the targeted elements are quite distant from the real situation, which might be due to the insufficient ray coverage (two sides were not covered). Nevertheless, the area in the tomograms that correspond to the wood beam and the polystyrene were calculated approximately. This resulted in rather distinct values. While the area of to the polystyrene prism was 19 % smaller than the real area, the area of the wood beam was 17 % larger than its real area.

### 7.2.3. Summary

High frequency GPR was applied in simulated historic masonry walls in order to map masonry layers and embedded elements as well. The boundaries of the walls were detected, although the maximum depth was naturally limited by the antenna’s high frequency.
Moreover, the signal loses energy and experiences significant scattering when propagating through irregular masonry, causing that lower contrast interfaces such as between the masonry panels and the infill can only be detected at shallow depths. Nevertheless, the thickness of the first stone layer was assessed in both walls when the acquisition was carried out over the most regular surface. The same did not happen in the case of the infill/masonry panel deeper interface or when the acquisition was carried out from the irregular surface. The wood beam was clearly detected with the 1 GHz and 1.6 GHz antennas, although the last one showed better definition of the wood beam. The position was found to be slightly different from the expected one. Most probably the wood beam suffered some displacements during the construction. However, the polystyrene prism was not detected, despite presenting a cross-section larger than the wood beam.

Finally, the tomography carried out in both walls resulted in satisfactory results. Both polystyrene prism and wood beam were located. However, this methodology was limited by the small area of investigation, insufficient ray coverage and a significant number of artefacts in the final results that masked partially the targets of the investigation, especially in the case of the wood beam.

7.3. Stone/brick masonry wall – Obelix

7.3.1. Description of the specimen and methodology

A complex multi-leaf stone/brick masonry wall was built with the aim of simulating typical characteristics of historical walls. This structure, called Obelix and illustrated in Figure 7.16, was erected in the installations of BAM (Federal Institute for Materials Research and Testing, located in Berlin, Germany) in the framework of the ONSITEFORMASONRY European project. This specimen was specially designed for the testing and calibration of non-destructive techniques currently used in the diagnosis of historical structures.

Figure 7.16 – View of the wall from the (a) North and (b) South side.
The wall is constituted by three main parts, where different construction materials are used and where several heterogeneities, voids, steel and wood inclusions, different kinds of plaster, punctual application of distinct material, degraded material and cracks were present in order to simulate the aspect and condition of typical historic masonry walls. This wall was specially built to calibrate NDT and MDT techniques to verify the effectiveness of the applied methods.

The GPR investigation focussed on a small area of the “Part I”, where 2D acquisitions were carried out to map voids, steel and concrete elements placed inside the wall. The two areas of investigation are illustrated in Figure 7.17 and correspond to an area of $120 \times 100$ cm$^2$. With respect to the first area (Figure 7.17a), the targets are constituted by a steel anchor and four cylindrical voids located at different depths (Figure 7.18a). In the second area (Figure 7.17b), the targets are constituted by a concrete baluster (average dimensions of $43 \times 16 \times 16$ cm$^3$), one cylindrical void and, at the bottom, a small area where a delamination occurred in the lime mortar layer has been repaired with cement mortar (Figure 7.18b).

![Figure 7.17 – Overview of the areas for GPR investigation and description of the targets. (a) In the North side. (b) In the South side.](image)

That part of the wall is composed by two different masonry typologies. From the base up to 150 cm, it is a three-leaf brick wall (Figure 7.18a), with exterior panels made of modern clay bricks and an infill constituted by lime mortar, brick and stone fragments, and rubble. From 150 cm to the top, the wall section is constituted by clay brick masonry (Figure 7.18b).
Radar profiles were acquired with the intent of building a 3D image of the investigated area in order to obtain more realistic data from the objects inside the wall. Thus, a convenient positioning system was adopted in order to assure the following requirements: parallelism and high density of profiles. For that purpose, a special cardboard with parallel and closely spaced trails was attached over the investigation area. The space between consecutive trails was 0.78 cm. The antenna was then equipped with a special plastic board that fitted in the cardboard trails (Figure 7.19a). This system allowed the acquisition of parallel profiles distanced by 1.56 cm, that is, every two trails, as illustrated in Figure 7.19b.

The 3D reconstruction that is discussed here corresponds to the volume constituted by all the 2D profiles placed one after another. Afterwards, the volume is created by performing linear interpolations between successive profiles. At this stage, the software available to create these volumes requires the individual radargrams to have the same number of traces, the same length and the same time window.
7.3.2. GPR Results

The average velocity of propagation was obtained by acquiring a profile in time through the wall with a steel plate placed on the opposite side, to easily detect the interface. However, the interface’s signal was very weak and, to increase it, the radargram in Figure 7.20 was obtained by removing the background signal and applying AGC. This resulted in an average radiowave velocity of 12.6 cm/ns.

![Profile acquired in time of the “Part I” of the brick wall.](image)

7.3.2.1. Detection of the baluster and void in the South side of the wall

The profiles acquired in the South side of the wall show essentially the signal from the concrete baluster. See for example, Figure 7.21a and Figure 7.21b. The concrete baluster is the only feature observed in almost all the profiles. This seems to be the direct result of the lack of penetration of the antenna of 1 GHz and the poor contrast between bricks and the baluster. The centre of the diffraction is located between 8 and 10 cm of depth and might correspond to the interface brick/baluster. Figure 7.21c shows the void located under the baluster. However, the signal is rather poor and does not transmit very well the circular shape of the target, although it is considered the most appropriate shape for radar detection. The signal might also be affected by brick layers (Figure 7.18b) or by a deficient construction. The opposite surface was not detected neither any internal interfaces.

Afterwards, the 2D profiles were combined into a 3D volume, and the data was properly processed and focussed. Figure 7.22 shows the final result after migration, with the shape of the baluster being rather well perceived and exhibiting high reflection intensity. At the depth of 22 cm, the void is also detected. However, its location does not correspond exactly to the design plans that were made available.
Figure 7.21 – Radargrams showing the baluster signature at (a) 17.2 cm and (b) 32.8 cm. (c) The void can be seen in the profile at 61.0 cm from the first profile.

Figure 7.22 – Horizontal slice showing the baluster at 22 cm of depth.
With respect to the external dimensions of the objects that were obtained from the 3D volume, they show to be relatively close to the real dimensions. Figure 7.22 and Figure 7.23 show the focussed images of the baluster and the void with the indication of the average dimensions read from the radargram. It is noted that what is obtained from the 3D images is the result of the linear regression between consecutive 2D profiles, which depends on the resolution from the antenna of 1 GHz and acquisition method.

![Diagram](image)

**Figure 7.23** – Migrated profiles from the (a) void and (b) baluster, with the respective dimensions.

It can be seen that the migrated shapes are far from matching the real shapes of the objects. Thus, the dimensions of the baluster and void were estimated from the external envelop limited by the signals with a relative intensity higher than $1.5 \times 10^6$. The dimensions of those
objects are reported in Figure 7.22 and Figure 7.23. Concerning the baluster, the dimensions from the 3D image show an error of 15% relatively to the real dimensions (see Table 7.1), while in the case of the cylindrical void, the differences are more significant (see Table 7.2). An approximate shape of the baluster and void as an isosurface (corresponds to the points with a particular single scalar value within the volumetric data field) is shown in Figure 7.24.

Table 7.1 – Comparison of the dimensions of the baluster taken from the drawings and the profiles.

<table>
<thead>
<tr>
<th></th>
<th>Design drawings (cm)</th>
<th>3D volume (cm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
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<td>38</td>
<td>13</td>
</tr>
<tr>
<td>Width</td>
<td>16</td>
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</tr>
<tr>
<td>Depth</td>
<td>16</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 7.2 – Comparison of the dimensions of the void taken from the drawings and the profiles.

<table>
<thead>
<tr>
<th></th>
<th>Design drawings (cm)</th>
<th>3D volume (cm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
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<td>Diameter</td>
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<td>12</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>9</td>
<td>40</td>
</tr>
<tr>
<td>Depth</td>
<td>10</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 7.24 – Isosurface obtained from the 3D volume showing approximately the baluster and the void.

7.3.2.2. Detection of the iron element and voids in the North side of the wall

The profiles acquired in the North side of the wall showed only information about objects close to the acquisition surface. In fact, only the steel anchor was satisfactorily detected in the 2D profiles although the area of investigation illustrated in Figure 7.17 contained a significant
number of voids. These were rather difficult to detect in few radargrams. For example, the radargram in Figure 7.25 has been filtered and the background signal removed because no other information except the diffraction hyperbola of the steel anchor was expected. The position of the steel anchor is at 10 cm from the extremity of the radargram, while, in the wall, the steel anchor is at 22 cm from the “Part II” of the wall (end of the profiles). When the antenna stops, the centre of the antenna is at 11.5 cm from the “Part II”. Adding 10 cm (corresponds to the position of the hyperbola in the radargram) results in 21.5 cm. Thus, the location of the steel anchor position was rather accurate in the radargrams. Moreover, the steel anchor and two voids are detected in the radargram of Figure 7.26. The depth of the void located the most at the surface revealed to be quite accurate, with an error smaller to 5 % with respect to design plans, while the second exhibits an error around 30 %.

Figure 7.25 – Radargram located at 127.24 cm from the ground and showing the relative position of the steel anchor relatively to the on site location. The antenna is shown in the final position.

Figure 7.26 – Radargram crossing the steel anchor and the two voids at the bottom of the investigation area.
Then, the 3D volume obtained from the 2D profiles was accurately processed and focussed. A cross-sectional view of the 3D volume is represented in Figure 7.27, which shows the steel anchor and a void that is located in the bottom of the investigated area and closer to the surface. It is noted that the position of the steel anchor is in the right instead of being in the left as observed in the design plans. This is essentially due to technical issues related to the software application. 2D profiles were inserted as they were acquired and were not flipped before the 3D volume was built. No other void could be detected, although in few profiles two or more voids have been apparently detected (Figure 7.26). It must be noted that the signal processing prior to produce the 3D volume included the removal of the background signal. This step could have affected the voids, which are mainly horizontal signals, despite their cylindrical shape towards the radar beam. However, as very few profiles present signals from other voids, these voids do not present a significant area in the 3D volume.

