

Forestry applications of ground-penetrating radar

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Abstract

Ground-penetrating radar (GPR) is a geophysical and close-range remote sensing technique based on the use of radar pulses to obtain cross-section images of underground features. This method is characterized by the transmission of an electromagnetic short length pulse (1-2 ns), presenting a centre frequency ranging from 10 MHz to 2.5 GHz. The principles of GPR operation are based on the ability of low frequency radar waves to penetrate into a non-conductive medium, usually subsoil, but also walls, concrete or wood. Those waves are detected after suffering a reflection in electromagnetic discontinuities of the propagation medium. Therefore, this is a suitable method to study changes in those physical properties, and also to characterize different mediums and the reflective targets providing information about their physical properties. The aim of this work is to describe and demonstrate different applications of GPR in forestry, showing the obtained results together with their interpretation. Firstly, in this paper, it is illustrated how GPR is able to map shallow bedrock, subsoil stratigraphy and also to estimate shallow watertable depth. Secondly, different tree trunks as well as dry timber are analyzed, evaluating the different radar data obtained in each particular case, and observing differences in their electromagnetic properties related to the GPR response. Finally, several measurements were taken in order to analyze the use of GPR to detect tree root systems using polarimetric techniques, being possible to detect medium and big size roots, together with groups of small roots.

Key words: GPR, remote sensing, bedrock, watertable, trunk, root system.

Resumen

Aplicaciones forestales del radar de subsuelo

El geo-radar o radar de subsuelo (GPR), es una técnica de teledetección cercana que puede emplearse como herramienta de prospección geofísica y que se fundamenta en la emisión de un pulso electromagnético de muy corta duración (1-20 ns) caracterizado por una frecuencia central que puede variar entre los 10 MHz y los 2,5 GHz, en función de la antena seleccionada. Tras su emisión mediante una antena transmisora, las ondas de radar experimentan reflexiones en las discontinuidades electromagnéticas existentes en el medio por el que se propagan, siendo detectadas por una segunda antena receptora. El análisis de las reflexiones puede utilizarse para caracterizar tanto el medio de propagación como los reflectores, por lo que resulta un método adecuado para el estudio de determinadas propiedades físicas. El objetivo principal de este trabajo es mostrar diferentes aplicaciones del GPR en el ámbito forestal. Para ello se exponen los fundamentos básicos del método y su aplicabilidad como herramienta versátil en el ámbito forestal, así como posibles resultados que se pueden obtener en casos concretos. Como primera aplicación se presentan dos ejemplos que ilustran la capacidad de este método para detectar sustratos rocosos a poca profundidad, para analizar la estratigrafía superficial de un suelo y para localizar el nivel freático. Como segunda aplicación se analizan troncos de árboles sanos y también madera seca, analizando los datos obtenidos y mostrando que es un método que podría llegar a utilizarse para determinar las diferencias existentes en sus propiedades electromagnéticas. Como tercera aplicación se evalúa la utilización del GPR para detectar raíces en el subsuelo, habiendo sido posible determinar la posición de raíces de tamaño medio o grande, así como los grupos de pequeñas raíces.

Palabras clave: radar de subsuelo, teledetección, manto rocoso, nivel freático, troncos, raíces.

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Introduction

Ground-based radar, also known as ground-penetrating radar (GPR), is a remote sensing and geophysical prospecting method based on the emission of very short time domain electromagnetic pulses (1-20 ns) in the lower frequency radar bands (ranging from 25 MHz to 2.5 GHz). It has been used by various groups all over the world since the 1970's. This is when the first references of mining and geological applications of short pulse radar with sensors in-situ appeared (Annan and Davis, 1976; Rubin and Fowler, 1977). The GPR principles of operation are based on the ability of radio waves and micro waves to penetrate into the subsoil, from the first few centimetres to several metres deep, depending on signal frequency and electromagnetic properties of the medium. Those waves are detected after suffering a reflection in the electromagnetic discontinuities of the propagation medium. The characteristics of the received signal depend on the electromagnetic properties of the materials, which depend on the type of matter of the medium and its physical properties (mainly water content and porosity).

Later, in the 1980's, GPR began to be used for shallow investigations, in low attenuating media, using 500 MHz to 1 GHz centre frequency antennas, which give a submetre resolution (Ulriksen, 1982). In the 90's, GPR was increasingly used to perform analysis of constructive materials like pavements or concrete (Saarenketo and Roimela 1998, Spagnolini and Rampa, 1999; Olhoeft, 2000). These authors demonstrated the capability of the GPR technology to determine layers and voids in pavements, and reinforcements and internal cracks in concrete. Also, during the last ten years, it has become possible to find the first applications of GPR in agriculture and forestry studies. Hruska *et al.* (1999) used it to study the three-dimensional distribution of root systems of large oak trees. The results were acceptable in homogeneous soils, but the authors doubt the applicability in more complex environments, and no iso-surfaces of 3D images were obtained from GPR data. Yoder *et al.* (2001) mapped agricultural fields identifying areas with high potential for subsurface offsite movement of agrochemicals. The results were associated to water content in the soil and lateral flow of water and obtained from an integrated evaluation using GPR and Electromagnetic Induction. Cermak *et al.* (2000) studied maple tree root systems growing in clay soil in both shaded and non-shaded sites in an urban environment; GPR was only used to determine

