Application of Ground-Penetrating Radar for Living Trees Detection

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Abstract. In order to evaluate the potential hazards, researchers are working on revealing the inner structural of a living trunk using different diagnostic techniques. Nondestructive techniques (NDTs), such as stress wave method and ultrasonic wave method, have become increasingly convenient and economical in trees detection. To improve forest management and to prevent collapses of trees, it is necessary to investigate the internal part of tree trunks. In order to do it non-invasively, ground-penetrating radar (GPR) appears as a promising inspection device. Each of these NDTs has its pros and cons. Among all, the GPR is capable of multiple measurements with hardly any damage to the body of a tree, perfect for investigations on roots and trunks of living trees. 15 camphor trees are selected and subject to GPR testing for the study. The results of inductive method and GPR wave signals indicate that the GPR image shows “wavy” features when an eccentric void is found inside a tree, meaning that the travel time is the shortest for the return signals when the antenna is closest to the void. However, GPR wave signals appear to be discontinuous and fluctuate when there are irregular cavities. The signal time is defined by using the metal plate to generate strong reflection in the case of on-site monitoring. The internal condition of tree trunk is usually tested based on detecting 2D image of tree trunk by the stress wave method, as to confirm that the application of GPR is feasible to detect the trunk of camphor tree. The method proposed in this paper can realize the accurate localization and imaging distribution of the internal defects of the trees by the radar wave scanning images.

Keywords: Ground-Penetrating Radar (GPR); Nondestructive Testing (NDT); Living Trees Detection; Cinnamomum camphora.

1. Introduction
A type of nondestructive testing device, ground-penetrating radar, or GPR, is widely used in civil engineering studies and investigations, such as investigation of underground voids and study of buried structures like culverts. Nondestructive techniques (NDTs), such as stress wave method and ultrasonic wave method, have become increasingly convenient and economical in trees detection. Each of these NDTs has its pros and cons. Among all, the GPR is capable of multiple measurements with hardly any damage to the body of a tree, perfect for investigations on roots and trunks of living trees.

2. Literature Review
Wen et al. (2017) used GPR to test living tress. In theory, if there is a void or decay in a tree, it will reflect electromagnetic waves, showing the difference from healthy trees. The trunk of a tree consists of bark, sapwood and heartwood. 2D simulation yields 3 horizontal signals indicating the interface between bark and sapwood; Wen et al. (2017) used the radar produced by Tree Radar with an antenna frequency at 900 MHz to test willows indoors for various types of void, and obtained radar images.
The image is horizontal layered signals if the void is a concentric circle, whereas there are fluctuations if the void is irregular in shape. When measuring a living tree, the measurement is made with the GPR circling around the tree. Jana Ježová et al. (2016) explained the phenomenon with experiments and simulations on cylindrical targets. The antenna receiving time is the shortest when the GPR antenna is closest to the void, and the longest when the GPR antenna is the farthest from the void. Unlike the hyperbola usually obtained from the application of GPR on the ground, the features obtained are “wavy” curves. Numerical simulation is also used to determine voids and multiple paths in the cylindrical targets. Le et al. (2017) used a GPR produced by Tree Radar with antenna frequency at 900 MHz in a series of tests and produced results of void size vs. radar images in Pinus massoniana.

2.1 GPR Principles

GPR transmits and receives radar waves and detects anomalies as signals are generated due to the physical characteristics of different media. The physical characteristics of different media have profound influence on the results of GPR and their interpretations. Table 1 shows the dielectric constants, conductivities, and attenuations of different materials.

\[ \varepsilon_\gamma = \frac{\varepsilon}{\varepsilon_0} \]  

(1)

\( \varepsilon_\gamma \): dielectric constant or relative permittivity

\( \varepsilon \): permittivity, F/m

\( \varepsilon_0 \): permittivity of free space, 8.854*10^{-12} F/m

**Table 1.** The dielectric constants, conductivities, wave speed, and attenuations of common substances (from A.P. Anna, 2003).

| Substance          | Dielectric constant, \( \varepsilon_\gamma \) | Conductivity, \( \sigma \) (mS/m) | Wave speed, \( v \) (m/ns) | Attenuation (dB/m) |
|--------------------|-------------------------------------------|---------------------------------|--------------------------|-------------------|
| Air                | 1                                        | 0                               | 0.3                      | 0                 |
| Pure water         | 80                                       | 0.5                             | 0.033                    | 0.1               |
| Dry sand           | 3-5                                      | 0.001                           | 0.15                     | 0.01              |
| Water-saturated sand | 20-30                                 | 0.1-1                           | 0.06                     | 0.03-0.3          |
| Powdery soil       | 5-30                                     | 0-100                           | 0.07                     | 1-100             |
| Clay               | 5-40                                     | 2-1000                          | 0.06                     | 1-100             |