![3D view of the steel anchor and one of the four voids present in the investigation area.](image)

The steel anchor did not produce a uniform signal, as it can be perceived from Figure 7.28a. Part of the signal produced a rather strong reflection of energy, while the second part exhibited a weaker signal. It seems that the steel anchor’s shape changes with depth. It must be also noted that the volume of the signal reflected by the steel anchor is much larger than the steel anchor itself. This is mainly due to the strength of the reflection, which is rather
important in the case of the steel element, and to the lack of resolution of the antenna, which, consequently, causes the migration of the data to output an area larger than the real object. Thus, the thickness for the steel anchor obtained from the 3D volume was more than four times the real one (2 cm). Similarly, the void that is detected together with the steel anchor does not exhibit dimensions close to the real void. In this case, the cross-section of the object is around three times smaller than the real one, confirming the detection difficulties. Additionally, isosurfaces of the objects are shown in Figure 7.24.

![3D volume of steel anchor and void](image)

**Figure 7.28 – Depth slices extracted from the 3D volume showing (a) the steel anchor and (b) the void.**
7.3.3. Summary

GPR was applied in a brick masonry wall to map one concrete baluster, one steel element and several voids. Data was acquired in a way to produce a 3D volume from 2D profiles. The number of features resolved was limited by the antenna of 1 GHz, which caused some of the deepest voids to not be resolved. Nevertheless, the 3D volume allowed a better perception of the location and size of the objects with respect to the 2D radargrams. However, in some cases, the dimensions presented by the objects in the radargram were significantly different from the original ones. In the case of the steel anchor, the resolution of the antenna caused the dimensions of the steel anchor to be overestimated. Finally, the cylindrical shape of the voids caused surprisingly the electromagnetic pulses to be reflected away from the antenna, making its detection more difficult.

7.4. Castle of Pisece, Slovenia

7.4.1. Description of the monument

The Pisece Castle is a monumental construction from the first half of the 13th century. It is a complex structure (Figure 7.30), built with different kinds of materials, namely, stone and irregular brick masonries (Figure 7.31). At the time of the measurements, the building exhibited many damages and several situations of eminent ruin. The experimental campaign was carried out within the ONSITEFORMASONRY European funded project.
Part II – NDT in masonry using Ground Penetrating Radar

Figure 7.30 – Aspect of the buildings in the Castle of Pisece. (a) Tower with crack. (b) Main yard.

Figure 7.31 – Aspect of the materials present in the Castle. (a) Rubble stone masonry column with exterior layer of clay brick masonry. (b) Rubble brick masonry. (c) Regular stone masonry.

The GPR investigation in the Pisece Castle focussed on the characterization of the masonry in order to evaluate the load bearing capacity of the Castle (Bosiljkov et al., 2005; Binda et al., 2004). This included the localization of homogeneous material and heterogeneous or damaged portions of structural elements, which was, essentially, carried out in three different locations of the central tower (see Figure 7.32). Radar investigations in positions TOW1 (4th floor) and TOW 2 (3rd floor) focussed on the determination of the material’s homogeneity and location of cracks. In TOW3, the objective was the detection of a significant vertical crack that spanned almost through the entire central tower. Finally, in position POS5, the aim was to detect the interface between different masonry materials. Additional details about this monument can be found in Binda et al. (2004).
7.4.2. Results

7.4.2.1. Homogeneity of the 3rd and 4th floor walls of the central tower

Firstly, a velocity analysis was carried out to calculate the average radiowave velocity in the wall. In the 3rd and 4th floor of the tower, the thickness of the wall is around 2 m. The methodology consisted of placing a steel plate against the opposite surface in order to enhance the signal from that interface. The acquisition in time in both walls can be observed in Figure 7.33a for the wall in the 4th floor and in Figure 7.33b for the wall of the 3rd floor. Taking into account the respective thicknesses, the average radiowave velocity resulted in 12.2 cm/ns.

![Figure 7.32](image1)

![Figure 7.33](image2)

Figure 7.32 – Localization of the sites where were carried out radar measurements.

Figure 7.33 – Acquisition in time in the wall of the 4th floor (TOW1), with a thickness of 198 cm.
Then, reflection profiles were performed along the wall at different heights. Both walls exhibit irregular surfaces and several large cracks reaching up to 5 mm of width. In addition, these cracks seemed to be continuous and to spread through the top of the tower to the bottom. Figure 7.34 shows the aspect of the surface of the walls of the tower, as well as the position and shape of the cracks that were observed. It must be noted that in the wall from the 4th floor three significant cracks can be observed, while in the 3rd floor, mainly one crack is observed at the far right. This crack is considered as the continuation of the crack from the 4th floor.

![Cracks](image1.png) ![Continuous crack](image2.png)

Figure 7.34 – Aspect of the wall’s surface in (a) the 4th floor and in (b) the 3rd floor.

The profiles made on these surfaces aimed to determine the areas of the wall that were in good state of conservation and to locate the cracks and how much they spread inside the wall. Generally, the walls were not constituted by a layered material but a rather homogeneous material. Thus, the only horizontal signals were those from the wall’s external surfaces. Thus, in order to better see the area affected by the cracks, the background signal was subsequently removed in every profile. Figure 7.35 shows a horizontal profile (line 7) where the area affected by the cracks can be clearly seen in the 150-400 cm range. This area is mainly constituted by diffraction hyperbolas at different levels, which extend up to the middle of the wall’s cross-section. The radargram exhibits several additional dip events that came from the edges and corners of the wall see Figure 7.36.

The other two profiles were acquired above and below the profile of line 7, with the line 6 represented in Figure 7.37a and line 8 in Figure 7.37b. It is noted that the time axis has been converted in depth using a propagation velocity of 12 cm/ns. The area affected by the cracks
in the profile from line 6 is clearly visible in the 150-400 cm range and it affects more than one third of the wall’s section. However, in the case of line 8 (Figure 7.37b), the affected area increases slightly to 100-400 cm, which could mean that the damaged area decreases with the height. The information obtained with the higher frequency antenna (1 GHz) showed the same results that were obtained with the 500 MHz antenna. Thus, they are not presented in this research work.

Figure 7.35 – Horizontal profile with the 500 MHz antenna from the line 7.

Figure 7.36 – Origin of the dip events in the radargrams from the 4th floor of the tower.
Concerning the radargrams obtained in the wall from the 3rd floor, they exhibit also numerous hyperbolas essentially grouped in the right side of the radargram. Thus, they represent damage endured by the wall. With no surprise that disturbed area coincides with the location of a significant crack, much like the one saw in the 4th floor in the same location (right). This situation is illustrated in Figure 7.35. This strongly suggests that this crack is continuous between the two levels and spread out towards lower levels. However, in this case, the hyperbolas are much more present along the entire section of the wall and not only until a certain depth, as it was the case of the radargrams from the 4th floor. The disturbed area is limited with a dashed line in all radargrams of Figure 7.38. They all exhibit the same pattern: the damaged area starts at 200 cm from the beginning of the profile and goes up to a depth of 15 ns, which is equivalent to 92 cm. At 300-350 cm, that area spreads through the entire thickness, which seems to suggest that a crack is likely to be observed from the exterior. Figure 7.39 seems to further support that last hypothesis.

It is noted that this wall has a significant area covered by lime plaster in the 3rd floor, see Figure 7.38a. That layer is slightly detached in its limits, which suggest that it was applied some time after the construction of the wall. Table 7.3 shows the distance at which the plaster layer is from the beginning of the profiles. Apparently, it seems that the plaster layer covers partially the disturbed area of the radargrams in Figure 7.38. Thus, it can be concluded that this plaster layer was applied in the wall to repair some apparent damages already caused by the formation of cracks in the tower. Furthermore, because the large crack in the right happened after applying the lime plaster, it suggests that the cracks are occurring since a long time and continued after the repair was applied.
Table 7.3 – Distance of the limits of the plaster layer from the beginning of the radar profiles.

<table>
<thead>
<tr>
<th>Line</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
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<tr>
<td>Distance (cm)</td>
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<td>253</td>
<td>230</td>
</tr>
</tbody>
</table>

Figure 7.38 – Horizontal profiles from the wall in the 3rd floor with the 500 MHz antenna. (a) Aspect of the wall. Radargrams of the (b) line 1, (c) line 2 and (d) line 3, which were filtered and the signals enhanced with SEC gain.
7.4.2.2. Exterior crack in central tower

The central tower was further investigated from the exterior, in a position close to the ground. Figure 7.40a illustrates that position. The aim of GPR investigation was to detect a large crack, which was visible from the outside, and to verify its path in the interior of the wall. Because the crack was around 70 cm from the surface, the 1 GHz antenna was preferred due to the higher resolution obtained. Practical reasons such as its weight influenced the choice of this antenna. An extension arm was used with the 1 GHz antenna to be able to make this profile (Figure 7.40b).
The radargram obtained from that position is reported in Figure 7.41. The first event that is indicated in the radargram corresponds to two events, both located between 60 and 80 cm of depth. Although it seems that the signal matches the crack visible from the exterior, which stands 70 cm from the edge of the acquisition surface, the signal is not continuous but divided in two. One occurred in the first 50 cm and a second one in the last 15 cm, from top to bottom, respectively. This could mean that the crack is thinner in some part, turning more difficult its detection with the radar.

Another event is located deeper in the top of the radargram, at a depth of 100 cm, and measuring 50 cm. It is almost a copy of the signal that occurs in the same position but at a deeper depth (60-80 cm). This could indicate another crack inside the wall but with no visible evidence from the exterior. Moreover, other signals confirm the existence of other detachments, voids or cracks, like the 15 cm long signal found at a depth of 140 cm. Still, no uninterrupted signal indicating a continuous crack was detected. Only large and isolated detachments are. However, as those signals are located deeper than the signals from the visible crack, it indicates that the crack visible from the exterior continues towards the interior of the tower, in a sloping direction.