the maximum root depth and was not verified by root excavation. Butnor *et al.* (2001) expanded the aforementioned work of Hruska *et al.* examining the ability of GPR to outline roots under a range of soil conditions and trying to estimate root diameter, concluding that GPR did not appear useful for mapping roots over diverse terrain. Also, the authors conclude that the greatest impediment to mapping complete root systems is that tight clusters of roots give one large parabolic reflection. Wielopolski *et al.* (2002) proposed a non-invasive imaging procedure for examining roots in-situ with a 1.5 GHz centre frequency antenna. Butnor *et al.* (2003) studied the utility of GPR to measure tree root biomass in situ with the aid of digital signal processing, obtaining the root biomass to a depth of 30 cm. Barton and Montagu (2004) estimated root diameters under optimal conditions by using radar pulses, and Niltawach *et al.* (2004) studied the adverse effects of buried biomass on radar systems and radargrams. In this evaluation, mathematical models using cylinders were developed in order to compare the numerical results to the field data obtained under controlled conditions. The authors conclude that the distribution of roots introduce clutter in the data. This fact introduces high false-alarm rates. Cox (2005) investigated the utility of GPR to characterise reflector signals from peach root fragments. Stover *et al.* (2007) who used GPR to quantify coarse root biomass from an open-top chamber experiment in a scrub-oak ecosystem. A 1.5 GHz antenna was used to detect large and coarse roots. As a result, the authors established correlations between GPR data and root biomass, finding an important relation between the root biomass and the reflected energy. The last reference we have found is attributable to Butnor *et al.* (2009), who test GPR to non-destructively estimate decay volumes in living coniferous trees.

In this article, some forestry applications of GPR are disclosed. We present some selected examples showing the capability of in-situ sensors to map shallow bedrock, subsoil stratigraphy and, in some cases, to estimate water table depth. In this study, we also present examples that illustrate the possible differences that could be obtained in various types of wood. Different tree trunks were analysed in order to determine the possibilities of making a diagnosis of living trees. Owing to the natural origin of (solid) wood, its electromagnetic properties have a high level of variability. Electromagnetic properties of dry timber, in some particular cases, are also estimated. The measurements taken during this study allow us to detect considerable

variations in wave velocity. Finally, the results of several measurements, which have been performed to show the ability of using two antennas of 900 MHz and 1 GHz to detect tree root systems by applying radar polarimetry techniques using GPR sensors, are presented. Our purpose was not to perform a full validation of the potential applications and accuracy of GPR in forestry but to describe and provide some illustrative examples of how GPR can be useful for estimating different types of variables.

Principles and method

Ground penetrating radar

GPR is a geophysical survey methodology based on the transmission to the medium and a later reception of an electromagnetic wave. This wave is travelling in the medium and reflections occur in boundaries between zones characterised by different electromagnetic parameters. A complete description of this methodology can be found in Daniels (2004). Data are acquired along profiles, and the results are 2D sections of the medium where the x-axis is the distance on the surface and the y-distance is the two-way travel time. This time could be converted into depth using the wave velocity. In these sections, the reflected waves are recorded as changes on the wave amplitude. These recorded anomalies could be associated to different targets embedded in the medium or to changes in the physical parameters of the medium. This survey is usually applied to shallow-surface prospecting (*e.g.*, Daniels, 2004; Pérez-Gracia *et al.*, 2009a) due to the quick radar data acquisition and the accurate results. 3D radar images and iso-surfaces of the inner medium could be also obtained by interpolating the 2D radar diagrams obtained in the profiles (*e.g.*, Novo, 2009). In this case, the amplitude of the reflected wave is used to create a map of the sub-surface features at a given depth. At the present, GPR is commonly applied in studies related to shallow geology (*e.g.*, Neal *et al.*, 2002), civil engineering (*e.g.*, Lorenzo *et al.*, 2001) or archaeology (*e.g.*, Goodman *et al.*, 1995).

The GPR antennas are broad-band antennas, characterised by its centre frequency. The bandwidth is in the order of the centre frequency. Resolution (the capacity to detect two close targets as two different anomalies) depends on many factors: the most important are the antenna frequency, the electromagnetic parameters of the surrounding medium, and the properties of the

targets (shape, size, electromagnetic properties). In the same conditions, higher frequencies provide better resolution. Penetration depth and capacity to detect targets also depends on the same factors, but in this case, the lower the frequency, the higher the penetration depth. Also, the possibility to detect deeper targets is greater in the case of higher contrast between their medium's and the surrounding medium's electromagnetic properties.

Theoretical background

A typical short time domain GPR pulse waveform is about $1\frac{1}{2}$ or 2 periods of the central frequency that characterises the antenna. As the time pulse width Δt decreases, the frequency bandwidth Δf increases ($\Delta t = 1/\Delta f$). Most commercial GPR antennas are designed to achieve bandwidths that are similar to the central frequency and thus the pulse period is inversely proportional to the centre frequency. Figure 1 shows the waveform and spectrum of the pulse of a 900 MHz centre frequency antenna used in this work. GPR data are normally displayed with antenna position along the horizontal axis and two-way travel time (*twt*) on the vertical axis.

If the velocity (v) in the propagation medium is known, the vertical axis can be converted to depth (z)

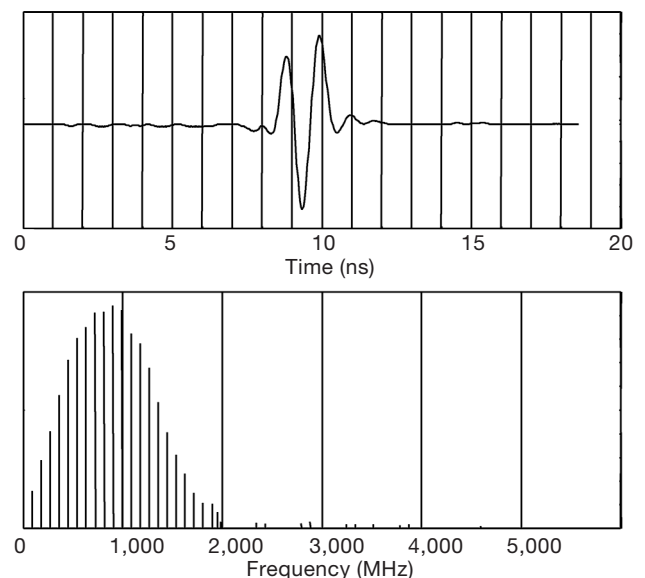


Figure 1. Pulse waveform and spectrum of the 900 MHz centre frequency antenna used during tree trunk analysis and mapping tree root systems.