2.2 Estimating Wave Speed

The time that GPR transmits and receives is the two-way time, which is determined as follows:

\[ D = v \times T \]  

(2)

where

- \( D \): two-way distance, m
- \( v \): wave speed in the tested object, m/ns
- \( T \): two-way time, ns
Figure 1. Estimating wave speed in a tree.

Figure 1 shows that the distance that electromagnetic waves travel, $D$, is determined from the diameter of the tree ($D_{\text{diameter}}$) and half of the distance between antenna transmitter and receiver (14 cm in this case), as shown in equation (2) below:

$$v = \frac{2}{T} \sqrt{\frac{D_{\text{diameter}}^2 + \left(\frac{d_s}{2}\right)^2}{T}}$$  \hspace{1cm} (3)

where

$v$: speed of electromagnetic wave, m/ns

$D_{\text{diameter}}$: diameter of the tree, m

$d_s$: distance between the transmitter and receiver of antenna; 0.14 m for 800MHz

$T$: two-way time, ns

In general, GPR does not produce underground depth. Therefore, the speed is estimated by rearranging the expression of light speed vs. dielectric constant, as shown below:

$$v = \frac{C}{\sqrt{\varepsilon_{\gamma}}}$$  \hspace{1cm} (4)

where

$v$: wave speed, m/ns

$C$: light speed, $3 \times 10^8$ m/s

$\varepsilon_{\gamma}$: dielectric constant

The dielectric constant can be expressed by rearranging equation(4) as follows:

$$\varepsilon_{\gamma} = \left(\frac{C}{v}\right)^2$$  \hspace{1cm} (5)

3. Methodology and Materials

3.1. Instruments Used

The RAMAC/GPR produced by MALÅ GeoScience is used for the purpose of the study. The device consists of a full-cover antenna, ProEx unit, MALÅ XV logger, and distance measuring wheels, details of which are provided as follows; full-cover antenna: 800MHz antenna is selected for the study along with Mala CX Concrete Scanner 1.6GHz high-frequency antenna equipped with antenna interface module and optical fiber module connected to the ProEx unit. The full-cover antenna features
good shielding effect against noises. The transmitter and receiver of the antenna are 0.14m apart.

3.2. Analysis Program and Subject of Study
The analysis program REFLEXW V8.2.2, developed by K.J Sandmeier, is selected for the study for file reading and filtering. The data files are in mala.RD3 format and 2D numerical analysis is performed. MATLAB R2017a is used for image processing, where single A-scans in the files are captured and difference plots plotted to define the time at the tree side. Adobe Creative Cloud Photoshop CC 2017 is used for image conversion. The time into the tree and that out of the tree are known. The time of tree radius is defined as half of the time difference. The plots on Cartesian coordinates are converted to polar coordinates. A single species is selected for the study, which is camphor shown in Figure 2, also known as camphor wood or camphor laurel, and the scientific name is Cinnamomum camphora.

3.3. Confirming the Effectiveness of Metal Plate
The key to tree measurement is how to define the signals at the tree side. Literature reviews suggest a metal plate fixed on the other side of the tree produces stronger reflections and, therefore, better signals at the tree side. For indoor experiment, a section of log is selected for comparison between the presence and absence of metal plate on the back of the log. MATLAB is used to isolate the A-scans with metal plate from those without. By subtracting the signals without metal plate from those with metal plate, the difference plot is obtained, and from it the time corresponding to the highest peak is selected and defined as the time of substance interface, which is the interface time between tree and metal plate in the study as the basis for tree time determination. With a metal plate placed on the tree, the antenna is fixed at the same location to transmit and receive signals from that location just by rotating the measuring wheel. The metal plate generates strong reflection of signals. Figure 3 shows the different curve by subtracting the signals with metal plate (red) from those with metal plate (blue), and it determines that the time into the tree is 3.4664 nanoseconds; with the metal plate placed on the far side of the tree, the machine transmits signals and receives them from the same location in the same way. Figure 4 shows the different curve by subtracting the signals with metal plate (red) from those with metal plate (blue). Knowing that the time into the tree and out of the tree is approximately 6.185 nanoseconds, the diameter of the log is 21 cm and the transmitter and receiver of the antenna are 14 cm apart:

\[
\text{Equation (3) is used to estimate wave speed, } v = \frac{\sqrt{0.21^2 + (0.14 / 2)^2}}{6.185 - 3.4664}, \text{ which is 0.162848 m/ns;} \]

\[
\text{equation (5) is then used to estimate the dielectric constant, } \\
\varepsilon_r = \left(\frac{0.3}{0.162848}\right)^2, \text{ which is 3.393. According to Weilin Li et al. (2018), the dielectric constant ranges from 5 to 13 for typical living trees. On other hand, the dielectric constant of a log in lab is estimated lower than 5, which is to say, the inside of the indoor log is drier.}
\]
4. Outcomes and Discussions
The park in National Chiang Kai Shek Memorial Hall was selected for the living trees detection. Samples were selected at the site encircled in the red rectangles in Figure 5. To minimize factors of influence, such as physical structure, a single species, camphor tree, was selected for testing, and 15 living camphor trees were selected as the samples. Several samples representative of the study are presented herein. For the antenna settings, the sampling points were 512 points with the sampling frequency at 15 times and distance interval at 0.01 m. The number of iterations was set at AUTO in order to reduce signal errors.
The configuration was to measure 3 sets of data at the same cross section around the trunk of every tree. The set with better presentation of images was used for image processing. The post-processing flow is shown in Figure 6. The bandpass butterworth filter was used to define the high and low thresholds to keep the frequency bands in between. For the 800M Hz antenna used for the study, the high and lower thresholds were set at twice and 1/3 of antenna frequency, which are 1.6GHz and 266MHz, respectively; in other words, signals at frequencies lower than 266MHz and those higher than 1.6 GHz were removed and those in between were kept. Background removal was used to eliminate consistent noises and better data signals were produced. For the 1.6 GHz antenna, the high and low thresholds were set at twice and 1/3 of antenna frequency, which are 3.2GHz and 533MHz, respectively, to remove signals with frequencies beyond the two and keep those in between. Finally, background removal was used to eliminate consistent noises. It is worth noticing that the increasing number of filtering often leads to distortion. For the purpose of this study, the number of filtering was limited. The GPR results were compared and discussed based on the stress wave method provided by Taiwan Forestry Research Institute, Council of Agriculture, Executive Yuan. 4 of the 15 samples are presented below.

4.1. Case 1: tree no. Ac-008-021
Figure 7 shows the tree no. Ac-008-021. The 800 MHz antenna was used to measure in north, east, south and west in that order. It is clear that there was no distinct plant growth on the bark.
The filtered results are provided in Figure 8. The red lines were the signals into the tree, the fluctuations indicated that the bark was not even and it was difficult for the antenna to stay tightly against on the bark. According to literature review, there should be tree boundaries of signal in a healthy tree, namely between air and bark, bark and sapwood, and sapwood and heartwood; the signals from No. Ac-008-021 were mostly horizontal layered signals and, therefore, it is safe to say this is a healthy tree.

The images were converted into polar coordinates, as shown in Figure 9 (B), since it is rather difficult to read the signals directly from radar images; 2D images of inside of tree trunk were generated by the stress wave method, as shown in Figure 9 (A), and indicated that the tree Ac-008-21 is relatively healthy inside despite slight rots on the west-side bark. The interpretation of the radar images corresponded to the 2D images from the stress wave method, suggesting the tree is healthy.

4.2. Case 2: tree no. Bb-008-039

Figure 10 shows tree no. Bb-008-039. 800 MHz and 1.6 GHz antennas were used for the measurement from north, east, south and west in that order. On the east side, there was plant growth on the bark.
Figure 10. Tree no. Bb-008-039.

Figure 11. Boundaries in no. Bb-008-039 and interpretation (red lines are the tree boundaries and yellow line is the signal of problem).