Figure 7.41 – Detecting the evolution of the external crack in the interior of the exterior wall of the tower. (a) Aspect of the crack and (b) radargram.
7.4.2.3. Detection of a thin layer of brick masonry

One of the columns located in the ground floor of the castle (81×130 cm$^2$) showed signs of repairs, which consisted in the increase of the cross-section by a thin layer of clay brick masonry. The column is illustrated in Figure 7.42a and two aspects of the masonry layer are shown in Figure 7.42b and Figure 7.42c. The dimensional characteristics of the brick masonry layer are illustrated in Figure 7.43 and consist in one rather large layer of 20 cm made of clay bricks and mortar and two others layers with 7 and 8 cm, with rather strong mortar and thin clay tiles. The 4$^{th}$ side, exhibited in Figure 7.42a, is original.

![Figure 7.42 – Overview of the investigated column. (a) Front view with vertical acquisition (with and without neoprene board) and aspect from the (b) 20 cm and (c) 7 cm brick masonry layers.](image)

The objective of the radar measurements were of exploring the potential of radar in detecting these additional layers of masonry. Usually, the strong direct surface signal tends to cover the presence of very shallow features (Figure 7.44a). Thus, the strategy passed by increasing
slightly the travel time that the signal needs to reach that interface. Thus, this would create a different radargram that, by comparison with the radargram carried out without the neoprene dielectric pad, or by difference between the two signals, would reveal the interface’s signal. The increase of the thickness was made by inserting a neoprene board with a thickness of 3 cm between the antenna and the column’s surface (Figure 7.44b). The neoprene board was chosen due to its dielectric constant \(4.0 < \varepsilon_{\text{neoprene}} < 6.7\), close to the dielectric constant from masonry \(\varepsilon_{\text{masonry}} \approx 6.0\). Thus, the direct surface signal will remain mostly unchanged, which would allow the detection of the interface signal at a deeper depth (Figure 7.44b). Its detection could be done by direct comparison or by a subtraction between the two radargrams.

![Figure 7.44 – Aspect of the traces acquired (a) without and (b) with the neoprene board.](image)

The equipment was the RAMAC/GPR with the antenna of 1 GHz. The preliminary calibration of the velocity of propagation resulted in a radiowave velocity of 11 cm/ns, which is lower than the velocity found in the tower walls, which suggests a different material.

Based on the thickness of the masonry layer, neoprene board and on the velocity of the radiowaves (considering that the velocity found for the masonry applies also to the neoprene board), the signal from the interface between brick layer and original masonry was estimated to be found in the range 1.3-3.6 and 1.8-4.2 ns, whenever the acquisition was done directly over the column’s surface or over the neoprene board, respectively. The results from the acquisition carried out on the side with a brick layer of 20 cm (Figure 7.42b) are shown in Figure 7.45. It can be seen that the differences between the two methodologies are not very important and the results from the other sides did not provide clearer results.

Technically, the neoprene board increases the travel time from the desired interface in a maximum of 0.5 ns, which seems to be hardly noticeable without a careful observation at the level of individual traces. To verify that hypothesis, two partial traces are compared in Figure 7.46. The signal’s amplitude and travel times are different when the measurements are carried...
out with or without neoprene board. Relatively to the traveltme, the difference is very small and was estimated around 0.3 ns, which seems to corroborate the fact that introducing the neoprene board increases the travel time between the acquisition surface and the desired interface. Regarding the location of the layer interface, the signal is contained in the ground signal in the case of the measurements done without the neoprene board. With the neoprene board, a slight difference that could be considered the expected interface is observed. However, that difference is very small, thus unreliable in unknown situations. To produce a large difference, a thicker dielectric pad is required, which is unlikely in most cases.

![Figure 7.45](image1.png)

**Figure 7.45** – Vertical acquisitions in the side with a layer of 20 cm of brick masonry. (a) Profile carried out directly over the surface and (b) over the neoprene board.

![Figure 7.46](image2.png)

**Figure 7.46** – Partial traces obtained from the vertical profiles performed in the side with a masonry layer of 20 cm. (a) Directly in contact with the column’s surface and (b) with the help of the neoprene board.
An additional purpose was to explore the internal morphology of the section of the column by performing a tomographic acquisition. This will allow to retrieve information about radiowave velocities in the interior of the cross-section as well as determining additional layer information. As this method requires the maximum coverage of the section by the electromagnetic rays, several station points were fixed for the receiver antenna in three sides of the pillar, while the transmitter antenna was performing transmission measurements in the remaining sides, at an approximate height of 200 cm. The station points for the receiver antenna are illustrated in Figure 7.47. Each station point was separated by 5 cm. It must be noted that columns are adequate places to perform tomography measurements since they allow a proper covering of the cross-section with electromagnetic rays.

All acquisitions were carried out with two 1 GHz antennas. The profiles performed by the transmitter antenna begin, usually, with the back of the antenna’s body in one edge of the pillar’s side (Figure 7.48a) and finish with the centre of the antenna in the opposite edge of the column (Figure 7.48b). In this way, the profiles have the maximum length possible with the adopted apparatus, thus, covering the largest area.

Figure 7.47 – Station points for the receiver antenna during tomography measurements.

Figure 7.48 – Transmitter antenna at the (a) beginning and (b) end of profiles in side 1 (usage of the survey wheel on the side allowed longer profiles than if the wheel was located at the end of the antenna).
The measurements resulted in the ray coverage illustrated in Figure 7.49. The corners suffer from insufficient covering, due, essentially, to the irregular shape of the edges. The reconstruction algorithm, which transforms the raw data into velocity and attenuation maps, depends on the quality of the grid. So, several attempts were made to find the optimum solution by changing the grid pattern, which final shape is reported in Figure 7.49.

Figure 7.50 showed the results obtained from the tomography experiments. The interior of the section possess a rather heterogeneous distribution of velocity, with high velocity values concentrated in several small areas in the interior of the column’s cross-section, while most of the cross-section exhibit average speeds, inclusive the additional masonry layers. This may suggest that the original masonry is rather deteriorated, with the presence of voids (which justify the higher velocities). Globally, the main velocity seems to be around 10 cm/ns, though ranging from 8 to 14 cm/ns. Additionally, a small area close to the surface exhibits a velocity higher than 20 cm/ns, but due to its position, it is only an artefact created by the joint-effect of the grid and column’s cross-section geometries.
7.4.3. Summary

GPR was applied in several elements of an old masonry castle to assess their structural condition. In general, it seems that the walls were constituted by a rather homogeneous material. The presence of cracks was detected through a “damaged area”, characterized by a large number of hyperbolas that represent deteriorated material. With respect to the detection of thin clay brick masonry layers around one of the columns from the main court-yard using transmission measurements, the detection was unsuccessful due to the small dimensions of the masonry layers and, especially, to a rather low contrast between the two layers. However, tomography showed quite clearly that the interior of this column is heterogeneous and local deterioration was found.

7.5. Altes Museum, Berlin, Germany

The Altes Museum is a monumental building designed by the architect Karl Friedrich Schinkel (1781-1841) and built between 1816 and 1818. The building has a large entrance rotunda, based on the Roman Pantheon, and represents the most renowned example of Berlin Classicism. It is located in the Unter den Liden Avenue, in a zone where other four neo-classical museums are located, near the Spree River. The Altes Museum is the first Royal Museum that was originally built to accommodate royal art treasures for public viewing and first opened in 1830. A view of the building exterior is illustrated in Figure 7.51. The GPR evaluation of this monument was carried out in the framework of ONSITEFORMASONRY European project.
7.5.1. Description of test sites and results

7.5.1.1. Assessment of the column joints

In the entrance-hall of Altes Museum are eighteen columns that measure about 12.3 m in height, with an average diameter ranging from 140 cm at the base and 120 cm at the top (Figure 7.51 and Figure 7.52). These columns are constituted by large cylindrical drums of natural sandstone placed one on top of the other. These cylindrical drums have different heights, in the range 1.0 to 1.7 m. The joint between drums has little or no mortar, which led to the hypothesis that the stone drums have another type of connection system. The possibility that the stone segments were connected through iron dowels located in the centre of the stone drums was therefore to be investigated with GPR. An example of the possible kind of connectors can be viewed in Figure 7.52.

Firstly, acquisitions in time were carried out to determine the average velocity of the radiowave wave in the sandstone. The methodology used is illustrated in Figure 7.53. These measurements were performed in the middle of the 5th stone element with the help of a steel plate in the opposite side. Two profiles were acquired in order to verify that the 1 GHz antenna’s energy was sufficient to travel through twice the diameter of the selected column. Figure 7.54 shows the result after the removal of the background and the amplification of the signals by AGC. The decision of making two measurements with different antenna orientations was to verify if there would be any interference of the signal due to the irregularity of the column surface. The travel time in both cases was estimated in 16.9 ns (see Figure 7.54a), which, with the thickness of the column of 132.6 cm, resulted in an average
wave velocity of 15.7 cm/ns. The velocity is rather high, which could indicate relatively porous stones.

Figure 7.53 – Methodology used during the acquisition in time and section of the drum number 5 with the numbering adopted for the column’s edges.

Figure 7.54 – Profiles acquired in time but with (a) horizontal and (b) vertical polarizations.

Then, reflection profiles were performed along the 24 edges of the column, see Figure 7.53. An adequate positioning of the starting point, set at 89 cm above the joint 6, and ending point, set at 89 cm below joint 5, has allowed the radar profiles to cross two bed joints and, thus, providing information about two possible iron connectors. Firstly, radar profiles were carried out with the antenna in the vertical position, which was the more adequate manner to detect the joints (Figure 7.55a). Afterwards, the same measurements were carried out with the antenna in the horizontal position. Additionally, GPR survey profiles crossed several small stone pieces that were applied in the column to repair the damages due to material deterioration and damages endured during the Second World War. One example of such pieces is shown in Figure 7.55b.
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Figure 7.55 – Example of (a) a joint between stone drums and (b) detail of a replacing stone.

Figure 7.56 illustrates the radargram from the line 24. This profile crossed two joints, which were detected by means of two diffractions close to the surface. The distance between the centres of the hyperbolas is 152 cm, and correspond to the height of the element investigated, namely the 5th drum. To better observe those hyperbolas, the background signal was removed. Additional signals come from one of the replacing pieces. In this case, there is no flagrant hyperbola to signal its presence, only a higher amplitude signal identifies these elements. The opposite side was also observed, with the inclination due to the decreasing of the diameter with height. However, its definition is significantly blurred because of the irregular surface of the column.