through the simple relation $z = v \cdot twt/2$. The velocity can be obtained from the following equation:

$$v = \frac{1}{\sqrt{\frac{\mu\epsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} + 1 \right)}} \quad [1]$$

where ϵ is the permittivity of the material, σ is its conductivity, μ is its magnetic permeability and ω is the angular central frequency of the emitted pulse. In low conductive materials, where $\sigma \ll \omega\epsilon$, velocity can be approximated by:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad [2]$$

where c is the propagation velocity of the electromagnetic waves in free space and ϵ_r is the relative permittivity of the material. In common materials, velocity varies between 0.3 cm/ns (air) and 0.03 cm/ns (fresh water).

Velocity [Eq. 1 and Eq. 2] is mainly associated with the relative permittivity of the material. High values of wave velocity indicate low permittivities and low velocities are related to high permittivities. The water content and the porosity of the studied material could be gauged from this parameter. In the presented preliminary evaluations, the relative permittivities obtained studying stone pines (in Barcelona, Spain) are close to seven, and those obtained from the measurements in dry wood are close to three; these results illustrate the possible existence of a significantly large difference between the two types of wood. The values of the velocity are obtained by using two methods of analysis: the application of two-way travel time (time delay from emission until detection of the reflected signal) by using a known thickness test material, and the analysis of the amplitude obtained from the reflected wave.

The antenna produces a short pulse that is transmitted into the ground, waiting to detect the energy reflected from discontinuities or interfaces present in the subsoil. By moving the antenna, a cross-section of the reflections is obtained; this image is usually known as a radargram. The technique is similar to sonar or reflection seismic techniques, but uses electromagnetic waves, and, in some cases, users like to show radargrams with the same aspect as seismic profiles (wiggle plot format).

Part of the energy is reflected back to the antenna, and part is transmitted to the new medium when the emitted pulse detects an electromagnetic discontinuity

(for example, a change in the properties of the propagation medium or a new layer of material). The reflected energy on the interface of two media depends on the contrast between their impedances (η) through the reflection coefficient (r), which can be expressed by the following equation, assuming normal incidence:

$$r = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} \quad [3]$$

being the reflected power $R = r^2$. This expression admits a simplification in the case of low conductive materials, as in [2], having r as a function of the contrast between relative permittivities of the materials

$$r = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \quad [4]$$

Two factors are necessary in order to detect an anomalous target embedded in the medium: (1) enough electromagnetic contrast between the medium and the target [Eq. 4], and (2) a low-loss medium. In low-loss media, the attenuation of the energy is lower, and penetration depth is higher than in other kind of media. These low-loss media, where $\sigma \ll \omega\epsilon$, are those most suitable to be investigated with GPR.

Equipment and experimental settings

Radar data were obtained with a commercial GPR radar SIR-10 from Geophysical Survey Systems Inc. (GSSI) (trunks and roots) and RAMAC from Mala Geosciences (water table and geological applications), by using a common offset device. The shielded antennas used in these preliminary evaluations were characterised by nominal centre frequencies of 200 MHz, 500 MHz, 800 MHz and 1 GHz. Resolution and penetration depth of high frequency antennas are experimentally described by Rial (2007), Pérez-Gracia *et al.* (2008) and Pérez Gracia *et al.* (2009a) and Rial *et al.* (2009a,b,c). The experimental results seem to indicate that, in the case of the higher frequencies, it is possible to discriminate shallow close targets embedded in the medium separated horizontally between $0.6 \lambda - 0.8 \lambda$. Vertical resolution was found between 0.5λ and λ . Notwithstanding, resolution depends on the antenna frequency and on the medium electromagnetic properties, mainly the conductivity and dielectric permittivity. These two parameters depend on different physical properties of the medium: minerals of chemical composition, water content and porosity. Subsequently, the size of the

targets to be clearly detected with GPR is directly associated to the surrounding medium characteristics. This fact implies the necessity to evaluate experimentally the possible applicability of the methodology in each different case.

The preliminary evaluations presented in this paper are related to three different aspects: (1) detection of shallow geological features that could affect the forestry evaluations, (2) application of GPR measurements to determine physical properties of trees and timber, and (3) evaluation of the use of GPR data to analyze roots.

The geological evaluation was carried out in Galicia (Spain), in two different sites. The first site was characterised by a sandy soil and limestone outcrops in various points of this zone. The wave velocity in the sandy soil was estimated to be about 10 cm/ns. The second zone was a coastal sandy area near Vigo. In these applications, we used the 500 MHz and 200 MHz centre frequency shielded antennas with a time window of 40 ns and 100 ns, respectively.

The application of GPR to evaluate properties of trees and timber was carried out in the geophysical laboratory of the Polytechnic University of Catalonia, in Barcelona. In these preliminary evaluations, we used two different type of ornamental trees in Pedralbes (Barcelona): silver wattle (*Acacia dealbata*) and stone pine (*Pinus pinea*), and maritime pine (*Pinus pinaster*). Fifty silver wattles were evaluated with GPR. These trees were planted on the campus of the Technical University of Catalonia, in the internal streets. The five stone pine specimens evaluated were planted in the Torre Girona gardens.