Figure 11 was obtained by filtering, the red lines indicating signals into the tree; the fluctuations were due to the not completely even bark and the antennas not being able to rest flat on the bark. Literature review suggested that the signals of a healthy tree in theory come in three types, the layered signals from air through bark, from bark through sapwood and from sapwood through heartwood. In tree no. Ac-008-039, signals became “wavy” at 7.5 ns, as indicated by the yellow line in Figure 11. According to literature review, this feature could be caused by an eccentric void; literature review suggested that this feature might come from an eccentric void; it is learned from the image that the signal time was the longest when the measuring line was at 0.5 m, i.e., the farthest from the void; whereas the time was the shortest with measuring line between 1.1 m and 1.2 m, meaning that the void was closest to the antenna. This information indicated that tree no. Ac-008-039 had a problem.

Figure 12 (A) is the radar image from the 1.6 GHz antenna after filtering. Clearly in the figure, the signals fluctuated as the surface of bark was not even. A signal suggesting a void occurred at 6-7 nanoseconds, the antenna was the farthest from the void at 0.4-0.5 m and the closest to the void at 0.8 m. It is clear in the figure that the signals into the tree were difficult to identify, because the resolution from high antenna frequency is better than that from low antenna frequency. However, the high-frequency signals attenuated rapidly and, therefore, the penetration was poor; the signals became vague after 9 nanoseconds.

Figure 12. Radar images of the same cross section in tree no. Bb-008-039 at different frequencies; (A) 1.6 GHz; and (B) 800 MHz.

The images were converted into polar coordinates, as shown in Figure 13 (B), since it is rather
difficult to read the signals directly from radar images; 2D images of inside of tree trunk were generated by the stress wave method, as shown in Figure 13 (A), and indicated that the tree Ac-008-39 showed signs of rotting inside on the northwestern side and, therefore, could be sick. The interpretation of the radar images corresponded to the 2D images from the stress wave method, suggesting the tree is sick.

![Figure 13](image)

**Figure 13.** 2D stress wave images and radar images of the same cross section on tree no. Bb-008-038: (A) 2D stress wave image (courtesy of Taiwan Forestry Research Institute), and (B) radar image.

### 4.3. Case 3: tree no. Bb-008-048

Figure 14 shows tree no. Bb-008-048. 800 MHz antenna was used for measurement from north, east, south and west in that order. There was no plant growth on the bark.

![Figure 14](image)

**Figure 14.** Tree no. Bb-008-048.

![Figure 15](image)

**Figure 15.** Boundaries in no. Bb-008-048 and interpretation (red lines are the tree boundaries).

The filtered results are provided in Figure 15. The red lines were the signals into the tree, the fluctuations indicated that the bark was not even and it was difficult for the antenna to rest flat against the bark. According to literature review, there should be tree boundaries of signal in a healthy tree, namely between air and bark, bark and sapwood, and sapwood and heartwood; the signals from No. Ac-008-048 were mostly horizontal layered signals and, therefore, it is safe to say this is a healthy tree.

The images were converted into polar coordinates, as shown in Figure 16 (B), since it is rather difficult to read the signals directly from radar images; 2D images of inside of tree trunk were generated by the stress wave method, as shown in Figure 16 (A), and indicated that the tree Bb-008-48...
is relatively healthy inside. The interpretation of the radar images corresponded to the 2D images from the stress wave method, suggesting the tree is healthy.

**Figure 16.** 2D stress wave images and radar images of the same cross section on tree no. Ac-008-038: (A) 2D stress wave image (courtesy of Taiwan Forestry Research Institute), and (B) radar image.

### 4.4. Case 4: no. 459

Figure 17 shows the tree no. 459. The 800 MHz antenna was used for measurement from north, west, south to east in the order. Apparently, there was a hole in the south on the trunk.

**Figure 17.** Tree no. 459.

The filtered results are provided in Figure 18. The red lines were the signals into the tree, the fluctuations indicated that the bark was not even and it was difficult for the antenna to rest flat against the bark. Figure 18 provides the information as whether the tree is healthy. According to literature review, there should be tree boundaries of signal in a healthy tree, namely between air and bark, bark and sapwood, and sapwood and heartwood; in Figure 18, the yellow lines were “wavy” signals that indicated a problem. The void at the east side at approximate 1.3 m to 1.4 m was the closest to the antenna. Therefore, it is obvious that this tree is sick.

The images were converted into polar coordinates, as shown in Figure 19 (B), since it is rather difficult to read the signals directly from radar images; 2D images of inside of tree trunk were generated by the stress wave method, as shown in Figure 19 (A), and indicated that there was a void at the center of tree no. 459 slight to the east. The interpretation of the radar images corresponded to the 2D images from the stress wave method, suggesting the tree is sick.