Figure 7.56 – Profile number 24 with the antenna oriented vertically.
Additional radargrams that resulted from the acquisitions along the lines 1 and 23 are illustrated in Figure 7.57a and Figure 7.57b, respectively. In the profile from line 1, the joints are detected as hyperbolas and the replacement pieces as higher amplitude signals, like in the profile from line 24. However, in the profile 23, no such hyperbolas appear, just higher amplitude signals below the background signal (after background removal). Analysing the path of the line 23, a near-surface signal can also be received from a repaired area crossed by the profile. This means that the repairing material has dielectric properties sufficiently different from the stone of the column so that the radar signal is modified. The insertion of mortar in the joints resulted also in the decrease of the contrast between electrical properties of the materials. Thus, these joints were not detected through a diffraction hyperbola.

Figure 7.57 – Two radargrams done with the antenna oriented vertically. Profile from (a) line 1 and (b) line 23.

Figure 7.58a and Figure 7.58b shows the radargrams from lines 18 and 11, respectively. The diagram from line 18 is still in time units while the diagram from the line 11 was transformed in depth units using the wave velocity value of 15.7 cm/ns. This confirms the diameter in the 120-140 cm range. An AGC was applied to explore the weak signals coming from inside the columns, this way, decreasing the amplitude’s difference between the signals of the exterior surfaces and the interior. Weak signals resembling a diffraction can be observed in
the middle of the section and appeared to be at the level of the joints and located in the middle of the column’s cross-section. Thus, these signals are probably related with the steel connectors that, supposedly, were used to connect the stone drums of the column. However, these signals seem to appear stronger in the part below the joint.

Figure 7.58 – Radargrams showing the signals from steel elements located in the joints between stone blocks. Examples from (a) profile 18 and (b) profile 11.

Figure 7.59 shows two additional radargrams from lines 6 and 10, which show rather clearly the diffractions from the joints. However, when compared to the radargrams of Figure 7.58, no signals or very weak signals were found in the interior of the columns. A strong attenuation can be observed below the diffractions at the surface. This suggests that there are no iron connectors in the centre of the column or that the material/feature that is located in the centre of the column does not exhibit a large contrast between dielectric properties.
Additional reflection profiles were carried out in a lower position of the column to try to confirm the presence of similar signals between others drums. Figure 7.60 illustrates one radargram from line 22, acquired with the antenna in the vertical position. The opposite surface of the column is detected at 17 ns, which is equivalent to 133.5 cm, considering a wave velocity of 15.7 cm/ns. The real dimensions range between 138 and 140 cm. The joint that is in the middle of the profile correspond to the diffraction observed in the radargram at 160 cm from the beginning of the profile. An additional signal is detected at the same level, but 9 ns later, which correspond to a depth of 71 cm (middle of the column). That signal appears stronger in the part below the joint.

To have a better image of it, a closer look of the area around the central joint was produced from the profile of line 17. The radargram was filtered and all unnecessary data cropped. Because the processing was focussed in determining diffractions in the interior of the column, the background signal was removed and a strong gain was applied (SEC followed of AGC). The final radargram is shown in Figure 7.61. It shows the curved signal that is considered to be from the iron connector. However, the signal is divided in two parts, which indicates that it is not from a single iron element, but rather from two different events separated by the joint. A possible explanation might be that both planes of the two drums had been prepared with a concave shape before mounting. Thus, the diffraction may not indicate an iron connector as primarily suggested but mounting holes. However, the fact of the lower part of the signal...
being always stronger than the upper part suggests that the hole made on top of the drums was larger.

Furthermore, additional radar profiles were carried out along the same paths but with the antenna in the horizontal position. The objective was to see if, with the antenna oriented this way, it was possible to better detect the iron connectors between the stone elements of the column and to check if no additional irregular elements were detected. In the precedent
acquisitions, the electric field was perpendicular to the joints of the column but it was parallel to the vertical elements. In these new measurements, on the contrary, the antenna is oriented to detect these vertical elements in a more proper way. However, the results showed profiles that look almost the same as the ones obtained with the antenna in the vertical position, and no additional signals from the steel elements were found. An example of these measurements is showed in Figure 7.62 carried out in the first position, over the drum number 5.

![Figure 7.62 – Radargram from line 20 with interpretation of the signals (antenna in the horizontal position).](image)

Figure 7.63 illustrates profiles acquired with the antenna in the horizontal position in the second position. The profile from line 4 is exhibited in time (Figure 7.63a), while the profile from line 10 in depth (Figure 7.63b). The signals from the joints are visible, although not as intense as in case of perpendicular orientation of the antenna. The signals in the centre of the column are observed as well. The signal in the center presents also the same pattern, with a lower part much stronger. Thus, it seems that all drums were treated in the same way as they exhibit the same signals in the joints.
7.5.1.2. Assessment of a lead plate in the joints

A final experiment was carried out to identify the constitution of the joint or the presence of any element embedded. Additional radar profiles were carried out to look for the presence of lead plates within the joints of stones, as it was frequent that these kinds of plates were present where iron connectors were used. For that purpose, specific measurements were performed over the joint number 5. The technique used was based in performing several acquisitions in time with the 1 GHz antenna kept in the same position while a steel plate was moved to different positions in pre-establish time intervals, above and below the joint. Figure 7.64 illustrates the followed methodology. Technically, it was expected that the lead plate played the role of a magnetic shield and masked the reflection from the reflecting shield when in position 2, thus, accusing its presence. Two acquisitions were carried out: the first with the antenna oriented upwards and the second with the antenna oriented downwards relatively to the transmitter element of the antenna.
Figure 7.64 – Methodology used to verify the existence of an iron/lead plate in the joints of the column. In this case, the antenna is oriented upwards.

With respect to the first case, the final radargram is presented in Figure 7.65, while the second acquisition is illustrated in Figure 7.66. The same processing steps were applied in both radargrams, which include, in the following order: band pass filter, time zero calibration (first positive peak), and gain (SEC). No background removal was applied as the important horizontal signals would be removed.

As it can be observed, the signal from the opposite side is always present at the same depth, which is 125 cm (8% of error relatively to the real diameter of 135 cm considering a velocity of 15.7 cm/ns). This is due to the reflection from the opposite surface of the straight ray path. When the steel plate is positioned above the antenna’s location (position 3), an additional signal appears, parallel to the signal of the opposite surface, but 2 ns later (15 cm). This means that the signal travelled a longer distance than the straight distance and that the interface it detected has a higher contrast of dielectric properties, which correspond to the steel plate located above the antenna. Considering that the lower part of the steel plate is located 50 cm above the antenna, the minimum ray path could be inclined 20-25° relatively to the horizontal, which is equivalent to an additional distance of 8-13 cm, which was explained by the profile.

With the steel plate in the position 1, the signal relative to the steel plate appears just after the signal from the opposite surface, and with a higher energy. This was the expected behavior, as the steel plate was located just in front of the antenna and metal is a very efficient reflector. Furthermore, only the signal from the opposite surface is visible when no steel plate was applied in the surface of the column. With the steel plate applied in the position 2, the distance
traveled by the wave signal would be equivalent as when the steel plate was in position 3, but no signal should be visible at the level. However, a parallel signal with a rather low energy is visible 15 cm in the right. This suggests that some radiowave energy passed through the joint and hit the steel plate. Thus, the hypothesis that a hole, eventually filled with mortar, exist between the column’s drums, instead of an iron connector, as expected.

Figure 7.65 – Profile in time performed with the transmitter oriented upwards.

Figure 7.66 shows the results from the profile with the antenna oriented downwards, presented in time units. The results confirm what was found with the transmitter oriented upwards. When the steel plate is in the position 2, the parallel signal seems to have higher amplitude than in the previous case. Consequently, the feature present in the joint only prevents partially the radiowaves to reach the steel plate applied in the opposite side.
7.5.1.3. Locating steel anchors and dome constitution

The intrados of the main dome was inspected with GPR with the aim of detecting iron support anchors. The dome of the museum is constituted by a membrane built of different types of brick masonry. The intrados is covered by a series of cavities where are exposed paintings, sculptures and other artworks (Figure 7.67a). The extrados is illustrated in Figure 7.67b.

Figure 7.67 – Views of the dome: (a) intrados of the dome viewed from the pavement, and (b) extrados surface.

The possibility that these artworks are attached to the main dome through iron anchors embedded in the mortar layers of the masonry structure was assessed. Examples of an exposed anchor and the scheme of the likely anchorage system are given in Figure 7.68.
Two long profiles with a length superior to 250 cm, which location is reported in Figure 7.69, were acquired at two different heights, parallel to the pavement and along the latitude of the dome. Figure 7.70 and Figure 7.71 illustrate the radargrams obtained from these measurements. The profiles illustrated in Figure 7.70 do not cross any of the cavities present in the intrados of the dome. Thus the intrados’ surface is shown as a horizontal signal at 8 ns of depth. Taking into account that a time measurement with a iron plate in the opposite surface for the calibration of the propagation velocity was impracticable, the thickness of the dome below the profiles’ lines was estimated as 48 cm with a velocity of 12 cm/ns. From the survey drawings that were made available, the thickness of the dome was not constant in the entire section, but presented an average thickness of 50 cm at heights accessible by hand with the radar from the extrados of the dome. Thus, the initial hypothesis was rather correct, with the wave velocity ranging between 12 and 12.5 cm/ns.
The cavities existing in the intrados were detected in the radargrams illustrated in Figure 7.71, where the thickness of the dome decreases 1-1.5 ns. This corresponds to a total thickness between 37.5 and 41 cm. No evidence was found of different types of masonry though. The radargrams in Figure 7.70 and Figure 7.71 show several small diffractions located at 4 ns (25 cm), suggesting an interface between different materials. However, as these diffractions were perceived after applying the AGC in the data, there is no certainty if they come from real features or appeared due to the gain function.