The 900 MHz and 1 GHz shielded antennas were used to obtain data in two different ways: with dynamic measurements (moving the antenna along the trunk or the timber) and static measurements. The antenna and a metallic sheet were placed on the opposite surfaces of the medium (tree trunk or timber). Data were acquired with a 12-ns time window, with 1 scan per 2 centimetres in the dynamic measures. This sampling allowed us to obtain sufficient scrutinising details of the medium. In the static measurements, data were obtained with five scans per second, during two minutes. These measures gave more than 600 scans at the same point, providing an accurate estimation of the average value of the two way travel time of the wave.

The 900 MHz and 1 GHz centre frequencies shielded antennas were used in the application to evaluate the roots, applying an 18-ns time window. This application was done in a grid near isolated trees. The aim was to

determine the zone affected by the roots and to observe the possible effects of the antenna polarisation in the radar images. In all cases, data were acquired using 1 scan per 2 centimetres, and the distance between profiles was 20 cm.

Experimental measurements and results

Some selected examples of forestry applications of GPR are shown in this section. Firstly, we present two cross-section images illustrating that in-situ sensors are able to map shallow bedrock, subsoil stratigraphy and the water table. Secondly, an analysis of the differences between various types of wood (different tree trunks as well as dry timber) is carried out, based on the variation in their reflection coefficients. Finally, several measurements are taken in order to study the application of GPR in mapping tree root systems.

Shallow subsoil cross-section images

Bedrock mapping

GPR can provide information about the depth to the bedrock, useful in some agricultural and forestry studies. As an example of bedrock detection, Figure 2 is a cross-section image of the detection of bedrock using a 500 MHz centre frequency antenna. The radargram is shown in both wiggle plot and line scan formats. The reflections detected are due to the electromagnetic contrast between relative permittivities of limestone rock (between 6-8) and the layer of sedi-

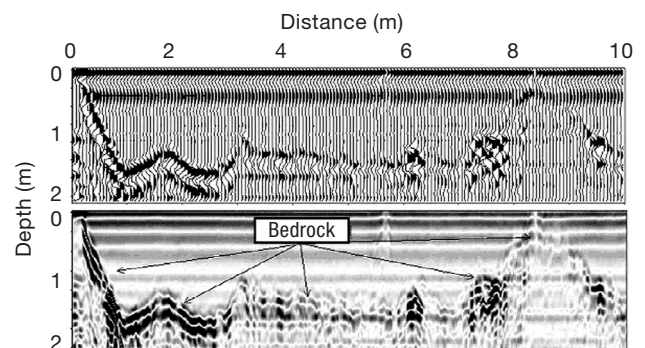


Figure 2. Wiggle plot (up) and line scan format (down) of a 10 m long radargram detecting bedrock under a layer of sediments. Time window: 40 ns.

ments over it (mainly dry sandy soil, 3-5). The maximum depth to the bedrock is about 2 m, but the depth to this layer presents important lateral changes along the GPR profile. A previous visual inspection indicated two outcrop zones of this rock layer (at the beginning of the profile and near the point 8 m). In this type of soil, with a 500 MHz antenna, the maximum penetration depth expected is between three and four metres. Other antennas (200 MHz and 100 MHz) could supply penetrating depth of about 10 and 15 metres, respectively.

The profile is 10 m long and two-way travel time of 300 ns was selected. Of the 512 samples, the most interesting data were in the first 70 samples, equivalent to 40 ns (this is the time window shown). Accepting a typical velocity of 15 cm/ns for dry sandy soil, the estimation of maximum bedrock depth detected is at about 2 m. It can also be seen how the depth of bedrock varies along the profile, especially at the start and in metre 8.5, where rock was visible on the surface. Velocities and results are similar to those obtained by other authors that compared GPR results with boreholes and other different measurements (*e.g.*, Pérez-Gracia *et al.*, 2009; Gerber *et al.*, 2007; Pérez-Gracia, 2001).

Subsoil stratigraphy and water table depth

Another useful application is the detection of the water table and the estimation of the depth to this layer. GPR could provide helpful information, as Figure 3 denotes. This figure shows a 50 m long cross-section

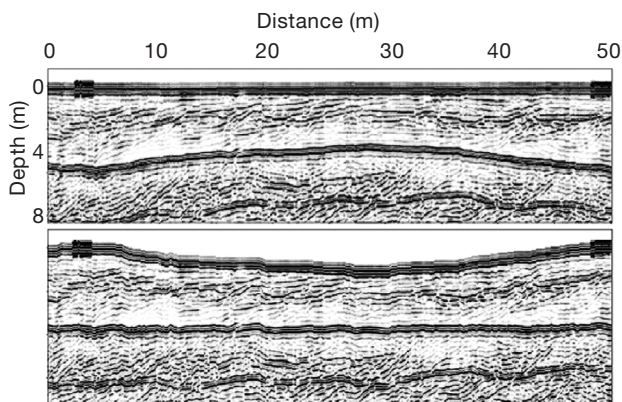


Figure 3. Radargram before (up) and after (down) apply topographic correction. It shows sand progradation (1-3 m depth), watertable (5 m depth) and bedrock (7.5 m depth) in a coastal beach environment. The 50 m long cross-section was acquired with a 200 MHz antenna.

image of shallow subsoil, vertically corrected to allow for surface elevation effects, reaching a depth of 9 m. The profile was acquired with a 200 MHz antenna near the coast of Galicia. As in the last figure, bedrock is seen, but now at a deeper depth of 7-8 m. The flat reflector at 5 m depth corresponds to the fresh water table, which is one of the most interesting applications of GPR for hydrological studies. Reflections can also be seen in the first few metres due to sand depositional effects, which appear to be pro-gradated layers.