**Figure 18.** Boundaries in no. 459 and interpretation (red lines are the tree boundaries and yellow lines are the signals of problem).
Figure 19. 2D stress wave images and radar images of the same cross section on tree no. 459: (A) 2D stress wave image (courtesy of Taiwan Forestry Research Institute), and (B) radar image.

The speed was determined from the times into and out of the 15 trees using equation (3). Then, equation (5) and dielectric constant expression were used to determine individual dielectric constants. Table 2 provides the results of dielectric constant, speed and diameter. It is clear in the table that the dielectric constants of these 15 camphor trees ranged from 5.16 to 11.82, as opposed to the results of Weilin Li et al. (2018) ranging from 5 to 13 for typical living trees.

Table 2. Wave speed, dielectric constant and diameter of camphor tree samples.

| Tree no. | Time into the tree (ns) | Time out of the tree (ns) | Time difference (ns) | Dia. (cm) | Wave speed (m/ns) | Dielectric constant, εγ |
|----------|-------------------------|--------------------------|----------------------|-----------|------------------|------------------------|
| 008-038  | 3.794                   | 11.71                    | 7.916                | 45.5      | 0.11631          | 6.6529                 |
| 291      | 3.711                   | 11.22                    | 7.509                | 40.1      | 0.10842          | 7.6563                 |
| 008-026  | 3.959                   | 10.06                    | 6.101                | 36.28     | 0.12112          | 6.1345                 |
| 008-015  | 3.216                   | 13.94                    | 10.724               | 59.52     | 0.11177          | 7.2045                 |
| 008-010  | 3.381                   | 14.68                    | 11.299               | 66.2      | 0.11783          | 6.4821                 |
| 008-019  | 3.629                   | 13.53                    | 9.901                | 54.74     | 0.11148          | 7.2425                 |
| 008-021  | 3.876                   | 9.567                    | 5.691                | 27        | 0.09802          | 9.3666                 |
| 292      | 3.959                   | 9.567                    | 5.608                | 24.5      | 0.09087          | 10.8990                |
| 008-039  | 2.969                   | 12.45                    | 9.481                | 41.06     | 0.08787          | 11.6576                |
| 008-049  | 3.134                   | 14.1                     | 10.966               | 53.47     | 0.09835          | 9.3042                 |
| 008-048  | 3.216                   | 14.19                    | 10.974               | 58.25     | 0.10692          | 7.8722                 |
| 008-018  | 2.557                   | 13.11                    | 10.533               | 45.5      | 0.08725          | 11.8237                |
| 459      | 3.711                   | 12.21                    | 8.499                | 55.7      | 0.13211          | 5.1571                 |
| 008-013  | 3.051                   | 12.54                    | 9.489                | 55.07     | 0.11701          | 6.5740                 |
| 008-011  | 2.887                   | 9.402                    | 6.515                | 35.7      | 0.11168          | 7.2159                 |

5. Conclusions
GPR was used to test the trunks of 15 living camphor tree as the examples of this investigation. 2D images were produced using the stress wave method for reference to determine the feasibility of testing living camphor tree trunks using GPR. The diameters of the trunks were defined as the distance of radar wave transmission during the living trees detection to identify the location of the signals into the tree and find out the range of the times into and out of the tree. The signals obtained were considered the internal signals of the trees. The features of internal signal images were used for radar image interpretation.

When radar images show irregular bouncing or wavy patterns, the feature may indicate a void or defect in the trunk. When the trunk is healthy inside, the signal pattern is continuous horizontal signals
without distinct fluctuation or wavy pattern. The results of the 2D images from stress wave method and those from radar images are consistent. The compilation of investigation, radar images and analysis data lead to the following conclusions:

1. When there is eccentric rotting or void in the trunk of a living tree, the image pattern is wavy or fluctuating up and down; therefore, the radar image pattern is suitable for identifying the relative location of eccentric void.

2. When the trunk of a living tree is healthy, the primary image pattern is continuous horizontal signals.

3. The dielectric constants determined for the 15 camphor trees in the study ranged from 5 to 12, corresponding to existing literatures.

4. The comparison between the 1.6 GHz antenna and 800 MHz antenna used in the study reveals that the resolution of the former is better than that of the latter; however, the 1.6 GHz antenna provides inferior penetration.

5. For the application of GPR in living trees detection, the image signals as the result of radar produce wave patterns that are difficult to interpret. The conversion to polar coordinates will make the interpretation easier.

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