With respect to the profiles that resulted from the acquisitions over the grid drawn over a quarter of the dome, the scheme followed was the one illustrated in Figure 7.72. Generally, profiles were done from top to bottom and from left to right. Figure 7.73 represents the radargram from line 1, with data filtered and background signal removed. The amplitudes were enhanced with AGC in order to perceive better the signals from the intrados. The profile
shows the shape of one of the cavities present in the intrados of the dome, showing that the length of those cavities is around 1.5 m. It shows also several diffractions from different origin. Firstly, a group constituted by three low amplitude hyperbolas between 2 and 4 ns, or 12.5 and 25 cm from the surface, most probably coming from detachments or joints between masonry units. Secondly, a strong diffraction appears very close to the surface, which is likely to come from a system similar to the one showed in Figure 7.68. The diffraction corresponds to the anchor at the surface that supports the object placed in the cavity. However, no sign of the wire was found.

Figure 7.72 – Scheme of the grid of measurements carried out in the extrados of the dome.

In Figure 7.74 is presented the profile from the vertical line 2, which is almost identical to the radargram from the line 1. In this case, SEC gain was applied instead of AGC. Two diffraction hyperbolas appear over the disturbance from one the cavities. These signals might come from the anchors that are part of the supporting system that sustain the cavity’s fill.
However, only one was detected in the profile from line 1. In this case, a second one appeared higher, and it is probably from a second anchor.

The next radargrams from lines 3 and 4 are illustrated in Figure 7.75a and Figure 7.75b, respectively. The radargram from line 3 seems to present the signal from the extremity of a cavity in the intrados, recognizable by its long and dip diffractions at its extremities. It shows also the signal from the anchor located at the bottom of the cavity (same position as profiles from lines 1 and 2). The radargram from line 4 do not represent the cavity but rather the space between two consecutive cavities. Figure 7.75b present also at 4 ns of depth (25 cm) a series of aligned diffractions that could represent the interface between the two types of masonries, and correspond to what was already noticed in Figure 7.73.
Furthermore, Figure 7.76a and Figure 7.76b represent the profiles from the two last vertical lines of the grid, respectively, line 5 and line 6. In these radargrams, the cavity’s shape is more accentuated due to the fact that the line is crossing the cavity (especially in line 6). However, the radargram from line 5 does not present any signal from the anchor at the surface, while the radargram from line 6 shows two diffractions. The one located in the range 200-250 cm from the beginning of the profile is from the anchor system as it exhibits similar characteristics as the other signals in other radargrams. With respect to the signal located at the beginning of the profile, it is not possible to define it as being from the same anchorage system. Firstly, it is not located in the same position and it presents an opposite polarity, similar to the polarity of the interface intrados/air, meaning that it could be from a void or crack located close to the surface.

Figure 7.76 – Radar profiles from the vertical lines (a) 5 and (b) 6.

Figure 7.77 illustrates the radargram from horizontal line 11 that shows two lines approximately parallel. In fact, the line does not cross any cavity. The thickness is about 46 cm, which is inferior to the thickness close to the base of the dome (50 cm) and several diffractions appear at 4 ns (≈ 25 cm), which could be from a possible interface between two types of masonries. However, because it was not observed in all profiles and AGC was always applied to perceive those signals, nothing can be concluded. Figure 7.78 presents the next profile, from line 12, which crosses two cavities. A signal close to the surface is from the support anchor. The profile from line 13 is illustrated in Figure 7.79. It is possible to observe the signal from the anchor and an additional event that extends through more than 35 cm in the interior of the dome. Although this signal was not found in another profile, it is likely to be from the iron wire attached to the anchor. With respect to the profile from line 14,
illustrated in Figure 7.80, a dip hyperbola that can be observed is related to the event that occurred in the previous radargram. No evidence of signals at 4 ns was found in these profiles as in Figure 7.77.

Figure 7.77 – Radargram from the line 11. The signals have been enhanced with AGC.

Figure 7.78 – Radargram from the line 12, where the background signal has been removed to better see the signal from the anchor close to the surface.

Figure 7.79 – Radargram from the line 13, with a disturbance at 70 cm that prolongs more than 35 cm in depth.
7.5.2. Summary

GPR was applied in several locations of the Altes Museum to assess the structural integrity of the structure and to look for iron elements that were frequently used in historical constructions to connect and support other elements. With respect to the columns of the museum’s entrance, the stones appear to be rather homogeneous but the high velocity of propagation of the stone could indicate a rather high porosity level. The detection of elements inside the column was made difficult by the irregular surface of the columns, which produced significant clutter in the radargrams. However, it was possible to conclude that during the construction of the columns the drums were aligned using some specific system. It has been proven that the use of iron connectors was rather unlikely.

Moreover, the changes in the thickness of the dome were conveniently detected during the radar measurements carried out in the extrados of the dome. The iron elements that support the objects in the cavities of the intrados of the dome were found and, in some cases, two signals from two possible connectors were evidenced. The anchorage system is, apparently, constituted by an iron element below the plaster layer and an iron wire connected the object to the anchor, although the iron wire was hardly detected. Generally, that anchor was not placed in the middle of the cavity but rather in a lower position. Finally, no real evidence was found of the two layers of masonry, although some interface signals indicated such a possibility.

7.6. Church of the Monastery of Jerónimos

7.6.1. Description of the monument

The Monastery of Jerónimos, located in Lisbon, is one of the most important monuments in Portugal and belongs to the UNESCO’s World Patrimony list since 1984. An aerial view of
the monument is illustrated in Figure 7.81a and an image from the interior of the Church is shown in Figure 7.81b. The Monastery of Jerónimos is considered a jewel of the “Manuelino” architecture’s style, which integrates architectural elements from the Neo-Gothic and Renaissance as well as numerous marine decorative elements.

In 1496, the Portuguese King D. Manuel I asked Pope Alexander VI the permission to establish a monastery for the religious community of S. Jerónimo. The construction began in 1501, under the orders of master Diogo de Boitaca, the first of the numerous masters entrusted with the construction of this ambitious monument. The construction lasted one entire century, approximately, and was occupied by the monks of the Order of S. Jerónimo until 1833, date when the religious orders were dissolved in Portugal. The Church, object of the study, is located in the south-east corner of the monastery and presents a traditional plant in Latin cross shape. It is constituted by three naves united by a single vault, which spans through the transversal 30 m of the building, and is supported by eight octogonal columns that feature high slenderness (Figure 7.81b). The columns currently exhibit a large out-of-plumbness. Thus, the investigation with georadar focused on the structural homogeneity of the material.

### 7.6.2. Testing sites and results

The columns measure more than 20 m in height (Figure 7.82 and Figure 7.83). They have an average exterior diameter of 100 cm and are composed by single segments of 50 cm of height, approximately. At the base, the diameter increases to 120 cm. The construction material of most of the elements is the Lioz rock, which is a local calcareous rock.
Given the major influence of the columns in the structural response of the building, a radar inspection was carried out aiming at defining their internal constitution, to determine their structural integrity and to detect any unknown construction feature or deficiencies caused by long term effects. The prospect of determining if the stone segments are constituted by one or more blocks was also addressed.

7.6.2.1. Assessment of the velocity of propagation

The velocity was determined with the methodology illustrated in Figure 7.84, with profiles acquired in time with a steel plate applied in the opposite side of the column. Several positions were investigated on each column. Generally, in each position, three profiles in time were acquired in the top, middle and bottom of each one of the stone segments. The surface of the tested columns is heavily ornamented and did not allow the full contact of the antenna and steel shield over the surface, with the exception of one segment that had a plane surface.
The non-processed radargrams from the acquisitions in time in the base of two of the four columns are illustrated in Figure 7.85 and Figure 7.86. They show the position of the steel plate located on the opposite surface at an average traveltime of 21.6 \text{ ns}. Taking into account that the average thickness of the base elements is 120 cm, it resulted in an average wave velocity of 11.1 cm/\text{ns}, which is a rather common velocity for masonry elements.

The radargram shown in Figure 7.86 is from column 1 and illustrates a first example from the segments without ornamented surface. The signal from the opposite side is very strong, even without the presence of the steel plate, and a similar situation was observed relatively to the other profiles. The average arrival time was estimated in 18.7 \text{ ns}. The diameter of the column at that height was calculated as 96 cm, while in the rest of the column the average diameter is 100 cm. The ornamented layer increases the diameter in 4 cm, approximately. This resulted in an average velocity of 10.3 cm/\text{ns}. 

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**Figure 7.84** – Location and positioning of the radar and steel shield for the acquisitions in time.

**Figure 7.85** – Radargrams acquired in time from the base of the columns (a) 2 and (b) 4.

**Figure 7.86** – Radargram from column 1 and illustrates a first example from the segments without ornamented surface. The steel shield is removed from the opposite surface at a depth of 21.6 \text{ ns} in both cases.
In the subsequent stone segments, the diameter of the column increases due to the presence of the ornamentation over the entire surface of the column. Figure 7.87 illustrates two profiles acquired over the ornamented segments of the columns, where only an AGC was applied over the filtered data in order to increase the amplitude of the opposite surface. As expected, the opposite surface is clear and the average travel time increases to 19.4 ns. At this level, the columns exhibit a diameter of 100 cm, which resulted in an average velocity of 10.3 cm/ns. The AGC (window of 10 ns) applied in the time data of the profile in Figure 7.87b revealed an additional and low amplitude signal located, approximately, in the centre of the column’s section. This signal was already perceived in other radargrams, in particular in Figure 7.86.

In Figure 7.88, the section of column 4 is illustrated together with a single trace, which came from the time profile acquired over an ornamented surface of the column 4, shown in Figure 7.87b. The signals from both surfaces and in the centre are clearly visible after an AGC was applied in the filtered data to increase the amplitude of the signals from the opposite surface.
and from the centre of the column, which exhibited low amplitude. The analysis of the polarity of the signals showed that they differ from the radargram in Figure 7.86. This could be due to the different boundary conditions of acquisitions carried out over the ornamented surface, or due to a different nature of the feature located in the centre of the column.

![Figure 7.88 – Single trace from radargram acquired in time showing the extreme and central signals’ amplitudes in the interior of column 4 enhanced with AGC.](image)

It was difficult to obtain any useful information about the nature of the feature that caused that central signal due to a lack of common evidences in several profiles. However, it must be mentioned that this signal is very weak so, the interface that caused such signal is rather thin. In fact, this could be a thin air layer (created by a crack, a thin joint or detachment between adjacent stone blocks). Some profiles do not exhibit such signal, which may indicate that this is a localized phenomenon and cannot be extrapolated along the entire column.