GPR is being widely used in combination with drilled boreholes (*e.g.*, Pérez-Gracia *et al.*, 2009b). The information gathered by means of these boreholes is used to estimate the velocity of electromagnetic waves in the medium, showing the relationship between reflections in the radargram with the materials in the stratigraphic column extracted. Knowing depth z of a particular target, the antenna is moved close to the borehole drilled to take a reflection from that target at a particular twt . Hence, it is easy to estimate the velocity of waves in the medium using $v = 2z/twt$. Radar is usually used to extend the information of core drills along profiles over the surface (*e.g.*, Costas *et al.*, 2006; De Menezes Travassos and Menezes, 2004), reducing drilling, which is an expensive and destructive technique.

Wood analysis

GPR is used in different media to determine changes in the electromagnetic parameters of these media (*e.g.*, Lambot *et al.*, 2004). These changes are caused by variations in materials, in humidity and also variations of physical properties, such as the porosity. Application of GPR to evaluate water content in soils provides suitable results (*e.g.*, Saarenketo, 1998; Topp, 2003; Grote *et al.*, 2003). As GPR is non-destructive in its application, it could well be a suitable means of obtaining living-tree characteristics and information about the health of those trees.

Several measurements were taken in order to illustrate the capability of GPR to study living trees, detecting internal reflectors caused by humidity, damages or diseases. These parameters can be obtained from the study of the anomalies recorded in radar data and from the differences in the wave velocity. Measurements were recorded in silver wattles and stone pines. The expected results are constant reflections obtained while the antenna is moving along the trunk because of the

healthy aspect of the trees. Velocities are measured in every studied case so as to compare the results and to determine the usual parameters of a healthy tree.

Living tree trunks

Measurements were performed in Barcelona (Spain), and they were used to analyse different silver wattle and stone pine specimens. The 1 GHz and the 900 MHz antennas were used in this study because of their high resolution and compatibility to the size of the studied objects (Pérez-Gracia, 2001). The 900 MHz antenna provides satisfactory radar records, even though no quantitative data could be determined, whereas the 1 GHz antenna provides more obscure records, possibly due to its low transmitter output (Pérez-Gracia, 2001).

The procedure used in all cases was to develop profiles by moving the antennas along the trunk. A marker wheel was coupled to the antennas in order to obtain the exact position of each anomaly of the radar data. Figure 4 shows the procedure of the radar data acquisition during the study of the silver wattles. Radar profiles were 120 cm long and the time range of the radar data acquisition was 12 ns. In the case of the specimen shown in Figure 4, the diameter of the trunk was 58 cm at the beginning of the profile and 56 cm at the end of the profile. In the radar data presented in Figure 4, it

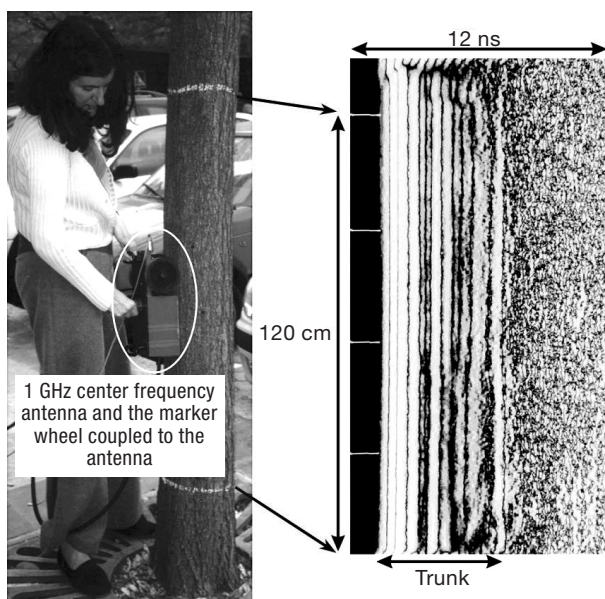


Figure 4. Radar data acquisition with 1 GHz antenna, and the radargram obtained.

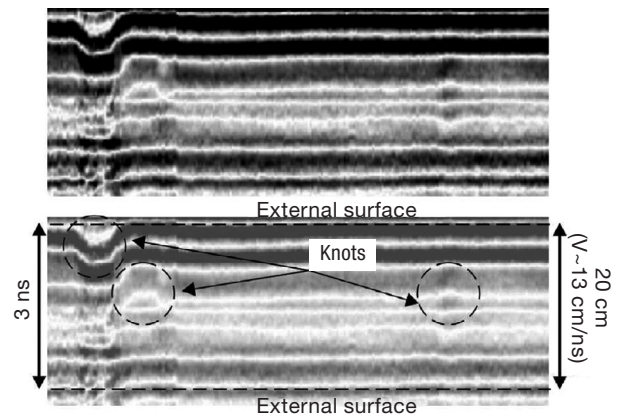


Figure 5. Detection of knots in radar data acquired with a 1 GHz antenna.

is possible to observe that no knots or anomalous zones are detected. The visual inspection allows for determining that this tree presents good external conditions in the surveyed zone. Two main anomalies indicate the external surface of the tree. These reflections, clearly detected, allow us to estimate the average wave velocity. Other internal anomalies are probably related to the separation between the bark and the heart wood. These anomalies are continuous along the whole profile. Most likely, the continuity of the internal reflections could be related to the healthy condition of the tree trunk. Figure 5 shows data obtained in a *sophora japonica* tree trunk, where anomalies could be associated to knots that are detected as irregular anomalies and changes in the wave amplitude.

Another example of the GPR application in trees is shown in Figure 6, where it is possible to observe the radar data acquisition procedure during the study of the stone pine tree and a segment of the radargram obtained during the study with a 1 GHz centre frequency antenna. In this analysis, only two weak internal reflections were obtained together with the clearly detected front and back surface reflections.