### 7.6.2.2. Analysis on the base elements

Vertical reflection profiles were carried along the first 7-8 m of the four columns under investigation. It was impracticable to perform reflection profiles in direct contact with the column’s surface due to the ornamented layer in almost all segments. Only in the highest segment (Figure 7.82) it was possible to perform a reflection profile directly over the column’s surface. Thus, a neoprene board with a thickness of 3 cm was used between the antenna and the column’s surface in order to perform reflection profiles without having any direct contact between the stone and the antenna. This methodology is illustrated in Figure 7.89.
With respect to the profiles carried out in the base segments of the columns, it was noticed that the length of the radargrams was different, which indicated that the height of those elements was different in the four columns. The length of the profiles carried out in each base element is reported in Table 7.4. It resulted that the columns closer to the transept seem to have the highest base elements, probably due to a deficiency during the ground levelling of the foundation soil, at the time of the construction of the Church.

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>50</td>
<td>34</td>
<td>52</td>
</tr>
</tbody>
</table>

Figure 7.90 illustrates the profile from the base segment of column 1. A signal along the entire profile is observed almost at the centre of the segment. It must be noted that the signal in the middle of the profile has been enhanced by a 10 ns aperture AGC, which resulted in a substantial increase of its amplitude and from the opposite surface as well. This central signal crosses the entire profile, which means that it is from a feature present from the top to the bottom of the stone element. However, a closer analysis of that signal showed that it is not continuous but rather constituted by two different signatures, whose polarity changes along the profile, which may suggest that the boundary conditions are not equal along that interface. Thus, it is reasonable to assume it represents a crack or an irregular joint between stone segments. Furthermore, the opposite surface was found at 21.9 ns, which resulted in a total diameter of 113 cm (slight error of 8% in comparison to the actual dimension, which is 121.5 cm).
A visual analysis of the surface of the base element showed evidences of several significant cracks and joints. Figure 7.91 illustrates two examples of rather straight cracks/detachments in the lowest part of the column that stop at the horizontal joint. The complete survey of that element showed that several joints/cracks like those shown in Figure 7.91 occur around the column. Additionally, in the top segment of the base, the same type of cracks/detachments occurs. However, Figure 7.92 shows a pattern of thin and irregular cracks, typical of a cracked element, that occur in the area were GPR surveys were carried out. Thus, the signals detected by the radar could be somewhat connected with these cracks.

Figure 7.90 – Profile from the base element of column 1, with the relative location of a joint or crack in the centre of the element.

Figure 7.91 – Examples of rather straight filled joints and cracks in the base element of column 1.
Figure 7.92 – Irregular cracks in the base element of column 1 that match the area investigated with GPR.

The profile carried out in the base element of column 2 is illustrated in Figure 7.93. It exhibits a slightly different pattern of signals, with a strong signal located close to the acquisition surface, at a depth of 7.7 ns (≈ 40 cm). It must be noted that AGC or SEC were not applied in the radargram illustrated below. Only the scale saturation level was shifted to give more focus to lower amplitudes. In this case, the original amplitudes are much stronger than in the case of the column 1, which suggest a remarkable detachment in the interior of the segment. When applying an AGC in the dataset, it is possible to observe additional dip events at the top and bottom of the profile, which point to possible cracks or joints at those levels.

Figure 7.93 – Profile from the base element of column 2.

The survey of the cracks in the surface of this element revealed several detachments filled with mortar in the larger segments of the base element. One first example in Figure 7.94a illustrates a regular detachment in the lower segment of the base element. Due to its shape, this detachment looks more to a joint between stones than a crack, which would have looked

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more irregular. The second example illustrated in Figure 7.94b shows a crack starting in the
top of the base element towards higher elements. In this case, the fissure is irregular and is not
following a straight path.

![Figure 7.94 – Examples of cracks and detachments in the base element of column 2. (a) Segment in the bottom
and (b) irregular cracks in the upper segment of column 2.](image)

The non-processed radargram from column 3, illustrated in Figure 7.95a, exhibits a crack or a
detachment at the centre of the column’s section, approximately. It must be noted that the
opposite side boundary is rather irregular and the precise location of the signal from that exact
surface was complex to define. On the other hand, the profile from column 4 (Figure 7.95b)
does not display any significant signals than the signal from the opposite side.

![Figure 7.95 – Radargrams from the base elements of columns (a) 3 and (b) 4. To preserve horizontal signals, the
data was only filtered from random noise.](image)
In this case, it can be presumed that the stone segment is constituted by well-in-contact stone fragments. The thin joints reflect a low amount of energy, which resulted in weak or inexistent signals. The hypothesis of the base element to be constituted by a unique stone is somewhat improbable due to the large dimensions of that segment. Yet, two very weak dip signals in the extremities of the profile, and very much similar to those observed in the base of column 2, were also observed. Figure 7.96 and Figure 7.97 illustrates the base element of the columns 3 and 4, respectively, which show that the larger segments of the base element are constituted by two or three pieces. However, any cracks or detachments were not perceived from the surface in the thinner elements, which means that in most cases the signals obtained by the radar belong to internal cracks.

Figure 7.96 – Base element of column 3, showing regular joints in the lower and upper segments.

Figure 7.97 – Base element of column 4, showing a regular joint in the lower segment.
7.6.2.3. Analysis of the segments without ornaments

The segment without ornaments at the surface will be analyzed in detail as it was the only one carried out without the neoprene board. Three profiles were acquired from different sides of the column’s octagonal cross-section, according to Figure 7.84: side 1, side 2 and side 8 (side 7 in case of the column 1).

The referred segment from column 1 was firstly analyzed, with the three radargrams shown in Figure 7.98. Although the signal’s penetration is good, the reflected energy from the interior of the column is rather weak. All radargrams exhibit systematic events that are essentially constituted by wide hyperbolas that occur at the top of the profiles, at 9-10 ns (≈ 49 cm) of depth, and at the level of the horizontal joint, detected at 12 ns (≈ 62 cm). Furthermore, in the profile from side 1 (Figure 7.98a), a strong energy reflection can be observed at 6 ns of depth (33.5 cm) that can be attributed to a localized detachment or crack in the stone. The same does not happen in the bottom of sides 2 (Figure 7.98b) and 7 (Figure 7.98c), although a vertical signal appears close to the opposite surface. However, these signals are much weaker than the signal detected from side 1. Thus, they might correspond to different features.

![Figure 7.98 – Radargrams from segment “A” of column 1: (a) side 1, (b) side 2 and (c) side 7.](image)

The wide hyperbolas are located at the level of the horizontal joint crossed by the radar path. However, the signal from the joint was not immediately visible as it was covered by the
surface signal. To uncover it, the average trace had to be removed from the dataset. This operation is illustrated in Figure 7.99 and shows the signal of the joint, which was entirely covered by the surface’s signal. It must be noted that this signal enhanced the hyperbola present at 9 ns and the diffraction at the level of the joint but removed completely the strong signal at 6 ns in the bottom of the profile. It created also additional signals and artefacts with no particular meaning, but that could mislead the interpretation. This small diffraction could be also from some iron connectors that are usually used to align the drums of stone columns. However, the polarity of the signal does not suggest that hypothesis, although a crack around such connectors might be picked up.

Moreover, the analysis of the non-ornamented segment of column 2 revealed two situations. With respect to the radargrams obtained from sides 1 and 2, illustrated in Figure 7.100, no particular events were found. The material seemed to be rather homogeneous. However, in the radargram from side 8, a strong signal is visible from the top of the radargram along 45 cm, and reported in the radargram and in the trace in Figure 7.101a as well. The trace shows the real amplitudes of the signal and shows that the reflected energy is of the same order of the signal from the coupling surface, which is rather strong. This indicates a highly contrasting interface such as a detachment between stones due to the presence of several stones in this segment, or a deep crack at roughly 6 ns (31 cm) from the acquisition surface. Figure 7.101b shows the same radargram after the subtraction of the average trace. This operation allowed the exposure of a diffraction hyperbola at 40-50 cm from the beginning of the radar profile, which corresponds to the horizontal joint between stone segments. This way, it was possible to conclude that the interior vertical signal that was pointed out as a detachment starts from a
higher level of the column 2 and propagates through the element until the horizontal joint present in the non-ornamented segment of the column. However, analysing the surface of the column, no apparent crack or detachment was visible.

Figure 7.100 – Radargrams obtained from sides (a) 1 and (b) 2 of column 2.

Figure 7.101 – Radargrams from side 8 of column 2: (a) before and (b) after removing of the background signal.

The radargrams from the same segment but from column 3 are illustrated in Figure 7.102. Those radargrams are shown with real amplitude information and were only filtered with a band pass filter in order to remove unwanted high frequency components of the wave spectrum. The same kind of signals already observed are detected, namely, a 30 cm long signal located at 10 ns (52 cm) and 5 ns (26 cm) from the acquisition surface, in the
radargrams from sides 2 and 8, respectively. It must be noted that these vertical signals stop at the horizontal joint, conveniently located in the profile acquired from the side 1 (Figure 7.102a) by a diffraction hyperbola that can be perceived under the surface’s signal. The radargram from line 1 exhibits also a wide hyperbola in the joint but at about 5 ns (26 cm) of depth that could derive from some significant event due to the high energy reflected. Several other weak artefacts can be observed in these profiles, such as wide hyperbolas, dip lines crossing all the profile. However, their nature is very difficult to define but can be considered as coming from thin cracks that spread within the stone.

The incidence of these very weak signals is systematic in columns 1, 2 and 3, which probably come from some thin detachment or crack.

Finally, Figure 7.103 illustrates the radargrams from the non-ornamented segment of column 4. No significant reflections from the interior of the column were obtained from side 1 acquisition (Figure 7.103a). However, the radargrams from sides 2 and 8 exhibit a vertical signal at the bottom of the radargram at the 7.6 ns, approximately, which correspond to 39.1 cm. Both exhibit 40 cm of length, which clearly indicates that the signal comes most probably from the same event, despite the lack of signals from side 1, located between side 2 and side 8.
The radargram from side 2 was further processed and is reported in Figure 7.104. The background signal was removed and the amplitudes enhanced by AGC. The position of the horizontal joint was located at 30 cm from the beginning of the profile. At that level, the vertical signal that rises from the bottom stops. The two signals located above the horizontal joint could be from small cracks. The same happens in the case of the radargram acquired from side 8 (Figure 7.103c), where the signal continues through the joint but, with a lower amplitude, which could indicate the propagation of the detachment in the form of crack.

From the radargrams obtained in these segments resulted the sketches illustrated in Figure 7.105. They show the location of the events detected in those segments. It seems that most of the events occurred in the centre of the column, with the exception of the column 1, where some events are located close to the surface.
7.6.2.4. Analysis of the segments with ornaments and overview of the four columns

An overview of the entire column 1 is illustrated in Figure 7.106, with the exception of the base element, exhibiting real amplitude information. Verify the signals continuity through the stone segments was fundamental in order to conclude about the constitution of the columns. So, with the profiles assembled that way, it was possible to confirm the alignment of the signals from the opposite surface and to validate that the material that constitute the columns is homogeneous. The energy of the signals coming from hypothetical internal interfaces is very low and mainly occurs in two locations of column 1: at the bottom of segment “A” and between segments “C” and “D” (see Figure 7.106). Thus, it is possible that some stone segments are constituted by several blocks, with thin layers.

The radargrams illustrated in Figure 7.107 represent the ornamented segments of columns 2, 3 and 4. Very few events occur inside the section of these segments, which suggest a rather homogeneous constitution of the columns. The signals from the acquisition and opposite surfaces show good continuity despite the irregularity shown by the total travel time. Several attempts were carried out in order to extract any additional information that could be hidden by the background signal or amplifying low amplitude signals but no results were obtained.

However, several isolated signals can be observed. Small signals that might come from fissures inside the stones can be observed in segment “E” of column 3 (Figure 7.107b) and in the top and bottom of segments “E” and “D” of column 4, respectively (Figure 7.107c). Furthermore, the radargrams from segment “C” in column 2 and segments “B” and “C” in column 4 exhibit a signal reaching almost half the energy of the acquisition surface signal and are located very close to the surface. These can be possible air gaps between stones caused by detachments or cracks. According to tests carried out in the Polytechnic of Milan, the antenna of 1 GHz is sensitive to cracks or detachments with a minimum width of 1 cm. Thus, these cracks or separations observed in some points of the column may have 1-2 cm as it is the minimum separation that can be detected with the antenna of 1 GHz.
The difference of 2-3 ns between the two radargrams can be accumulatively attributed to the neoprene board and to the absence of the ornamented layer in segment “A”.

This very strong signal did not propagate through the next segment, which can suggest that it is a single signal from a localised crack in segment “A”, and was not detected in other profiles.

This signal here suggests the existence of a crack, which is the most probable due to the discontinuity of the signal below or above, or a thin layer between stones.

Figure 7.106 – Reflection profiles along the column 1.
Figure 7.107 – Radargrams from reflection along the columns (a) 2, (b) 3 and (c) 4 without the non-ornamented segments.
7.6.3. Summary

The radar acquisitions carried out in four stone columns of the Church of the Monastery of Jerónimos allowed the assessment of several parameters. The velocity of propagation of the radiowaves through the masonry was confirmed to be in the range 10-11 cm/ns, corresponding to normal values for such material.

The radar inspection allowed to confirm that the columns are characterized by homogeneous material, because the radar signal does not present any significant event, essentially constituted by stone segments of a single block or two/three blocks with thin vertical joints. Due to the strong intensity of the signals, it is prudent to assume that some of these joints are wide open and not filled. No conclusive visual evidence of cracks or joints was found in the surface but the distribution pattern of the events for the non-ornamented segments seems to confirm the occurrence of cracks in the centre of the column. The larger elements of the base of the columns can be constituted by two/three blocks, which joints are filled with mortar. Because the radar measurements were carried out in three adjacent sides, no definitive conclusions can be drawn.

7.7. Boutaca’s bridge

The Boutaca’s bridge is a stone masonry bridge built in the middle of the 19th century (1860) during the reign of the Portuguese King Luís I and correspond to a typical public architecture of that period. It is constituted by a rectilinear deck, where an asphalt layer was laid in the last decades (Figure 7.108a), that extends for more than one hundred and fifty meters. The deck is partially supported by six pointed arches (Figure 7.108b) and a circular arch located at the opposite extremity. The complete profile of the bridge is illustrated in Figure 7.109.

Figure 7.108 – General view of the (a) pavement in the bridge deck and (b) supporting arches.
7.7.1. Description of the testing site and results

A large number of iron tie-rods, plastic pipes and several drainage tunnels used for the removal of rain water from the bridge deck are visible along the entire structure. Some examples are illustrated in Figure 7.110. However, no accurate design plans exist of the positioning of all these features as well as from the thickness of the masonry elements, namely, thickness of the arches’ stones. Thus, GPR investigation was proposed to give an answer to some of these questions. Due to the depth of the majority of these targets, the 500 MHz and 250 MHz antennas were preferred to the antenna of 1 GHz, whose depth penetration was not sufficient.

Two time measurements were preliminary acquired with the 500 MHz antenna in order to estimate the average speed of propagation of the radiowaves. The methodology illustrated in Figure 7.111 considers a steel plate positioned in contact with the surface of the road to help in the detection of the surface’s signal. The measurement resulted in the radargram presented in Figure 7.112. There, the signal showing the removal of the steel plate is detected at a depth of 70 ns, which resulted in an average radiowave velocity of 8.6 cm/ns. Typical radiowave
velocities found in literature for dry masonry and dry soil are between 12 cm/ns and 17 cm/ns. Thus, the velocity found in this case is significantly low, which indicates the presence of water in high amounts. This is confirmed by the existence of large areas of the bridge covered with vegetation and by internal water coming from the river and rainwater from the bridge deck. The infill material is likely to be constituted by rubble material and clay soil, which could explain the high amount of moisture and the growth of such a vast area of vegetation.

![Figure 7.111](image1.jpg)  
(a) Adopted methodology for time measurements. (a) Location of time acquisitions, (b) measurement being carried out and (c) view of the distance between antenna and steel plate.

![Figure 7.112](image2.jpg)  
Figure 7.112 – Radargram from acquisition in time with the 500 MHz antenna.

Further GPR investigation consisted on a series of longitudinal profiles in reflection mode carried out along the entire length of the bridge deck with the two antennas available. These
resulted in profiles long of 120 m. The first profile of each series was located at 30 cm from
the side walkway in front of the right-wing pavilion, as illustrated in Figure 7.113. Then,
successive profiles were carried out every 50 cm until the opposite side of the bridge was
reached, which correspond to 6.35 m, approximately. A total of 11 profiles were acquired
with each antenna that resulted in 22 profiles.

Figure 7.113 – Location of the first profile and start and end of the profiles carried out in the bridge pavement.

A first analysis of the reflection profiles showed, unexpectedly, that the acquisitions carried
out with the lowest frequency antenna produced the best results. In fact, the survey with the
antenna of 250 MHz provided better results than those obtained with the 500 MHz antenna,
which produced very poor data, showing significant clutter and attenuation.

Figure 7.114 illustrates the radargrams from lines 5 and 1 obtained with the 250 MHz
antenna, which show a general view of the bridge. The signal from the six pointed arches that
sustain the bridge deck between the two pavilions is rather clear in both radargrams, and,
generally, in most of the radargrams. The distance between hyperbola crests was rather
regular and was determined around 7.50-7.60 m. The distance between the 4th and 5th arch
measured 7.85 m, approximately, as shown in Figure 7.114a. The distance from survey
drawings was 7.60 m, thus, the radargrams showed a good accuracy. The circular arch located
in the opposite end was also detected but not as frequently as the other arches. The
explanation is related with the high moisture content present in that part of the bridge. The
depth of the crests of the hyperbolas (Figure 7.114a) was estimated between 1.60 and 1.80 m
with the velocity of 8.6 cm/ns. Once more, the accuracy was rather satisfactory, with the
depth obtained from survey drawings indicating a depth of 1.67 m, approximately.
Moreover, Figure 7.114a shows several disturbed areas that are located where major features occur, namely, the large abutments in the extremities of the arched part of the bridge, which include the foundations of the pavilions, and the circular arch in the opposite end of the structure. It was possible to understand, approximately, the different stages of the construction of the bridge or, at least, how certain features were built. Figure 7.114b shows also the soil layers that existed during the construction or recent works in the bridge, which also coincide with the depth of a certain number of drainage channels.

One major objective was to determine the thickness of the stones that are found in the arches, which detection depends mostly on the resolution of the antenna. The 250 and 500 MHz
antennas have a theoretical resolution of 30 and 15 cm, respectively, when propagating in air, assuming that minimum resolvable distance is $\lambda/4$ (Padaratz and Forde, 1995). However, when propagating in stone, the radiowave’s peak frequency decreases substantially as well as the wavelength, which causes the resolution of the antennas to decrease. Figure 7.115 shows the signal from the roman arch in the extremity of the bridge, where it is possible to observe that the infill/stone interface was detected as well as the stone/air interface, with the consequent shift of the signal’s polarity. The distance between crest was estimated in 13.1 ns, which resulted in 56.3 cm. The stone arch measure 53-54 cm (from exterior measurements), thus, the radargram resulted in a very good estimation (about 6 % difference).

Moreover, Figure 7.116 illustrates the six pointed arches acquired along the profile 5, which show the signal from the stone/air interface. These are characterized by a rather strong signal due to the strong contrast between dielectric properties of stone and air. Besides, some of the arches present a second signal located 12-14 ns above that correspond to the interface between the infill and the stone. The polarity of the signal is not as evident as in Figure 7.115, probably due to irregularities in the interface (presence of voids), but the resultant thickness ranged from 51.6 to 60.2 cm (Table 7.5), which result in an error around 15-30 % relatively to the real dimensions, approximately 45 cm in the key (measured from the exterior). The same error level was found with respect to the depth of the interface stone/air when compared to the road pavement, which was affected by the large deformation verified in the road pavement (which is the acquisition surface).
Figure 7.116 – Radargram from profile 5 focusing the first 50 m to observe the signals from the gothic arches (250 MHz).