As in the case of the *sophora japonica* trees, these anomalies could be associated to the inner discontinuities between the bark and the internal trunk. Reflections are most likely associated to the differences in the water content between these two different parts of the tree.

Velocity analysis

The wave velocity was obtained from the two-way travel time (*twt*) measured on the radargrams and

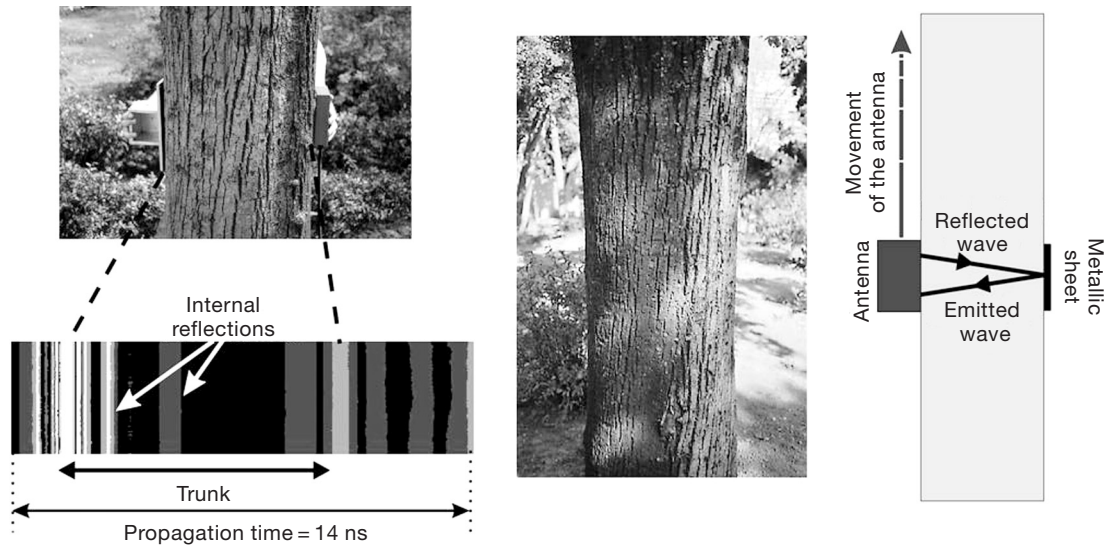


Figure 6. Stone pine trunks studied, radar data acquisition procedure and radargram obtained in a trunk.

bearing in mind the diameter (z) of the studied trunk by using the known equation $v = 2z/twt$. Velocity allows us to estimate the relative permittivity of those trunks by using Equation [2]; considering that the trunks are of low-conductive materials. Also, velocity was estimated from the amplitude reflection on the trunk surface. The obtained reflections were compared with those taken from a metallic surface. The antenna was placed at the same distance from both surfaces. Considering both these surfaces to be non-conductive media, the reflection coefficient could be expressed as a function of the relative permittivities of the interface media (air and trunk). Using the assumption of $r = 1$ in the metallic surface, r being the reflection coefficient of Equation [4], the relative dielectric permittivity ϵ_r of the trunk can be obtained from the amplitude of the compared waves

$$\epsilon_r = \left(\frac{1 + A_0 / A_t}{1 - A_0 / A_t} \right)^2 \quad [5]$$

where A_0 is the amplitude of the wave reflected on the metallic surface and A_t the amplitude of the wave reflected on the trunk (air $\epsilon_r = 1$).

Both methods were analysed using different materials. The dispersion of the velocity and permittivity values was greater by using [5] than with the first method. Then, values obtained in the first case were considered to be more accurate results (Pérez-Gracia, 2001; Pérez-Gracia *et al.*, 2001). Velocity obtained was 13.5 ± 0.8 cm/ns using the first evaluation (and 13 ± 2 cm/ns using the second one) in silver wattle trees, and

the average dielectric permittivity calculated from this velocity was about 5. The velocity in the stone pines was 11.3 ± 1 cm/ns and its average relative dielectric permittivity was about 7. Therefore, these preliminary results seem to indicate that different values of velocity, or permittivity, could be associated to different tree types.

Dry timber

Measurements of the velocity were also carried out by using dry timber, so as to compare the results of that parameter with the values obtained during the study of living trees. Methods are quite similar to the procedures used in the study of living trees. Five samples of dry maritime pine wood were used in the test. Velocities obtained were between 21.2 cm/ns and 18.6 cm/ns, which correspond to the relative permittivities of about 2 and 2.6. It is important to note that, when the medium is that of a high velocity, small changes in its characteristics could produce significant changes in the wave velocity. Comparing the results obtained in dry timber with those in living trees, the preliminary measurements presented in this paper seem to indicate that the difference in the wave velocity or in the relative permittivity in living trees and in timber could be significant. Lower velocities correspond to living trees, while higher velocities are associated with timber. The significant influence of the water content upon the wave velocity is one of the causes of the detected differences.



Figure 7. Preparation of the grid of profiles near an isolated tree.

Root systems

Several measurements were also performed in order to analyse the capability of the radar survey to detect roots. Preliminary results of that analysis are presented in this paper. Two antennas were used in the study: 1 GHz and 900 MHz centre frequency antennas. They were selected because of the required resolution.

A grid of profiles near an isolated small silver wattle was designed; Figure 7 shows this grid, in which the distance between profiles is 20 cm. Radar data were acquired using two different polarisation arrays for the transmitter and receiver antennas.

The 900 MHz dipoles were both fixed in a plastic box and it was not possible to make cross polarisation surveys. The 1 GHz antenna is just one dipole that is used to transmit and receive the pulse. As in Annan *et al.* (2002), XX denotes that the transmitter and receiver dipoles are both aligned in the antennas movement direction, and YY that the dipole axes are aligned orthogonal to it.

900 MHz antenna

Roots are usually detected as hyperbolic records due the radiation pattern of the antenna. Parallel profiles permit us to follow the roots into the subsoil. Figure 8 shows radar data obtained on three parallel profiles using a YY configuration, showing reflections on approximately the first half-metre of subsoil where medium to small size roots were evident. In the radar data shown in Figure 8, roots were detected as small hyperbolas, and two small groups of superficial roots

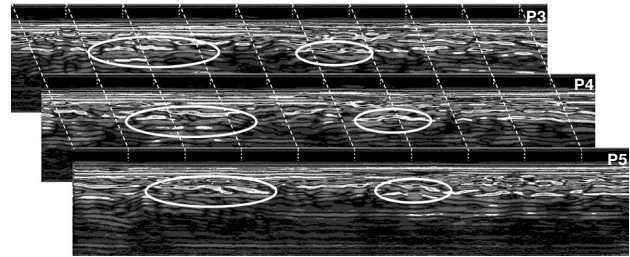


Figure 8. Two groups of superficial roots are indicated in these three parallel cross-sections images. These groups are deeper in profile P3 than in profile P5. Time window is 18 ns. Studied distance: 340 cm.

are pointed out. Notwithstanding, radar data interpretation is difficult due to the complexity of the root system and the small size of many of these anomalous targets. The processed data, using an inverse distance interpolation, allowed us to determine the zone of the ground affected by the roots of the tree. Figure 9 shows the slice obtained at a depth of about 16 cm, where the single roots are not detected, but groups of roots and zones of the ground disturbed by the roots are clearly determined.

In Figure 9, it is possible to observe the area of the ground affected by the roots at a given depth. Radar data in Figure 8 allow us to observe that root depth is variable and appears to be deeper in profile P3 (the

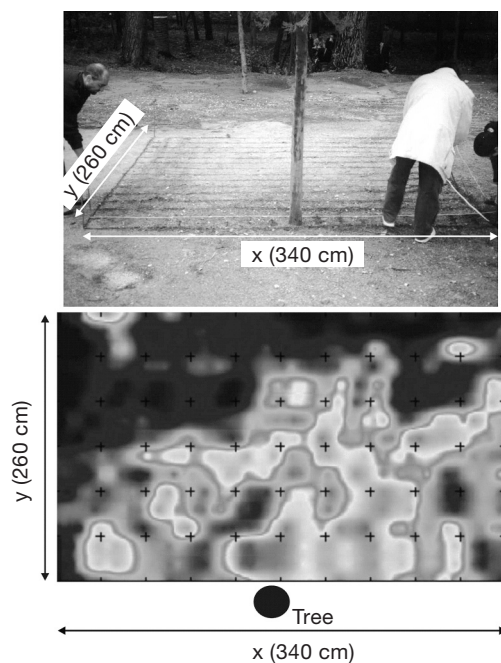


Figure 9. 1-2 ns Slice obtained using an inverse distance interpolation between all the parallel profiles. Radar data obtained with a YY configuration.

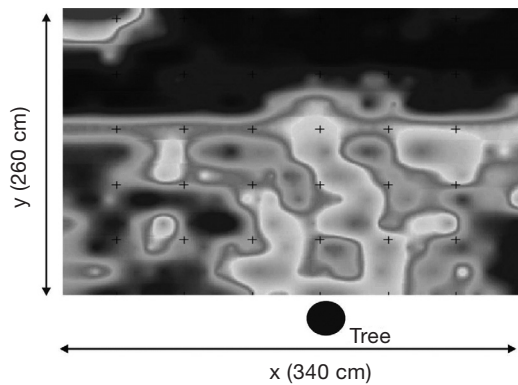


Figure 10. 1-2 ns Slice obtained using an inverse distance interpolation between all the parallel profiles. Radar data obtained with a XX configuration and a 900 MHz antenna.

furthest profile taken from the tree) than in profile P5. Profile P5 is the nearest of the three profiles shown. Depths could be calculated by obtaining the wave velocity in the medium. Several measurements performed near this area indicate that velocity is approximately 10.5 cm/ns. This velocity is according to the shape of the recorded hyperbolas. Using this velocity, roots in the marked areas are between 12 and 35 cm deep.

YY profiles acquired with the 900 MHz antenna enabled us to detect shallow anomalies corresponding with tree roots. Figure 10 shows a time slice obtained in the same place as Figure 9 and at the same depth, with a 900 MHz antenna but with an XX configuration. Both configurations provide information about the situation of the groups of roots, but high resolution is obtained in the case of a YY configuration, providing a most complete map of the altered soil due to the roots.

1 GHz antenna

Measurements performed by using the 1 GHz centre frequency antenna are of poor quality compared with the radargrams obtained with the 900 MHz centre frequency antenna, as can be observed in Figure 11. Both the 900 MHz and 1 GHz antennas were manufactured by the same company, but the 1 GHz is designed for construction/structures inspection. An absorbent medium, such as soil, produces a great attenuation on the pulse energy of this particular antenna, reducing the penetration of the survey and making target detection difficult. Only the most superficial targets could be detected with this high frequency antenna. Also, noise caused mainly by the ground surface conditions (roughly surface and changes in materials and water content) distorted greatly the signal, producing complex and obscure records.