Table 7.5 – Thickness of the arch relatively to the road pavement obtained from radargrams.

<table>
<thead>
<tr>
<th>Arches</th>
<th>Interface</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stone/air (ns)</td>
<td>40.0</td>
<td>41.8</td>
<td>41.4</td>
<td>41.0</td>
<td>38.3</td>
<td>39.6</td>
</tr>
<tr>
<td></td>
<td>Stone/air (cm)</td>
<td>172.0</td>
<td>179.7</td>
<td>178.0</td>
<td>176.3</td>
<td>164.7</td>
<td>170.3</td>
</tr>
<tr>
<td>Thickness</td>
<td>Infill/stone (ns)</td>
<td>28.5</td>
<td>27.0</td>
<td>25.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infill/stone (cm)</td>
<td>57.2</td>
<td>61.9</td>
<td>53.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Generally, a significant number of diffractions that correspond to steel tie-rods, plastic pipes and small drainage tunnels are observed in most radargrams, which an example is illustrated in Figure 7.117. Figure 7.117b presents a part of a radargram that correspond to the part of the bridge that is illustrated above, where a dozen diffractions can be observed. It must be noted that although only one radargram is presented when introducing a new feature, these features are also observed in most of the radargrams although without the same cleanliness. Generally, these diffractions are limited to the 10-20 ns band, which means that they correspond to features located at a depth around 4.3 and 8.6 m (considering a radiowave velocity of 8.6 cm/ns). In the sketch of the structure (Figure 7.117a), two horizontal lines at 4 and 6 m represent approximately those limits. The correspondence of the diffractions with the features indicated in the survey drawings was difficult due to the much larger number of hyperbolas relatively to drainage tunnels and steel tie-rods of data indicated by the survey drawings. Nevertheless, it seems that most of the drainage tunnels and steel tie rods were detected at this level. However, with the strong signal from the soil layer, it was impractical to reliably discern the diffractions coming from the steel elements.
Almost all diffractions are located at the same level of a soil layer that was created during the construction of the bridge or, at least, for the construction of these drainage tunnels. It seems also that some of these tunnels were not foreseen initially and were built later. Two examples of two drainage tunnels are illustrated in Figure 7.118.

Figure 7.117 – Detection of drainage tunnels and pipes. (a) Survey drawing and (b) radargram from profile 8 (250 MHz) showing diffractions that correspond essentially to drainage tunnels and pipes.

Figure 7.118 – Examples of regular and irregular drainage tunnels.

Strong diffractions can also be observed shortly after the starting point of the profiles, above the first pointed arch. These features are illustrated in Figure 7.119, where the plastic pipes for water evacuation were successively detected. From the radargram in Figure 7.119, the
location of these pipes was estimated between 49 and 64 cm below the road pavement surface. The accuracy of these measurements is rather poor but it must be noted that the 250 MHz antenna pulse is larger than these objects, which caused that wide interval for the location of the pipes. However, in reality, the distance between each of them was difficult to confirm due to difficulty to assess the pipe’s location.

![Radargram from profile 9 (250 MHz antenna) showing the location of the pipes](image)

The difficulty of detection was also increased by the fact that these pipes might not be embedded in the masonry but rather put into irregular holes surrounded by rubble material. Thus, the air gaps of these holes and the lack of constant contrast between dielectric properties might have also influenced the pipes detection. Also, these diffractions were only observed in the profiles closer from the sides of the bridge and that the profiles from the
middle did not show such signals. It must be noted that these pipes are made of plastic, thus, they were added recently. Then, it can be concluded that they do not span over the entire width of the bridge but only penetrate some length.

Finally, Figure 7.120 shows the profile 9 acquired with the antenna of 500 MHz, which shows several events related with the original construction and later works. In particular, it shows soil layers in the interior of the structure that might correspond to the different phases of the construction. It presents also the location of the abutments, which are clearly seen as a discontinuity of the upper layer. Marks of digging are observed in the case of the large abutment but also in the case of the construction of the circular arch, in the opposite extremity of the bridge. Figure 7.121 illustrates a closer look into the upper soil layer of the area around the circular arch, showing clearly the traces of digging. Apparently, this arch was probably built for flood drainage after the construction of the bridge.

Figure 7.120 – Radargram from profile 9 acquired with the 500 MHz antenna showing soil layers.
7.7.2. Summary

GPR investigation employing low to medium frequency antennas was carried out in a 19th century masonry bridge. The detection of the geometry was limited to the determination of the thickness of the stones of the arches, which was succeeded with good accuracy if those stones present the same dimensions obtained from the exterior. It detected also the presence of some of the drainpipes (new and original) that exist under the pavement and most of the drainage channels that exist along the bridge. The low velocity of propagation of radiowaves confirmed the presence of an important amount of moisture within the whole structure.

Different layers of soil were also evidence here, which served for the construction of drainage tunnels and probably during the placement of iron tie-rods. Although the drainage channels were well evidenced in most radargrams, the steel tie-rods signature was much difficult to discern due to the rather large amount of clutter.

It was also found that the circular arch located in one of the extremities of the bridge was most probably built after the bridge was finished, which means that arch was opened due to a particular goal, such as flood drainage or even railway passage.
8. Conclusions (Part II)

The present research work addressed the inspection and diagnosis of ancient structures using Ground Penetrating Radar (GPR). GPR was used extensively in several applications in stone and brick masonry to verify its efficiency in assessing structural integrity and mapping internal features and heterogeneities in old structures and laboratory specimens. Measurements in laboratory were carried out in three masonry specimens that simulated ancient structures, namely, two three-leaf stone masonry walls in the laboratory of the Department of Civil Engineering of the University of Minho and one complex stone and brick masonry in the Federal Institute for Materials Research and Testing (BAM), in Germany. Other measurements were carried out in four different monuments: Pisece Castle in Slovenia (13th century), Altes Museum in Germany (19th century), Church of the Monastery of Jerónimos (16th century) and the Boutaca’s bridge (19th century), both in Portugal.

It was concluded that GPR is a robust tool to assess the relative homogeneity of masonry elements using simple 2D profiles and to detect the presence of foreign elements inside masonry elements using more advanced 3D volumes and transmission measurements. Both high and low frequency antennas were used. Generally, antennas were chosen on site, taking into account the dimension of the elements and the probable depth and nature of the targets.

It has been observed that the presence of individual and isolated strong diffractions indicates the presence of single and small elements such as tunnels, pipes, joints and embedded elements (steel, wood, etc.). However, the presence of significant areas covered by a large amount of diffractions seemed to indicate the presence of deteriorated or heterogeneous material, characterized by cracks, voids, detachments or broken material. Long signals parallel to the acquisition surface correspond to joints, detachments or cracks in masonry.

Additionally, GPR detected rather well metallic elements as well as elements that exhibited distinct dielectric properties from the material around, which happened in the case of wood element embedded in masonry. The same did not happen in the case of void simulated through polystyrene element though. The shape of the interface revealed to be very important as it conditioned the correct reception of the reflected wave signals in the case of the cylindrical voids (constituted by polystyrene cylinders embedded in the wall) inside the masonry wall Obelix.

Furthermore, 3D volumes were used to provide the end-user with more realistic shapes of the targets and their real position. This technique provided rather good results in detecting solid
elements inside masonry rubble. However, in the case of steel bars, the 3D reconstruction resulted in elements with larger dimensions. This situation happens when the resolution of the antenna is not high enough to accurately map small objects and caused the migration algorithm to overestimate the diameter of those objects.

Finally, tomography was used to retrieve information from thin layers of brick masonry applied in a deteriorated stone masonry column and in mapping embedded objects in three-leaf masonry walls. In the first case, the results showed a deteriorated infill that corresponds to the original and deteriorated masonry material. However, no information was obtained from the thin masonry layers. In the second case, the targeted objects were mapped as areas of high velocity (or low attenuation). The tomography carried out in both walls resulted in satisfactory results, and both polystyrene prism and wood beam were located. However, this methodology was limited by the significant number of artefacts that appeared in the final results that masked partially the targets of the investigation, especially in the case of the wood beam. These areas do not exhibit the true shape of the objects but rather a round shape, which value are around 20 % larger than the real cross-section of the targeted elements.

8.1. Suggestions for future developments

The use of Ground Penetrating Radar in ancient structures is still rare, which is mainly due to the difficulty with the interpretation of the results and with the scepticism and doubts of the engineering community. Additionally, this technique requires civil engineers more time to train and acquire the necessary knowledge to use this technique. The potentialities and limitations of this technique and its advanced methodologies have been demonstrated here.

Ancient structures are characterised by a significant number of problems that GPR can detect, and some of them were described in this research work. Additional parameters such as moisture and salt content are very important to detect and quantify due to the frequent occurrence of such situations on ancient structures and their influence in the durability and strength of materials.

Because GPR gathers continuous information about structures, radargrams taken from the same position during several times in the year can provide a valuable indication of the deterioration processes, the formation of voids/cracks and the evolution of the moisture during long periods of time. Frequent inspections can provide the engineer with a tool to evaluate and trace the evolution of particular structures/elements or the application of a particular repair or strengthening measure.
Moreover, there is an urgent need to establish correlations between GPR data and data from other commonly used NDT and MDT. Establishing correlations with destructive techniques, used for the assessment of mechanical data, is also of great significance. It is important to verify how appropriate would be using Ground Penetrating Radar as a general detection tool in association with other NDT or MDT as local tools, such as coring, drilling, etc. Additionally, the need to use the results from radar data in numerical models for integrity assessment of the structure is important.

Furthermore, the need to increase the reliability of the information and to employ more frequently advanced techniques makes essential the development of more accurate and sophisticated indoor positioning systems, for use with advanced techniques such as 3D and tomography, and more efficient software algorithms. Additionally, the increase of antenna’s resolution and the efficiency of software reconstruction algorithms will allow to provide more accurately the shape and position of objects.
References (Part II)


Part II – NDT in masonry using Ground Penetrating Radar


Hülsenbeck, & Co. (1926). German patent 489 434.