Discussion

In this work, some selected examples of in-situ radar sensors that can be used in forestry applications are shown. The principles of the technique are not very different to air-borne or space-borne radar remote sensing, but the results obtained appear as cross-section images of underground features and not as earth surface images. In-situ sensors can be used to obtain relevant information on shallow subsoil, for instance, or forestry purposes such as estimating bedrock depth, locating the water table or knowing more about shallow subsoil stratigraphy and soil type classification. Measurements taken from tree trunks indicate that GPR is a suitable

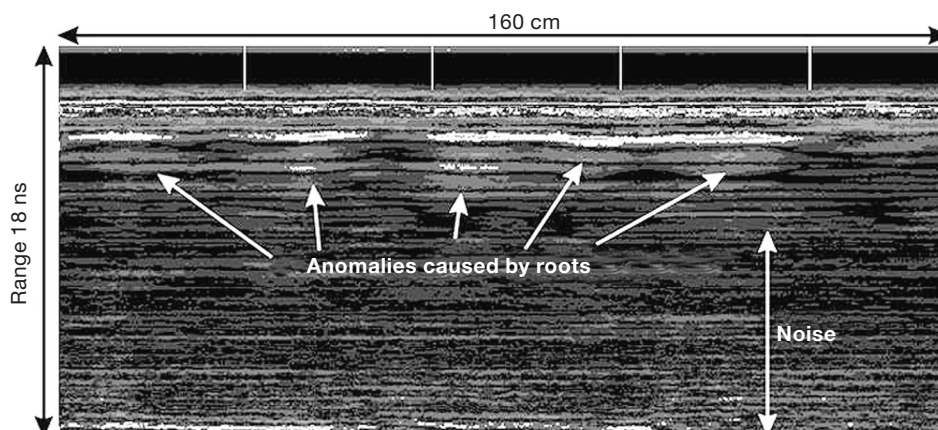


Figure 11. Segment of a characteristic radargram obtained with the 1 GHz centre frequency antenna. Anomalies produced by roots are detected in the shallow area of the profile.

tool for the study of the internal structure of trees, being a non-destructive and non-invasive technique that does not harm the tree in any way. Radargrams have continuity along the profiles performed along the trunk when the tree is healthy. Anomalous bodies in the trunks, like knots or density changes, cause discontinuities on the trunk radar cross-sections. Velocity is a parameter that allows characterising of the studied materials. Velocity values obtained are quite similar in the same tree species, although different tree species present small variations in the propagation velocity. The biggest variation was observed between living trees and dead wood. Velocity of waves in timber is rather high when compared to the velocity in living trees. This is probably caused by the variation in the water content of the studied media. Detection of roots using GPR is also possible. Preliminary results of several experimental measurements indicate the location of large and medium size roots and groups of roots. A grid of parallel profiles provides a method to follow the roots and to detect the subsoil areas where they are located. Measurements performed with a 900 MHz nominal frequency antenna, with transmitter and receiver dipole axes aligned orthogonal to the antennas movement direction, provided the best results in this preliminary study.

This method could provide useful information about the shallow geology (stratigraphy and water table), which is valuable in the case of reforestation. It could also be applicable to the determination of seasonal changes in the water content depth. Other useful applications could be the evaluation of the root biomass of trees. GPR images provide information about the ground affected by roots, which could be used to estimate this biomass. Many previous works related to root diameters or biomass evaluation were carried out in perfect environments (dry sand or laboratory conditions). The results presented in this paper seem to indicate that valuable results could be also obtained in real grounds. Furthermore, the rough conditions and the attenuation produced in these media might indicate that antennas with centre frequencies higher than 1 GHz could not be suitable in these evaluations. Notwithstanding, antennas with frequencies equal to or lower than 900 MHz seem to be appropriate, although the results presented in this paper are not accurate enough to determine the position of small roots. As in the previous works, the clutter introduced in the data, the possibility of non-detected roots and the impossibility of distinguishing roots from stones or other anomalous

targets existing in the medium, indicates, most likely, that the best way to obtain approximate data of the root biomass could be the evaluation using iso-surfaces. Notwithstanding, results do not delineate the roots, and the diameter of individual roots perhaps could be approximated, but only in the case of coarse roots. In spite of these limitations, the results shown in this paper indicate the capability of the GPR data to provide information about the roots extension. This information could be useful, per example, in the case of transplanting some trees. This is a common problem in cities, where centenary specimens must be moved to new emplacements due to urban changes. Consequently, a denser grid (separation between profiles about 5 cm instead of 20 cm) and higher density of scans per metre could improve the results, providing more information and showing small roots as isolated anomalies. With the grid and the sampling used in our preliminary evaluations, the information must be considered as qualitative information, and only an approximation of quantitative data could be inferred from GPR data. It must be considered that denser grids are time-consuming, and also that it is difficult to obtain accurate data in a forest or in places with irregular topography that could complicate the evaluation of the root biomass in many sites. All the previous evaluations of root biomass, as well as our measurements, were performed in isolated trees, and in many cases, under controlled conditions.

The results of the evaluations of specimens of trees seem to indicate that the wave velocity could be a characteristic of these specimens. However, these preliminary results are insufficient to indicate if this relation could be considered. It is possible that changes in the habitat of the trees (differences on the ground minerals, ground water content or types of rock or soil) introduce important changes in this parameter. For example, changes in water content introduce significant variations in the wave velocity, as could be inferred when comparing the results obtained in trees and in timber in this paper. In this way, a more detailed study should include many different specimens and a larger number of each in similar and dissimilar conditions. However, the preliminary results presented in this paper seem to indicate that the method can be potentially useful to determine the health of specimens and also to detect knots and anomalous zones in timber. Also, taking into account the differences in the radar data obtained in the case of dead wood and living trees, this survey could be useful to determine an approximation of the relation between the living and dead trees in a

forest. For this case, and in future works, the difficulty in acquiring data in forests and irregular topography, as discussed in the case of the detection of the root biomass, must be considered.

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